Facies and early diagenesis of rainwater-fed paleospring calcareous tufas in the Kurkur oasis area (southern Egypt)

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Abstract
The Quaternary calcareous tufas precipitated in the Kurkur Oasis area in the southern Western Desert of Egypt were analyzed to determine their implications for the construction of environmental conditions during their formation. X-ray diffraction analysis showed that the tufas consist of low-Mg calcite, whereas macroscopic and microscopic analyses showed the presence of both allochthonous (clastic) and autochthonous components consisting predominantly of pisoliths, oconoids, intraclasts, lithoclasts, stromatolites and encrusted plant materials. These tufas form four facies associations that represent pisolithic intraclastic/lithoclastic oncoidal rudstones, phytohermal/bryophyte framestones, stromatolite-algal boundstones, and speleothem-like flowstones. These tufa associations were formed within a karstified carbonate terrain by a rainwater-fed paleospring system comprising waterfalls, slopes, dammed areas, lacustrines-paludal, and fluvial channel margin environments. Early diagenetic features are cementation, neomorphism and subaerial dissolution. Isotope-geochemical analysis indicated that the negative δ18O values (between –13.26 and –8.89‰ V-PDB) and the negative δ13C values (between –3.16 and –1.62‰ V-PDB) of the studied tufas are consistent with carbonates deposited from meteoric water in regions with much precipitation.

Keywords Facies analysis · Depositional environments · Early diagenesis · Tufa · Kurkur oasis

Introduction
The term “tufa” is commonly used for terrestrial carbonate sediments precipitated primarily under subaerial conditions from water saturated with calcium carbonates. This can take place in a wide variety of depositional settings (e.g. Pedley 1990; Ford and Pedley 1996; Das and Mohanti 2005; Gandin and Capezzuoli 2008; Arenas et al. 2014; Nicoll and Sallam 2017; Rodríguez-Berriguete 2020; Kele et al. 2021). Tufa formation is most likely associated with karstification processes and later carbonate precipitation in fluvial and spring-fed systems (e.g. Goudie et al. 1993; Pazdur et al. 2002; Dabkowski 2020; Ruban et al. 2021). The genesis of tufas is the result of complex interactions of both organic and inorganic processes that occur under different flow regimes and climatic conditions (Pedley 1994; Pedley et al. 1996; Riding 2000; Rodríguez-Berriguete et al. 2021). The precipitation process is presumed to be microbially-induced since phytoherms, bryophytes (commonly mosses) and microbial mats contribute and facilitate tufa genesis (e.g. Pedley 1990; Das and Mohanti 1997; Carthew et al. 2003; Pentecost 2005).

Tufas are characterized by highly porous textures with poor stratification and by elongated shapes, and commonly contain abundant remains of macrophytes (marginal pond plants such as reeds, rushes and shrubs) and microphytes (tiny plants or photosynthetic organisms such as cyanobacteria, epiphytes and diatoms) that are coated by calcium carbonates (e.g. Ford and Pedley 1996; Arenas et al. 2000, 2010; Capezzuoli et al. 2014; Nicoll and Sallam 2017; Kele et al. 2021; Sallam and Abou Elmagd 2021). Tufas are, like most terrestrial carbonates, very sensitive to environmental and climatic fluctuations during their origination (e.g. Andrews 2006; Ford and Pedley 2006; Pedley 2009; Sallam 2022), particularly, the plant remains (including pollen records) in tufas may provide important clues (e.g. Taglia-sacchi and Kayseri-Özerb 2020).

Tufa layers build up mounds, pinnacles, aprons and fissure ridges with flanking slopes, self-built channels or tabular units (e.g. Pentecost 2005; Nicoll and Sallam 2017;...
Sallam et al. 2018). These morphologies are mainly controlled by the morphology of the underlying substrate, the tectonic setting, and the sedimentary (erosion vs. sedimentation) and hydroclimatic regimes involved (e.g. Pedley 1994; Pedley et al. 1996; Riding 2000; Viles et al. 2007; Arenas et al. 2014).

In the Kurkur Oasis area in the southern Western Desert of Egypt, tufas precipitated on top of several erosional surfaces at various elevations along the south-eastern edge of the Sinn El-Kaddab Plateau (Butzer 1965; Issawi 1968; Ahmed 1996). These tufas have characteristic textures resulting from complex interactions between organic and physicochemical processes during both precipitation and early diagenesis (e.g. Sultan et al. 1997; Hassan 2014; Nicoll and Sallam 2017; Sallam and Ruban 2019; Kele et al. 2021). Gaber et al. (2018) dated these tufas as Pleistocene for the older, upper levels (~345 m a.s.l.) to Holocene for the younger, lower levels (~270 m a.s.l.). Crombie et al. (1997) and Gaber et al. (2018) indicated that the older tufas at the higher topographic levels were formed under warm pluvial conditions, whereas the younger tufas in Wadi Kurkur and at the bottom of the oasis were formed under drier conditions. Kele et al. (2021) documented that the tufas in the Kurkur-Dungul area originated from paleosprings that were active during glacial periods with low sea-level (below~50 m), and these tufas date between 368 ± 14 and 11.7 ± 1.2 ka (from marine isotope stage (MIS) 11 to MIS 1).

