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Late Miocene karst system at Sheikh Abdallah, between Bahariya and Farafra, Western Desert, Egypt: Implications for palaeoclimate and geomorphology

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ABSTRACT

The extensive spelean deposits in the Western Desert of Egypt at Crystal Mountain (Gebel Bellorat) are considered to be 11-10 Ma, confirming the 'Vallesian' estimate made by Heissig (1982). Several new faunal elements have been discovered including anurans, snakes, soricids, bats, galagids, hystricids and glirids. This fauna indicates that the region was appreciably more humid 11-10 Ma than it is today, with at least 750 mm and possibly as much as 1,200 mm mean annual rainfall. The role of karst processes in the development of the oases of the Western Desert that may have been underestimated by previous researchers is emphasized.

KEYWORDS **Late Miocene. Egypt. Karst. Palaeontology. Palaeoclimatology. Geomorphology.**

INTRODUCTION

The discovery of late Miocene fossiliferous karst-fill breccia in the Farafra-Bahariya region of the Western Desert of Egypt is important, not only because it helps to fill a geographic and chronological gap in the African Miocene fossil record, but also because of the information it yields about the geological history of the region, including its palaeoclimatology and geomorphology. The information has implications for understanding the evolution of Old World palaeoclimates during the Late Neogene by providing evidence of a palaeoclimatic nature, including climate sensitive faunal elements and karstic geomorphological processes.

Karst and related phenomena are sensitive to environmental conditions (Faniran and Jeje, 1983). Study of karstification in carbonate sedimentary sequences of the Western Desert of Egypt has been increasingly employed in palaeoenvironmental reconstructions (El Aref et al., 1987; El-Sayed, 1995; Brook et al., 2002; Halliday, 2003 and references therein. Heissig (1982) has recorded preliminary micromammals within the karst infillings in the Western Desert of Egypt). However detailed sedimentological and palaeontological studies of karst-related deposits in the studied area have not been carried out. In this contribution, we focus on the study of the sedimentological characteristics and fossil fauna of karst infillings in the Western Desert in order to throw light on the palaeoenvironmental conditions that prevailed at the time of their deposition and to deduce aspects of the region's late Miocene palaeoclimatology. In addition, this study discussed the role of karst processes in origin of the great oases in the Western Desert.

Surveys by the authors in September, 2005 and January, 2008, allow a more accurate description of the geographic location, faunal list (Table 1), age and geological setting of the Sheikh Abdallah (Farafra) site (Figs. 1A and 2A). The nearest known faunal assemblages of comparable age occur in the Maghreb and East Africa (Fig. 3).

PREVIOUS WORK

The presence of a fossiliferous karst system in the Western Desert of Egypt has been known since 1979, when K. W. Barthel found breccia rich in the remains of micromammals in a roadside exposure which he reported to be 83 km north of Farafra Oasis. Fossils freed from the breccia by acid treatment were examined by Heissig (1982) who listed a lacertilian and 13 species of micromammals (Table 1). On the basis of the fauna Heissig estimated a late Miocene age, more specifically a basal Vallesian correlation and suggested that the relative abundance of Ctenodactylidae and Myocricetodontinae indicated a grassland palaeo-environment.

According to Barthel, the fossils were found in a karst filling associated with coarse calcite crystals exposed immediately west of the Farafra-Bahariya road in a well exposed cave system which formed in "chalk". This chalk is known as the Khoman Chalk and is of Maastrichtian age (Said, 1962) (Fig. 1A). Brief mention of the site was made by Coiffait (1991) and Halliday (2003).

TABLE 1 **Mammal list: Sheikh Abdallah, Egypt (from Heissigh, 1982).**

Insectivora
    Erinaceidae
Macroscelidea
        Rhynchocyon sp.
Rodentia
    Ctenodactylidae
        Africanomys major
        Africanomys minor
    Cricetidae
        Cricetus sp.
    Myocricetodontinae
        Myocricetodon aff. *parvus*
        Myocricetodon aff. *cherifensis*
        Myocricetodon cf. *irhoudi*
        Myocricetodon magnus
        Myocricetodon sp.
    Dendromurinae
    Muridae
        Progonomys cathalai
        Leakeymys sp.

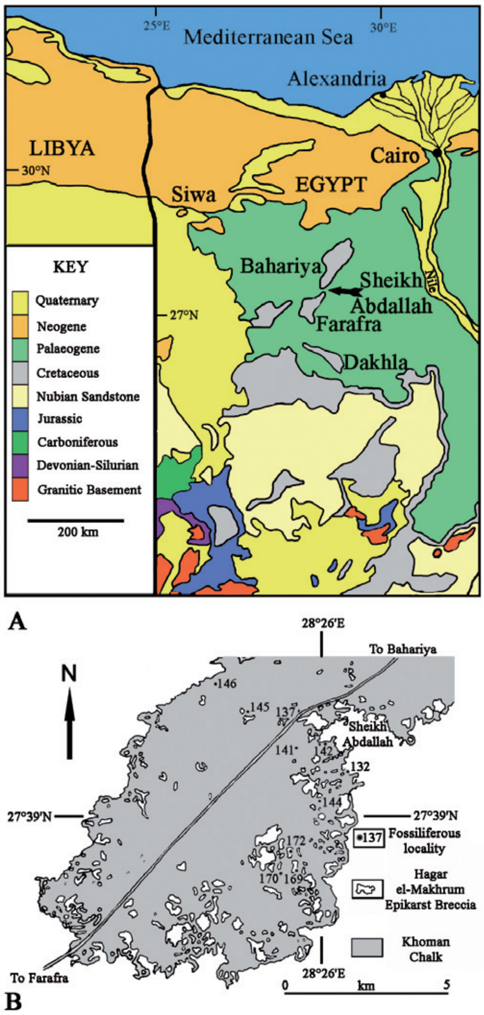

FIGURE 1 **A) Geological sketch map of Egypt showing location of Sheikh Abdallah, Central Egypt; B) Geological sketch map of the depression immediately south of Sheikh Abdallah, showing the location of late Miocene fossiliferous karst breccias.**

The fossiliferous deposits illustrated by Heissig (1982) are about 5 km further north than positioned by Barthel. Photographs in Heissig's paper correspond to an outcrop near Sheikh Abdallah [27° 39' 466"N: 28° 25' 495"E (WGS 84 datum)] commonly known as Gebel Bellorat (Crystal Mountain) which is part of the White Desert.

