Chapter 4

Magnetostratigraphy of the Baynunah Formation

Daniel J. Peppe, Terrestrial Paleoclimatology Research Group, Department of Geosciences, Baylor University, One Bear Place #97354, Waco, TX 76798-7354

David A.D. Evans, Department of Geology and Geophysics, Yale University, P.O. Box 208109, New Haven, CT 06520-8109

Mark Beech, Historic Environment Department, Abu Dhabi Department of Tourism & Culture, PO Box 2380, Abu Dhabi, United Arab Emirates

Andrew Hill, Department of Anthropology, Yale University, PO Box 208277, New Haven, CT 06520, USA

Faysal Bibi, Museum für Naturkunde, Leibniz Institute for Evolution and Biodiversity Science, Invalidenstrasse 43, Berlin 10115, Germany.

Abstract

The Baynunah Formation in the Al Gharbia region of Abu Dhabi Emirate was deposited by a major fluvial system and preserves the only known late Miocene terrestrial fossils in the Arabian Peninsula. We analyzed paleomagnetic samples from six sections (Jebel Barakah, Shuwaihat 2, Hamra 5, Mleisa 1, Mleisa 2, and Kihal 2) to develop a polarity stratigraphy for the Baynunah Formation. Based on these analyses, we documented a magnetic polarity stratigraphy, which, in combination with lithostratigraphy, allows us to propose a correlation of these six sections and their fossil localities. We show that first-order facies variations in the Baynunah Formation are diachronous. Confident correlations with the Geomagnetic Polarity Time Scale during the late Miocene cannot be determined; however, correlations based on the local polarity stratigraphy and biostratigraphy suggests that the Baynunah Formation was deposited over a duration of less than 750 kyr between ~7.7 and ~7.0 Ma during the late Tortonian and early Messinian. These results suggest that the fossil sites occurring throughout the lower part of the Baynunah unit and the fossil trackway sites found in the upper part of the formation are likely no more than a few hundred thousand years apart and could have been generated by the same taxa.

Introduction

The late Miocene Baynunah Formation is discontinuously exposed along the Gulf coast in the Al Gharbia region of the Abu Dhabi Emirate in the United Arab Emirates (Figure 4.1) and is composed of a combination of terrestrial fluvial, alluvial, palustrine, and algal mat deposits (Whybrow, 1989; Whybrow et al., 1999; Ditchfield, 1999; Friend, 1999; Schuster, Ch. 3 this volume; Mazzini and Kovacova, Ch 6 this volume). The Baynunah Formation is up to ~50 m thick and records a generally fining upward succession characterized by conglomerates and medium- to coarse-grained quartz-rich sandstones at the base, which grade into a series of interbedded siltstone and fine- to medium-grained sandstone beds, which grade into interbedded fine-grained sandstones and micritic limestones that are capped by a resistant unit of gypsum and anhydrite beds with abundant tabular chert (Whybrow, 1989; Whybrow et al., 1999; Ditchfield, 1999; Schuster, Ch. 3, this volume). The first appearance of the white micritic limestones is typically used as the informal division between the upper and lower parts of the formation (e.g., Schuster, Ch. 3, this volume).

The Baynunah Formation deposits preserve the only late Miocene terrestrial fossils in the Arabian Peninsula, and more than 30 years of paleontological collection have documented a diverse assemblage of small and large vertebrates (e.g., Hill et al., 1999; 2012; Bibi et al., 2013; Bibi et al., Ch. 19, this volume). Almost all of the body fossils come from the lower parts of the Baynunah Formation, particularly from the coarse-grained fluvial deposits; while they are rare in the upper fluvial, palustrine, and algal mat deposits (e.g., Bibi et al., 2013; Bibi et al., Ch. 17, this volume). However, the micritic limestones, which were deposited by fresh and saline ponds and algal mats, preserve vertebrate trackways (Bibi et al., 2012; 2013; Ch. 17, this volume), as well as mollusks, ostracods, algal cysts, and pollen (Mazzini and Kovacova, Ch. 6, this volume).

