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Correlation of the Marsawdad Formation, Oman, Late Miocene (Turolian-Ventian), based on fossil avian eggshells

Correlación de la Formación Marsawdad, Omán, Mioceno Superior (Turoliense-Ventiense), basada en las de cáscaras fósiles de huevos avianos

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ABSTRACT

The discovery of fossilised struthious eggshell fragments on outcrops of the Marsawdad Formation, Rub' Al-Khali, Oman, permits estimation of the age of the deposits, indicating correlation to the Late Miocene (Turolian-Ventian: Tortonian-Messinian) ca 8-7 Ma. The eggshells are described and are located within a revised biostratigraphy of the Cenozoic terrestrial deposits of the Arabian Peninsula.

Key Words: Struthionidae; Eggshells; Biostratigraphy; Oman; Cenozoic; Neogene.

RESUMEN

El descubrimiento de fragmentos de cáscaras de huevos de tipo avestruz en los afloramientos de la Formación Marsawdad, Rub' Al-Khali, Oman, permite la estimación de la edad de los depósitos, correlacionada con el Mioceno Superior (Turoliense-Ventiense: Tortoniense-Messiniense) ca 8-7 Ma. Las cáscaras de huevo se describen y se sitúan en una biostratigrafía revisada de los depósitos terrestres de la Península de Arabia.

Palabras clave: Struthionidae; Cáscaras de huevo; Biostratigrafía; Omán; Cenozoico; Neogeno.

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Introduction

The correlations and geochronology of the diverse sedimentary units in the Arabian Peninsula have been the subject of debate ever since the first studies were undertaken in the 20th Century (Cavelier, 1975; Powers, 1968; Powers et al. 1966; Tleel, 1973; Simmons et al. 2007; Steineke et al. 1958; Ziegler, 2001). Due to the presence of hydrocarbons in many areas of the peninsula, the marine deposits in particular, have been extensively studied not only in surface exposures but also in drill logs (Sharland et al. 2004) but there are still some problematic issues concerning the correlations and ages of the deposits. For example, the Taqah unit (Oman) is considered by Sharland et al. (2004) to correlate to both the Chattian and to the Aquitanian, yet fossil mammals from the Taqah site indicate that it is late Rupelian in age (Figs 1, 2) (Crochet et al. 1990, 1992; Gheerbrant et al. 1993, 1995; Harrison, 2001; Pickford, 2015c; Pickford & Thomas, 1994; Pickford et al. 1994, 2014; Privé-Gill et al. 1993; Roger et al. 1992, 1993; Seiffert, 2006, 2007; Senut & Thomas, 1992, 1994; Sigé et al. 1994; Thomas & Gheerbrant, 1992; Thomas et al. 1982, 1988, 1989, 1999).

During the 2022 palaeontological field survey of the Rub Al-Khali, Oman, the authors recovered struthious eggshell fragments from several outcrops of the Marsawdad Formation, some of the unabraded and unsculpted specimens having most likely eroded in recent times from the reddish calcareous sands of the formation. This discovery is of interest because struthious eggshells are known to be reliable biostratigraphic markers in African and Arabian Neogene deposits (Bibi et al. 2006, 2013; Harris & Leakey, 2003; Pickford, 1998, 2014; Pickford & Dauphin, 1993; Pickford & Senut, 2000; Pickford et al. 1995; Ségalen et al. 2002; Senut, 2000; Senut & Pickford, 1995; Senut et al. 1994, 1998; Stidham, 2004, 2008).

The aim of this contribution is to report on the fossil struthious eggshells from the Marsawdad Formation and to propose a correlation to the Geological Time Scale. This will help to stabilise part of the stratigraphy of the continental deposits of the Rub Al-Khali where the Marsawdad Formation crops out extensively in the neighbourhoods of Muqshin, Marsawdad and Montasar (Berthiaux & Platel, 1992; Chevrel et al. 1992; Platel & Berthiaux, 1992a, 1992b).

Material and Methods

The fossils described in this paper comprise 17 eggshell fragments from locality 25.RAK, Rub' Al-Khali, Oman, which are curated at the Oman Natural History Museum, Muscat, under catalogue number ONHM-F-4779. Measurements were made with vernier calipers, and images were captured with a Sony Cybershot Camera, and treated with Photoshop Elements15 to enhance contrast and to clean the background. Comparisons were made with fossils from Namibia (Pickford, 2014), Kenya (Harris & Leakey, 2003), Tanzania (Harrison & Msuya, 2005; Pickford, 2014) and the United Arab Emirates (Bibi et al. 2006) as well as with specimens from Bou Hanifia (Algeria) (Arambourg, 1959).

The meanings of some of the Place Names mentioned in this paper are provided in Table 1.

Abbreviations

MNHN – Muséum National d'Histoire Naturelle, Paris
NHMUK – Natural History Museum of the United Kingdom, London
ONHM – Oman Natural History Museum
RAK – Rub' Al-Khali

Background to stratigraphy of the Arabian Peninsula

Whilst the stratigraphy of the marine deposits of the Arabian Peninsula has been reasonably stable on account of the presence of abundant marine molluscs, foraminiferans and other fossils in them, there is much less consensus concerning the terrestrial (continental) sediments (Fig. 1), with the literature showing large offsets between the estimated ages of the sedimentary units and their contained faunas. For example, the Hofuf Formation (Thralls & Hassan, 1956), was correlated by Al-Saad et al. (2002) to the Late Miocene to Pleistocene and by Sharland et al. (2004) to the Tortonian-Pleistocene, yet at Al Jadidah, close to the type area, it has yielded char-

Table 1.— Meaning of Place Names mentioned in this paper (when known).

Place Name	Meaning
Ad Dabtiyah	Administer
Ain Sala	Sala Spring
Al Hafrah	Hole / the Pit
Al Ruwais	The small head
Al Uruq	The veins
Al' Ayn	The Spring
Al-Jadidah	The New
An Nafud	Run out
Ar Rhyashia	Feather
Ar Rimal	The Sands
Arba	The fourth
Ashawq	Longings
As-Sarrar	Squeaky
Bani Ma'Aridh	A group of exhibitions or families
Barzaman	Ancient Plain
Baynunah	In between or clearly viewed (clearly visible, unobscured)
Dam	Dam
Dammam	House roof
Dawkah	Evil and rivalry
Ghaba	Forest
Ghubbarrah	Dust
Harrat Al-Ujayfah	Al-Ujayfah neighborhood
Hofuf	Blow (windy)
Jabal Mishra ash Shamali	North Mishra Mountain
Jabal Uray-Irah	Uray-Irah Mountain
Jiddat al Harasis	The Plain of Harasis
Khasfah	A substantial palm leaf envelope
Marsawdad	?Observed, ?Predestined
Montasar	Victor (Conqueror)
Muqshin	Peeled (Exposed)
Qa'Amiyat	Lists
Qitabit	Fasten, Tether (as in pull strings around camels or around poles)
Ramlat al Hawz	Al Hawz Sand
Ramlat ar Tabkha	Ar Tabkha sand
Ramlat Mashash	Soft ground sands
Ramlat Musah	Musah Sand dune
Ramlat Umm Daysis	Umm Daysis sand
Ramlat Yi La	Yi La sand
Rub' Al-Khali	The Empty Quarter
Shigag	Interdune corridor or street (generally flat interdunal areas)
Shisr	Sew (Bunt)
Shuqqat Al Khalfat	The interdune corridor of Khalfat
Taqah	Energy (or a different meaning in the Shehri language)
Tayma	The wide land
Thabhloten	The Blue Tent (local rendering of the English name)
Ulla al-Qurun	On the horns
Umm Tina	Fig tree
Wadi Bin Khawtar	Abundant goodness wadi
Wadi Sabya	Wadi of low land and sands

