Rise and Fall of an Egyptian Oasis: Artesian Flow, Irrigation Soils, and Historical Agricultural Development in El-Deir, Kharga Depression, Western Desert of Egypt

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The present study examines the geoarchaeological history of an oasis in Kharga Depression in central Egypt. El-Deir is renowned for its Ptolemaic temple and Roman fortress on the road from former Hibis (Kharga) to the Nile Valley. During the survey, spring mounds and irrigation soils belonging to an ancient agricultural zone were discovered, and further documented by ceramics found on the site. Our methodology combines the geomorphological interpretation of landforms (especially yardangs) with ceramics and ^{14}C-dated charcoal to distinguish and date former agricultural areas in El-Deir. The results show that the oasis experienced several phases of soil accretion and destruction through time. Playa sediments were deposited in the humid early Holocene and severely eroded by deflation before the onset of irrigated agriculture between Pharaonic and Persian times. Very fast vertical soil accretion occurred in the Ptolemaic period, but irrigation soils were later destroyed during the Roman period by a combination of wind deflation and flash floods (second to fourth century A.D.), suggesting a period of climate instability. The case of El-Deir invites reevaluation of constructive agencies for the development of irrigated land and destructive agencies as limiting factors for the sustainability of agricultural practices in late antiquity. © 2016 Wiley Periodicals, Inc.

INTRODUCTION

Recent studies have demonstrated the influence of early Holocene hydroclimatic changes on the human occupation of the Western Desert of Egypt (Haynes, 2001; Hoelzmann et al., 2001; Bubenzer, Hilgers, & Riemer, 2007; Kindermann & Bubenzer, 2007; Kröpelin & Kuper, 2007). In the area of northern Africa presently covered by deserts, current arid climate conditions progressively developed (deMenocal, 2011), making the forms and densities of human occupation dependent upon the availability of nonmeteoric water and allowing either mobile pastoralism or denser settlement in relict oases (Brooks et al., 2005). Occupation of ecological refuges and episodic transhumant settlements occurred *ca.* 5600–5400 B.C. (Wendorf & Schild, 2001) during the so-called "regionalization phase" identified by Kuper (Kuper, 2005; Kuper & Kröpelin, 2006). Herding practiced by both nomadic pastoralists and sedentary groups living in oases (Hassan, 2002) progressively gave way to agriculture *ca.* 5000 B.C. (Hassan, 1986). Such climate-induced changes in livelihoods seem to have had major political consequences (Brooks, 2006). In the Nile Valley and possibly in the oases of the Western Desert, agricultural development was foundational for Dynastic Egypt (Midant-Reynes, 2006). In central and southern Syria, studies have documented various types of pre-Roman hydraulic systems, which increased productivity in food production

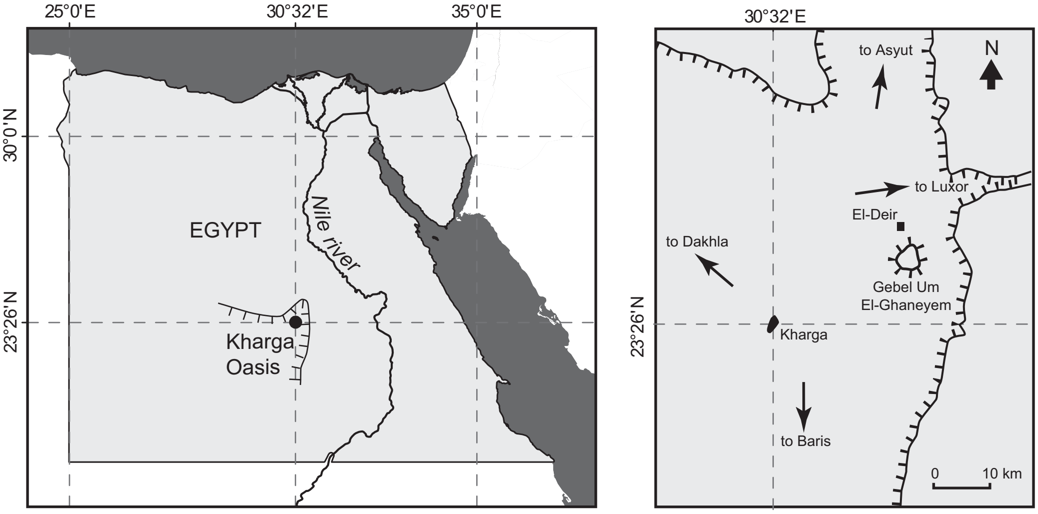

Figure 1 Location map of El-Deir, Kharga Depression.

(Braemer et al., 2010). In the southern Fezzan of North Africa, the development of the Garamantian civilization is arguably predicated on similar climate-ecological processes (Wilson & Mattingly, 2003; Cremaschi & Zerboni, 2009).

Although no detailed studies or testimony exist for the inception of agriculture in the Kharga Depression (Figure 1) before Pharaonic times, Pharaonic (Giddy, 1987) and classical sources attest to the lushness and fertility of the western oases of Egypt: Herodotus, Strabo, and Olympiodorus celebrated the abundance and quality of oasian wine, fruit, wheat, barley, and millet. Such was the agricultural wealth of some large estates in the oases that some oasian products were traded into the Nile Valley, as both ceramological and papyrological sources attest (Tallet, Gradel, & Letellier-Willemin, 2012). Agricultural development in the oases was a consequence of intense colonization efforts over a period of a least a millennium (Darnell & Darnell, 2013). Colonization led to the erection of remarkable buildings and fuelled the area's growing demography: in Kharga, elaborate temples (e.g., the temple of Hibis), strong fortresses (e.g., El-Deir), and large towns such as Hibis or Kysis (Dush) are telling archaeological evidence for the past wealth and population density of the oases in the Kharga Depression.

In Kharga and other desert depressions, the availability of fresh underground water from the Nubian Aquifer enabled populations to adapt to and even thrive under intensifying desert conditions. Technological and organizational features enabled past societies to tap into the water resources necessary for agricultural development in a desert environment. After the pioneering geological and archaeological work of Ball (1900), Beadnell (1909), and Caton-Thompson and Gardner (1932) that sought to explain the powerful artesianism observable in Kharga and identified "underground irrigation tunnels" or *qanats* (Beadnell, 1909) in the northernmost area of the depression, the archaeology of irrigation in Kharga was not further explored before the late 1980s, under the direction of Hassan (2002).

Following the discoveries made in Dakhla under the auspices of the Dakhla Oasis Project (Youssef, 2012), a large system of *qanats* was identified and studied at Dush, south of the Kharga Depression (Bousquet & Reddé, 1994; Bousquet, 1996; Bousquet & Robin, 1999; Reddé, 1999). Ceramics found at nearby Ayn Manâwir confirmed that the *qanats* were built in the Persian period (*ca.* sixth to fifth century B.C.) (Wuttmann et al., 1996, 1998) and yielded information on the distribution of *qanat* water between 480 and 380 B.C. (Chauveau, 1998, 2001, 2005). Few water-related documents have been found in the oasis for the subsequent Ptolemaic period. For the late Roman period, the wealth of written documents and archaeological evidence found at Kysis (Dush) and north of the Kharga Depression suggests that Roman rule induced a vast expansion of irrigated agricultural land (Schacht, 2003).

The discovery of *qanats* and discontinuous documentation have opened up a whole slew of new questions pertaining to the chronology and the forms of agricultural development and irrigation in late antiquity in the depression of Kharga and more generally, on the fringes of Sahara (Sterry et al., 2011). Bousquet (1996) offered an interpretative model to account for the expansion and retraction of irrigated land in Dush. Before the Persian conquest, farmed land was irrigated from the spring mounds that naturally brought artesian water to the surface. The progressive dwindling of this fossil resource was addressed by the introduction of *qanats*, which tapped into water tables perched on slope sediments and increased surface-water availability. The expansion of irrigation in Roman times was predicated upon a massive deepening of the existing *qanats* and the boring of wells into Nubian sandstone outcrops (restoring former artesian springs or digging into nonartesian aquifers). Such a technological fix to water scarcity was however severely limited by the very low, if not inexistent, replenishment of water tables and could not be sustainable in the long term, opening the way for a drastic reduction of irrigated areas at the end of the Roman period.

Although stimulating, Bousquet's model for Dush is spatially and technologically specific and cannot be readily generalized over a broad area. In this paper, we provide a detailed account of El-Deir Oasis (Figure 1) in the larger Kharga Depression (Embabi, 2004).[1] Set at the foot of the Eastern Plateau, El-Deir was a strategic entry point into the Kharga Depression for it controlled two tracks of considerable commercial and military importance joining the oasis and the Nile Valley: the Rufuf and Nabq Sigawal (Tallet, Gradel, & Guédon, 2012). Despite extensive archaeological study, no *qanats* have yet been found and it is unlikely that any exist.