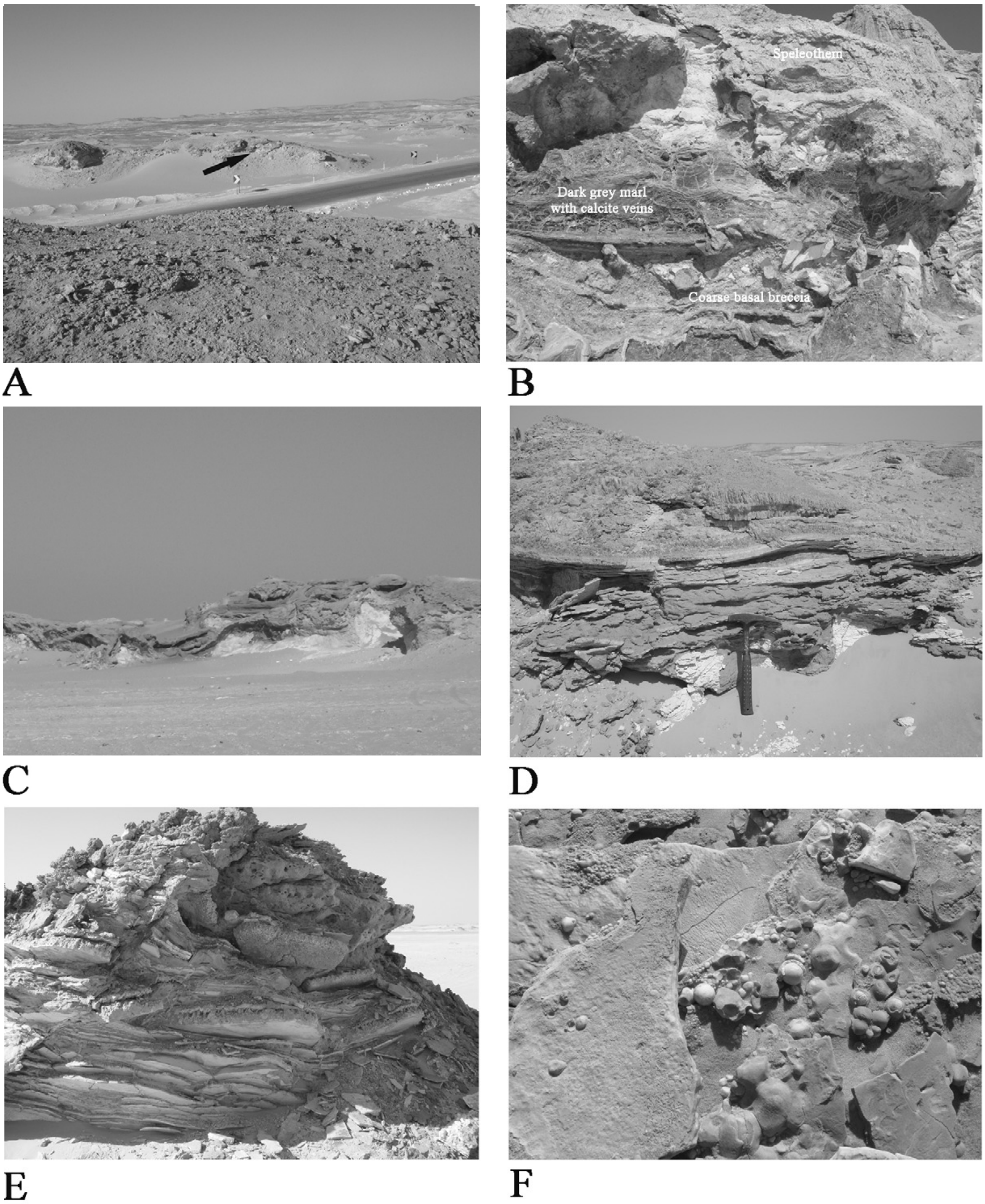

FIGURE 2 | **A) Sheikh Abdallah locality 137 (marked with an arrow), fossil site immediately est of the Bahariya-Farafra road, Central Egypt; B) The base of the karst infillings at Sheikh Abdallah is often comprised of black marl with calcite veins and coarse breccia, overlain by speleothems; C) Uneven surface of white Khoman Chalk overlain by coarse basal breccia, bedded red sandstone and speleothems at Sheikh Abdallah. Relief of outcrop is ca 10 metres; D) Red sandstone at Sheikh Abdallah overlain by coarsely recrystallised speleothems (geological hammer for scale); E) Intercalated laminated speleothem and red sands at Sheikh Abdallah (height of outcrop ca 2 metres); F) Laminated speleothem at Sheikh Abdallah containing abundant cave pearls (large pearls are 2 cm in diameter).**

THE SHEIKH ABDALLAH KARST SYSTEM

Over much of the oval depression south of Sheikh Abdallah (Figs. 1B and 2A), the Khoman Chalk, in which the ancient cave system formed has been almost entirely eroded to the palaeocave floor level, leaving the cave fillings as positive relief features some 5-10 m high on a relatively planar landscape. To the east, Cretaceous and Palaeogene limestones rise to an altitude of about 40 metres above the Bahariya-Farafra road, but west of the road the countryside is flatter, albeit with small hillocks here and there. To the southeast, an extensive area of unroofed palaeocave system is preserved over a distance of 5 km, exposing an extensive network of galleries, separated by chalk walls and hills. These ancient galleries contain vast quantities of speleothems and spelean breccia here attributed to the Sheikh Abdallah Spelean Breccias. There is a widespread, but discontinuous, horizon of dark grey epikarst breccia capping all the chalk hills and ridges in the area that we call the Hagar el-Makhrum Epikarst Breccia. On existing geological maps this unit is mapped as Cretaceous chalk, but even though the blocks within it are mostly derived from the Cretaceous layers, strictly speaking it is a late Miocene formation.

FIGURE 3 | **Sheikh Abdallah in relation to other late Miocene fossiliferous localities of Africa. The Egyptian locality helps to fill a vast geographic gap in our knowledge of late Miocene faunas of Africa. Its nearest neighbours of similar age (11-10 Ma) are in the Maghreb, 1,900 km West-North-West and in East Africa 2,250 km South-South-East.**

The Sheikh Abdallah Spelean Breccias

We define the Sheikh Abdallah Spelean Breccias as the karstic infillings cropping out in the vicinity of Sheikh Abdallah that repose unconformably on a karstified surface of Cretaceous Khoman Chalk and topographically beneath the Hagar el-Makhrum Epikarst Breccias (Fig. 1B).