Tectonically-induced cracks, fissures and fault planes cut through the underlying rocks (Issawi 1968; Abou Elmagd et al. 2015). This facilitates enhanced groundwater recharge and the development of springs with water that is saturated with calcium carbonate. Their sources are shallow perched karstic aquifers above the Post-Nubian Aquifer System (PNAS) that were formed during Pleistocene stages of increased rainfall (e.g. Bakhbakhi 2006). Such hydroclimatic conditions resulted in a continuous soil cover and a high soil activity induced by plants.

The present contribution is aimed at increasing the insight into the sedimentological and early-diagenetic modifications of clacareous tufas in the Kurkur Oasis area, as well as to determine their geochemical (δ13C and δ18O) patterns. The sedimentological features of the studied tufas include the macroscopic and microscopic facies types, which are analyzed to determine their depositional environment and spatial distribution. The facies characteristics are integrated with the isotopic data for a reconstruction of the environmental conditions under which the Kurkur tufas accumulated.

Geological setting and lithostratigraphy

The Kurkur Oasis is located at the south-eastern edge of the Sinn El-Kaddab Plateau in the southern Western Desert of Egypt, about 60 km west of Aswan City. This area is dissected by numerous faults, which run mostly E-W and N-S (Issawi 1968; Abou Elmagd et al. 2015; Issawi et al. 2016; Issawi and Sallam 2018). The Kurkur Oasis consists mainly of thick sedimentary successions of Cretaceous, Paleocene and early Eocene age (Fig. 1). These successions are made up of fluvial cross-bedded sandstones of the Cretaceous Nubia Formation, which unconformably overlies Precambrian crystalline rocks, and is conformably overlain by calcareous shales of the Maastrichtian Dakhla Formation. During the Paleocene, the Neo-Tethys transgressed over the Kurkur area and deposited the fossiliferous limestones of the Kurkur Formation, which is followed upward by chalky limestones of the Garra Formation. The transgression continued during the early Eocene and resulted in the deposition of shallow-marine reefal limestones of the Dungul Formation (Issawi 1968). During the middle Eocene, the Kurkur Oasis area was uplifted, which resulted in a gradual retreat of the sea from the area so that a landmass originated (the Sinn El-Kaddab Plateau) that still is present. Since the uplift, no marine conditions were present any longer and the area was subjected to deep weathering, erosion and deflation (Ahmed 1996). Several outliers and erosional remnants in the form of mesas and knolls remained all over the plateau, but also some small depressions were formed (the Kurkur and Dungul oases). The most remarkable depositional process that occurred in the Kurkur Oasis during the Quaternary was the precipitation of tufa carbonates from freshwater springs (Issawi, 1968; Ahmed 1996). These tufas were preserved above several topographic elevations along the Sinn El-Kaddab Plateau, the bottom of the Kurkur Oasis and its surroundings, and in the Nubian plain (Issawi 1968; Ahmed 1996; Nicoll and Sallam 2017). Other Quaternary sediments in the area are represented by conglomeratic sheet-like deposits and mud playas.

Materials and methods

Sampling

Detailed fieldwork on the tufa deposits in the Kurkur Oasis area in southern Egypt was carried out to describe their lithological and macromorphological characteristics. A total of 67 tufa samples were collected from seven outcrops (sites 1 through 7) located at different topographic elevations throughout the studied area (Figs. 1, 2). The tufa sites 1 to 4 are located at the lower erosional surfaces along the Nubian
Fig. 1  A Google Earth image of the Kurkur Oasis area showing the sampling sites (sites 1 through 7) of the studied calcareous tufas. B Geological map of the Kurkur Oasis area (after Issawi 1968; Ahmed 1996)
plain, the downstream of Wadi Abu Gorma and the scarp face of the Sinn El-Kaddab Plateau, whereas the tufa sites 5 to 7 are located at relatively higher elevations along the upstream of Wadi Abu Gorma and the surface of the Sinn El-Kaddab Plateau. Using U–Th age data, Jimenez (2014) and Kele et al. (2021) dated the Kurkur tufas between 326 ± 14 ky for the older tufas at the higher levels, and 139 ± 11 ky for the younger tufas at the lower levels.

A detailed petrological study was carried out on hand-specimen tufa samples, supplemented by microscopic observations of 67 thin-sections using an Olympus BX51 polarizing microscope attached by an Olympus LC20 digital camera.

**Geochemical and XRD analyses**

Twenty-seven samples collected from the above-noted sites were analyzed for stable isotope geochemistry (δ18O and δ13C) using an automated carbonate preparation device (Gasbench II) and a Thermo Fisher Scientific Delta Plus XP continuous flow mass spectrometer. The carbon and oxygen isotopic compositions are expressed in the conventional delta notation against the international standard V-PDB. The isotopic geochemistry was carried out at the Institute for Geological and Geochemical Research, Hungarian Academy of Sciences, Budapest, Hungary.