This paper seeks to illuminate the chronology and features of historical agricultural development in El-Deir Oasis. Crucially, it focuses on irrigation soil formation and destruction rather than on water provision *stricto sensu*. Data from high-resolution satellite imagery have been supplemented by a detailed field survey of irrigation soils and canals, flood deposits, evidence of deflation, and archaeological structures—some of which have been dated by AMS ^{14}C. Geomorphic features and human artifacts were positioned using geographic positioning system (GPS) and mapped into a geographic information system (GIS), providing a time series of oasis expansion and contraction in historical times.

Our results suggest that in late Holocene and historical times, the oasis of El-Deir experienced several phases of agricultural land expansion and erosion. Such phases are indicative of changing equilibria between accretive agencies (water derived from spring mounds and soil production) on the one hand and depletive agencies (wind deflation and flash floods) on the other. The El-Deir model suggests that change is not entirely predicated on human action and is suggestive of climate pulsations in historical times that need to be further explored and documented.

STUDY AREA

Geological Setting and Artesianism

El-Deir Oasis is located on the western rim of the plateau standing between the Nile Valley to the east and Kharga Depression to the west (Figure 2). The upper part of the rim is composed of two thick levels of limestone (the Eocene Al-Rufuf Formation culminating at 360 m above sea level and the lower Late Paleocene Tarawan Formation) separated by thick layers of Esna Shale (Embabi, 1967). A north–south oriented fault zone with some compression folds separates those eastern units of the rim from the western piedmont units made of thick Late Cretaceous Quseir "Purple Shale." Sapping and runoff originating from the plateau rim during Quaternary wet periods have shaped large Quaternary pediments of decreasing altitude, covered by thick sheets of gravel. Generally speaking, since the Late Quaternary, runoff has been scarce and limited to the wettest periods of the Holocene and intense events occurring in limited areas.

The floor of El-Deir Oasis, standing below a series of pediments formed into the Quseir Purple Shale, is a heritage of the Pleistocene. Pleistocene runoff was probably continuous from the eastern escarpment down to the Kharga Depression floor, as suggested by the continuity of braided outwash. Large shale outcrops were prone to weathering and deflation during dry phases. In historical time, the eastern escarpment and in particular Um El-Ghaneyem Butte could generate runoff, but Holocene deposition and erosion were local processes compared to large-scale Pleistocene dynamics. On the occasion of rare contemporary storm downpours, water flows from the eastern plateau down into the valley heads, forming an incision into the scarp that decreases downstream.

Modern rainfall in Kharga Depression averages 5 mm per year (Egyptian Meteorological Authority, 1996). Underground aquifers have provided much of the water for human settlements in the Kharga Depression since the middle Holocene. Investigations of the hydrogeology of the area started in the early 20th century (Ball, 1900; Beadnell, 1909) and the continuity of the Nubian Sandstone Aquifer between Sudan, Chad, and Egypt was established in 1925 (Ball, 1927). Geological investigations helped explain the origin of the many artesian springs found in the depression (locally known as *Ayn*).

Kharga Depression springs provided permanent but decreasing flow during the Holocene because the deep aquifers have not been refilled by monsoonal rains since

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[1] For reasons of consistency and clarity, we follow Embabi's (2004) distinction between "Kharga Depression" (as a topographic and structural megaform) and the "oases" (watered spots within the depression). El-Deir is an oasis in the Kharga Depression.

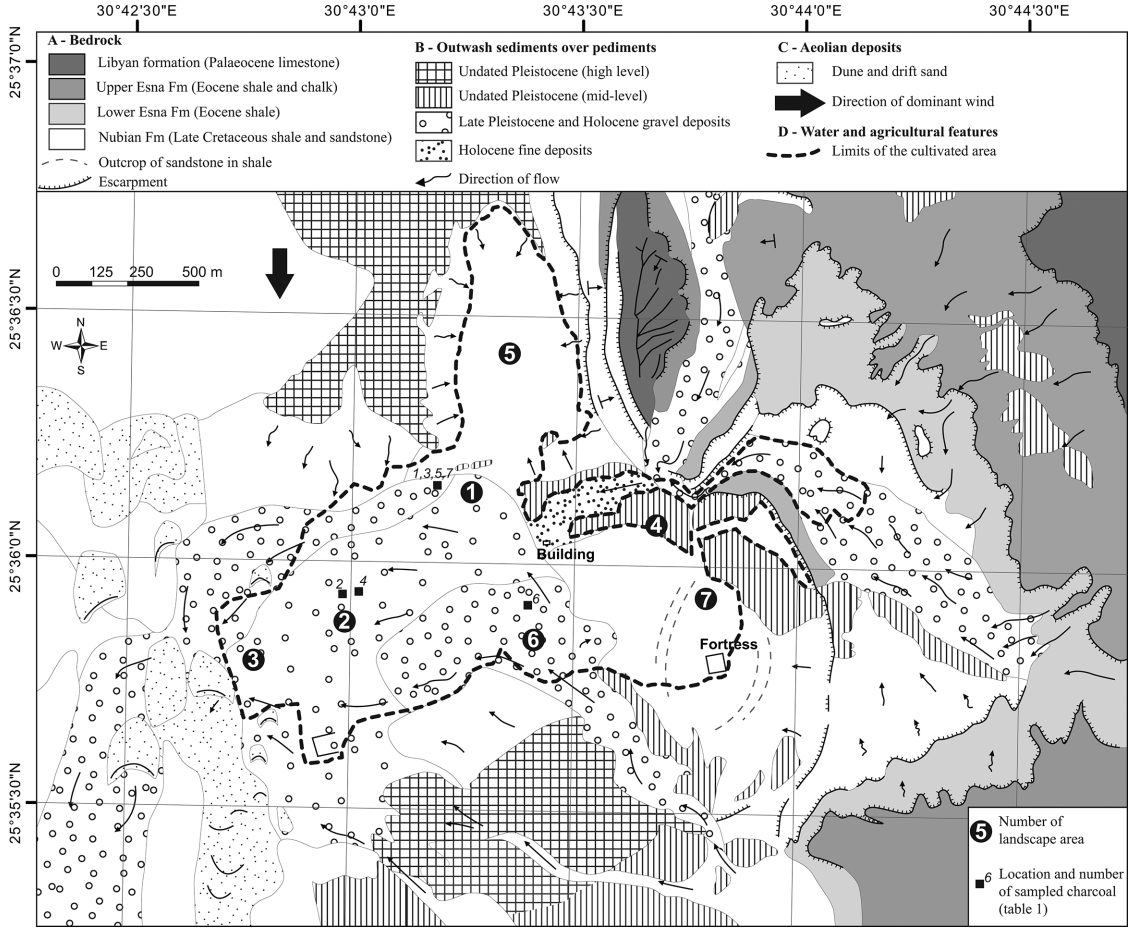

Figure 2 Geomorphological sketch map of El-Deir area.

the end of the humid Holocene. Locally, wells—known as *Bir*—were dug to reactivate declining spring mound flow when artesian pressure decreased (Beadnell, 1933; Bousquet, 1996) or tap directly into the aquifers. Some natural springs were still active in the early 20th century but intensive irrigation and deeper pumping after the onset of British rule in the area (1882) led to the gradual depletion of most remaining natural springs. However, at the archaeological site of El-Deir, artesian springs were so strong that they delivered enough underground water to allow natural runoff and irrigation into the 19th and 20th centuries, after minimal reactivation (Schweinfurth, 1875; Beadnell, 1909). Geological faults facilitated vertical integration between the deep, 120-m-thick "artesian-water sandstone" and the 45-m-thick "surface-water sandstone" separated by the 75-m-thick "impermeable gray shales." These layers belong to the Nubian series, dated Campanian (Upper Cretaceous) (Beadnell, 1909, 1933). In El-Deir Oasis, the surface-water sandstone is protected by the impermeable purple shales eroded by runoff and deflation.

Irrigation Soils and the Origin of Yardangs

Continuing artesian spring flow throughout the Holocene has had major impacts on oasian landscape formation. Artesian flow provided the necessary moisture for sedimentary deposition at the bottom of Kharga Depression and in various other places, including in El-Deir Oasis. Sedimentary deposits have been wind-sculpted into yardangs, most notably at the bottom of the Kharga Depression. Beadnell, who first described them, thought they were of lacustrine origin (1909). Upon later examination the yardangs were believed to be composed of loess-like deposits, Pleistocene spring overflow, and historic well deposits (or "dredging mounds") consisting of well cleanings (Caton-Thompson & Gardner, 1932: 383).