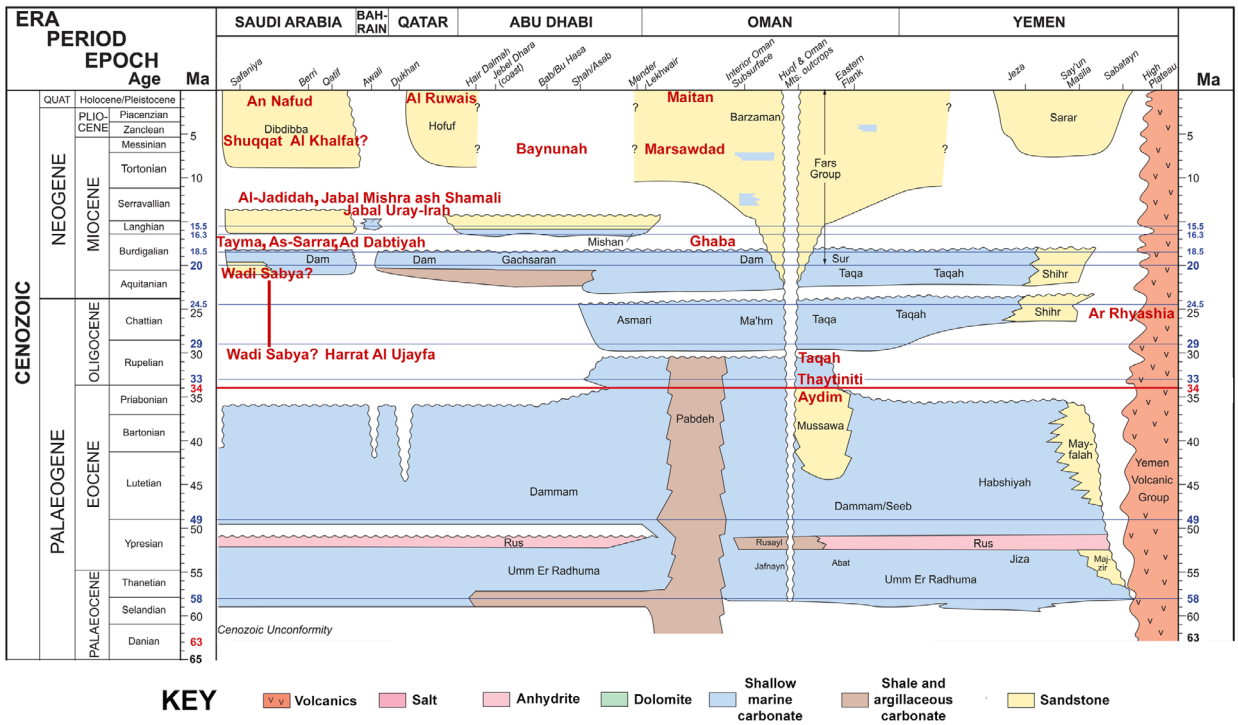

Figure 1.— Sequence stratigraphy of Cenozoic rock units of the Arabian Peninsula. Chart modified and abbreviated from Sharland et al. (2004) with addition of localities (in red letters) that have yielded geochronologically informative terrestrial vertebrates. NB: The fossil vertebrates from Ghaba occur in a continental facies of the Dam Formation which locally underlies the unfossiliferous Ghaba Formation and the Barzaman Formation.

acteristic late Middle Miocene faunal remains aged between 14 Ma and 12 Ma (Anonymous, 1975; Hamilton et al. 1978; López-Antoñanzas, 2004, 2009; Morales et al. 1987; Thomas, 1982, 1983, 1985; Thomas et al. 1978; Sen & Thomas, 1979; Whitmore, 1987) and the fossiliferous deposits thus correlate to the Serravallian. This inconsistency raises the possibility of a mis-correlation between the so-called Hofuf Formation in Qatar (Cavelier, 1975; Al-Saad et al. 2002) and the Hofuf Formation in its type area in Saudi Arabia (Thralls & Hassan, 1956; Sharland et al. 2004), or indicates that, as currently understood, it comprises a composite unit of two or more formations.

An overview of the available evidence concerning vertebrate palaeontology of the Arabian Peninsula reveals that there are diverse localities which have yielded fossils of terrestrial animals and plants, spanning the period from Late Eocene to Recent (with gaps) but none are yet known from the period spanning the Late Cretaceous to Bartonian (Figs 1, 2).

Several named formations of continental deposits in Oman (e.g. Barzaman Fm, Ghaba Fm, Roger et al. 1994) have not yielded fossils, so there is inherently some uncertainty about their ages. One such unit which previously yielded only charophyte zoogonia, is the Marsawdad Formation which crops out widely in the Rub Al-Khali, Oman (Chevrel et al. 1992; Platel & Berthiaux, 1992a, 1992b). This unit was correlated to the Late Miocene-Pliocene by the authors because, in its type area, it overlies the Dam Formation (Burdigalian) and the Montasar Formation (which overlies the Dam Formation), and underlies supposed Pliocene to Recent deposits. Elsewhere in the Rub' Al-Khali, the Marsawdad Formation overlies the Dammam Formation (Eocene) and Dawkah Formation (possibly Oligocene to Burdigalian). Chevrel et al. (1992) considered that the Marsawdad Formation may be equivalent in part to the Hofuf Formation of Saudi Arabia (Powers, 1968; Cavelier, 1975) but fossil mammals from several localities near the type area of the latter unit indicate that it is