The whole-rock mineralogy of some tufa samples was analyzed using X-Ray Diffraction (XRD) technique. Analytical X-Ray Diffraction equipment model X’Pert PRO with Secondary Monochromator, Cu-Kα radiation (λ = 1.542 Å) operating at 45 K.V., 35 M.A., and scanning speed 0.04°/sec, were used.
The diffraction peaks between $2\theta = 2^\circ$ and $60^\circ$, corresponding spacing (d, Å) and relative intensities ($I/I_0$) were obtained. The diffraction charts and relative intensities are obtained and compared with ICDD files. The samples were carried out using zero background holder. XRD analysis was carried out at the Central Laboratories of the Egyptian Mineral Resources Authority (EMRA) in Cairo, Egypt.

**Mineralogical and chemical compositions**

XRD scans showed that the analyzed tufa samples are composed mainly of calcite ($\text{CaCO}_3$; 96–100%) with very minor quartz content in some samples (4%) (Fig. 3). Aragonite, dolomite or evaporite minerals have not been detected. Elemental geochemical analysis for seven samples showed that the studied tufas consist mainly of low-magnesium calcite ranging from 1.2 to 2.8 mol % $\text{MgCO}_3$. 

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Fig. 3  A, B X-ray diffraction pattern of the encountered minerals in the analyzed tufa samples
Field and macroscopic observations

The studied tufas were described in the field for their texture, components and geometry. They were sampled from seven outcrops (sites 1–7) throughout the Kurkur Oasis area (Figs. 1, 2). A detailed lithological and macromorphological description of these tufa sites is given below and outlined in Table 1.

Tufa site 1

This tufa outcrop is located at 243 m a.s.l. (the lowest elevation – the youngest tufa) between lat. 23° 53’ 08” N and long. 32° 26’ 03” E. It consists of earthy gray, hard, porous tufa, which is characterized by pisoid-bearing layers intercalated with fine-grained siltstones. This type of tufa unconformably overlies the Cretaceous Nubia Fm. along the pediment of the Nubian plain. Preserved thickness of this tufa outcrop is about 4 m covering an area of approximately 50–60 m length and 8–10 m width, with a linear orientation of NE-SW direction.

Table 1 Lithological and macromorphological description of the tufa deposits in the Kurkur Oasis in the southern Western Desert of Egypt

| Sampling sites | Coordinates | Elevation (m a.s.l.) | Lithology | Thickness (m) |
|----------------|-------------|---------------------|-----------|---------------|
| Site 1         | 23° 53’ 08” N 32° 26’ 03” E | 243 | Tufa outcrop located on the piedmont surface overlying the Nubia Formation (Cretaceous) in the Nubian plain. It consists of earthy gray, hard, porous, cross-laminations, pisoids and conglomeratic materials interbedded with fine-grained siltstones. This tufa outcrop attains 50–60 m long and 8–10 m wide, with a linear orientation of NE-SW direction | 4.0 |
| Site 2         | 23° 52’ 04” N 32° 22’ 06” E | 272 | Tufa outcrop located at the downstream of Wadi Abu Gorma. It unconformably overlies the Dakhla Shale (Late Cretaceous). Tufa is gray to whitish gray, hard, vesicular, cavernous and brecciated. It includes lithic fragments from bedrock and contains very rare plant imprints. Laminated tufa, dense crystalline, hard, porous in parts, having convolute lamination and stromatolitic texture. This tufa outcrop occurs in the form of high hillocks or mounds with stromatolite layers occupying an area of ~ 0.5 km² | 8.0 |
| Site 3         | 23° 52’06” N 32° 21’ 31.6” E | 320 | Porous phyothermal tufa located at the scarp face of the Sinn El-Kaddab Plateau. It unconformably overlies the Kurkur Formation of Paleocene age. Tufa is vesicular, dark gray to blackish in color, hard, fence-like, porous, and is highly rich in empty molds of reed stems in vertical or horizontal positions | 10 |
| Site 4         | 23° 52’ 9.7” N 32° 19’ 25” E | 325 | Tufa and crystalline prismatic calcite deposits located at the scarp face of the Sinn El-Kaddab Plateau. They overlie the limestone strata of the Paleocene Kurkur Formation. Tufa is earthy gray, hard, laminated, having concentric and laminated cellular structures, and is very rich in empty casts of reed stems and shrubs | 3.0 |
| Site 5         | 23° 52’ 26.5” N 32° 18’ 58”E | 350 | Tufa associated with crystalline calcite located at the upstream of Wadi Abu Gorma, and it unconformably overlies the Kurkur Formation and/or the lower beds of the Garra Formation (Paleocene). Tufa is earthy gray in color, hard, showing cellular structure, and is very rich in empty molds of reeds and bushes. Laminated tufa, hard, concentric wavy laminated and cavernous. Crystalline calcite is dark gray to black, exhibiting prismatic structure | 40–50 |
| Site 6         | 23° 53’ 16.6” N 32° 18’ 55.2”E | 330 | Tufa outcrop bordering the Kurkur Oasis. Tufa is earthy gray, hard, preserving abundant vegetal and vesicular framework, and parallel to inclined lamination structures. Laminated tufa is crystalline, showing concentric ball-like structure | 7.0–8.0 |
| Site 7         | 23° 53’ 9.8” N 32° 17’ 27.5” E | 375 | Tufa outcrop located atop the plateau surface overlying the hillocks of the Garra Formation (Paleocene). Tufa is gray to dark gray, hard, porous and highly cavernous | 6.0 |
stromatolitic texture. This tufa occurs in the form of lentil- 
cular mounds with stromatolite layers occupying an area 
of approximately 0.5 km². Preserved thickness of this tufa 
outcrop is about 8 m. This type of tufa unconformably over-
lies the Maastrichtian Dakhla shale at the downstream of 
Wadi Abu Gorma.