Although the detailed stratigraphy of the cave infilling at Sheikh Abdallah varies from place to place, in general there are four facies of spelean deposition (Figs. 2B-F and 4): 1) a coarse basal breccia comprising material derived from the country rock, comprising blocks of white chalk, limestones and some chert (Fig. 2B and C); 2) locally distributed black carbonate-rich sediments usually associated with poorly sorted marl and broken speleothem layers which may be rich in organic matter or contain manganese concentrated from the Khoman Chalk. The black deposits are patterned by a network of pale calcite veins (Fig. 2B); 3) red well-bedded fossiliferous sandstone breccia (Fig. 2C and D) often interlarded with thin layers of white to pink flowstone deposits, the latter sometimes containing cave pearls (Fig. 2E and F); and 4) coarsely crystalline grey calcite speleothems, occasionally forming masses up to 4 metres tall, 5 metres wide and many metres long (Fig. 2C and D). Calcite in the speleothems varies from microcrystalline varieties to layers of huge crystals up to 20 cm diameter. On account of its resistance to erosion the last rock type is by far the most voluminous of the four spelean facies, comprising well over 90% of the volume of exposed cave fill, but it was in any case probably the most abundant kind of spelean deposit in the palaeokarst system at the time of deposition.

Numerous speleothems at Sheikh Abdallah contain layers of large calcite crystals, many of which reach 20 cm in diameter, sandwiched between finely crystalline layers that resemble normal speleothems. Nevertheless, there remain layers that have not been recrystallised, and these preserve clear evidence of their spelean origins (cave pearls, Fig. 2F), drapery (Fig. 2C), calcitic efflorescences, gour pools, crystal rafts, and other morphology typical of speleothems).

The Hagar el-Makhrum Epikarst Breccia

This unit caps many of the chalk hills south of Sheikh Abdallah. It consists of a coarse breccia of more or less angular, remanié and reworked boulders of Cretaceous and Early Cenozoic marine sediments with a matrix of red sands in its lower half. It crops out widely in the vicinity of Sheikh Abdallah in central Egypt (Figs. 5A, B, and C).

The Hagar el-Makhrum Breccia accumulated at the same time as the Sheikh Abdallah spelean sediments. In

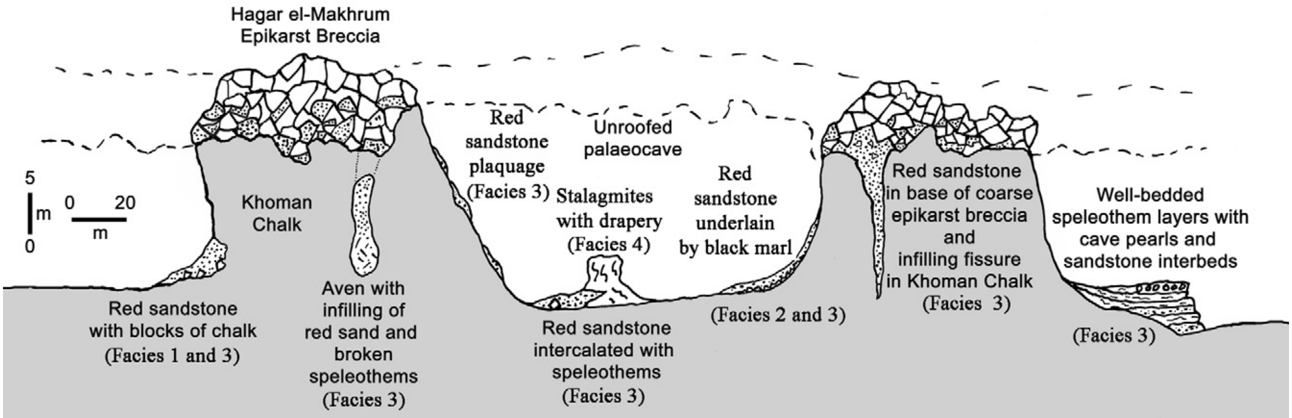

FIGURE 4 | **Idealised section of the Sheikh Abdallah depression showing the relationships of the main rock units and karst facies. Note the different vertical and horizontal scales. The coarse breccia at the tops of the hills comprises the Hagar el-Makhrum Epikarst Breccia, the various spelean facies: 1) Basal breccia of blocks of chalk; 2) Black marl; 3) Red sands and well bedded speleothems; 4) Stalagmites with drapery (often with large calcite crystals) within the ancient palaeocave comprise the Sheikh Abdallah Spelean Breccia. Bedrock is comprised of Khoman Chalk.**

places it is possible to trace the red sand in the lower half of the epikarst deposits downwards through avens into the ancient cavern system, the upper ends of the avens often being funnel-shaped (Fig. 5C). These outcrops indicate that the red sand of the Sheikh Abdallah Formation entered the palaeocaves by the action of water flowing through the epikarst breccia rather than by aeolian activity (Fig. 5D).

In the breccia at Sheikh Abdallah, large angular blocks of chalk (Fig. 2B and C) originated from proximal environments, as shown by the absence of attrition, abrasion and rounding (Selley, 1988). The bulk of the chalk blocks represent roof or wall collapse of the palaeocave system. The black carbonate-rich marly sediments appear to be composed of fine grained insoluble residues derived by dissolution of the Khoman Chalk, and subsequently cemented by carbonate. Overlying the black deposits there are at least two types of sand grains that form the matrix of the sand breccia. The most abundant are red well-rounded grains with extensive fine pitting (Fig. 6A) while the less abundant are pale yellow to white and are less well-rounded and the surface is generally smoother (Fig. 6B). The roundness of the grains indicates long distance transportation and possibly aeolian action (Margolis and Krinsley, 1971) as does the smooth and pitted surface of the grains. The residual clays consist mainly of kaolinite (detected by XRD) which reflect an acidic medium of deposition in a humid climatic regime (Keller, 1970).

An exceptional aspect of the Sheikh Abdallah fossil assemblage is that empty spaces in bones, such as medullary cavities of long bones, nerve canals in jaws and other bones and large cells in cancellous bones have been infilled by masses of clear quartz (Fig. 6C-F). The quartz, comprising abundant sub-parallel crystals, forms masses which follow the form of the cavities, producing semi-faithful molds of them. The pulp cavities in teeth are usually empty, but some specimens also contain quartz. These authigenic quartz crystals probably grew under atmospheric pressure at ambient temperatures prevalent in the cave system at the time of growth. Such authigenic silica can form at low pH medium (Selley, 1988) and its presence at Sheikh Abdallah is compatible with growth in a humid tropical climate (Wilding et al., 1977).