The age of the Baynunah Formation contains no datable tuffs or volcanic deposits, and its age constraints rely primarily on biostratigraphic correlations to better-dated East African and Asian fossil faunas (Whybrow and Hill, 1999; Bibi et al., 2013). For example, the occurrence of the early

hippopotamid *Archaeopotamus qeshta*, the ratite bird *Diamantornis laini*, the suid *Propotamochoerus hysudricus*, an early Stegotetrabelodontid elephant, and the early thryonomyid rodent *Protohumus*, all suggest an age of between about 8 and 6 Ma, and likely older than 6.5 Ma (Bibi et al., Ch. 19 this volume).

Previous magnetostratigraphic analyses from six sections in the Baynunah Formation documented up to four polarity reversals (Whybrow et al., 1989; Hailwood and Whybrow, 1999). Hailwood and Whybrow (1999) used their polarity stratigraphy to correlate sections from Jebel Barakah, Shuwaihat, Hamra, Mirfa, and Sila, and a correlation of their calculated paleomagnetic pole positions to the Cenozoic apparent polar wander curve for the Arabian plate to suggest an age of 6 ± 3 Ma for the Baynunah Formation. Based on the reversal stratigraphy of Hailwood and Whybrow (1999), Bibi et al. (2013) suggested that deposition of the Baynunah Formation may have lasted over 300 ka. However, the sampling by Hailwood and Whybrow was relatively discontinuous and several of their sections were only a few meters thick, limiting the ability to make among-site correlations or correlations to the Geomagnetic Polarity Time Scale (GPTS).

In this study we develop a revised polarity stratigraphy for the Baynunah Formation from six sections (Hamra 5, Shuwaihat 2, Mleisa 1, Mleisa 2, Kihal 2, and Jebel Barakah) and place fossil sites from these sections within our polarity stratigraphy. We then suggest potential correlations of the Baynunah formation to the late Miocene GPTS between 8 and 6 Ma (Ogg, 2012) and use those correlations to estimate a maximum duration for the Baynunah Formation.

<FIGURE 4.1 ABOUT HERE, width = 2 columns>

Methods

Lithostratigraphic sections were measured at six locations: Shuwaihat 2, Al Hamra 5, Kihal 2, Mleisa 1, Mleisa 2, and Jebel Barakah. Stratigraphic sections were measured at all locations where paleomagnetic

87 samples were collected. The basal contact of the Baynunah Formation is well exposed at Shuwaihat and
88 Jebel Barakah; however, the intervals between the contact and the bases of our sections at those localities
89 were either covered or made of poorly consolidated, coarse-grained sandstone and conglomeratic beds
90 that were not appropriate for paleomagnetic sampling. Thus, we began our lithostratigraphic and
91 paleomagnetic sections above the covered or non-sampled intervals. At the other localities (Kihal 2,
92 Mleisa 1, Mleisa 2, and Hamra 5) the base of the Baynunah Formation was not exposed and thus the base
93 of each section represents the lowermost well-exposed outcrop that could be sampled. Prior to
94 measurement, the sections were trenched to remove modern weathering and to expose bedding contacts.
95 All sections were measured to the nearest decimeter using a Jacob's staff and an Abney hand level. The
96 lithology, grain size, stratigraphic thickness, sedimentary structures, and any biological features (e.g.,
97 roots, vertebrate fossils) were documented for each stratigraphic unit.

98 Paleomagnetic block samples were collected from our lithostratigraphic trenches after weathered
99 material was removed. The lowermost sample was generally collected as close to the base of the
100 lithostratigraphic section as possible. At each sampling horizon, one oriented block sample was collected
101 (Figure 4.2) using an electric masonry saw to cut a rectangular block from the outcrop and then using a
102 chisel to remove the sample. The strike and dip of the upper surface of the cut block was measured prior
103 to removal. Block samples were collected from a range of lithologies and grain sizes from mudstone to
104 fine-grained sandstone to carbonate. Sample spacing was primarily dictated by lithology. In the
105 laboratory, the block samples were dry cut into $\sim 4 \text{ cm}^3$ cubes using a lapidary saw, with each block
106 sample typically yielding four specimens.