Tufa site 3

This tufa outcrop is located at 320 m a.s.l. between lat. 23° 
52’ 06” N and long. 32° 21’ 31.6” E. It is composed of dark 
grey to blackish-gray, porous, hard, lenticular profile, vesicu-
lar tufa containing rich macrophytes of empty cylindrical 
molds of reed stems and shrubs occurring in horizontal, 
oblique and vertical (growth) positions. Preserved thickness 
of tufa outcrop in site 3 is about 10 m. This tufa unconform-
ably overlies the Paleocene Kurkur Fm. at the scarp face of 
the Sinn El-Kaddab Plateau.

Tufa site 4

This tufa outcrop is located at 325 a.s.l. between lat. 23° 
52’ 9.7” N and long. 32° 19’ 25” E. It consists of vesicular 
tufa and crystalline prismatic calcite. Tufa is earthy gray, 
hard, laminated, exhibiting concentric cellular structure, 
and is very rich in empty cylindrical casts of reed stalks 
and shrubs. The prismatic calcite fills cavities and vuggs 
occurs in host tufa rocks. Residual thickness of this tufa 
outcrop is about 3 m. This tufa outcrop unconformably over-
lies the Paleocene Kurkur Fm. at the scarp face of the 
Sinn El-Kaddab Plateau.

Tufa site 5

This tufa outcrop is located at 350 a.s.l. between lat. 23° 
52’ 26.5” N and long. 32° 18’ 58” E. It is made up of vesicu-
lar and laminated stromatolite tufas associated with crys-
talline calcite pockets. Tufas are earthy gray, hard, display-
ing cellular structure, and is very rich in empty cylindrical 
molds of reed stems and bushes. Laminated stromatolite 
tufas are gray to dark gray, hard, cavernous, exhibiting 
undulating convolute laminations. Crystalline calcite is 
dark gray to blackish-gray, showing prismatic structure. 
Preserved thickness of this tufa outcrop is 40–50 m. It 
overlies the Kurkur Fm. and/or the lower limestone strata 
of the Garra Fm. at the upstream of Wadi Abu Gorma.

Tufa site 6

This tufa outcrop is located at 330 m a.s.l. between lat. 23° 
53’ 16.6” N and long. 32° 18’ 55.2” E, bordering the Kurkur 
Oasis. It consists of earthy gray, hard, porous, vesicular tufa 
preserving abundant vegetal and vesicular framework with 
abundant empty cylindrical casts of plant stems. Associated 
tufa is laminated, crystalline and concentric, exhibiting a 
characteristic ball-like structure. Residual thickness of this 
tufa outcrop is about 8 m.

Tufa site 7

This tufa outcrop is located at 375 m a.s.l. (the highest eleva-
tion- the oldest tufa) between lat. 23° 53’ 9.8” N and long. 
32° 17’ 27.5” E. It is composed of gray to dark gray, hard, 
massive, porous, highly cavernous tufa including no plant 
casts. Preserved thickness of this tufa outcrop is 6 m. This 
type of tufa covers unconformably the top of the Garra For-
mation (Paleocene) above the surface of the plateau. The 
absence of plant remains in this site suggests a poor veg-
etated area and arid climate (cf. Rodriguez-Berriguete et al. 
2021).

Facies analysis and depositional 
environments

Various facies types are distinguished in the studied 
Kurkur tufas on the basis of both macroscopic and micro-
scopic observations. Following the terminology proposed 
d by D’Argenio and Ferreri (1987) and adopted by Pedley 
(1990), both allochthonous (encrustation around clast 
fragment) and autochthonous tufas (in situ encrustation 
around organismal templates) are recognized, in addition 
to the associated speleothem–like crusts. These tufas form 
four facies associations that are comprised essentially of 
pisolitic intraclastic/lithoclastic oncoidal rudstones, phyto-
thermal/bryophyte framestones, stromatolite-algal bound-
stones, and speleothem-like flowstones. The characteristics 
of these facies associations and their depositional environ-
ments are presented in Table 2 and discussed below.