The broad category of "well deposits" also includes "irrigation soils" identified by Haynes (1983) and Brookes (1989) and defined as "anthropogenic irrigation sediment" (Brookes, 1990). Their origin is to be found in the deposition of wind-blown particles and silt-rich sediment

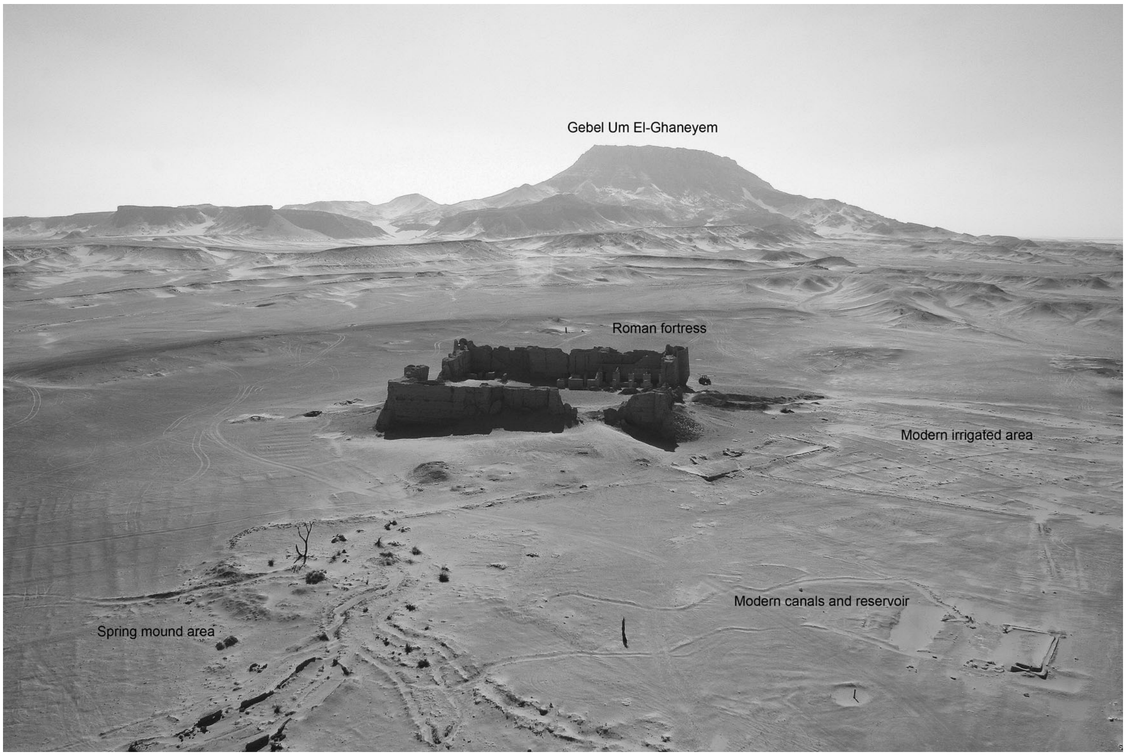

Figure 3 Oblique aerial photograph of part of El-Deir area. Dead palm trees and dunes help locate spring mounds and wells in the foreground. The Roman fortress and Um El-Ghaneyem butte are in the background. View from the northeast (photo courtesy by B.-N. Chagny).

on irrigated areas. Most of rolled and drifted wind-blown particles were trapped by vegetation and locally moist areas (Adelsberger & Smith, 2010; Haynes, 1983 cited by Brookes, 1989). Such soils, most notable in the southern part of Kharga Depression, cover large areas. When exposed to drier conditions (linked to the dwindling of irrigation water), irrigation soils become loose and are easily deflated and sculpted by the wind into yardangs that constitute a precious source of information on past agricultural sites.

METHODS

This paper is based on an interdisciplinary collaboration between geomorphologists, historians, archaeologists, ceramic specialists, and historical geographers. Investigations on the past environment of the Kharga Depression started in 2008 as part of the OASIS Project funded by the French *Agence Nationale pour la Recherche*. El-Deir Oasis was selected because the project could build upon the work of Françoise Dunand's team who explored the site's five necropolises beginning in 1998 (Dunand & Lichtenberg, 2008; Dunand, Heim, & Lichtenberg, 2010, 2012). Dunand's team also conducted archaeological research on the Ptolemaic-Roman temple and the late third century A.D. fortress pictured in Figure 3 (Brones & Duvette, 2007). The site was occupied from the Saito-Persian period (Dunand, Heim, & Lichtenberg, 2012; Tallet, 2014) to the Byzantine period (Dunand, Coudert, & Letellier-Willemin, 2008; Coudert, 2012). The long period of occupation at El-Deir and its excellent state of preservation from modern encroachments qualified it to be an outstanding geoarchaeological laboratory of land change during the historical period (Tallet, Garcier, & Bravard, 2011; Tallet et al., 2013; Garcier & Bravard, 2014).

Large expanses of former fields and their stone-lined boundaries are still clearly visible at El-Deir, with remains of irrigation canals and vessels used for watering the land. Large amounts of ceramic potsherds are spread upon the site, sometimes grouped into clusters. Combined with AMS ^{14}C dating of charcoal and geomorphological interpretation of landforms, potsherd assemblages have been used as a tool for dating site use. This approach is useful to engage with the complex dynamics of an irrigated landscape that lacks persistent water infrastructure (such as *qanats*) and where very little textual or archaeological documentation exists.

Table I Radiocarbon ages.

Sample Number	Sample Reference	Sampling Date	Coordinates	^{14}C yr BP	Cal. yr BP (2 σ; 95.4 %)
1	ED2010/301/11/811.Yardang UCIAM76667/ULA-1624	2010	25°35′879N 30°43′332E	8010 ± 25	7056–6827 B.C.
2	Deir Ch 24- Top of Sand Mound UGAMS-1124/ULA-3179	2012		2810 ± 25	1026–900 B.C.
3	Yardang, top of unit II UGAMS-11244/ULA-3180	2012	25°35′879N 30°43′332E	2210 ± 25	369–202 B.C.
4	Deir Cha P5. Irrigation canal, W Sand Mound CEDAD-LTL13096A	2012	25° 35′923N, 30° 43′012E	2138 ± 40	260–40 B.C.
5	ED2010/301/1/811.Yardang UCIAM76668/ULA-1625	2010	25°35′879N 30°43′332E	2130 ± 15	338–97 B.C.
6	Deir Cha P2. Buried soil Poz-56029	2013		1850 ± 30	A.D. 85–235
7	ED2010/301/5/805.Yardang, canal filling UCIAM76668/ULA-1623	2010	25°35′879N 30°43′332E	1770 ± 15	A.D. 222–334

The following calibration curves were used: ULA, intcal09.14c (Reimer et al., 2009); CEDAD, OxCal Ver. 3.5 (Reimer et al., 2009); Poznan (Poz), OxCal v4.1.5 (Bronk Ramsey & Lee, 2012).

To help document landscape change, high-resolution satellite imagery (WorldView image, 50 cm pixel resolution), ancient maps, and 19th and 20th century explorers′ accounts were collected and integrated into a GIS database. Fieldwork was conducted between 2008 and 2014. A pedestrian geomorphological survey of the surrounding area (*ca.* 25 km²) was undertaken in order to understand the site context and the logic of settlement and was supplemented by interviews with local residents. GPS references were collected with dem-precision using an integrated satellite correction; differential ground positioning system (DGPS) is forbidden in military zones such as Kharga Depression and no permanent reference station exists nearby. General altitudes and slope direction are derived from a SPOT digital elevation model (DEM) of 30-m resolution. Altitudes for specific points (e.g., yardangs) and channel boundaries were measured with a total station within a locally established datum, yielding relative altitudes of centimeter precision. A detailed geomorphological appraisal of the archaeological site *sensu stricto* (*ca.* 4 km²) was conducted, with a particular focus on artifact-rich locations. The investigation was limited to natural stratigraphic exposures because excavations were prohibited.

Field areas were identified on the basis of agricultural evidence (e.g., presence of irrigation soils or cultivated

Table II Stratigraphy of Yardang A (see Figure 5).

Stratigraphic Units	Subunits	Texture	Age (^{14}C yr BP)
IV	2	Parallel layers of sand and silt, with distinct lenses of sand. Scattered potsherd inclusions.	2130 ± 15; see Table I, No. 5
IV	1	Unconformity over Unit III, same type of texture; undated. Includes trapezoidal section of a dated canal (flat bottom 35-cm-wide, east–west orientation), about 40 cm below the present top of the yardang.	1770 ± 15; canal; see Table I, No. 7
III		Succession of laminae made of sand and particles from the reddish shale substrate. Deep crack or root cast infiltrated by well-sorted yellow sand below a truncation surface.	2210 ± 25; see Table I, No. 3
II	3	Compact silt and sand. Parallel layers of sand and silt. Distinct lenses of well-sorted blown sand.	8010 ± 25; see Table I, No. 1
II	2	Subhorizontal reddish silty sand.	
II	1	Compacted and cemented particles of shale and sand.	
I		Gravel reflecting watershed rock composition (limestone, sandstone, shale. Cohesive sandy matrix (carbonates from limestone units, gypsum from shale layers).	