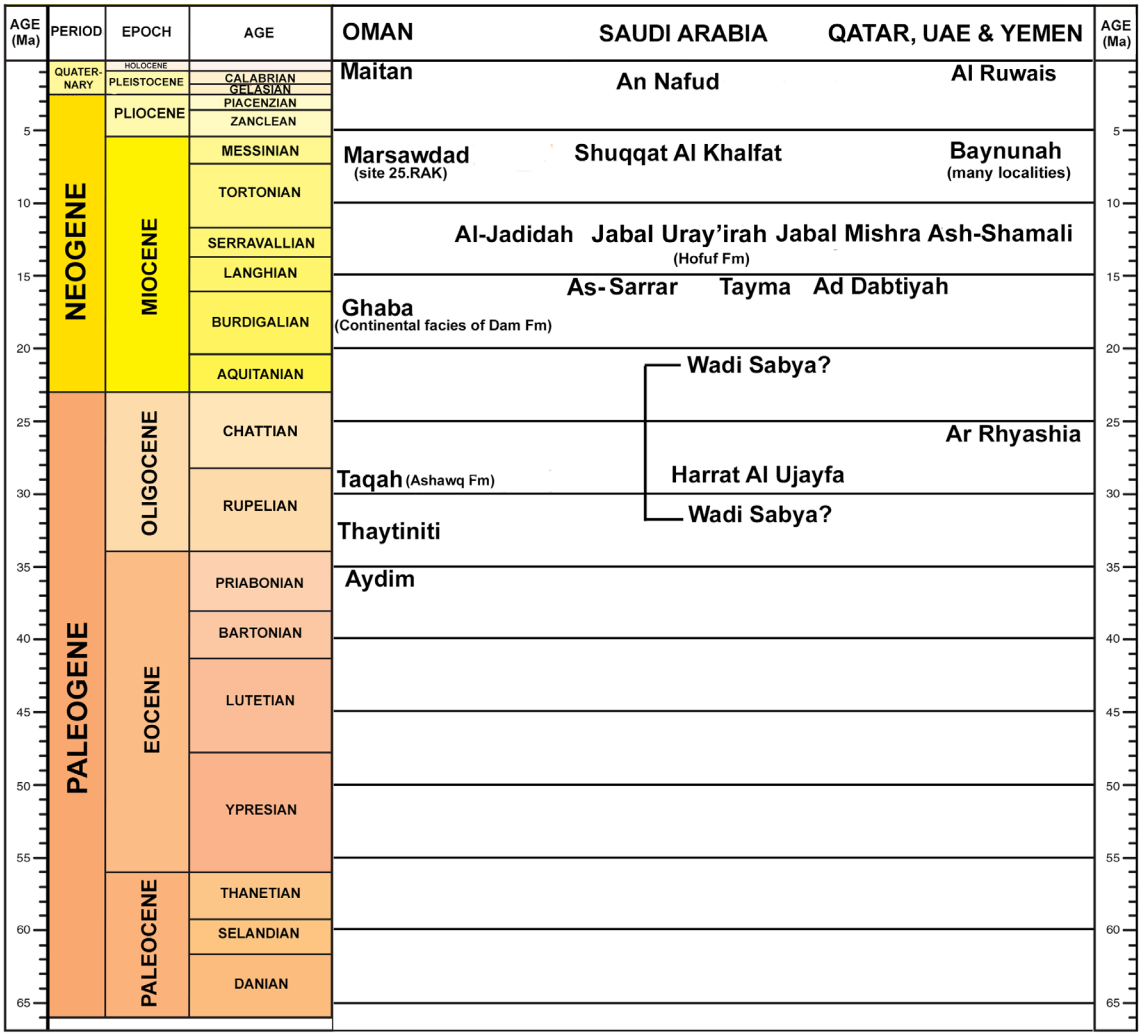

Figure 2.— Biostratigraphic placement of localities in the Arabian Peninsula that have yielded fossil remains of terrestrial vertebrates. The identification of the anthracothere from Wadi Sabya, Saudi Arabia (Madden et al. 1978) is uncertain (*Bothriogenys* or *Brachyodus*?). Two correlation possibilities are provided. The fossil eggshell from Shuqqat Al Khalfat is similar to specimens from the Baynunah Formation and the Marsawdad Formation, so is correlated to the Late Miocene.

of Middle Miocene age, and thus substantially older than the Marsawdad sediments.

Geological setting Marsawdad Formation

The Marsawdad Formation crops out extensively in the Rub' Al-Khali, Oman (and probably also in Saudi Arabia) with outcrops mapped in three of the 1:250,000 geological map sheets of Oman (Sheets, NE 40-01, NE 39-04 and NE 39-08; Chevrel et al. 1992; Platel & Berthiaux, 1992a, 1992b) (Fig. 3). The Marsawdad Formation (map symbol MPlms) is comprised of well-bedded sequences of reddish to yellowish clayey siltstone grading upwards to grey marly limestone and grey to brown micritic limestone with palaeosols. In several outcrops the surface exposures comprise tilted and folded beds (Fig. 4), probably resulting from dissolution of gypsiferous underlying strata accompanied by localised slumping, let-down structures and solution collapse (Le Blanc, 2009, figs 5.5 and 5.7).

Platel & Berthiaux (1992a) interpreted the depositional environment of the Marsawdad Formation as a '*large continental basin surrounded by palustrine and, more rarely, lacustrine deposits, regularly en-*

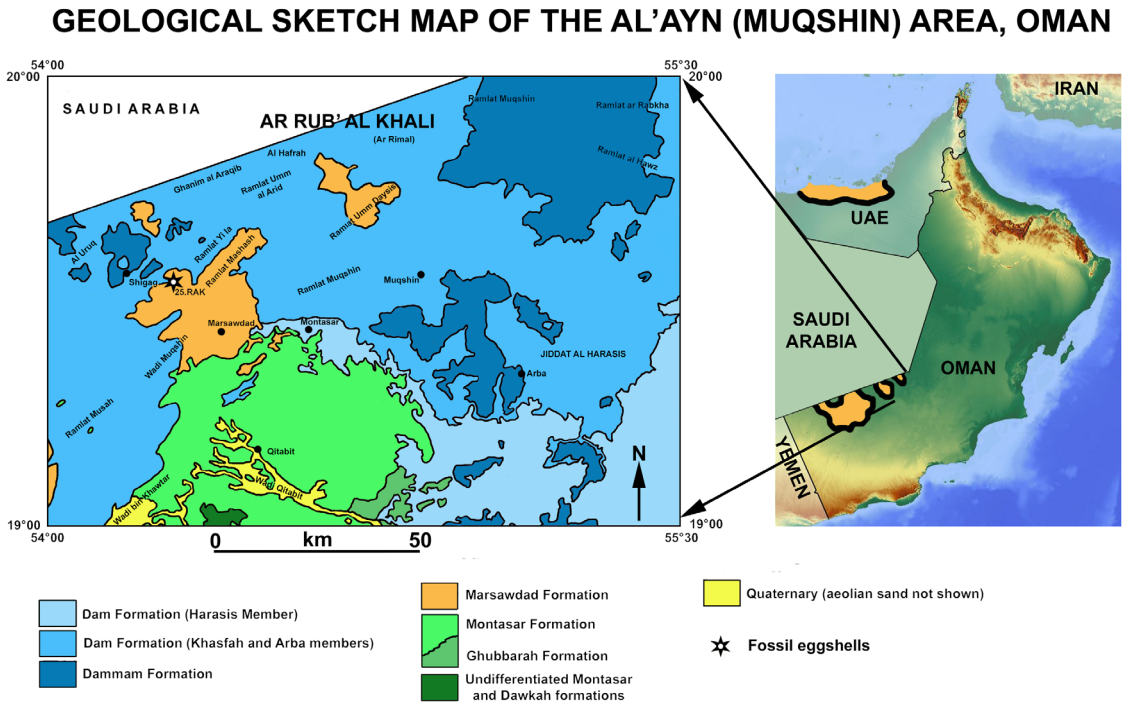

Figure 3.— Geological sketch map of the Al'Ayn (Muqshin) area, Oman, showing the discovery locus of the struthious eggshells and the local extent of the Marsawdad Formation. Map in left column is modified from Platel & Berthiaux (1992a). Map at right shows the extent of the Marsawdad Formation (orange) in the Omani part of the Rub' Al-Khali and the Baynunah Formation in the United Arab Emirates, 500 km to the north.

