Chapter 3

Sedimentology and Stratigraphy of the Baynunah Formation

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Abstract:

The Baynunah Formation (8–6 Ma) outcrops along the western coast of Abu Dhabi Emirate and has produced the only known late Miocene continental vertebrate fauna from the Arabian Peninsula. This chapter presents an overview of the geology of this formation with a focus on its stratigraphy and sedimentology. Remains of vertebrates are mainly found in the lower to middle part of this formation, which is dominated by fluvial deposits and associated paleosols containing rhizoliths and insect nests. Whitish carbonate beds occur towards the top of the formation, and preserve numerous trackways of large mammals (proboscideans and ungulates). Photographs in this chapter provide a comprehensive illustration of the most remarkable aspects of the Baynunah Formation, from outcrop conditions down to depositional structures.

Running head: Sedimentology & stratigraphy

Introduction

This chapter provides key information and observations on the geological context of the Baynunah Formation. The aim here is not to describe its sedimentology in detail or to discuss its stratigraphy – this can be found in earlier papers – but to provide future workers with an overview of the geology of this formation, notably with illustrations of outcrops and information about its depositional environments, as a field guide would do.

The Baynunah Formation has produced, at this time, the only upper Miocene continental fossils (vertebrates, invertebrates and plants) known from the Arabian Peninsula. These fossils indicate a biochronological age for this formation between 8 and 6 Ma (Whybrow and Hill 1999; Bibi et al. 2006, this volume-a). Arabia lies at a critical junction for Old World biogeographic divisions (Hill and Whybrow 1999; Bibi 2011) and the Neogene is a crucial time period for the evolution of mammals especially for primates and early hominins (Hill 1999; Gilbert et al. 2014, this volume). The Baynunah Formation thus represents a unique window into the biogeography and evolutionary history of the fauna of Arabia. As such, geological data about this formation are crucial to help paleontologists understand the paleoenvironmental context of this fauna.

FIGURE 3.1 NEAR HERE, HALF PAGE WIDTH

General context

Outcrops of the Baynunah Formation are best exposed along the Gulf coast west of Abu Dhabi city (Figure 3.1), as discontinuous hills emerging from Quaternary and recent sedimentary cover. The Gulf is a shallow, asymmetric, Plio-Pleistocene foreland basin with a gentle slope at its southern end and a northern end which is steeper (median depth: 35m; maximum depth: ~ 100m; sill depth: 86m; Purser & Seibold 1973; Uchupi et al. 1999; Kassler 1973). It is associated with the Zagros orogeny, which is related to the collision of the Arabian and Eurasian plates that has been

developing since the Oligocene (~30 Ma, Agard et al. 2011). Large-scale maps, showing tectonic reconstructions of the Arabian plate in relation to the African and Eurasian plates, along with paleofacies evolution, have been compiled by Hempton (1987), Ziegler (2001), and Barrier and Vrielynck (2008). For the relatively short scale (time and space) represented by the Baynunah Formation, these maps only suggest continental depositional systems with no connection to the ocean. The Baynunah is only included in the synthetic paleogeography of the Gulf proposed by Hadley et al. (1998). The Gulf is considered to have been closed by the end of the Miocene (Adams et al. 1983), then flooded by seawater by the late Pliocene to mid-Pleistocene (Hadley et al. 1998; Kirkham 1998), after which it experienced repeated disconnection and drying during times of sea level lowering related to glacio-eustasy (Walkden & Williams 1998). The modern shallow epireic sea is the result of the rise in sea level after the Last Glacial Maximum which led to a rapid reflooding of the Gulf floor (Lambeck 1996; Teller et al. 2000).