The presence of a warm, humid palaeoclimate is supported by the red colouration of the sand in the Sheikh Abdallah Spelean Breccias because such climatic conditions, linked to the influence of vegetation (Mücke and Agthe, 1988) provide the reducing and weakly acid conditions that enable the mobilization of Fe and Mn out of manganese-bearing ilmenite and magnetite present in the sandstone in the parent rock unit (Mücke and Agthe, 1988). The red coloration inherited from this weathering process persists until re-sedimentation, in this case as karst fill breccia.

Patches of red sandstone at Sheikh Abdallah have been bioturbated by root systems (Fig. 5E), indicating the former presence of plants in the region.

THE VERTEBRATE FAUNA

Fossiliferous breccia and fossil extraction

There are many patches of red sandy breccia in Sheikh Abdallah depression, and fossils have been found (Fig. 5F) in more than 10 localities, both west and east of the road from Farafra to Bahariya (Figs. 1B, 5F). At Barthel's locality (our locality 137) (Fig. 1B), red sandy breccia fills an irregular cavity cut into limestone, which

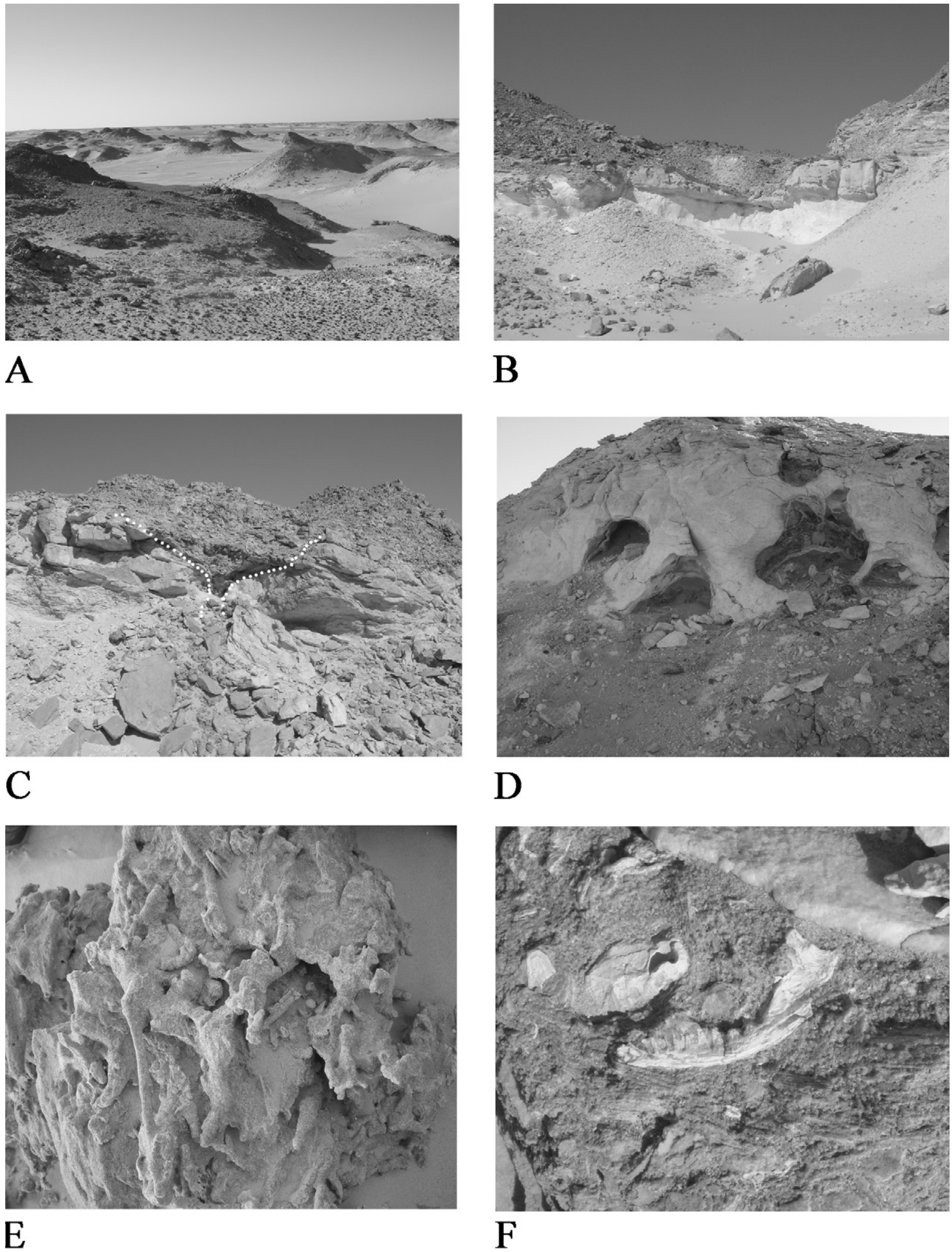

FIGURE 5 | **A) General view of the depression south of Sheikh Abdallah showing broken topography. The dark capping of the hills consists of the Hagar el-Makhrum epikarst breccia of late Miocene age, overlying Cretaceous Khoman Chalk (view towards the south); B) White Khoman Chalk unconformably overlain by dark epikarst breccia of the Hagar el-Makhrum Epikarst Breccias; C) Contact between White Khoman Chalk and the overlying Hagar el-Makhrum Epikarst Breccia. A funnel-shaped aven full of red sandstone (marked by white dotted lines) descends from the base of the epikarst breccia into the Sheikh Abdallah palaeocave; D) Avens piercing the Khoman Chalk west of Sheikh Abdallah. These avens are lined with a thin layer of calcite crystals and are infilled with dark grey marl and red sandstone; E) Red sandstone in the Sheikh Abdallah Spelean Breccias which has been extensively bioturbated by plant roots, providing evidence of the former presence of vegetation in what is now hyper-arid desert; F) Carnivore jaw and associated post-cranial remains in red sandstone underlying laminated speleothem at Sheikh Abdallah (mandible is ca 5 cm long).**