Pisolitic intraclastic/lithoclastic oncoidal rudstones

Facies description

The pisolitic intraclastic rudstone facies unconformably 
overlies the Nubia Formation along the Nubian plain. It 
occur largely at site 1. The pisolitic tufa is earthy gray in color, 
hard, granulated, cross-bedded and laminated. Pisoliths tend to form well-cemented layers show-
ing horizontal, cross bedding and normal gradded-bedding 
(Fig. 4A). The pisoliths vary from spherical, elliptical to irregular in shape, and sizes range between 0.3 and 3 cm
| Facies associations               | Textural characteristics and components                                                                 | Geometry of deposits                        | Depositional environment                                                                 |
|---------------------------------|-------------------------------------------------------------------------------------------------------------|---------------------------------------------|------------------------------------------------------------------------------------------|
| Pisolitic intraclastic/lithoclastic (oncoidal) rudstones | Spherical and elongated pisoliths and coated grains (intraclasts, phytoclats or fossil fragment as nuclei). Grain size from mm to several cm. Cortex of micritic to radially arranged lozenge-shaped crystals | Tabular-to-lenticular profile, up to dm in thickness and several m in lateral extent | Ubiquitous, depending on the facies type. Aggradation in slow-flowing water environments (water pools and and dammed areas) waters for water-energy fall (Pedley 1990) |
| Phytothermal/bryophyte (mosses-rich) frame-stones | Elongated, vertically oriented tubes (several cm long, 0.5–2 cm wide) of plants in growth position with clotted peloidal micrite, or prismatic crystals carbonate coatings (0.2–5 mm thick) | Lenticular, occasionally domed or tabular, up to 1 m thick | Slow-flowing paludal areas. Depending on facies type, it can represent inter-channel areas or lacustrine shores (Arenas et al. 2010) |
| Stromatolite-algal boundstones   | Subparallel, discontinuous, crusts (0.01–2 mm thick) of micritic peloidal and dominantly microsparitic laminae. Local presence of microbial filaments (mm long) | Undulatory or hemidomic. Locally tabular or lenticular, dm to cm in thickness, with set of mm/cm laminae | Fast-flowing waters in gently sloped, stepped channels. Depending on facies type, it can represent standing waters in lacustrine/paludal shores (Shiraishi et al. 2008; Pedley et al. 2009; Gradziński 2010) |
| Speleothem-like flowstones       | Prismatic to lozenge-shaped crystals (0.05–2 mm long), turbid appearance, undulate extinction, locally sub-parallel growth laminae; crystals formed by elongated, sub-crystals in a feather-like arrangements (local as fan-like), often with uniform extinction | Tabular, locally lenticular or hemidomic. Up to several dm in thickness and variable in lateral extent | Fast-flowing, smooth to stepped slopes, rims of pools (Guo and Riding 1998; Jones et al. 2000) |
in diameter (Fig. 4B, C). The pisoliths are single or composite coated grains showing concentric encrustations of alternating light and dark laminae of micrite and microsparry calcite around an intraclastic, quartz grain, lithic or fossil fragments (e.g. nummulites) (Fig. 5A–D). The pisoliths are cemented by microsparry calcite. Porosity is always biomoldic and intra-particle.

The pisoliths of the Kurkur tufas show multiple stages of growth (at least 5 stages of growth; Fig. 6). The nucleus of a pisoloid is an intraclast or fossil fragment surrounded by a series of concentric and alternating laminae of micrite and microsparite that are enveloped by mm-thick outer cortices of micrite or radially arranged lozenge-shaped crystal coatings. Similar pisoloidal formations have been described by Das and Mohanti (2005).

The lithoclastic tufa unconformably overlies the Dakhla Formation at the downstream of Wadi Abu Gorma. It occurs dominantly at site 2 in the form of high hillocks or mounds with stromatolite layers (Fig. 7A) occupying an area ~0.5 km². The lithoclastic tufa facies is gray to whitish gray in color, hard, porous (Fig. 7B), cavernous and brecciated, includes lithic fragments derived from the bedrocks (Fig. 7C). It contains very rare plant remains. It consists of reworked coarse-grained lithic fragments derived most probably from fragmentation of older bedrocks. Lithoclastic tufa is coated pebbles (oncoids) formed by laminated encrustations around lithoclasts (Fig. 7D). Preserved thickness of pisolitic intraclastic tufa at site 1 and lithoclastic oncoidal tufa at site 2 ranges between 8 and 4 m, respectively.

**Interpretation**

Freshwater pisoliths and oncoids form primarily as the result of the accretion of carbonates centrifugally around a nucleus (e.g. Schreiber et al. 1981; Peryt 1983). The nucleus is most often intraclast, phytoclast or fossil fragment. The carbonate accretion is developed by alternating deposition of micritic and microsparry laminae. Alternating light and dark laminae of micrite and microsparite around a nucleus suggest seasonal deposition in alternating dry and wet conditions (Das and Mohanti 2005). Pisoliths and coated grains (oncoids) were most likely formed in situ or underwent a short distance of transport. Pisoliths commonly develop in low-energy fluvial channel margin environments, e.g. dammed areas, water pools, and shallow lakes (Pedley 1990) or along active channels trapped for water-energy fall (e.g. Jones and
These environments are characterized by a low agitation, with a relatively high microbial activity and evaporation (Das and Mohanti 2005). Pisoliths can develop by microbial growths, which may form laminated or clotted textures (e.g. Riding 1983; Gradziński 2010).

Accordingly, the studied pisolitic intraclastic/lithoclastic oncoidal rudstone facies association was most probably formed during alternating dry and wet conditions in a shallow stagnant pool environment where its components suffered little or no transport (in situ).

**Fig. 5** Photomicrographs of the pisolitic rudstones showing: A–D single and composite pisoliths show concentric encrustation consisting of alternating light and dark laminae of micritie and sparry calcite around a nucleus, cemented by sparry calcite. The nucleus may be nummulites or quartz grain, intraclast or lithic fragment.