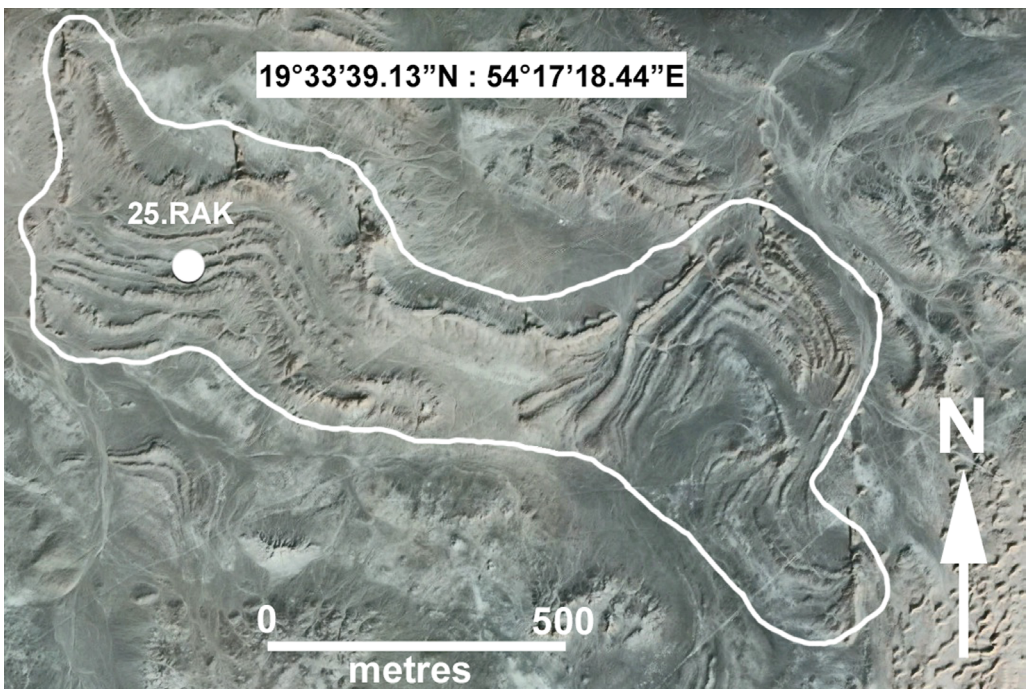

Figure 4.— Locality 25.RAK one of the many outcrops of tilted and folded beds of the Marsawdad Formation in the Rub Al-Khali, Oman. Map modified from Google Earth.

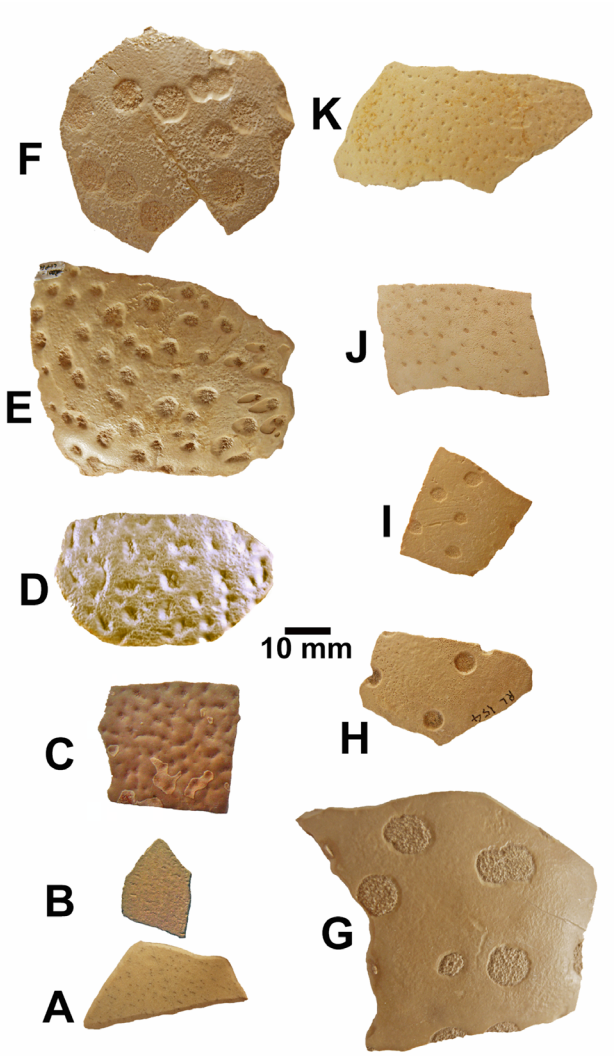

Figure 5.— Succession of fossil eggshell types from the Namib Desert (A oldest to K youngest). A) *Tsondabornis minor*, B) *Tsondabornis psammoides*, C) *Namornis elimensis*, D) *Namornis oshanai*, E) *Diamantornis corbetti*, F) *Diamantornis spaggiarii*, G) *Diamantornis wardi*, H) *Diamantornis laini*, I) *Struthio karingarabensis*, J) *Struthio daberasensis*, K) *Struthio camelus*. The eggshell fragments from the Marsawdad Formation, Oman, and some of the specimens from the Baynunah Formation, United Arab Emirates, are closest in morphology and shell thickness to specimen 'H' – *Diamantornis laini*.

croached by fluvio-deltaic fans and very fine-grained detrital material that had been transported over long distances'. West of Montasar the formation is up to 100 metres thick, comprising 15 or more sequences 3-6 metres thick. The base of the succession is reported to be an iron-stained calcrete or a brown limestone palaeosol which locally has a travertine-like aspect.

The only fossils previously recorded from the Marsawdad Formation are charophyte oogonia (Platel & Berthiaux, 1992a) and two eggshell fragments that were collected from deflated surfaces of the formation by Rosén et al. (2021).

Avian eggshell biochronology of Afro-Arabia

Research in Namibia during the past three decades has led to the establishment of a biostratigraphic scale employing struthious eggshells (Figs 5, 9) (Pickford, 1998, 2014; Pickford & Dauphin, 1993; Pickford & Senut, 2000; Pickford et al. 1995; Ségalen et al. 2002; Senut, 2000; Senut & Pickford, 1995; Senut et al. 1994, 1998). The scale spans the entire Neogene Period, the ages of the eggshell morphotypes being based on mammal fossils found associated with the eggshells (Pickford, 2014). Studies on fossil struthious eggshells from other African countries (Kenya, Harris & Leakey, 2003; Tanzania, Harrison & Msuya, 2005; Algeria, Arambourg, 1959; Malawi, Stidham, 2004; South Africa, Stidham, 2008) and the Arabian Peninsula (United Arab Emirates, Bibi et al. 2006; Mikhailov & Zelenkov, 2020) which were also associated with fossil mammals, have confirmed the utility of the eggshells for biostratigraphic correlations (see Table 2 for references to the geology and palaeontology of the Late Miocene Baynunah Formation). We are therefore reasonably confident that the Marsawdad eggshells will yield a reliable age estimate of the deposits in which they were fossilised. Even though the preservation of the Marsawdad eggshells is not perfect, a few fragments that are lightly eroded are informative enough about surface structure to yield interesting data linking them to the genus *Diamantornis* rather than to the aepyornithoid type which also occurs in the Late Miocene deposits of the Arabian peninsula (Bibi et al. 2006).

Fossil eggshells from Oman

Struthious eggshell fragments from the Rub' Al-Khali, Oman, were described by Al-Kindi et al. (2021) and Maiorano et al. (2020) and attributed to *Struthio camelus* and an extinct species (*Diamantornis laini* or *Struthio daberasensis*).

Other eggshell fragments were reported, but not described in detail, by Rosén et al. (2021) (see Table

Table 2.— Fossiliferous Cenozoic terrestrial localities of the Arabian Peninsula and main references to them.