107
108 <FIGURE 4.2 ABOUT HERE , width = 2 columns>

109
110 We measured the specimens at Yale University using an automated three-axis DC-SQUID
111 magnetometer housed inside a three-layer magnetostatic shield with a background field typically less than
112 200 nT. We typically analyzed three of the four specimens from each block sample. The specimens were

demagnetized using a combined alternating-field (AF) and thermal demagnetization strategy in which heating steps were performed in a nitrogen atmosphere. All specimens were first given a low-AF pre-treatment (maximum field = 10 mT) using a 3-axis automated static alternating field device to remove any low-coercivity viscous or isothermal remanence. Ten to fifteen thermal demagnetization steps were then performed from 70 °C to the maximum unblocking temperature (typically 350-580 °C) in a controlled nitrogen atmosphere to minimize oxidation reactions. Progressive thermal demagnetization was carried out until the magnetic intensity of the specimens fell below noise level or the measured directions became erratic and unstable.

The characteristic remanence for specimens with quasi-linear trajectories was isolated using principal-component analysis (PCA) (Kirschvink, 1980). Best-fit lines were calculated when a minimum of three consecutive demagnetization steps trended toward the origin and had a maximum angle of deviation (MAD) less than 20° (Appendix 4.1). A subset of specimens was analyzed by great circles and were used if MAD was less than 20° (Appendix 4.1). Specimens with an erratic demagnetization behavior were excluded. A mean direction for each block sample was calculated from the directions for all specimens from the block sample for which we were able to calculate a best-fit line with a MAD of less than 20°, using Fisher statistics (Fisher, 1953) (Appendix 4.2).

In the summary magnetostratigraphic sections, each reversal boundary was placed at the stratigraphic midpoint between samples of opposing polarities, which varied between ~0.5 and ~7 m, depending on sample spacing.

Results

Magnetostratigraphy: We analyzed 76 specimens from 26 block samples at Hamra 5, 31 specimens from 10 block samples at Mleisa 1, 64 specimens from 16 block samples at Mleisa 2, 64 specimens from 16 block samples at Jebel Barakah, 96 specimens from 34 block samples at Kihal 2, and 74 specimens from 25 block samples at Shuwaihat 2.

The magnetic moments of all analyzed specimens were weak. The magnetic moment at NRM of the strongest specimens was $2\text{E-}5$ emu, and the magnetic moment at NRM of typical specimens was $< 4\text{E-}6$ emu. The demagnetization trajectory of most specimens trended toward the origin after the first few temperature steps and was fully demagnetized between 350 and 580 °C (Figure 4.3). All specimens with a coherent demagnetization trajectory with a stable end point were characterized by line fits (Figure 4.3A, B, C). All specimens that had a demagnetization trajectory that trended toward an expected pole direction, but did not reach a stable end point, were characterized using a great circle fit (Figure 4.3D). In total, reliable magnetic directions were determined for 222 specimens from 112 block samples: 49 specimens (65% of total specimens) from 23 block samples from Hamra 5, 17 specimens (55% of total specimens) from 9 block samples from Mleisa 1, 32 specimens (50% of total specimens) from 14 block samples from Mleisa 2, 31 specimens (48% of total specimens) from 16 block samples at Jebel Baraka, 46 specimens (48% of total specimens) from 27 block samples at Kihal, and 47 specimens (64% of total specimens) from 23 block samples at Shuwaihat 2 (Figure 4.4A). The remaining 183 specimens (45% of total specimens), had erratic demagnetization trajectories such that a coherent direction could not be obtained (Figure 4.3E). The magnetic moment at NRM of most of the erratic specimens was $< 9\text{E-}7$ emu, suggesting, the high proportion of specimens without coherent directions is at least partially the result of their very weak magnetic moments. We calculated declination and inclination directions for 98 block samples, with 85 reversed samples and 13 normal samples (Figure 4.4C).