**Fig. 6** Photomicrograph of a pisoid grain showing at least 5 stages (from center to periphery) of growth. (1) Microsparitic nucleus. (2) Dark micritic laminae. (3) Light micritic and dark sparitic laminae. (4) Zone of micrite. (5) Cortical micritic to microsparitic lamina.
Phytothermal/bryophyte framestones

Facies description

The phytothermal/bryophyte framestones unconformably overlie the Paleocene Kurkur Formation, and are well developed at sites 3, 4, 5, and 6. The most distinguished macroscopic features of phytothermal tufas are illustrated in (Fig. 8A–D). The phytothermal-bryophyte framestone tufas consist predominantly of encrusted plant materials such as reeds, rushes, and bushes. These tufas exhibit highly porous texture, dark gray to blackish in color, hard, fence-like, and rich in plant stems and tubes that are present in vertical (growth), oblique and horizontal positions. Most macrophytes (at centimeter scale) are encrusted by carbonate laminae producing a rigid framework (corresponds to “phytothermal framestone” of Pedley 1990). Plant stems are decayed forming empty cylindrical molds and casts that are bounded by fine laminated or clotted micrite producing a highly porous, well-cemented megascopically vesicular framework structure (Fig. 9A). Diameter of some of these empty cylinders attains more or less 10 cm (Fig. 9B). Some biomoldic porosity is filled by sparry calcite cement. The thickness of the phytothermal tufa varies from approximately 3 m at site 4–50 m at site 5. Microphytothermal tufa is also associated with macrophytothermal facies, and it is formed by in situ encrustation on microphyta at millimeter scale (such as bryophytes) producing a reticulate fabric with a high porosity (Fig. 9C). Microscopically, phytothermal framestone facies shows a micritic to microsparry fabric with irregularly-shaped fenestral porosity (Fig. 10A–D). Some fenestrae are filled partially by fibrous crystals of calcite. Some of calcified mosses on cross sectional view show alternating micritic and microsparry laminae encrusted around a central mold.
Interpretation

Macrophytes, microphytes and bryophytes like mosses and some pteridophytic plants grow in freshwater regime of waterfalls and streams producing reticulate and rigid fabrics built by in situ encrustation (Pedley 1990; Ford and Pedley 1996). Pedley (1990) and Pentecost (1998) demonstrated the significant role of mosses for constituting the major part of tufas in waterfall and slope environments. These environments are characterized by high agitation with low to moderate microbial activity and low rate of evaporation (Das and Mohanti 2005). Mosses can represent a suitable substrate for growing of filamentous cyanobacteria, algal epiphytes and diatoms which in turn contribute to tufa deposition (e.g. Love and Chafetz 1990; Pentecost 1998; Chafetz and Guidry 1999; Pedley 1994). Tufa precipitation can be enhanced by photosynthesis process of both macrophytes and algal epiphytes (e.g. Das and Mohanti 2005). Encrustation of macrophytes is followed by decaying of organic matters producing a vesicular appearance to the rock, in addition to a porous fabric due to natural growth pattern (e.g. Ahmed 1996; Das and Mohanti 2005). Fenestral porosity forms during or slightly after tufa precipitation as a result of decaying organic components, dissolution of calcite via lateral migration of water and/or gas, and burrowing of organisms or plant roots (Nicoll and Sallam 2017).

According to Ford and Pedley (1996) and Arenas et al. (2010), the phytothermal/bryophyte framestones were deposited mostly by slow-flowing streams or developed in lacustrine areas and subsequent encrustation of accumulated plant debris such as plant stalks, branches, roots and leaves. It is also recorded from some marginal areas of modern hot springs (e.g. Schreiber et al. 1981; Guo and Riding 1998; Rainey and Jones 2009; Jones and Renaut 2010; Capezzuoli et al. 2014). The phytothermal/bryophyte framestone

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**Fig. 8** Field photographs of the phytothermal/bryophyte framestone tufas at sites 3, 4 and 5. For scale: pen is 12 cm long and hammer handle is 26 cm long. **A–D** Macrophytural tufas (framestones) consist of encrusting randomly-oriented, parallel to horizontally-aligned empty cylindrical casts of read stalks and shrubs.

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tufas can also represent the inter-channel areas and shores of palustrines and shallow lakes.

**Stromatolite-algal boundstones**

**Facies description**

This facies association occurs along the scarp face of the Sinn El-Kaddab Plateau (site 4), and also occurs at the bottom of the Kurkur Oasis and its surroundings (sites 5 and 6). The facies consists mainly of earthy gray, thinlineated, stromatolite tufas displaying hemidomic and lenticular structures. The stromatolite-algal boundstone tufas form planar undulating layers ranging in thickness from several millimeters to more than 2 cm, consisting of alternating lighter sparry and darker micritic undulatory laminae. The hemidomic-like tufa structure displays porous inner core in cross section containing rich phytoherms, whereas the cortical laminae are wavy and convoluted (1–2 mm thick each) displaying exfoliated structure (Fig. 11A–D). Few speleothemic crusts are associated within this facies association. Petrographic observations showed wavy laminated boundstones with an alternation of light microsparitic and dark micritic peloidal laminae (Fig. 12). Porosity is generally inter-laminae and fenestral, horizontally well-connected and locally enhanced by dissolution. Macro-pores are filled with a prismatic to equant calcite cement.