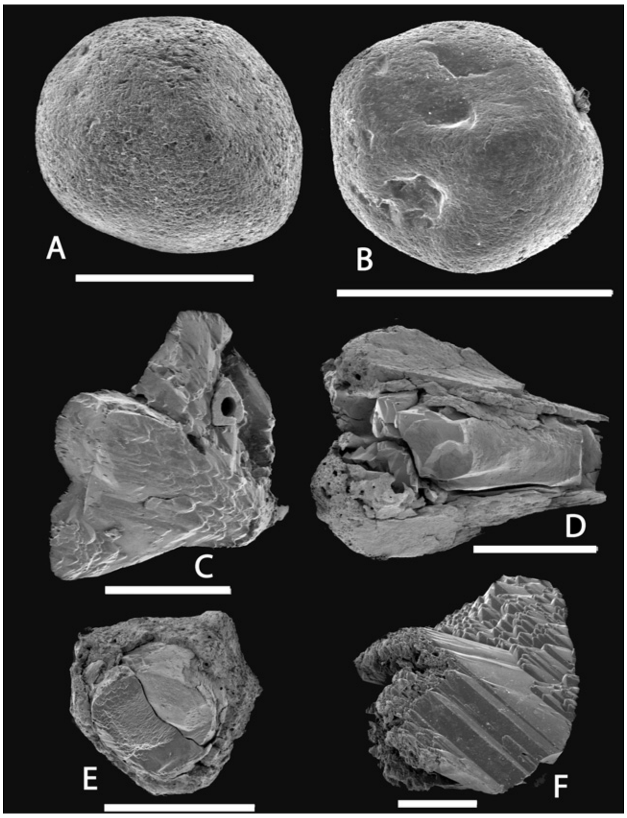

FIGURE 6 | **Sand in the Sheikh Abdallah palaeocave breccias consist of two kinds of quartz grains, A) with pitted surfaces and B) with smoother surfaces. The medullary cavities of rodent bones recovered from the breccia often contain authigenic quartz crystals C-F). Scale 1 mm.**

locally forms the summit of the hillock (Fig. 2A). The breccia is bedded and has layers of white flowstone parallel to the bedding. There are also remnants of stalagmites and stalactites up to 5 cm in diameter. The sand is fine to coarse, the coarse fraction being comprised of extremely well rounded grains. Nearby, this sandy breccia is overlain by coarsely crystalline speleothem.

At locality 137 (Fig. 2A), fossils are concentrated in six layers of the red sandy breccia separated from each other by barren or weakly fossiliferous sands. It is likely that the fossils were introduced into the palaeocave by raptors, such as barn owls.

The red fossiliferous breccia was treated in a solution of 10% formic acid. Large bones were coated in superglue prior to being bathed in acid.

The insoluble residue was then washed in water until neutral, dried and then classed by granulometry at 1, 0.8, 0.7, and 0.6 mm, each class being examined under the microscope in order to extract fossils.

Taphonomy and diagenesis

Many of the fossils at Sheikh Abdallah are cracked or scored by fissures. The kind of damage observed suggests that the remains were dehydrated before being fossilised which in turn indicates that they were not buried immedi-

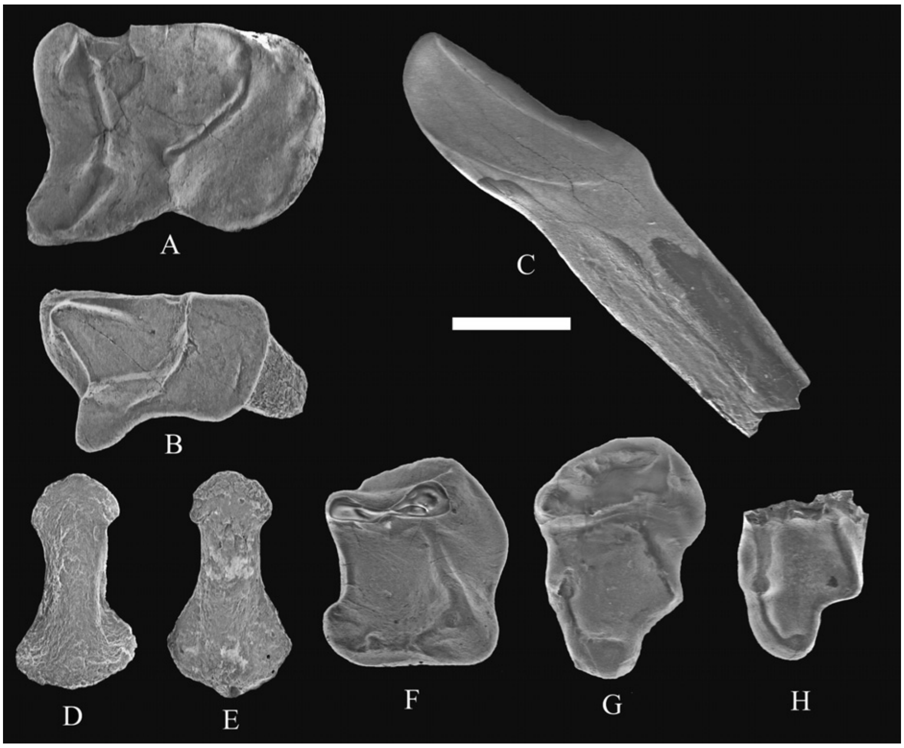

FIGURE 7 | **Scanning Electron Microscope images of specimens of *Galago farafraensis* from Sheikh Abdallah, MN 9, Western Desert, Egypt. A) SA 3'05, right M2/, occlusal view; B) SA 4'05, right M3/, occlusal view; C) SA 7'05, right c/1, lingual view; D) SA 15'05 terminal phalanx dorsal view; E) SA 14'05 terminal phalanx volar view; F) SA 9'05, right m/1, occlusal view; G) SA 10'05, right m/3, occlusal view; H) SA 11'05, talonid of right m/3, occlusal view (scale: 1 mm).**