FIGURES 3.2-3.4 NEAR HERE, EACH FULL PAGE WIDTH

Stratigraphy

The late Miocene Baynunah Formation (Figs. 3.2 and 3.3), was first described by Whybrow (1989) who defined its stratotype at Jebel Barakah (Fig. 3.1). Thanks to the documentation of several complementary geological sections, Whybrow et al. (1999) refined the stratigraphic framework of the Baynunah Formation and more fully documented its spatial extent. This work also introduced a new formation, the Shuwaihat Formation, which is well exposed on the island of Shuwaihat (Figures 3.1, 3.3 and 3.4). It is also exposed in the lowermost part of the type section at Jebel Barakah, and the decision to define it as a new lithostratigraphic unit was taken on the basis of differences in sedimentary facies (Bristow 1999; Whybrow et al. 1999). The Shuwaihat Formation consists mainly of aeolian dune deposits with prominent large-scale cross-stratified orange

sandstones, pin-stripe laminations, grain-flow and grain-fall deposits, and sabkha to playa lake deposits including sandstones, claystones, secondary gypsum, and small-scale soft-sediment deformation structures (e.g. Bristow 1999). The geology and the paleontology of the Baynunah Formation, in contrast, point mainly to fluvial paleoenvironments (e.g. Hill and Whybrow 1999).

The Baynunah Formation is made up of continental depositional systems with both terrestrial and aquatic environments. It is typically several tens of meters thick and exceeds 50m at the type section (Jebel Barakah). Locally, it is unconformably overlain by Quaternary aeolian dunes composed of wind-reworked oolites, and more often covered by recent aeolian sands (Figs. 3.3 and 3.4). The Baynunah Formation is best identified in the field by the presence of conglomerate beds, well-developed paleosols (containing rhizoliths and insect nests), its fossil content (notably continental vertebrate remains), and its whitish carbonate beds that mark the upper part of the formation. At many butte-like exposures, a cap-rock complex made of sandstone and carbonate with displacive gypsum-anhydrite and chert veins generally forms a resistant tabular top (Ditchfield et al. 1999; Whybrow et al. 1999).

The Shuwaihat and Baynunah Formations have distinct geological characteristics, however putting a sharp limit between them is not always straightforward. As noted by Bristow (1999), the contact can be erosive or transitional. Therefore both formations can be separated taking the highest sabkha or playa lake deposits as the top of Shuwaihat Formation and the lowest fluvial facies as the base of Baynunah Formation (Bristow, 1999). At Shuwaihat, the highest playa lake deposits can be found some few meters above an obvious sharp horizontal surface that truncates aeolian cross-strata, which is attributed to a Stokes surface (a wind-deflated surface, the depth of which is controlled by the water-table, Bristow and Hill 1998) and below the lowest fluvial conglomerate bed.

The most representative schematic section of the Baynunah Formation was proposed by Ditchfield (1999). It reveals a fining-upward vertical lithological evolution, from conglomerates and

coarse sandstones in its lower part, to sandstones and limestones in its upper part. It also shows the ideal situation of a lower erosive contact of the Baynunah Formation upon the Shuwaihat Formation. The synthetic section presented in this paper (Fig. 3.2) compiles various observations made on some of the key-outcrops (Jebel Barakah, Shuwaihat, Kihal, Umm al Kabir, Gerain al-Aysh, Hamra, Ghayathi; map Fig. 3.1). All of these deposits were formed in a continental setting, thus limited spatial extension and lateral facies changes are typical at outcrop scale. Unfortunately, exposure conditions at many sites are much poorer today than when the pioneering work was done due to vehicular traffic, development activities, land privatization, and sand and scree cover. Therefore the existing sections (Bristow 1999; Ditchfield 1999; Whybrow et al. 1999) helped greatly to control this synthetic log.

Sedimentology

Three of the most remarkable and typical sedimentary units of the Baynunah Formation are presented here. These include the fluvial deposits and associated paleosols from the lower part of the formation and the whitish carbonates from the uppermost part of the formation.

FIGURE 3.5 NEAR HERE, FULL PAGE WIDTH

Fluvial deposits (Figure 3.5) Gravels and sands from the lower part of the Baynunah Formation, from which most of the fossils originate, were deposited by rivers as evidenced by sedimentary structures (Friend 1999). Thick (up to several meters), broad (up to several tens of meters) and upwardly thinning lenses of trough cross-stratified conglomerates are typical of the lower part of the Baynunah Formation (Fig. 3.3). They are remarkable for their clasts, which are made of reworked pedogenetic carbonate derived from older paleosols (Ditchfield 1999; Friend 1999). Many have irregular nodular shapes, but some show a typical root-like morphology (elongated, circular section,