Figure 4 Yardang A (photo by J.-P. Bravard).

areas on bedrock, plot boundaries, irrigation canals), and on the basis of landform distribution and related processes (yardangs, fluvial features, and deflation features). Irrigation soils were identified by indirect methods (presence of canals and artifacts). Soil testing was not permitted but may be possible in the future. Soil descriptions were conducted at yardang exposures.

Agricultural field areas were interpreted and dated using a combination of temporally diagnostic ceramics (Rodziewicz, 1987; Ballet, 1998, 2004; Dixneuf, 2011) and AMS ^{14}C dating of micro-charcoal collected in natural exposures and submitted to four laboratories (CEN – University Laval, Quebec; Keck Carbon Cycle AMS Facility, University of California at Irvine; CEDAD-University del Salento; Poznan Radiocarbon Laboratory). Archaeological, geomorphological, and chronometric information was then incorporated into a series of GIS layers allowing us to identify seven distinct areas (Figure 2) and providing a time series of land use at El-Deir from the Ptolemaic to Byzantine periods.

RESULTS

Area 1: Yardangs

A group of yardangs is preserved on the northern edge of the main irrigated zone. Yardang A is the largest (2.5 m high) and composed of friable silt and sand, displaying the most complete stratigraphic sequence in the study area (Tables I and II; Figures 4 and 5).

Area 2: Sand Mound

Southwest of Area 1, a north–south oriented, 20-m-long, ovoid sandy mound stands 4–5 m above the present floor. It is the highest feature of the former irrigated area (Figure 6) located on the western edge of an outcrop of resistant bedrock probably bounded by faults. Densely covered by Roman potsherds from vessels used to carry water, the top of the mound is protected by a thin broken duricrust covering a layer of reddish oxidized compacted sand. Charcoal sampled in the upper layer of the sand dates 1026–900 B.C. (Table I, Sample No. 2).

Area 3: Western Irrigated Sector

On the western flank of the mound described above, six irrigation canal heads are dug into a layer of noncohesive sediment (Figure 7). They are 25 cm wide, regularly spaced (2–3 m apart) and roughly parallel to one another, with sides protected by aligned white limestone slabs cropping out of the modern surface. A charcoal sample inside the uncohesive sediment supporting the canals dates 260–40 B.C. (Table I, Sample No. 4). Two other distinctive features notable in this area are (1) alignments of stones probably belonging to former irrigation canals (Figure 8) and (2) regularly spaced piles of gravel and sand protected by a mixed superficial cover of stones, sandstone slabs, and potsherds in the formerly irrigated sector (Figure 9).

Area 4: Temple

A Ptolemaic temple stands on top of a gravelly terrace cut into a ridge of red shale with inactive spring mounds. The spring mounds located southeast of the temple are presently buried under sand dunes. No Persian and only a few Ptolemaic potsherds have been found in the vicinity of the springs, indicative of recent (modern) sand encroachment in the area. The ground surface is composed of weathered shale rich in nodules of quartz, which have been concentrated by deflation and currently protect the ground from erosion. According to historic maps, this area was still used for irrigation in the 1930s.

Area 5: Northern Irrigated Sector

This area is presently a closed depression where an extensive, disused, irrigated zone and a dense network of old canals can be found. Despite the blurring of the ancient landscape by deflation, Ptolemaic potsherds (some of them dated to the end of the Late Period) were discovered in two distinct undisturbed locations around an irrigation canal. Maps from the 1920s[2] show partial reuse of the southernmost part of this area in modern times: water was channeled from wells dug in the area immediately north of the fortress.

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[2] For example, map 320–582, "Village El Kharga", 1:10,000, 1929. Maps published by the Survey Department of Egypt, Giza, and consulted at the IFAO (Institut Français d'Archéologie Orientale).

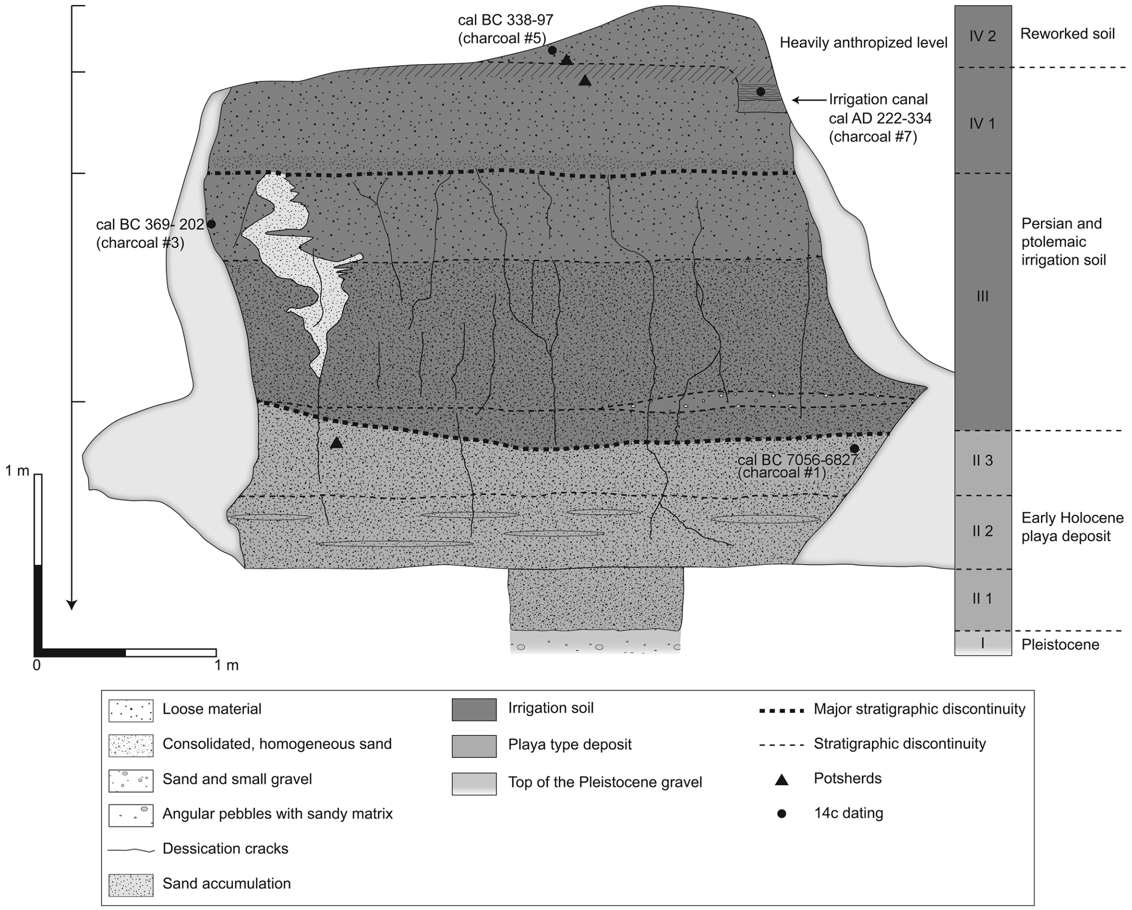

Figure 5 Cross-section of Yardang A and stratigraphic units visible in Figure 4.

Area 6: Wadi Flood Plain

The irrigated zone at El-Deir is located downstream of a wadi whose valley head is located on the northwest flank of the Um El-Ghaneyem (Figure 10). The narrow channels of an elongated watershed entrenched into folded Cretaceous strata and Pleistocene terraces provided a pathway for cobbles and gravel that shaped an alluvial fan broadly extending over El-Deir flat. We divide the watershed and alluvial fan into five zones (A, B, C, D1, D2). The watershed covers 2.56 km² including the 0.80 km² alluvial fan (Figure 10).

Zone A corresponds to the confined wadi channel inset into shale truncated by Pleistocene gravel. In the downstream part, a necropolis has been excavated. The material discovered inside the 150 tombs of the cemetery contained 120 individuals. Ceramics with painted motifs date from the end of the fourth to fifth century A.D., with some potentially as recent as the sixth century A.D. (S. Brones, 2008, oral communication). Textile fragments from the early fourth century A.D. were also discovered (F. Letellier-Willemin, 2015, oral communication). The proximal part of Zone B displays fluvial landforms shaped by high energy stream flow. Active channels are bounded by large boulders.

Zone C is a large area with partly eroded soft sediment overlaying red shale. Yardangs (Area 1) partly extend into Zone C. Most of Zone C may be defined as an area of irrigation soil made of shale fragments and sand, with high potsherd density. The distal part of the fan extends into the southern part of Zone C and contains a 1-m-thick sheet of gravel. Charcoal from the compact reddish soil buried under gravel northeast of Zone B is dated 85–325 A.D. at two sigma (Table I, Number 6) and 130–215 A.D. at one sigma.