LOCALITY	AGE	REFERENCES
Maitan, Oman	Late Pleisto-cene-Holocene	Al-Kindi et al. 2021; Maiorano et al. 2020
Mahadir Summan, Bani Ma'Aridh, Saudi Arabia	Recent	Lowe, 1933a, 1933b; Philby, 1933
Tuwairifa, Ain Sala, Ull al Qurun ; Umm Tina, Qa'amiyat, Abu Sabbau, Saudi Arabia	Pleisto-cene-Holocene	Lowe, 1933a, 1933b; Philby, 1933
An Nafud, Saudi Arabia	Pleistocene	Breeze et al. 2017; Garrard & Harvey, 1981; Rosenberg et al. 2013; Schultz & Whitney, 1986; Scerri et al. 2015; Thomas et al. 1998
Al Ruwais, Qatar	Pleistocene	Pyenson et al. 2022
Marsawdad, Oman	Late Miocene	Berthiaux et al. 1992; Chevrel et al. 1992; Platel & Berthiaux, 1992a, 1992b; This paper
Shuqqat Al Khalfat, Saudi Arabia	Possibly Late Miocene	Buffetaut, 2022; Lowe, 1933a, 1933b; Philby, 1933
Baynunah Formation (many localities including the site of Ruwais) United Arab Emirates	Late Miocene	Andrews, 1999; Barry, 1999; Beech, 2005; Beech & Hellyer, 2002, 2005; Beech & Higgs, 2005; Beech et al. 2003; Bernor et al. 2022; Bibi, 2022; Bibi et al. 2006, 2012, 2013, 2017, 2022a, 2022b, 2022c; Bishop & Hill, 1999; Boisserie & Bibi, 2022; Boisserie et al. 2017; De Bruijn, 1999; De Bruijn & Whybrow, 1994; Ditchfield, 1999; Eisenmann & Whybrow, 1999; Forey & Young, 1999; Friend, 1999; Gardner & Rage, 2016; Gentry, 1999a, 1999b; Gilbert & Hill, 2022; Gilbert et al. 2014; Glennie & Evamy, 1968; Greenwood, 1987; Grohe, 2022; Head & Müller, 2022; Higgs, 2005; Higgs et al. 2003, 2005; Hill, 1999; Hill & Gundling, 1999; Hill et al. 2012; Jeffery, 1999; Khalaf-Prinz Sakerfalke von Jaffa, 2010; Kraatz, 2022; Kraatz et al. 2009, 2013; Lapparent de Broin & van Dijk, 1999; Louchart etal. 2022; Madden et al. 1982; Mazzini & Kovacova, 2022; Otero, 2022; Peebles, 1999; Raube et al. 1999; Sanders, 2022; Schuster, 2022; Stewart, 2003, 2005; Stewart & Beech, 2006; Stimpson et al. 2015, 2016; Tassy, 1999; Whybrow, 1989, 1990; Whybrow & Bassiouni, 1986; Whybrow & Clements, 1999a, 1999b; Whybrow & Hill, 1999; Whybrow & McClure, 1981; Whybrow et al. 1990, 1999
Al-Jadidah (Hasa) Saudi Arabia	Middle Mio-cene	Anonymous, 1975; Hamilton et al. 1978; López-Antoñanzas, 2004, 2009; Morales et al. 1987; Thomas, 1982, 1983, 1985; Thomas et al. 1978; Sen & Thomas, 1979; Whitmore, 1987
Jabal Midra ash-Shamali, Saudi Arabia	Middle Mio-cene	Hamilton et al. 1978; López-Antoñanzas, 2004; López-Antoñanzas & Sen, 2006
As-Sarrar, Saudi Arabia	Early Miocene	Flynn et al. 1983; López-Antoñanzas, 2004; López-Antoñanzas & Sen, 2004, 2005, 2006; Pickford, 2009; Pickford & Tsujikawa, 2019; Thomas & Battail, 1980; Thomas et al. 1978, 1982; Whybrow et al. 1982
Tayma, Saudi Arabia	Early Miocene	López-Antoñanzas, 2004; López-Antoñanzas & Sen, 2004; Pickford & Tsujikawa, 2019
Ad Dabtiyah, Saudi Arabia	Early Miocene	Andrews & Martin, 1987; Andrews et al. 1978, 1987; Gentry, 1987a, 1978b, 1987c; Hamilton et al. 1978; Harrison, 2001; López-Antoñanzas, 2004; López-Antoñanzas & Sen, 2004; Pickford, 1987; Whybrow, 1987
Jabal Uray'irah, Saudi Arabia	Early Miocene	Gentry, 1987a
Ghaba, Oman	Early Miocene	Otero & Gayet, 2001; Pickford et al. 2021; Roger et al. 1994
Wadi Sabya, Saudi Arabia	Early Miocene or Oligocene	Madden et al. 1978
Ar Rhyashia, Yemen	Oligocene	Henrici & Baez, 2001
Taqah, Oman	Oligocene	Crochet et al. 1990, 1992; Gheerbrant et al. 1993, 1995; Harrison, 2001; Pickford, 2015c; Pickford & Thomas, 1994; Pickford et al. 1994, 2014; Privé-Gill et al. 1993; Roger et al. 1992, 1993; Seiffert, 2006, 2007; Senut & Thomas, 1992, 1994; Sigé et al. 1994; Thomas & Gheerbrant, 1992; Thomas et al. 1982, 1988, 1989, 1991b, 1999
Harrat Al Ujayfa, Saudi Arabia	Oligocene	Zalmout et al. 2010
Thaytiniti, Oman	Early Oligo-cene	Al-Kindi et al. 2017; Harzhauser et al. 2016; Neubert & Van Damme, 2012; Otero & Gayet, 2001; Pickford, 2015a, 2015b, 2015c; Pickford et al. 1994, 2014; Roger et al. 1993; Seiffert, 2006, 2007; Thomas et al. 1982, 1989, 1991a, 1999
Aydim, Oman	Late Eocene	Al-Sayigh et al. 2008

Table 3.— Location and shell thickness of struthious eggshell fragments from the Rub' Al-Khali, Oman, mentioned by Rosén et al. (2021).

Sample N°	Latitude : Longitude	Shell thickness (mm)
OES3-2015	18°45.296'N : 52°47.815'E	--
OES4-2016	19°00.530'N : 53°21.991'E	1.7
1701-0004	18°45.097'N : 53°11.260'E	1.6
1702-0055	18°55.183'N : 53°21.216'E	3.0
1702-0131	18°58.151'N : 53°28.426'E	2.6
1702-0138	18°58.406'N : 53°28.394'E	1.5
19-0152	19°13.677'N : 53°34.338'E	1.6
19-0161	19°10.835'N : 53°31.481'E	1.8
19-0210	19°21.201'N : 53°50.093'E	1.6

3). The latter authors estimated the ages of several specimens using the ^{14}C method. Six eggshells less than 1.8 mm thick that were attributed by them to *Struthio camelus syriacus* yielded Recent ages but two specimens (2.6 and 3.0 mm thick) attributed by them to *Struthio kakesiensis?* were beyond the range of the ^{14}C method. They commented « *Such thick shelled eggs are not attributable to modern Arabian ostrich (*Struthio camelus syriacus*), but rather to a larger form that became extinct at least 3 Ma ago, for example,* Struthio kakesiensis? *(Bibi et al. 2006) known from the Arabian Emirates* ». Two comments arise from this interpretation: (1) Bibi et al. (2006) did not report the presence of *S. kakesiensis* in the UAE, the two ootaxa from the Baynunah Formation listed by them being *Diamantornis laini* and an aepyornithoid, (2) the estimate of 3 Ma is too young, the Baynunah Formation being correlated by Bibi et al. (2006) to the Late Miocene (7.4-6.5 Ma).

The fossil eggshells from locality 25.RAK range in colour from dark chocolate brown (15 fragments) to pale chocolate (2 fragments), like specimens from near Maitan (Al-Kindi et al. 2021) and from several localities in Saudi Arabia (Lowe, 1933b). The darker specimens are all more deeply sculpted than the paler specimens (Fig. 6). Sculpting affects primarily the outer surface of the shell fragments (Fig. 8), this surface being exposed to the air when the specimens erode out of the deposits in which they were originally fossilised. The preferential orientation of the eggshell fragments is due to the curvature of the shells, their most stable position in windy environments being convex upwards.