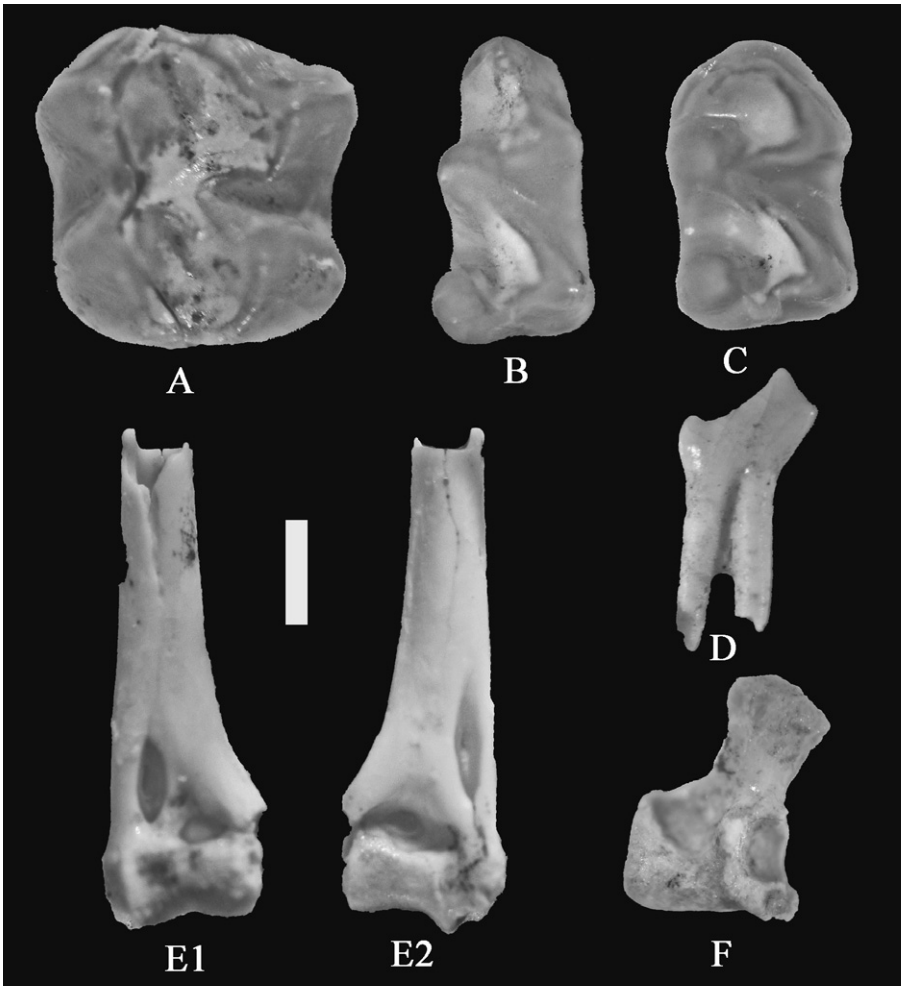

FIGURE 8 **Bones and teeth of *Rhynchocyon* from locality 137 at Sheikh Abdallah, late Miocene (11-10 Ma). A) Right upper molar occlusal view; B) Right lower premolar occlusal view; C) Right lower molar occlusal view; D) Right lower premolar buccal view; E) Distal end of left humerus anterior and posterior views; F) Left talus tibial view (scale: 1 mm).**

ately after deposition or that the sand in which they occurred was dry. Many of the teeth consist of enamel caps from which the dentine has disappeared.

The cave deposits are cemented by calcite, but it is not known whether the quartz crystals formed prior to, at the same time as, or posterior to the period of cementation.

Taxonomy, fossil assemblage

Well over 1000 teeth and abundant post-cranial remains were recovered from ca 40 kg of sediment at locality 137 at Sheikh Abdallah. Not surprisingly there are several new records of reptiles, birds and mammals (Figs. 7 and 8, Table 2).

The fauna listed in Table 2 is most similar to faunas occurring in MN 9 in the peri-Mediterranean region, not only in the Maghreb, North Africa, but also in Spain, France and Turkey. The high diversity of *Myocricetodon* and the presence of *Progonomys*, in particular, invite correlation to this zone. There are however, some faunal elements at Sheikh Abdallah that are characteristic of sub-Saharan Africa, including *Rhynchocyon*, *Ternania*, and *Preacomys*. Two genera stand out in this list, *Atherurus* and *Apocricetus*. The small hystricid teeth attributed to *Atherurus* (the tree porcupine of West Africa) represent the earliest record of porcupines in Africa, predating the earliest European record of the family which evidently had its origins in Asia. The genus *Apocricetus* is known from much younger (Late Miocene to Pliocene) deposits in France and Spain (Freudenthal et al., 1998) and its presence in considerably earlier deposits at Sheikh Abdallah is a surprise, perhaps indicating an African origin for this genus.

Biochronology

On the basis of about 100 teeth, Heissig (1982) concluded that the most likely age of the deposits was basal Vallesian, a conclusion that was supported by Coiffait (1991). Our own results based on a much enhanced sample of fossils (1000 + teeth) support this age, probably equivalent to MN 9 of the European mammalian zonation

TABLE 2 **Updated faunal list – Sheikh Abdallah, Egypt.**

Amphibia		Anura spp.
Lacertilia		Indet. spp.
Ophidea		Colubridae 2 spp.
Aves		Indet. spp.
Primates		
	Galagidae	*Galago farafraensis*
Insectivora		
	Erinaceinae	*Minuscule sp.*
	Crocidurinae	*Lartetium* sp.
Macroscelidea		
	Macroscelididae	*Rhynchocyon* sp.
Chiroptera		*Megaderma* sp.
		Rhinolophus sp.
		Syndesmotis sp.
Rodentia		
	Hystricidae	*Atherurus* sp.
Sciuridae		?*Atlantoxerus* sp.
Ctenodactylidae		*Africanomys major*
		Africanomys minor or *ketterati*
Gliridae		*Dryomys* cf *ambiguus*
Muridae		
	Cricetinae	*Apocricetus* sp.
	Gerbillinae	*Myocricetodon* aff *parvus*
		Myocricetodon aff *cherifensis*
		Myocricetodon aff *ihroudi*
		Myocricetodon sp.nov.
		Myocricetodon magnus
	Dendromurinae	cf *Steatomys* sp.
		cf *Dendromus* sp.
		Ternania sp.
	Murinae	*Progonomys* sp. and/or *Preacomys* sp.

(Mein, 1990). If this correlation is valid, then the Sheikh Abdallah deposits are probably between 11 and 10 Ma. However, in view of some residual uncertainty about the identification of *Progonomys* and/or *Preacomys* and the presence of a high diversity of *Progonomys* in pre-Vallesian deposits of Europe, there remains the possibility that the deposits could be somewhat older. The occurrence of *Apocricetus* at Sheikh Abdallah could indicate the presence of younger levels in the deposits. Further study is required, especially of the other fossil assemblages now known to occur in the breccias. Because the palaeocave system was extremely extensive, it is quite possible that there were many different episodes of deposition spanning a considerable period of time, as is usually the case in karst systems. Alternatively, there are faunal elements of different ages represented in locality 137.

DISCUSSION

Palaeobiogeography and palaeoenvironment and palaeoclimatology

Of major biogeographic interest is the presence in the Sheikh Abdallah fauna of two families of tropical African mammals, Galagidae and Macroscelididae (the latter family is also present today in the Maghreb) and of the arboreal porcupine *Atherurus*. These taxa occur in humid African phytochores III, IV, XI and XIII (Fig. 9) (White, 1983). Most of the fossil rodents and bats have a circum-Mediterranean distribution or are pan-African or even cosmopolitain. Megadermatid bats occur in the tropics but the two other families of bats from the site are extremely widespread.