In Zone C, two 1-m-wide master canals with east–west orientation are located on the northern edge of a flat area above a deeply eroded area shaped by running water. The canals show signs of destruction (Figure 11). The first canal runs in a straight line and is densely lined by distinctive second to third century A.D. potsherds from *sega*-like pots that are generally used for transferring water

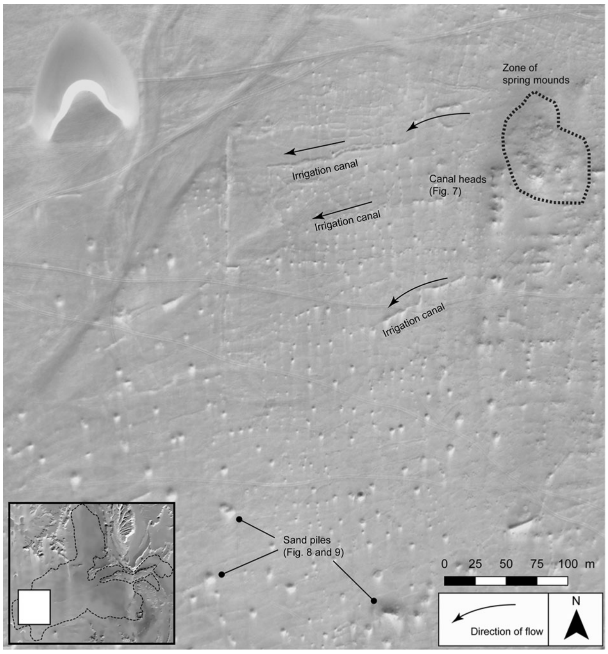

Figure 6 WorldView image of relict Ptolemaic irrigation canals and fields, Areas 2 and 3.

Figure 8 Sand piles covered with stones in the deflated western Ptolemaic area. Wind-blown sand occurs on the lee face of piles; dominant wind from the North (photo by J.-P. Bravard).

from canal to fields. It connects to a smaller north–south canal reinforced by limestone slabs. The second, smaller, sinuous canal is built directly over shale and runs parallel to the first master canal. It was used to deliver water to the south. Dense concentrations of potsherds dating to third to fourth century A.D. can be found on its banks, indicative of a later construction date than the first master canal.

Soils are notably absent north of the east–west canal in Zone C. The shale bedrock has been partly eroded by the abrasive action of alluvial boulders (intermediate axis

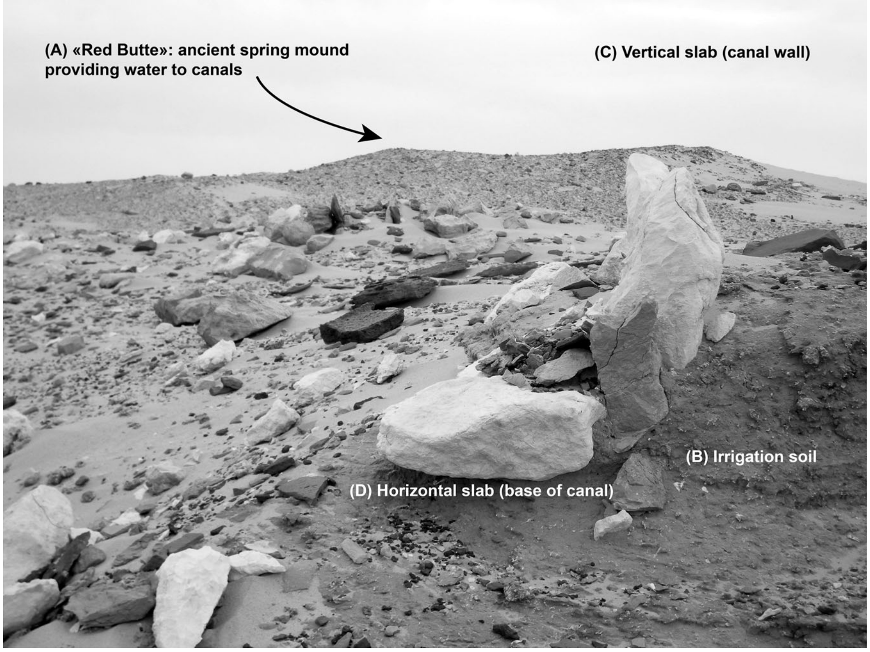

Figure 7 Cross-section view of a Ptolemaic canal on top of an irrigation soil. Horizontal and vertical slabs are still visible in the upper part of the stratified irrigation soil. Former spring mound is visible in the background (photo by J.-P. Bravard).

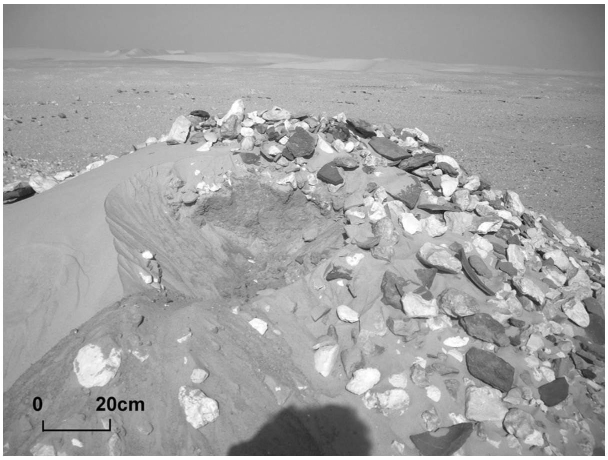

Figure 9 One-meter-high sand pile artificially protected by stones and potsherds in the deflated western Ptolemaic area (photo by J.-P. Bravard).

20–30 cm) and smaller pieces of limestone. Direction of flow was ascertained by topographical survey and gravel fabric. Several eroded brick-made structures or walls have been surveyed north and northwest of the two east–west canals. One of these structures is suggestive of housing (with the remains of an oven), another one is a pigeon house. All such structures are surrounded by a dense cover of potsherds characteristic of third to fourth century A.D. and are built directly on the eroded shale floor. Zone D, divided into D1 and D2, is an area of small gravel outwash. Channels display a braided pattern interspersed with high, isolated bars.

Area 7: Eastern Sector

The Eastern Sector is located between the Ptolemaic temple and the fortress (Figure 3). The El-Deir fortress was erected *ca.* A.D. 288 (Brones & Duvette, 2007) around a well used by the garrison and passing caravans for water provision (Tallet, Gradel, & Guédon, 2012; Darnell & Darnell, 2013; Ikram & Rossi, 2013; Tallet et al., 2013). In this area, water was procured from dredged spring mounds or wells. Upon abandonment of the site in the 1960s, this was the last area where water was extracted and is now covered by dunes. Satellite imagery reveals straight caravan tracks converging on the fortress well. Highly specific sherds from a subtype of Late Roman Amphora 1 have been recovered from test pits dug inside the fortress and from collection on the tracks departing from El-Deir to the Nile Valley. They can be dated from the end of the 5th or the beginning of the sixth century A.D.

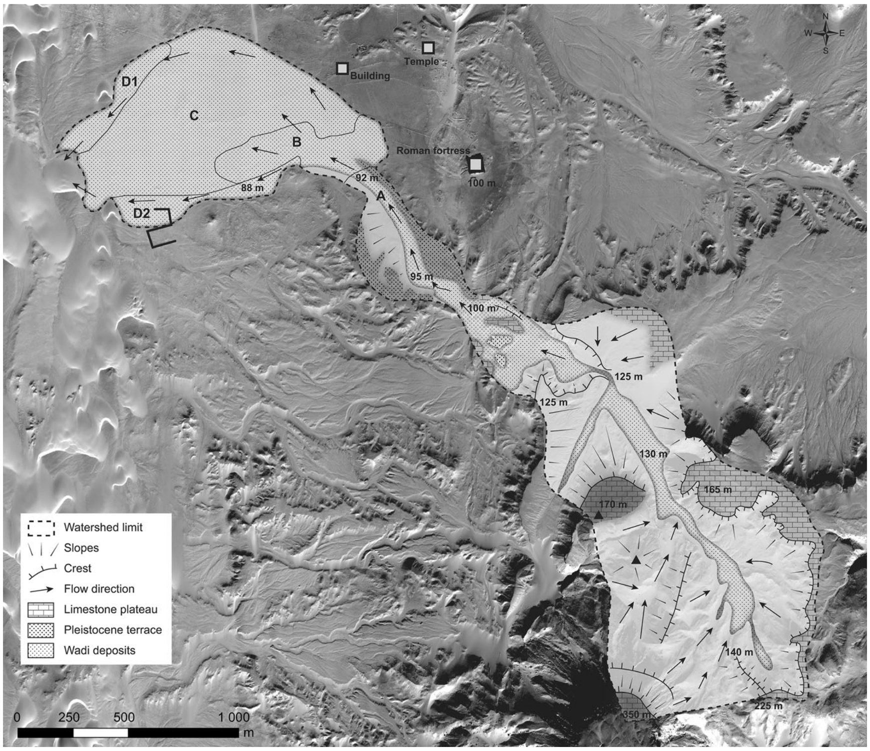

Figure 10 Watershed of the wadi flowing northwest from Um El-Ghaneyem Butte and responsible for the destruction of the Roman irrigated area.