The sculpting of the surfaces of the eggshells is due to two processes, sand-blasting (minor) and dissolution due to frequent episodes of wetting by dew (repeated many times). By these slow processes, the eggshells can lose much of their thickness and while doing so tend to develop complex systems of smoothly polished ridges and basins which pattern the surface of the shells.

The ten better preserved eggshell fragments from locality 25.RAK range in thickness from 2.4 to 3.0 mm, whereas seven deeply sculpted specimens are only 2.0 to 2.2 mm thick, but they must in any case have originally been appreciably thicker than eggs of *Struthio camelus* (Figs 6-8). Thickness measurements of the 17 specimens are as follows :- 3 specimens: 2.0 mm, 2 specimens: 2.1 mm, 2 specimens: 2.2 mm, 1 specimen: 2.4 mm, 1 specimen: 2.5 mm, 2 specimens: 2.6 mm, 2 specimens: 2.7 mm, 1 specimen: 2.8 mm, 2 specimens: 2.9 mm, 1 specimen: 3.0 mm.

Two of the 17 Marsawdad specimens are relatively unaffected by sand-blasting and dissolution by dew, so they provide reliable information about the surface texture of the shells. In both cases, there appear to be no pores on the outer surface, thereby resembling the large smooth surfaces that occur between the circular pore complexes in eggs of *Diamantornis laini* (Bibi et al. 2006; Pickford, 1998, 2014; Pickford & Senut, 2000; Pickford et al. 1995; Ségalen et al. 2002; Senut, 2000; Senut & Pickford, 1995; Senut et al. 1994, 1998). The larger of the two well-preserved Marsawdad fragments (Fig. 7) shows the edge of a depression on one side, which could represent the

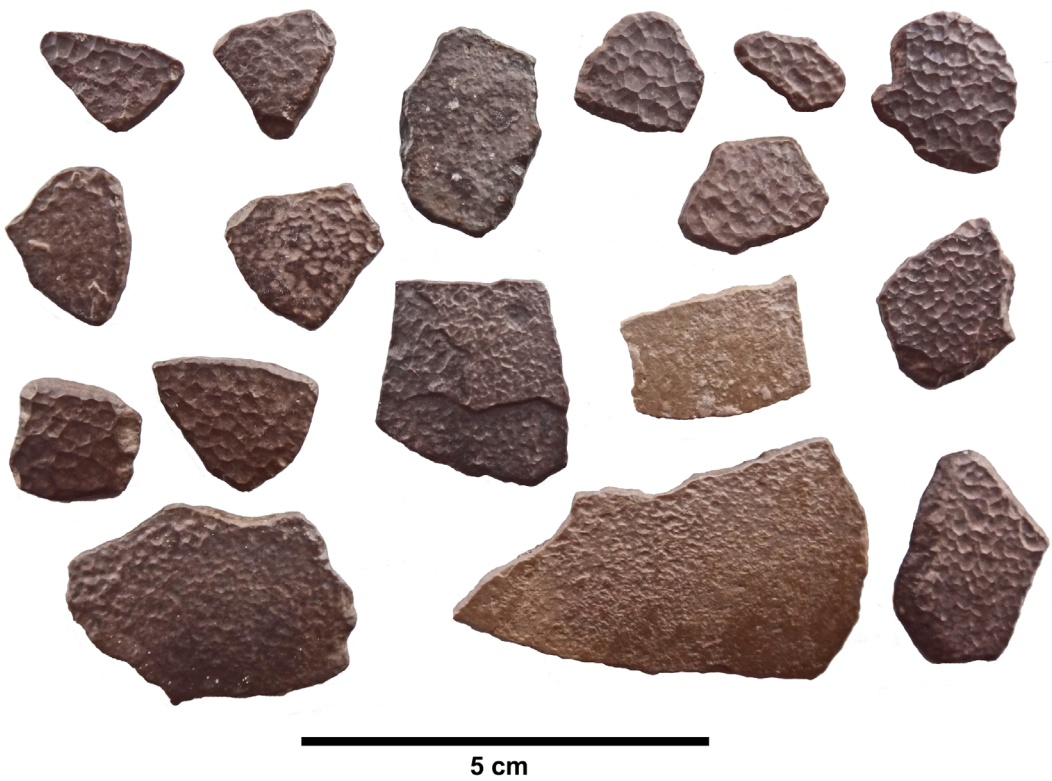

Figure 6.— ONHM-F-4779, fossil struthious eggshell fragments from site 25.RAK, where there are extensive exposures of the Marsawdad Formation, Oman.

margin of a circular pore complex as in shells of *D. laini* (Figs 5, 9).

Figure 7.— Inner and outer surfaces of ONHM-F-4779, a lightly eroded eggshell fragment of *Diamantornis laini* from site 25.RAK, Marsawdad Fomation, Oman. The arrow shows the margin of a depression that could represent the edge of a circular pore complex.

Implications of fossil avian eggshells from the Arabian Peninsula

Over the past nine decades, fossil struthious eggshell fragments have been reported from a variety of localities in the Arabian Peninsula (Lowe, 1933a, 1933b; McClure, 1984; Bibi et al. 2006; Hofmann et al. 2018; Al-Kindi et al. 2021; Mairoano et al.

Figure 8.— Outer surfaces of ONHM-F-4779, two deeply sculpted eggshell fragments of *Diamantornis laini* from site 25.RAK, Marsawdad Formation, Oman. The sculpting is probably due to a combination of sand blasting and dissolution by dew, repeated many times.