branching pattern). These clasts are mainly sandstone cemented by carbonate and range in size from granules to cobbles. They likely derive from the rhizoliths that are very common in the Baynunah Formation (see below). Among these clasts, it is worth noting that some of them are enclosed by a thin layer (up to 1cm) of very finely laminated pure carbonate (Fig. 3.4). Oncoids are here reported for the first time within the conglomerates of the Baynunah Formation. Oncoids form in various types of aquatic environments, notably in river streams or in the nearshore areas of marine or continental water-bodies. These oncoids, which here only appear as reworked clasts in the fluvial conglomerates, show possible evidence for paleolakes, now no longer preserved themselves. The trough cross-stratified conglomerate beds of the Baynunah Formation have been interpreted as of fluvial origin. The Baynunah rivers, with a local flow directions towards the ESE, have been proposed to be part of an ancestral Tigris-Euphrates river system (Friend 1999). More generally, fluvial depositional environments, from the main channel axis up to the alluvial floodplain, are also suggested by cross-bedded sandstones, mudstone rip-up clasts, inclined heterolithic stratifications, climbing ripples, laminations and terrestrial bioturbations.

FIGURE 3.6 NEAR HERE, FULL PAGE WIDTH

Paleosols (Figure 3.6)

Paleosols are well-developed in the Baynunah Formation, whereas only sparse rhizoliths and insect galleries and nests can be observed in the underlying Shuwaihat Formation. Paleosols are thus a distinguishing feature of the Baynunah Formation. However, they have received only scant attention that mainly outlined the presence of root related sedimentary structures (Glennie and Evamy 1968; Whybrow and McClure 1981; Friend 1999). Rhizoliths are indeed extremely well-represented in the sandstones, in the form of root molds, root casts, root tubules and rhizcretions. They are associated with galleries and nests of termites and possibly dung beetle brood-balls. The

presence of termite and ant nests has been previously reported from the Miocene of Abu Dhabi (Bown and Genise 1993). Comparable insect nests are common in penecontemporaneous terrestrial strata of Africa (e.g. Schuster et al. 2009), and some of the termite nests closely resemble the *Vondrichnus planoglobus* chambers described from the Chad Basin (Düringer et al. 2007). Rhizoliths and insect nests are organized in sometimes thick beds (up to several meters) forming extensive paleosol horizons characterized by various colors (red, green, white). These bioturbations are highlighted by colour changes, and by differential erosion. Where they are most abundant, primary sedimentary structures are completely overprinted, while elsewhere some can still be inferred. Thus, they evidently developed after the river flooded and after the deposition of fluvial bedforms, above the water-table, and before the next flood which might have reworked part of the pedogenic concretions. The prominence and the degree of preservation of some paleosol beds and the presence of soil-derived clasts within the conglomerates, suggest that in some places on the landscape (e.g. emerged fluvial bars, distal floodplains, abandoned channels) paleosols were able to sufficiently develop and mature before being reworked.

FIGURE 3.7 NEAR HERE, FULL PAGE WIDTH

Carbonate beds (Figure 3.7)

Whitish carbonate beds (up to several tens of centimetres thick) alternate with variably cemented sandstone beds and are typical of the upper Baynunah Formation. They outcrop in section as prominent tabular beds, or can be aerially exposed as extensive wind-deflated surfaces. They have until now received only scant attention, likely because vertebrate remains mainly derive from underlying siliciclastic levels. They have been briefly described as “*poorly consolidated micritic limestones*” and “*fenestral micrites*” in which shell molds of possible cerithid gastropods have been observed, and were considered to have been deposited in marine to brackish waters (Ditchfield

1999). Analyses of ostracods, charophytes, and pollen (Mazzini & Kovacova, this volume) show that these carbonates formed in shallow, freshwater environments that flooded and desiccated repeatedly, and with no evidence of any marine connections. These whitish carbonate beds show only few sedimentary structures, dominated by crude horizontal bedding, fine horizontal laminations, and rare bioturbations. When exposed as horizontal surfaces, as at Mleisa, they can reveal remarkable trackways of large mammals among wide desiccation cracks and polygons (Bibi et al., 2012, this volume-b; Schuster et al., in prep). These carbonate beds can be almost pure calcite but also often contain a variable amount of clastics (clay, silt and sand). Their apparently constant individual thickness at the size of available exposures suggests a wide original lateral extent.