<FIGURE 4.3 ABOUT HERE, LANDSCAPE FORMAT, WIDTH = 9.2 INCHES >

The block sample directions were averaged by each stratigraphic section according to their polarity to determine a mean locality normal and reversed direction for each section (Fig. 4.4B). All of the block samples from each section was also averaged to determine a mean normal and reversed direction for the Baynunah Formation (Fig. 4.4C). This direction was then used to calculate a mean VGP latitude and longitude for the Baynunah Formation (Table 4.1). The average locality-mean VGP for all normal

samples is 82.8°N, 301.6°E ($A_{95} = 8.3$, $R = 14.4$, $k = 22.2$, $n = 14$), and for all reversed samples is inverted to 80.7°N, 302.7°E ($A_{95} = 4.9$, $R = 74.8$, $k = 11.2$, $n = 84$). The result of the reversal test of McFadden and McElhinny (1990) for locality means was a positive, Class B test. These calculated VGPs overlap within uncertainty with the expected Miocene pole for Abu Dhabi recalculated from Torsvik et al (2008) (81.0°N, 296.7°E). However, it is notable that the uncertainty of the normal VGP also overlaps with the present spin axis, suggesting that we may have inadvertently included some partially overprinted directions in our dataset (Fig 4.4C, D).

<FIGURE 4.4 ABOUT HERE, width = 2 columns>

<TABLE 4.1 ABOUT HERE>

Figures 4.5 - 4.10 show the local magnetic polarity stratigraphy for all studied sections, including each specimen and block sample VGP latitude. In all sections, reversal boundaries, if present, were placed at the mid-points between block samples of opposing polarity (Table 4.2). Below, the nominal thickness of a reversal is the thickness based on this arbitrary placement of the reversal boundary.

The Jebel Barakah section (Fig. 4.5) is characterized by successive reversed-normal-reversed (R-N-R) polarity zones. The base of the N-polarity zone is relatively well defined at about 4 m in the measured section, but the succeeding transition back to R polarity is not well constrained in the stratigraphy. The medial N-polarity zone could be represented by no more than about 3 m of section.

At Shuwaihat 2 (Fig. 4.6), all magnetically stable horizons have R polarity.

At Hamra 5 (Fig. 4.7), there is a R→N transition at about 2.7 m in the measured section, constrained to within a 0.6 m interval between adjacent horizons of opposite polarity. The subsequent N→R transition at Hamra 5 is only constrained to lie within a 6.8 m interval between oppositely polarized sample horizons. The low resolution of this upper boundary is based on the occurrence of a thick set of cross-bedded sandstone and conglomerate beds that were deemed unsuitable for paleomagnetic study due to their coarse, porous, and cross-bedded textures. As a result, the middle N-polarity zone at Hamra 5 is

190 nominally 5.35 m thick, but could be as little as 1.65 m and as much as 9.05 m thick. At the top of Hamra
191 5, a single specimen from the uppermost sample (sampling horizon HN26 – shown in light grey in Fig.
192 4.7 and as magnetic zone ‘D+(?)’ in Table 4.2) produced a normal polarity direction. Because a normal
193 direction from only a single specimen is not robust enough to recognize a reversal, we do not interpret
194 this sample to represent a reversal at the top of the section. However, for completeness, we have included
195 it in tables and figures.

196 At Mleisa 1 (Fig. 4.8) and Mleisa 2 (Fig. 4.9) all samples showed reversed polarity.

197 The magnetostratigraphy from Kihal 2 (Fig. 4.10) is similar to those of Jebel Barakah and Hamra
198 5 in containing a succession of R→N→R polarity zones. In this section, the nominal thickness of middle
199 N zone is ~3.0 m, with a minimum thickness of 1.15 m and a maximum thickness of 4.9 m.

200
201 <TABLE 4.2 ABOUT HERE >

202 <FIGURE 4.5 ABOUT HERE, width = 2 column >

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208 209 **Discussion**

210 **Correlation of polarity stratigraphy**

211 At Hamra 5, Jebel Barakah, and Kihal 2, there is a thin interval of normal polarity bracketed by thicker
212 reversed polarity intervals (Figs. 4.5, 4.8, and 4.9; Table 4.2). We parsimoniously correlate the thin
213 normal polarity zone across these three sections based on the thickness of the polarity zone and the
214 lithostratigraphy of the sections (Fig. 4.11).