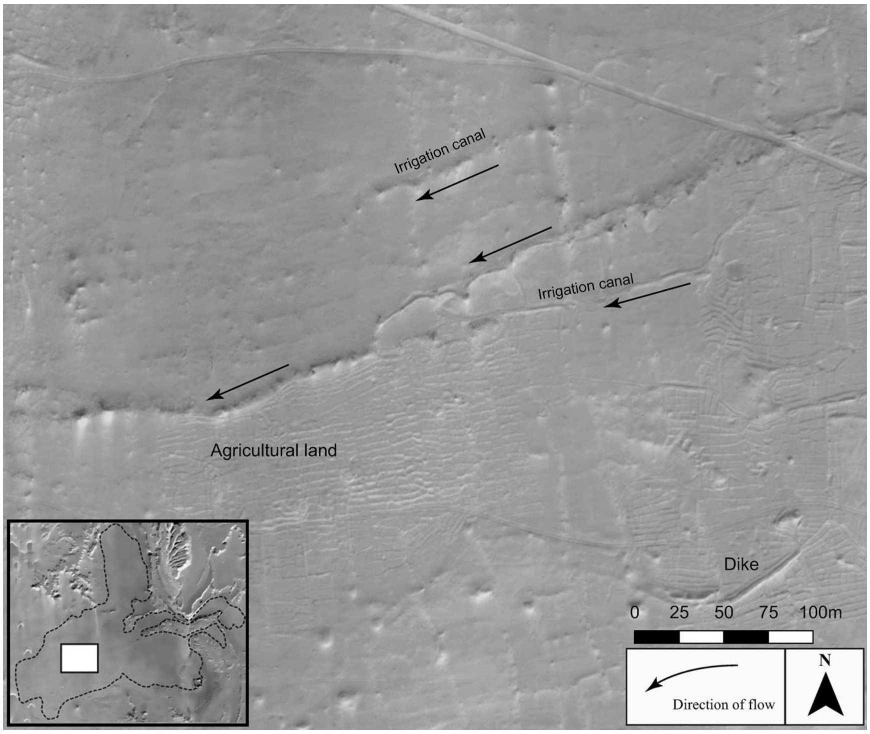

Figure 11 WorldView image of relict canals in Area 6, *ca.* second century A.D. Boulders and gravel used in canal construction are visible as ridges. Flow direction is right to left. The ground on the left has been lowered by erosion (water and possibly deflation). Fields have been cleared after the floods.

INTERPRETATIONS AND DISCUSSION

The areas we define at El-Deir document spatial and temporal changes in hydrology and surficial processes that influenced human settlement. Areas 1–5 and 6–7 document changes to the Pre-Roman and Roman landscapes, respectively.

The Pre-Roman Landscape

Area 1

Basal Stratigraphic Unit I in Yardang A is a gravel bottom layer attributed to Pleistocene outwash "overflow deposits" (Caton-Thompson & Gardner, 1932) combined with "semiplaya" deposits[3] (Embabi, 1972). Gravel is buried under a complex Holocene sequence (Units II, III, and IV). Unit II is a playa-type deposit composed of three subunits. Subunit II-1 contains particles of eroded shale that were deposited by runoff from local hills and by an artesian spring mound. These particles are mixed with sand transported by the wind and probably trapped by vegetation. Subunit II-2 is composed of lenses of well-sorted blown sand or of sand reworked and deposited by runoff. It was truncated by deflation and remains undated. Subunit II-3 contains charcoal from natural (wildfire) or human causes. Moisture related to permanent spring activity allowed vegetation development that increased surface roughness and trapped sand and silt. The anomalous contact between Units II and III suggests that wind erosion reduced Unit II to a low yardang at the end of the arid Holocene, which today is elevated *ca.* 1 m above the surrounding plain.

Unit III is composed of laminated eolian sand reworked by runoff and particles of purple shale. The upper part dates 369–202 B.C. and likely represents an "irrigation soil." This is overlain by an eroded surface suggesting severe deflation of late Ptolemaic age (Table II). Subunit IV-1 is undated but includes a trapezoidal canal segment with channel fill dated A.D. 222–334 (Table I). Subunit IV-2 dates to 338–397 B.C. (Table I) and is composed of reworked sediments.

Area 2

It is unclear if the sand mound formed by spring activity in Area 2 was still active during the late Holocene, but it is probable considering the number of inactive and

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[3] "Semi-playa deposits" are Pleistocene outwash deposits of scarp-drainage origin (coarser on upstream slopes than in downstream basins). The El-Deir case shows that the deposits may be mixed with sand of eolian origin, trapped in the vicinity of active Holocene spring mounds.

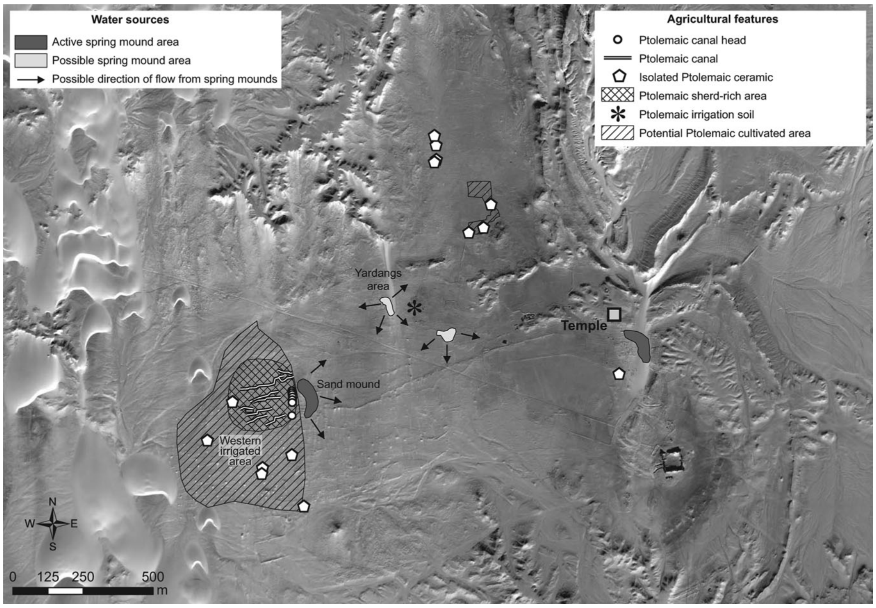

Figure 12 Map of water sources and agricultural features, Persian-Ptolemaic period.

deflated spring mounds and wells in the immediate vicinity (Figure 12). The charcoal dated 1026–900 B.C. (Table I) may indicate episodic human activity or an actual occupation of the site during the third Intermediate Period, pushing back in time the site's attested occupation (initially thought to be Saito-Persian at the earliest). The presence of Roman potsherds indicates that after a period when water naturally flowed (Persian and Ptolemaic periods), water had to be drawn from wells using ceramic containers.

Area 3

Radiocarbon ages (Table II) indicate that Area 3 may have been irrigated during the ancient Ptolemaic period, if not earlier. The canals are younger and likely of late Ptolemaic or Roman age. About 1.5 m below the irrigation canal heads, a heavily deflated area to the west is covered with sparse stones and potsherds. All sherds are Ptolemaic, including a very distinctive amphora from third to second century B.C. The origin and role of the alignments of stones and piles of gravel and sand are still hypothetical. They are surrounded by fluvial landforms (channels and bars) in which Ptolemaic and Roman potsherds can be found. This suggests that post-Ptolemaic floods (see below) destroyed and/or buried the northwest part of this area.

Area 4

As demonstrated by ceramics, the Persian and Ptolemaic irrigated agricultural system was primarily organized around a cluster of spring mounds located northeast of the El-Deir area. A large shallow depression is located south of the temple. Potsherds older than the fifth to sixth century A.D. are notably absent, indicating that this area was unoccupied before the late Roman period, possibly because of the existence of a shallow lake or a wetland fed by excess water flowing from spring mounds during the Persian and Ptolemaic period.

Area 5

The northern area occurs on a pediment formed into shale below a high terrace of Pleistocene gravel. We suggest that this area was not protected by gravel and that deflation inverted topography. Ceramics and the presence of canals advocate the presence of an extensive Ptolemaic (if not Late Period) irrigated area. The area may have been watered by local spring mounds or by spring mounds located south of the basin.

The progressive accumulation of irrigation sediment in Area 1 during the Ptolemaic period raised the level of the soil and groundwater levels. This increased the possibility of diverting water to the lower northern basin through canals originating from southern spring mounds. Also, seepage of groundwater present in the loose sediment of the southern area may have contributed water to the northern sector. In contrast, the lowering of irrigation soils of the southern area through erosion during the Roman period probably decreased water supply from the south to the north. Water supply to the northern basin was occasionally complemented by rainfall and runoff from the surrounding hills.