The presence of galagids at Sheikh Abdallah (Pickford et al., 2006; Fig. 7) represents a major northwards range extension compared with their present day distribution (Wolfheim, 1983) (Fig. 9). The family occurs today in a variety of habitats including semi-arid woodland and bushland, as well as forest, but none of the species can survive in hyper-arid deserts. Galagids are obligate arboreal nocturnal animals. The small species consume tree exudates (gum) which comprises an important part of their diet. They also require hollows in trees that provide shelter from predators and heat during the day when they are inactive. The presence of galagids at the fossil site, regardless of the species present, thus provides good evidence that central Egypt was appreciably more humid during the early part of the Late Miocene than it is today. The fact that the site is far from the riparian effects of the Nile (Fig. 1A), suggests that the entire region was probably more humid between 11 and 10 Ma than it is today. At present the most northerly record of galagids (*Galago senegalensis*) is 16° N in Sierra Leone and in the east it is near the junction of the Blue Nile and White Nile (ca 15°N latitude) in Sudan (Wolfheim, 1983) some 1,500 km south southeast of Sheikh Abdallah. In general galagids, such as *G. senegalensis*, require a mean annual rainfall of at least 300 mm, even in areas such as the Nile Valley where riparian effects on vegetation are marked. In regions removed from riparian effects they require a mean annual rainfall greater than 500 mm to survive. Given that Sheikh Abdallah is 220 km west of the Nile valley, the mean annual rainfall 11-10 million years ago was likely to have been about 500 mm or more. This contrasts strongly with its present day hyperarid climate.

The galagid from Sheikh Abdallah, *Galago farafraensis* (Fig. 7) is most similar in size to *Galagoides demidovii* which today is restricted to forested and well wooded habitats within 10° of the Equator. It's range falls within the 1200 mm annual rainfall isohyet. If the Egyptian fossil species had the same requirements as *Galagoides*, then it implies that 11-10 million years ago, the region around Sheikh Abdallah would have been considerably more humid than it is today.

The palaeoclimatic deductions based on the presence of galagids at Sheikh Abdallah find support from the rest of the microfauna, which includes *Atherurus*, a small arboreal porcupine today restricted to tropical forests of

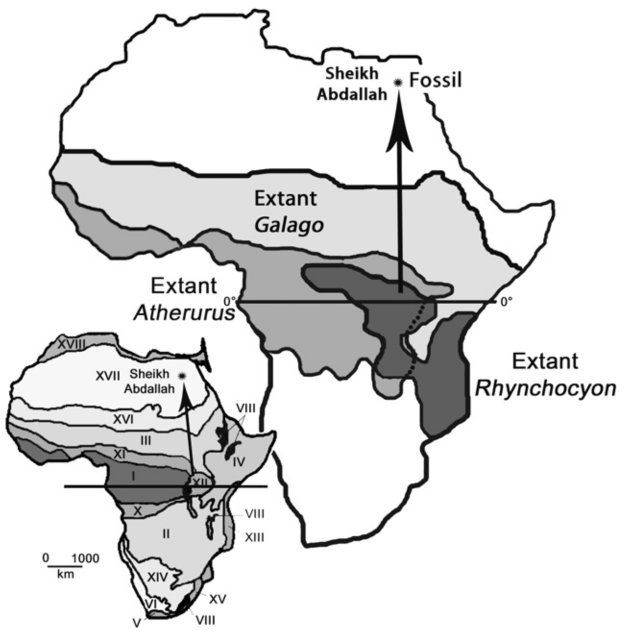

FIGURE 9 | **Extant distribution of *Galago*, *Atherurus* and *Rhynchocyon* in relation to present day African phytochores. The palaeovegetation at Sheikh Abdallah corresponds to phytochores III, IV, XI, and XIII. This suggests a mean annual rainfall of between 750 and 1,200 mm for Sheikh Abdallah at the time of accumulation of the fossil fauna. Phytochores based on White (1983).**

West Africa and the macroscelidid *Rhynchocyon* (Fig. 9), the glirid *Dryomys* which is an arboreal rodent, although it can survive in quite arid environments, and three species of dendromurines (two of which are arboreal mice, one a burrowing rodent) (Haltenorth and Diller, 1980; Wilson and Reeder, 1993; Kingdon, 1997; Schlitter, 2005). The large bat *Megaderma* is also usually found in forested areas, although being volant, it can fly over dry areas (Kingdon, 1997).

It should be pointed out however, that some of the rodent taxa such as the ctenodactylid *Africanomys*, indicate the presence of open country, possibly with grass, within the vicinity of the Sheikh Abdallah cave system (Heissig, 1982).

Origins of the great oases of the Western Desert

For more than a hundred years there has been debate about the origins of the great oases of the Western Desert of Egypt (Bahariya, Farafra, Dakhla) (Said, 1962) so far without resolution. Several factors or processes have been invoked including tectonic activity, aeolian deflation, fluvial erosion, salt weathering and karst processes.

The oases are vast generally ovoid depressions cut into Cretaceous and Early Cenozoic strata, and are underlain by Nubian Sandstone and rocks of the Basement Complex (Figs. 1A, 10) (usually not exposed). The Cretaceous and Cenozoic strata are dominated by carbonates, but do contain important quantities of clay, sandstone, chert and other insoluble rocks (basalt, iron ore and glauconite, for example).

Tectonic activity has been called in to explain some aspects of the formation of the Egyptian oases, mainly because they tend to occur on vast, low-angle anticlines, with signs of faulting and tilting of strata. However, the continuity of strata around the edges of the depressions over distances of hundreds of km indicates that tectonic activity on its own does not explain the formation of the depressions, which have no outlets. The importance of tectonics is that such activity produced the subterranean ingredients necessary to focus the activity of other processes into certain zones, with action taking place preferentially in areas that were anticlinal in tectonic style. Whether this focus was due to the expression of surface relief which enhanced erosion atop the initial positive relief of the anticlines, or whether it focussed groundwater flow along fissures and strata in anticlinal zones is not known, although this is likely given that anticlines tend to possess tensional structures, especially near surface, whereas synclines tend to be compressional, notably at the surface.