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Figure captions

Figure 3.1

Location maps of the study area with names of the main localities mentioned in the text (world map generated with *Marble/Ubuntu*; Landsat TM 2000 view of the Emirate of Abu Dhabi from *earthexplorer.usgs.gov*) [HALF PAGE WIDTH]

Figure 3.2

Synthetic log of the Baynunah Formation **A**, and general field views of the main sedimentological components of the section (**B-F**). Note that the limestone and the caprock beds protrude not because they are composed of coarse material but because they are much more lithified than the other beds. Locations: **B**, Shuwaihat, SHU 2. **C-D**, Gerain al-Aysh. **E**, Kihal. **F**, Gerain al-Aysh. [FULL PAGE WIDTH]

Figure 3.3

General views of exposure conditions of the Baynunah Formation. **A**, lower and **B**, upper parts of the formation (Jebel Barakah). **C**, orange cross-stratified beds of the Shuwaihat Formation in the foreground (Shuwaihat). **D**, coarse scree slopes derived from the erosion of overlying conglomeratic beds of the lower part of the formation (Gerain al-Aysh). **E**, fluvial beds of the lower Baynunah (Thumayriyah island). **F**, upper part of the formation (Gerain al-Aysh). Note the prominent whitish beds and cap rock topping the buttes, and the deflated remains of this cap rock (mainly cherts) in the foreground. [FULL PAGE WIDTH]

Figure 3.4

Miocene (Shuwaihat Formation; **A–C**) and Quaternary (**D–E**) aeolian dune deposits observed below and above the Baynunah Formation respectively. **A**, vertical and **B**, horizontal cross-sections of aeolian dune cross-stratification (Shuwaihat). **C**, sparse rhizoliths and/or bioturbation in the aeolian sands (Shuwaihat). **D**, large-scale aeolian dune cross-stratification of Quaternary aeolianites made of oolitic sands as shown in **E**, (Hadwaniyya). [FULL PAGE WIDTH]

Figure 3.5

Fluvial deposits of the Baynunah Formation. **A–B**, trough cross-stratified conglomerates in vertical cross section. **C**, plane bed view of trough cross-stratified sets of conglomerate, showing a paleo-flow toward the east. **D**, crudely laminated, clast-supported conglomeratic bed made of intraformational clasts. **E–F**, bones (arrows) as clasts within the conglomerate. **G**, crocodile skull (outlined by a dashed line) in planar cross-laminated sands. **H–I**, example of a lens of conglomerate with reworked oncoids as clasts (arrow heads). **J**, cross-section of an oncoid showing its nucleus (sandstone) encircled by millimetre-scale laminations of carbonate. [FULL PAGE WIDTH]

Figure 3.6

Paleosols of the Baynunah Formation. **A–C**, rhizoliths collected as part of rock fragments comprising present-day deflation lag. **D**, discrete root tubules overprinting current ripple laminations in sandstones. **E**, an extremely dense network of rhizoliths from which the hosting sediment has been removed by differential erosion. Note the branching and diameter changes typical of roots. **F–G**, *Vondrichnus*-like Termite nests (arrow heads) revealed by weathering (color change and erosion); note the complex network of rhizoliths, burrows, and galleries. **H**, spheroidal bioturbation (arrow heads) possibly corresponding to dung-beetle brood balls found in a dense network of petrified roots. **I**, plane bed view of a partly preserved termite nest exhibiting internal concentric laminations with apex oriented toward the entrance gallery (arrow head), a typical

feature of *Vondrichnus*. [FULL PAGE WIDTH]

Figure 3.7

Whitish carbonate beds from the upper Baynunah Formation. **A–B**, general views showing white beds (white arrows) of continuous thickness at outcrop scale, and the caprock (black arrows) forming the tabular top of the buttes, at Kihal and Mleisa 2, respectively. **C–D**, displacive evaporites (gypsum-anhydrite) interbedded with laminated and sandy white limestones (**C**, Mleisa 2. **D**, Gerain al-Aysh). **E–F**, carbonate surface at Mleisa 1 showing well-preserved desiccation cracks and polygons, as well as proboscidean trackways (individual footprints indicated by arrows).

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Figure 1

Figure 2

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