The Roman Landscape

Area 6

Indications of significant Holocene wadi activity at El-Deir are scant. No coarse particles were found in the basal units of the yardangs except some of human origin embedded in the irrigation soil. However, several deposits and fluvial features associated with the alluvial fan (Figure 13) indicate that channels were probably active during the Pleistocene and late Holocene. Erosion possibly destroyed the upper part of the soil that may have been younger than A.D. 85–235. Zone D2 contains Pleistocene deposits that were reworked by historical floods whose extension was controlled by artificial berms made of large blocks to prevent the floods from further destroying the cultivated zones in Zone B. Zone C was the main agricultural area during the Roman period. In the northern part of Zone C, charcoal from the upper layers of the sandy sediment filling an irrigation canal dated A.D. 222–334 (Table I), although the canal itself is probably older. This means that the irrigated area corresponding to the field of yardangs described earlier was still active during the third and early fourth centuries A.D. The geometry and appearance of the canals suggest that they were built sequentially, after floods that partially destroyed the first irrigation system at some point in second to fourth centuries A.D. The low elevation of the buildings compared to the yardangs suggests that local irrigation soils were already severely eroded when the architecture was constructed.

Finally, a *terminus ante quem* age for potential flash floods is provided by the Coptic necropolis located in the flood corridor (Unit A in Figure 13), with graves dug into the alluvial deposits or red shale. This indicates that no significant flood occurred after the period dated early fourth to sixth centuries A.D. Thus, we conclude that severe floods in the El-Deir irrigated area occurred during the second to early fourth centuries A.D. (85–325 A.D. and post 222–334 A.D.), and ceased completely thereafter.

Area 7

Radiocarbon dates and archaeological evidence from Area 7 suggest a change of site specialization in late third century (from an agricultural area to a Roman trading center), with increased trade during the fifth to sixth century A.D. (Figure 14).

HUMAN RESPONSES TO THE EXHAUSTION OF WATER RESOURCES

Current research has shown that within the larger context of post-5000 cal. yr BP hyperarid conditions, there were finer chronological sequences of human responses to aridity in the Sahara (Brooks et al., 2005). A few examples exist of the long-term unsustainability of human responses to increased aridity. Changing livelihoods called for novel sustenance strategies—for example, switching functional specialization from irrigated farming to trade as shown in the Fezzan where the rise of the complex Garamantian urban society was initially predicated on the development of irrigation around 1000 B.C., and later on trade (Mattingly & Sterry, 2013). Overexploitation of water and trade reduction at the end of the Roman period led to the Garamantian demise around A.D. 700. In the Tanezrouft (southwest Fezzan), tree-ring (*Cupressus Dupreziana*) records showed that the oasis reached its maximal extension between 2800 and 2200 cal. yr BP and that occupation ceased *ca.* 1600 cal. yr BP with the onset of very dry conditions (Cremaschi & Zerboni, 2009). It may be concluded that within the larger context of aridity, specific historical trajectories were related to the local availability of dwindling underground water resources.

Diverse historical sequences have also been documented in the oases of the Libyan Desert. In Dakhla, Brooks (2006) and Brookes (1989) have shown the continuity of agricultural activities and caravan trade in a period ranging from the Old Kingdom down to the Islamic period because of the continued availability of water. In Farafra, however, local societies collapsed *ca.* 4200 cal. yr BP, which coincides with the decline of the Old Kingdom (Mandel & Simmons, 2001; Nicoll, 2004; Riemer, 2005).

In Kharga, an interpretation of the chronology of oasian development is offered by Bousquet's three phase model of technological fixes to increased water scarcity. El-Deir augments and modifies this latter model: our research provides an example of changing specialization from agriculture to trade control due to water exhaustion but also provides insight into the role of landscape dynamics in the changing functional specialization of oasian spaces.

Accretion Processes: Early Holocene Playa Deposits and Irrigation Soils

Geoarchaeological research in the oases of the Libyan Desert has shown that many irrigated areas were developed on playas or semiplayas (Embabi, 1972; Donner, 1999; Zaghloul et al., 2013). Playas provided

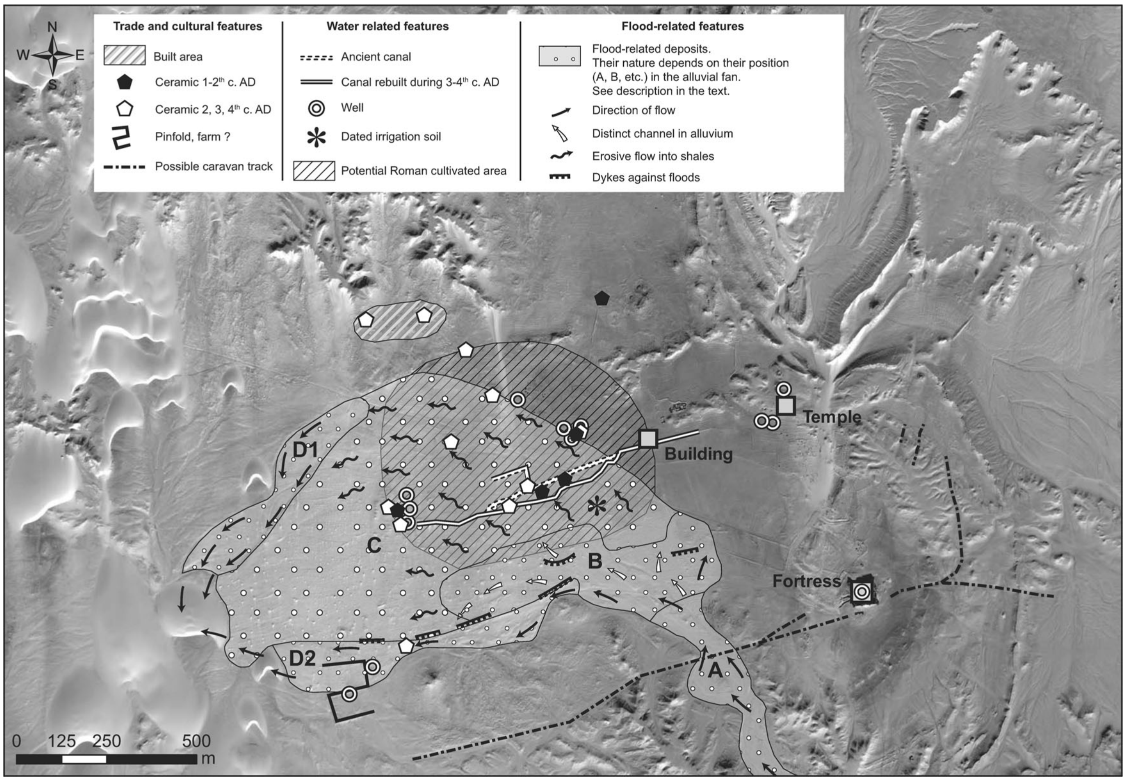

Figure 13 Map of flood features and aspects of human occupation, second to early fourth c. A.D.

an easy and fertile substrate to till and irrigate, where possible. Some playas were locally formed by the agency of spring mound outflow (Caton-Thompson & Gardner, 1932: 382). Haynes (1983) gives the example of an 18-m-high accretion south of Kharga. Wells were usually dug into drying spring mounds. Irrigation water facilitated the deposition of water-borne silty sand, wind-blown sand, with interspersed ceramic fragments (dated Persian to Byzantine) and gastropod shells. Overflow of irrigation water was collected in hollows and allowed the encroachment of vegetation and the entrapment of wind-blown sediment. Similar processes have been described in other desert settings. In Arizona, dust deposition explains the overprinting of soil chemical patterns in ancient agricultural soils (Nakase et al., 2014). Similarly, in the oases of Northeast Africa, eolian inputs may have contributed to maintaining agricultural fertility.

Irrigation soil continued to form as long as the respective topographic levels of flowing water and well deposits remained in balance. In Dakhla Oasis, Brookes (1990) described how water supply and pressure were limiting factors in the increasing elevation of the well deposits and in the vertical accretion of the fields. In El-Deir Oasis, the balance between accretion and erosion was upset several times.