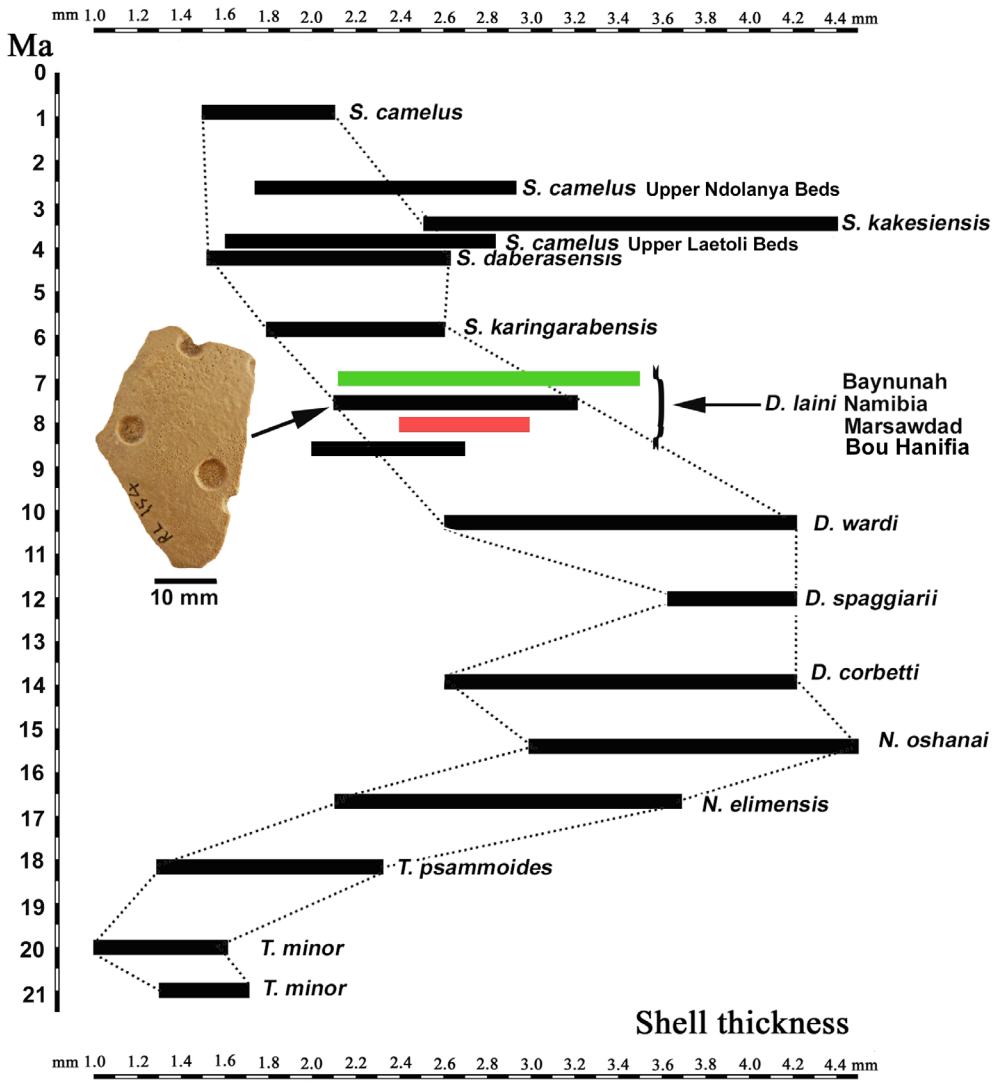

Figure 9.— Struthious and aepyornithoid eggshell thicknesses from the Neogene of Namibia, Tanzania, Algeria and the Arabian Peninsula. The range of variation is shown (red is the Marsawdad sample: n = 10, green is the Baynunah sample from Bibi et al. 2006). Measurements of *S. kakesiensis* and other Tanzanian levels are from Harrison & Msuya (2005) and those of the Namibian samples are from Pickford (2014). *D. Diamantornis, N. Namornis, S. Struthio, T. Tsondabornis*. Illustrated is an eggshell fragment of *D. laini* from Rooilepel, Namibia. Bou Hanifia is a Late Miocene locality in Algeria (Arambourg, 1959). N.B. The ranges of variation in the Tanzanian samples are plotted as published, but they require verification, mainly because the range of *S. kakesiensis* is appreciably greater than that of all the other taxa, which seems an unlikely scenario for an oospecies.

2020; Rosén et al. 2021; Buffetaut, 2022). The most common eggshell fragments reported from the peninsula belong to the extant ostrich, *Struthio camelus* (*Struthio syriacus* in Lowe, 1933a, 1933b). Specimens are known from the vicinity of Maitan, Oman (Al-Kindi et al. 2021), from various sites in Saudi Arabia (Lowe, 1933a, 1933b; McClure, 1976, 1978, 1984) (Table 2) as well as generally over much of the peninsula (Boug & Islam, 2018). These eggshells are thin (less than 2 mm) and generally show the pore arrangement typical of the extant ostrich. Near Maitan, such eggshells were exploited by Neolithic societies to fabricate beads (Al-Kindi et al. 2021).

A single fragment of an oospecies with a shell thickness of 2.6 mm (probably of *Diamantornis laini* but could belong to *Struthio daberasensis*) was found near Maitan, Oman (Al-Kindi et al. 2021; Maiorano et al. 2020). The eggshells of *D. laini* from Namibia are considerably thicker than those of *S. camelus*, ranging in thickness from 2.4 - 3.0 mm. In addition,

the pores in eggs of *Diamantornis laini* are concentrated into circular slightly depressed pore complexes, with large expanses of smooth surfaces devoid of pores between the pore complexes, thereby differing from the eggs of aepyornithoids which have pores liberally scattered over the surface of the eggs (Bibi et al. 2006).

Restudy of the eggshell fragment (NHMUK A 2043) from Shuqqat Al Khalfat, Saudi Arabia (near 21°57'13''N – 49°45'41''E) described by Lowe (1933a, 1933b) as suggested by Buffetaut (2022) was undertaken in March, 2023 (Fig. 10). It is 3.1 – 3.2 mm thick and the apparent lack of pores in the fragment suggests appurtenace to *D. laini*. On this basis the specimen indicates that the deposits from which it was collected are probably of Late Miocene age.

Arambourg (1959) described fossil struthious eggshell fragments from Bou Hanifia, Algeria, reporting that they range in thickness from 2.5 to 3.0 mm. Examination of the fossils housed in the Muséum National d'Histoire Naturelle, Paris (inventory n° 1951-9-295. Fig. 11) reveals that the outer surfaces appear to be devoid of pore structures, and they are thus similar to the surfaces between the circular pore pits of specimens of *Diamantornis laini*. Remeasurement of the specimens yielded the following data :- 1 specimen, 2.0 mm; 1 specimen, 2.1 mm; 3 specimens, 2.2 mm; 1 specimen 2.3 mm; 2 specimens, 2.4 mm; 2 specimens, 2.5 mm; 1 specimen, 2.6 mm; 1 specimen, 2.7 mm.

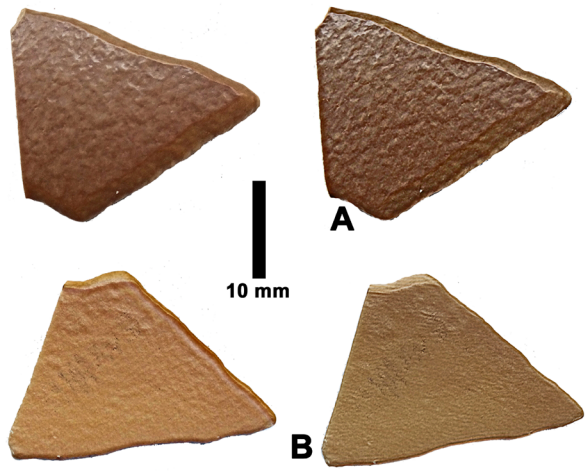

Figure 10.— Stereo images of NHMUK A 2043, eggshell fragment from Shuqqat Al Khalfat, Saudi Arabia. A) outer surface, B) inner surface.

Recent reassessment of the Bou Hanifia mammals (Pickford & Chaïd-Saoudi, in prep.) suggests that they correlate best with the Late Turolian to Ventian, rather than to the Vallesian, and the fossil eggshells found in the same deposits accord with this reinterptation of the age of the faunas. Thus Bou Hanifia and Marsawdad could be roughly contemporaneous.

Discussion and Conclusions

17 fossilised struthious eggshell fragments collected from exposures of the Marsawdad Formation,

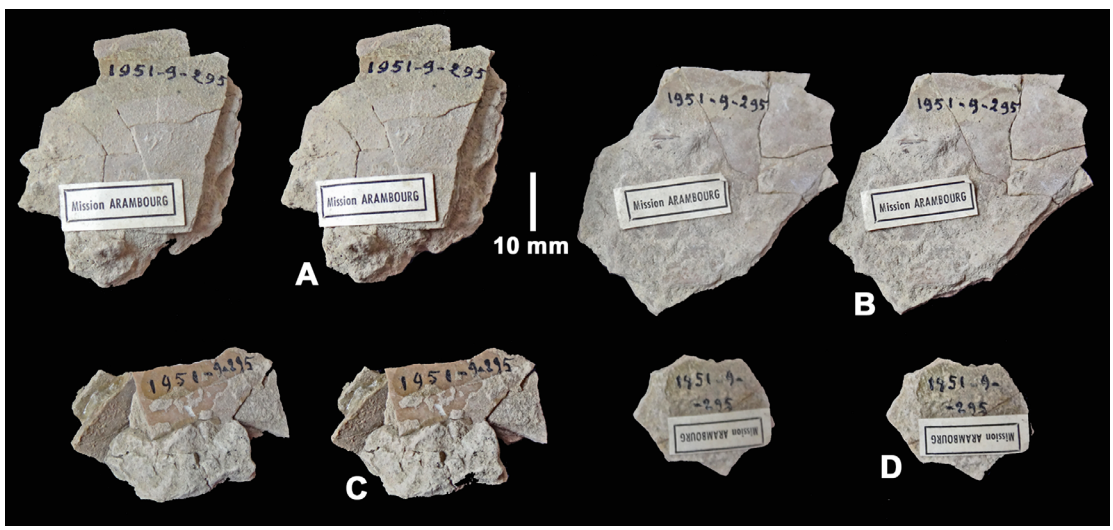

Figure 11.— Stereo images of fossil struthious eggshell fragments from Bou Hanifia, Algeria (MNHN 1951-9-295).