**Interpretation**

Stromatolites are defined as stratiform biochemical structures formed in shallow water by microbial mats, particularly cyanobacteria (Riding 2007). The laminated stromatolite-algal boundstone tufas (corresponds to “phytohermal boundstones” of Pedley 1990) are common in most freshwater carbonates. A microbial activity by cyanobacteria and algae plays an important role in the formation of stromatolite tufas (e.g. Merz-Preiß and Riding 1999; Shiraishi et al. 2008; Pedley et al. 2009; Gradziński 2010). Lamination of stromatolite tufas most probably signifies to the alternating seasonal deposition of sparry calcite (spring–summer periods) and micrite (rainy-winter periods) (e.g. Casanova 1994; Das and Mohanti 1997). The stromatolite-algal boundstones developed most likely in slope environment by fast-flowing waters in gently slope, stepped channels (e.g. Das and Mohanti 2005; Gradziński et al. 2013). These stromatolite-algal tufas can also develop in standing waters in lacustrine/paludal shores (e.g. Shiraishi et al. 2008; Pedley et al. 2009; Gradziński 2010).
Speleothem-like flowstones

Facies Description

Columnar calcite commonly occurs in the Kurkur Oasis area (site 4). It occurs as successive sheets of well-developed prismatic and fibrous calcite crystals or in the form of cavities-filling calcite (Fig. 13A–C). The cavities were most probably formed due to partial dissolution and re-precipitation of the earlier porous phytothermal tufas. This facies association builds dark gray to black tabular beds, locally lenticular or hemidomic, up to several dm in thickness and variable in lateral extent. Thin sections of speleothem-like flowstones showed coarse columnar prismatic and bladed sparry calcite crystals (0.05–2 mm long) displaying a characteristic radial extinction pattern and separated by fine micritic laminae (Fig. 14A, B). Crystals are formed by elongated sub-crystals mainly in a feather-like arrangement (Koban and Schweigert 1993) and with undulose extinction and locally as fan-like (e.g. Jones and Renaut 1995; Guo and Riding 1992) often with uniform extinction. The porosity results always very reduced, with sub-mm to mm-size inter-dendrite and inter-branching pores always filled by sparite cement. Sparitization with limpid blocky sparite replacement is locally present.

Interpretation

Speleothem-like flowstones are very common in tufa depositional systems, and are interpreted as precipitated by fast-flowing water in smooth to stepped slopes and rims of pools as a result of CO₂-degassing from water rich in carbonates (e.g. Guo and Riding 1998; Jones et al. 2000; Gandin and Capezzuoli 2014; Alçiçek et al. 2017). Speleothem-like crusts are dominantly abiotically-formed, crystalline and hard, and show fine laminae (e.g. Das and Mohanti 2005; Pedley and Rogerson 2010). Clotted micritic laminae are most probably the result of microbial activity (Ahmed 1996).
Inclusions within calcite crystals indicate multiple stages of calcite precipitation (Folk et al. 1985). The radially fibrous calcite crystals suggest precipitation from a colloidal solution in the presence of impurities like clayey and organic materials (Augustithis 1982).

**Facies model and sedimentary processes**

The textural and compositional characteristics of the investigated Kurkur tufas reflect varied physiochemical and biological conditions prevailing in continental carbonate depositional systems. These tufas form a suit of facies packages that are represented by pisolitic intraclastic/lithoclastic oncoidal rudstones, phytothermal/bryophyte framestones, stromatolite-algal boundstones, and speleothem-like flowstones. These verities of tufa associations were most likely deposited by a rainwater-fed alkaline spring and fluvial system including waterfalls,
slopes, dammed areas, palustrines and fluvial channel margin environments. Spring carbonate-rich waters were circulated and emerged through fissures and cracks from shallow perched karstic aquifers above the main Nubian Aquifer during periods of heavy rainfall and high levels of water table (Nicoll and Sallam 2017; Kele et al. 2021). CO2-degassing, plants and bacterial-algal mats helped in the precipitation of the calcareous tufas. Pisoliths and coated oncoids can develop in slow-flowing fluvial channels (Pedley 1990; Arenas et al. 2015). In situ up-growing encrusted plant stems indicate deposition in a low-energy lacustrine setting on fluvial floodplains (e.g. Arenas-Abad et al. 2010; Rodriguez-Berriguete et al. 2021). Intraclasts form as a result of multiple reworking of older sediments during flooding (e.g. Pedley 1990; Arenas-Abad et al. 2010). Stromatolite-algal tufas develop within stagnant pools of lacustrines (e.g. Gradziński 2010). Phytoherms and bryophytes form in low-energy paludal and barrage environments (e.g. Arenas-Abad et al. 2010).

From the above description of both macro- and microfacies textures, four different water flow systems that controlled tufa deposition in the Kurkur Oasis can be recognized. These flow systems include: (1) low agitation, slow-flowing water by which pisoliths and coated grains (oncoids) formed in fluvial channel margin, with high microbial activity and evaporation, (2) high agitation, low-energy conditions, which resulted in the encrustation of plant materials in lacustrine/paludal shores and the development of stromatolite-algal tufas, (3) high-energy conditions associated with flooding periods that led to the reworking of older tufas forming intra- and lithoclasts, and (4) karstification and carbonate re-precipitation in voids and cavities forming columnar, prismatic and laminated speleothem-like flowstones.