- It can be deduced from the limited net thickness of deposits (e.g., Unit II, Yardang A) that the balance between vertical accretion of the playa and wind erosion was slightly positive during the humid Holocene (*ca.* 7000–6800 B.C.). The upper part of Unit II is truncated but it corresponds to the end of the humid Holocene. No other Unit II type deposit has been found so far in the yardang area, suggestive of intense deflation after the onset of aridity.
- The 1026–900 B.C. (or third Intermediate Period) ^{14}C date obtained in Area 2 suggests that early irrigation practices, based on a network of canals developed around spring mounds, restarted the horizontal expansion of accretion processes. It is on the little-documented succession of later historical deposits that El-Deir provides the most novel insights. The stratigraphy and dating of Unit III in Yardang A suggest that accretion increased in the Ptolemaic period (330–30 B.C.), or even earlier (the top of Unit III has been dated 369–202 B.C. but the base could be Persian).
- Few unequivocal Late Ptolemaic (first century B.C.) to Early Roman potsherds have been found. Arguably, such ceramics are more difficult to date than potsherds from other periods, because of

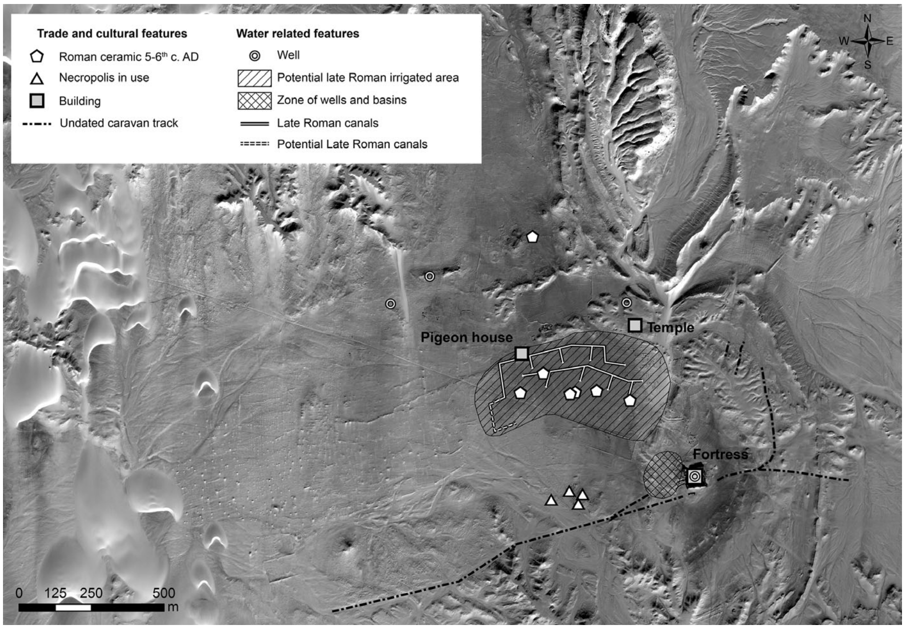

Figure 14 Map of the last occupation phase, end of the fourth to sixth centuries A.D. The residual agricultural area is located very close to the last active spring mounds.

less characteristic features and limited study of ceramics from that period. Likewise, there is no geomorphological or archaeological proof of spring mound activity during this period of time. Two explanations are offered to account for such an absence: either geomorphic processes destroyed irrigation soils and associated potsherds of that period or a quasi-abandonment of the site created a hiatus in irrigation sedimentation, soil formation, and artifact deposition.

- After some unspecified time, the Romans had to dredge the mounds or dig wells to obtain underground water for irrigation. The Roman irrigated area may be identified and delimited by dense concentrations of potsherds around wells and along canals because water extraction was made with large, distinct ceramic containers, similar to the present *sega*. Thus, increases in Roman potsherds densities are not related to higher population densities but to technical necessities, pointing to decreasing water availability between Ptolemaic times and the later Roman Empire. A major question remains the date of the shift from natural spring mound discharge to spring mound dredging once the water table fell below ground level.

Destructive Processes—Deflation and Floods

Destructive natural processes had a significant influence on the historical trajectory of oasian agricultural spaces and societies. The case of El-Deir points toward a reevaluation of destructive agencies as limiting factors for the sustainability of past agriculture. Irrigation soils were prone to deflation because they stood above the land and were made of recent, coarse, and loose material while exposure to dryer conditions drastically reduced their cohesiveness (Brookes, 1989). Oasian soils are coarser and less cohesive than typical "irragric anthrosols" (e.g., Woodson et al., 2015) and accordingly less resistant to post-depositional processes. Geomorphic features suggest that northern winds have long been a strong shaping agent for the physical landscape (Donner & Embabi, 2000). Deflation in the late Holocene was probably almost continuous and constant, while human activity may have enhanced its effects.

Our data further suggest that two main deflation phases occurred in the Late Persian-Ptolemaic period, during the phase of spring mound activity. The older one, dated between 369–202 B.C. and 338–97 B.C., is documented in preserved yardang stratigraphy (sandy filling of cracks in irrigation soil; see Figure 5). The most recent is deduced from stratigraphy and ceramic evidence and occurred in the second century B.C., between 260 and 40 B.C. (the age of irrigation soil predates the end of the last irrigation canal) and the second to third centuries B.C. Such deflation phases are indicative of substantial transformations in the circulation of water and of significant changes in the extension of irrigated areas. The ground surface is cut into the shale without any soil cover, which leaves open the question as to whether irrigation was developed directly on the weathered bedrock or if irrigation soils have been entirely eroded by deflation.

Another finding is that the El-Deir area was partly destroyed by one or several flash floods originating from the Um El-Ghaneyem Butte area between the second and fourth centuries A.D. Rare and seldom monitored, rain downpours are not unheard of in the Libyan Desert. For example, in February 1874, Rohlf's expedition experienced a protracted rain event on the trail between Dakhla and Siwa that produced 16 mm of water in two days (Rohlfs, 1875: 165). Thus far at El-Deir, flash floods cannot be documented before the Roman Period. However, during the Roman period, floods severely affected the fields, and limited rehabilitation of irrigated areas was made possible through canal reconstruction, well digging, sediment clearing, and field creation directly on shale.

The question remains open if such flash floods were purely random, isolated events, or if they were indicative of a more humid period in historical times in the Western Desert. This discussion opens up the old debate on historical climate pulsations in the depression of Kharga (Huntington, 1910; Beadnell, 1911). Two hypotheses have been offered to explain increased rainfall in the historical period: (1) Mediterranean winter rains could have shifted to the south, reaching the north of Kharga Depression, or (2) short-lived pulses of the Indian Ocean Monsoon reached north into the area. The first hypothesis would explain the *ca.* 2500 B.C. (end of the fourth dynasty) floods described by Butzer, Butzer, and Love (2013) in the Lost City of the Pyramid at Giza (10 floods recorded in 45 years with 200- to 300-mm rainfall events every four years). The second hypothesis may explain floods described in the Red Sea Hills, eastern Sudan, 2500 years ago (Mawson & Williams, 1984) or in Hadramawt, Yemen (Berger et al., 2012). However, the northern extension of these monsoonal rains does not fit well with the supposed lack of heavy rainfall. This point needs further exploration with a "fresh synoptic approach" into the behavior of the mid-latitude jet-stream in the late Holocene (Butzer, Butzer, & Love, 2013). Water availability in Kharga Depression may have been controlled by the coupling of these two rainfall systems, that is, increased activity of Westerlies from storms of Atlantic–Mediterranean origin coupled with increased monsoon activity associated with northward penetration of the Intertropical Convergence Zone over the Arabian and African continents (Smith et al., 2004; Larrasoaña, Roberts, & Rohling, 2013; Bar-Matthews, 2014).

CONCLUSION: RISE AND FALL OF AN OASIS

If water availability and provision are generally accounted for in the literature on oasian development, the three-dimensional spatial extension they afford is often understated. Four phases of areal development have been documented so far in the 1.6 km^2 El-Deir agricultural area:

- First, a period of accretion during the wet early Holocene and associated rise of groundwater level and consequent increased effective moisture of the area.
- A period of limited erosion and spatial contraction during the dry predevelopment period.
- A period of fast and significant accretion due to irrigation (mostly during the fourth to first centuries B.C.).
- Alternate periods of accretion/erosion and spatial expansion/contraction during the Roman period.

It is difficult to quantify the extent of irrigated areas for each historical period, because of the reworking of older irrigated areas by later colonization and irrigation. The presentation of our results in a series of cartographic layers should not obscure the fact that several destructive transitional periods can be hypothesized. They entail dramatic changes in the landscape, precluding any smooth and linear historical reconstruction of the oasis. Deflation occurred at the end of the Ptolemaic period or at the beginning of the Roman period, and lowered the ground surface, irrigation canals, and local water table levels. This change was exacerbated by the decrease of spring mound productivity due to progressive hydraulic pressure reduction in the deep aquifers. Also, wadi flash flooding destroyed 90% of the land cultivated during the second to fourth centuries A.D. in the southern zone. Part of the aquatic habitat may have been destroyed in the same area. The northern area was affected because canal irrigation was impossible and seepage thus decreased, limiting water withdrawal from wells. Such was the intensity of climatic hazards that we hypothesize that the site's specialization changed from agriculture to caravan watering and trade during the third to fourth centuries A.D. The fortress, dating back to the end of the third century A.D., was possibly built to protect a warehouse, a well, and watering devices fed by other wells in the immediate vicinity of the fortress.

El-Deir oasis provides an example of the ever-shifting balance between accretive and destructive agencies in the shaping of oasian landscapes. It exemplifies the complexity of the water/soil relationship in a spring-mound fed oasis and distances itself from the mechanistic logic of "hydraulic fixes" as an explanation of oasian historical trajectories.

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