Rub' Al-Khali, Oman, are attributed to the oospecies *Diamantornis laini*, a form that spans the period 8-7 million years in Namibia (Pickford, 2014), Kenya (Harris & Leakey, 2003) and the United Arab Emirates (Bibi et al. 2006) (Fig. 12). On this basis, the Marsawdad Formation is considered to be of Late Miocene age, corresponding to the Turolian-Ventian ages of Europe (Morales et al. 2013). The geologists who mapped the formation (Chevrel et al. 1992; Platel & Berthiaux, 1992a, 1992b) correlated it to the Tortonian-Zanclean but it more likely correlates only to the Tortonian-Messinian.

The Marsawdad fossils provide a biostratigraphic anchor for the late Neogene sedimentary deposits of the Rub' Al-Khali, and indicate that the Marsawdad Formation correlates to the Baynunah Formation which is widespread in the United Arab Emirates (Beech & Hellyer, 2005). The outcrop pattern of

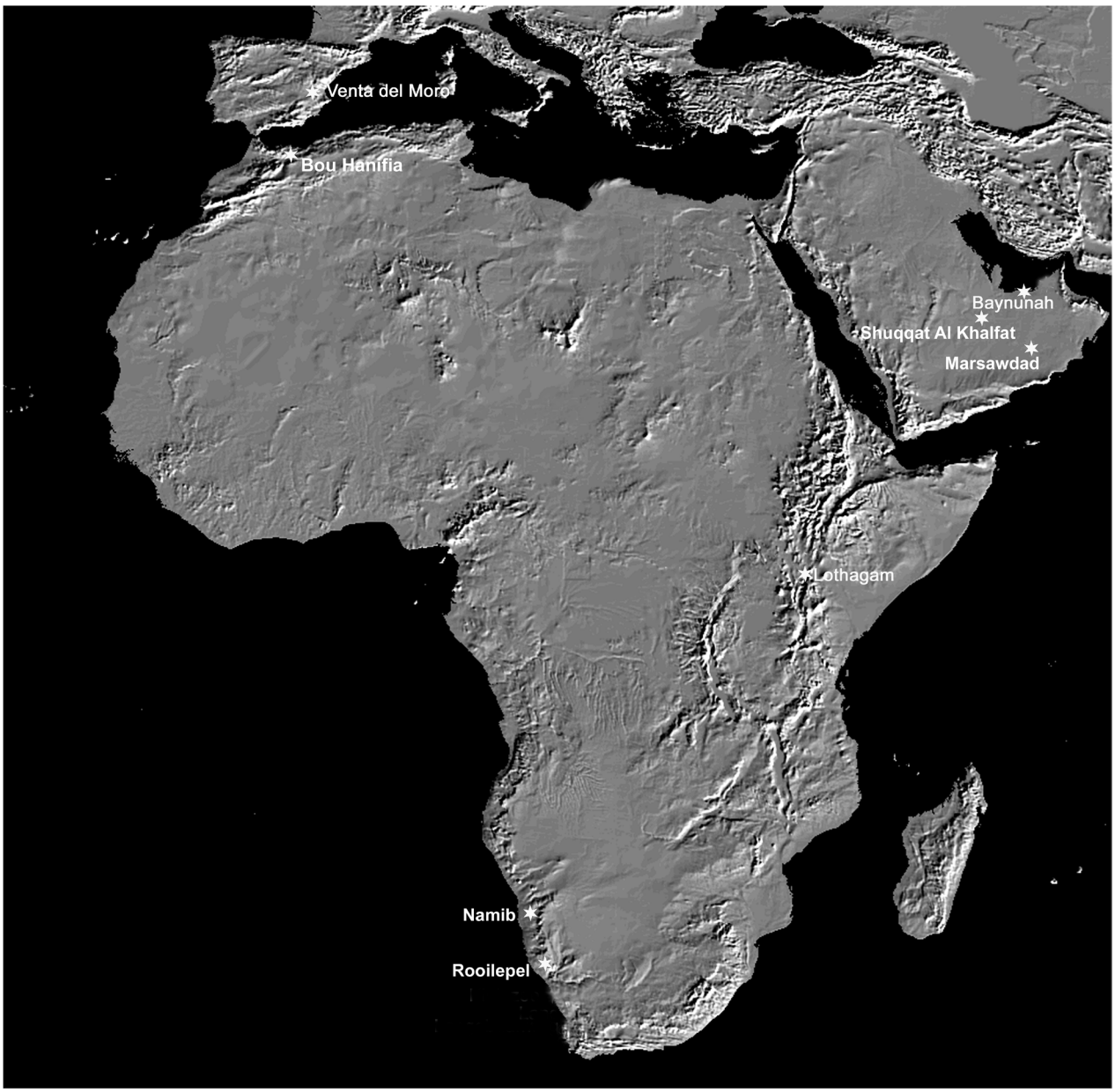

Figure 12.— Distribution of late Miocene (MN12-MN13) fossil struthious eggshells in the Arabian Peninsula and Africa. Also shown is Venta del Moro, Spain, the type locality of the Ventian land mammal age (Morales et al. 2013).

the Marsawdad Formation in Oman reveals that the unit probably extends into Saudi Arabia to the north (in the vicinity of Thabhloten) and that surveys in that country may yield fossils of the same species. As such it is interesting to note that a fossil eggshell fragment from Shuqqat Al-Khalfat, Saudi Arabia, collected in 1932 (Lowe, 1933a, 1933b) (Fig. 10) likely belongs to *Diamanornis laini* which is also present in the Baynunah Formation which is equivalent in age to Marsawdad.

The two ootaxa from the Baynunah Formation were reinterpreted by Mikhailov & Zelenkov (2020) as representing *Diamantornis laini* and *Tsondabornis psammoides*. We agree with the identification of the former species, but the latter possibly requires further study because *Tsondabornis* has not been reported from any other deposits younger than ca 17 Ma (Pickford, 2014). However, the genus and species identification could be valid because the known eggshells of *Tsondabornis psammoides* range in thickness from 1.2 to 2.2 mm, whilst the fossil eggshells from the Baynunah Formation range in thickness from 1.65 to 2.29 mm (Bibi et al. 2006) implying a marked degree of overlap in the ranges of variation. Further comparisons are required but are not the focus of this paper.

An implication of the identification of eggshells of *Diamantornis laini* in the Marsawdad Formation implying an age of ca 8-7 Ma (Tortonian-Messinian: Turolian-Ventian) is that the underlying Montasar Formation could be of Middle Miocene age (possibly Serravallian) as it overlies the Early Miocene Dam Formation (Burdigalian). More detailed mapping and stratigraphy as well as palaeontological surveys are required to refine the stratigraphy.

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