Isotope geochemistry and environmental implications

The δ13C and δ18O isotopic compositions of freshwater carbonates are useful to understand the environmental conditions that were prevailed during their deposition (e.g. Andrews et al. 2000; Gandin and Capezzuoli 2008; Pedley 2009; Capezzuoli et al. 2014; Pla-Pueyo et al. 2017). The results of stable δ13C and δ18O isotopic analyses of the studied tufa samples are given in Table 3 and plotted in Fig. 15. Generally, δ13C and δ18O values of the analyzed tufa samples from the Kurkur Oasis area (sites 1 through 7) range between –3.16 and –1.13‰ V-PDB and –13.26...
and – 8.89‰ V-PDB, respectively. The isotopic values
of the studied tufa (δ^{13}C: – 3.16 to – 1.13‰ V-PDB and
δ^{18}O: – 13.26 to – 8.89‰ V-PDB) are typical of fluvial
tufa deposits (e.g. Andrews 2006; Pla-Pueyo et al. 2017). The negative δ^{13}C values indicate precipitation from
meteoric water that have low δ^{13}C values as a result of

### Table 3 Carbon and oxygen stable isotopic composition of the analyzed tufa samples from the Kurkur Oasis

| Locality          | Site no. | Sample no. | δ^{13}C (V-PDB) | δ^{18}O (V-PDB) | δ^{18}O (V-SMOW) |
|------------------|----------|------------|----------------|----------------|-----------------|
| Kurkur Oasis area| Site 1    | 1          | – 2.10         | – 9.15         | 21.47           |
|                  |          | 2          | – 2.93         | – 10.29        | 20.30           |
|                  |          | 3          | – 3.16         | – 10.50        | 20.08           |
|                  |          | 4          | – 2.27         | – 9.96         | 20.64           |
|                  |          | 5          | – 1.60         | – 9.74         | 20.87           |
|                  | Site 2    | 1          | – 1.59         | – 10.07        | 20.53           |
|                  |          | 2          | – 1.77         | – 10.04        | 20.56           |
|                  |          | 3          | – 1.30         | – 8.89         | 21.74           |
|                  |          | 4          | – 1.74         | – 9.84         | 20.76           |
|                  |          | 5          | – 1.90         | – 9.86         | 20.75           |
|                  |          | 6          | – 1.13         | – 9.32         | 21.30           |
|                  | Site 3    | 1          | – 2.01         | – 9.10         | 21.53           |
|                  |          | 2          | – 2.97         | – 11.26        | 19.31           |
|                  |          | 3          | – 2.04         | – 9.71         | 20.90           |
|                  |          | 4          | – 2.17         | – 10.66        | 19.92           |
|                  | Site 4    | 1          | – 3.13         | – 11.44        | 19.12           |
|                  |          | 2          | – 2.62         | – 10.15        | 20.44           |
|                  |          | 3          | – 1.77         | – 9.64         | 20.97           |
|                  | Site 5    | 1          | – 2.90         | – 11.81        | 18.74           |
|                  |          | 2          | – 1.62         | – 9.88         | 20.72           |
|                  |          | 3          | – 3.14         | – 12.49        | 18.04           |
|                  | Site 6    | 1          | – 2.22         | – 12.69        | 17.83           |
|                  |          | 2          | – 2.57         | – 13.26        | 17.24           |
|                  |          | 3          | – 1.45         | – 10.68        | 19.90           |
|                  |          | 4          | – 1.81         | – 11.87        | 18.67           |
|                  | Site 7    | 1          | – 2.41         | – 10.30        | 20.29           |
|                  |          | 2          | – 2.69         | – 11.01        | 19.56           |

Fig. 14 Photomicrographs of speleothem-like flowstones showing: A, B Coarse columnar dendrite and bladed sparry calcite (lower and upper parts) with a distinguished radial extinction pattern, separated by thinly micritic laminae (middle part)
increased continental weathering and input of soil respired carbon during groundwater recharge (e.g. Andrews 2006). The more negative δ¹⁸O values are consistent with carbonates precipitating from meteoric waters in pluvial (rainy) humid regions (e.g. Andrews 2006).

Conclusions

Sedimentological, petrographical and isotope-geochemical studies of the Quaternary calcareous tufas in the Kurkur Oasis area in the southern Western Desert of Egypt yielded four important conclusions.

1) The tufas form four facies associations consisting primarily of pisolitic intraclastic/lithoclastic oncoidal rudstones, phytoclastic/bryophytes framestones, stromatolite-algal boundstones, and speleothem-like flowstones.

2) The facies associations of the Kurkur tufas indicate sedimentation in rainwater-fed alkaline spring and fluvial environments such as inter-channel areas and the margins of dammed areas, stagnant pools, and lacustrine-paludal shores.

3) The early-diagenetic features in the tufas are cementation, neomorphism and subaerial dissolution.

4) The negative δ¹³C values suggest increased CO₂-degassing and strong evaporation under arid conditions. The negative δ¹⁸O values are characteristic of carbonates precipitated from meteoric water in humid regions with a relatively heavy rainfall.

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Data availability

All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest

The author declares that he has no competing interests.

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![Fig. 15 Carbon and oxygen stable isotopic compositions of the analyzed samples](image-url)
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