Fluvial erosion has undoubtedly taken place in the Western Desert, but since all the oases are endorheic, such processes did not remove sediment from the depressions, but merely altered their surface configuration, tending to fill the depths of the depressions and back-wasting their scarp-like edges. Thus fluvial erosion can be discarded as the fundamental cause of the depressions, its role being that of modifying their form rather than being responsible for creating the depressions.

Aeolian deflation has featured prominently in explanations of the formation of the depressions, mainly because the evidence of wind erosion in the region is pervasive and spectacular. It is a simple matter of observation to notice that sand can be blown up the sides of the depressions and onto the surrounding flat desert. However, no studies have been done on the quantities of sand removed from the depressions on the one hand, and the amount carried into the depressions or originating by erosion of sediments already within the depressions, on the other. While wind-assisted erosion is undoubtedly a feature of the depressions, especially their edges and in many places in their bases, the overall role and rate of aeolian deflation at the scale of the basins is unknown.

Because the country rock surrounding the large depressions in which the oases occur is comprised largely of carbonates, and because the existence of caves in the limestones has been known for a long time (Rohlfs, 1875)

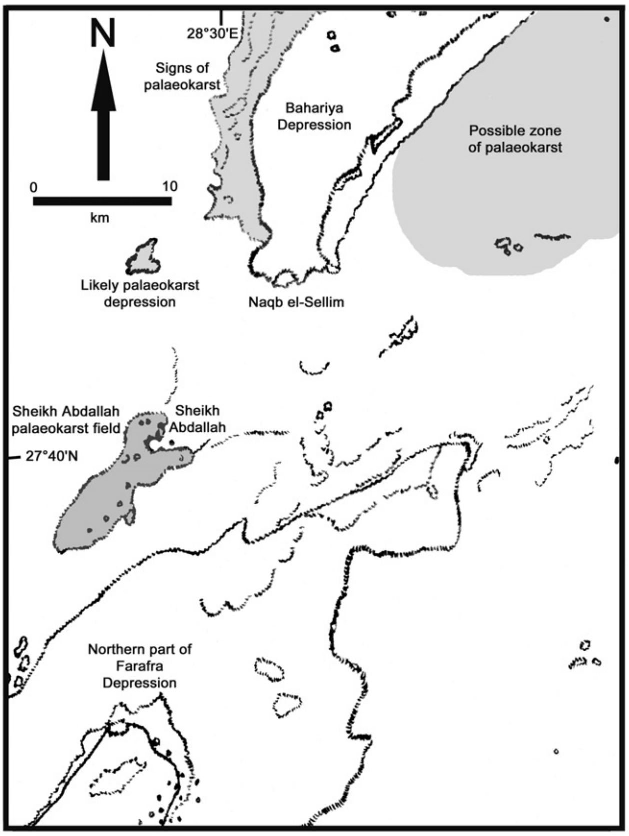

FIGURE 10 **Sketch map of the Sheikh Abdallah palaeokarst field and nearby areas where similar topography indicates the possible presence of other palaeokarst networks, although these areas have not yet been surveyed on the ground.**

karst processes have often been evoked in explanations of the formation of the depressions, but in general such an origin has not found favour or has been viewed as having played only a minor role in their formation. This is probably because signs of karstic activity have been noticed in only a few places and even there, they are not very spectacular. However, dissolution of carbonates may have been considerably more important than hitherto considered possible, mainly because the quantity of karst related deposits appears to have been underestimated by geologists, who generally failed to observe karst infillings or if they did, did not realise the implications of their observations. The discovery that extensive karst infillings are present in the Sheikh Abdallah depression, indicates that the role of karst processes in the formation of the oases depressions of Egypt needs to be reassessed. We have observed similar red sand breccias and speleothems near El Obeiyd Cave about 80 km southwest of Sheikh Abdallah, and we encountered similar deposits in many places between Sheikh Abdallah and El Djarra Cave, 180 km to the southeast. Examination of satellite imagery indicates the possibility of widespread palaeokarst systems both west and east of Bahariya Oasis (Fig. 10), but ground control needs to be carried out. The only way to do this is to map the depressions in detail, looking in particular for karst deposits. An important point about karst infillings is that they often contain faunal remains, and the time of infilling can therefore be determined, thereby providing a time scale for geomorphological processes in the depressions.

Karst deposits have the potential to provide evidence which is interesting, not only from the point of view of understanding the origins of the Egyptian oases, but by being repositories of palaeoenvironmental and palaeontological evidence, may also provide evidence about palaeoclimatic conditions in the region, and may thus throw light on the timing of the origin of the Sahara Desert.

Regional Palaeoclimatology

The discovery of fossiliferous late Miocene cave breccias in central Egypt is important not only because it helps to fill an enormous geographic and chronological gap in the African fossil record (Fig. 3) but also because of the information it yields about the geological history of the region, including its palaeoclimatology and geomorphology.

The clay content of the Sheikh Abdallah cave breccias, their diagenetic characters such as the presence of authigenic quartz inside cavities in fossil bones, and the composition of the late Miocene (MN 9) fauna that they yield, all indicate that a relatively humid tropical environment prevailed during the deposition within the karst system between 11 and 10 Ma. This in turn indicates an abundance of vegetation during that time interval.

The timing of the onset of aridification in the Sahara Desert is poorly constrained, with estimates varying widely, some authors proposing a middle Miocene origin, whilst others have suggested a late Miocene one (Pickford, 2000; Schuster et al., 2006). Consideration of the available palaeoclimatological evidence on a continental scale, suggests that the Sahara was well wooded to forested during the middle Miocene (Pickford, 1999, 2000) but was semi-arid in parts by the end of the late Miocene (Dechamps, 1987).

The acceleration of aridification in the latest Miocene was probably related to expansion of the North Polar Ice Cap and the establishment of the monsoon weather system in the Indian Ocean hemisphere, both of which may be related to uplift of the Tibetan Plateau to climatically important altitudes (Kutzbach et al., 1993; Fortelius et al., 2002; Hongbo Zheng et al., 2004; Pickford, 2004; Molnar, 2005) but the literature shows a wide range of ages during which these changes are thought to have occurred (10 Ma to 8 Ma). Because of the rather limited nature of the fossil record of Saharan countries, and the relatively poor chronological control on the age of the fossiliferous deposits, all new fossil discoveries within them are precious. For this reason, further study of the Sheikh Abdallah occurrence in the Western Desert of Egypt is important, as is the pursuit of the search for new localities (Halliday, 2003) as these may well provide better constraints on hypotheses about the onset of aridification in the Sahara, which at a larger scale, will impact on our understanding of the evolution of Old World palaeoclimates during the Late Neogene.

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