The sections at Shuwaihat 2, Mleisa 1 and Mleisa 2 are entirely reversed (Figures 4.6, 4.8, 4.9), thus correlation between these sections to Hamra 5, Jebel Barakah, and Kihal 2 was based on a combination of their polarity, sedimentology, and position relative to the Baynunah-Shuwaihat formational contact. The first paleomagnetism samples from Shuwaihat 2 were collected from ~5-10 meters above the basal contact of the Baynunah, and the first micritic limestone beds in the section occur above our uppermost paleomagnetism sample and at the top of our lithostratigraphic column. Thus, we are confident that the Shuwaihat magnetostratigraphic section includes the lower Baynunah Formation and is correlative to the lower R-polarity zone in the Hamra 5, Jebel Barakah, and Kihal 2 sections (Figure 4.11). Both the Shuwaihat 2 and Kihal 2 sections indicate that the entirety of the lower Baynunah Formation has reversed magnetic polarity.

The Mleisa 1 and Mleisa 2 sections were correlated based on physical tracing of stratigraphic beds between the sections. The lowermost sample from Mleisa 1 comes from the carbonate layer that preserves a proboscidean trackway (Bibi et al., 2012, and Ch. 17 this volume). The first sample at Mleisa 2 is from above the first carbonate layer that occurs in the valley bottom floor, and below the ungulate trackway described from there (Bibi et al., Ch. 17, this volume). Both of these sections are made up of fine- to very fine-grained sandstones, green siltstones, and micritic limestone beds, typical of the upper Baynunah Formation (e.g. Ditchfield, 1999; Bibi et al., 2013; Schuster, Ch. 3 this volume). Further, the elevation of the base of the Mleisa 1 section and the valley bottom floor at Mleisa 2 are at ~31 m elevation using a handheld GPS unit, which is a similar to the elevation of the upper Baynunah Formation at the coastal sites (Hamra 5, Kihal, Jebel Barakah). Based on their lithology and elevation, we correlate the Mleisa 1 and Mleisa 2 sections to the upper reversed polarity interval at Hamra 5, Jebel Barakah, and Kihal 2 (Figure 4.11). However, we cannot determine precisely where the sections fit within this upper reversed zone, and thus the positions of the Mleisa 1 and 2 sections in Figure 4.11 are approximate.

<FIGURE 4.11 ABOUT HERE, width = 2 columns>

The first occurrence of laterally continuous micritic limestone layers has been used informally to distinguish the lower and upper parts of the Baynunah Formation (e.g., Schuster, Ch. 3, this volume). The micritic limestone beds are interpreted to represent parts of the landscape that were covered by shallow freshwater ponds that were subsequently desiccated (e.g., Schuster, Ch. 3 this volume; Mazzini and Kovacova, Ch 6 this volume). It is plausible that the onset of these ponds was driven by changes to the regional climate regime through temporary increases in precipitation and/or decreases in evaporation, perhaps in response to precessional-scale variation in summer insolation (Bibi et al., Ch 19 this volume). However, our magnetostratigraphy demonstrates that these limestone layers occur diachronously in the Baynunah Formation from west to east, with the first carbonate beds appearing in the lower R-polarity zone at Jebel Barakah and Shuwaihat 2, and in the upper R-polarity zone at Hamra 5, Kihal 2, Mleisa 1, and Mleisa 2 (Fig. 4.11). Thus, while the onset of palustrine environments may have been driven by regional climate changes, the initial formation and the migration of palustrine depositional centers was also clearly affected by local controls related to the evolution of the Baynunah River system, such as the development of low-lying parts of the landscape in which such ponds may have developed.

Relationship of the Baynunah magnetostratigraphy to previous work

We sampled three of the same sections as Hailwood and Whybrow (1999) (Jebel Barakah, Shuwaihat 2, and Hamra 5), allowing us to compare our polarity stratigraphy to theirs. At Jebel Barakah, similar to Hailwood and Whybrow (1999), we identified a relatively thin normal polarity interval near the top of the Baynunah Formation exposures. Unfortunately, due to recent human modification at Jebel Barakah, we were unable to sample the lower Baynunah Formation that was sampled by Hailwood and Whybrow (1999) and in which they identified another thin normal polarity interval. It is possible that we did not recover this normal interval because we were unable to sample that part of the section but alternatively, Hailwood and Whybrow (1999) may have measured an overprint direction. These authors note that the samples from Jebel Barakah had weaker magnetic intensities, with more erratic magnetic behavior, and paleomagnetic vectors that were not as well defined as at other sites. In the case of the lone

sample that is shown from Jebel Barakah (figure 8.4C in Hailwood and Whybrow, 1999), they note that although the sample was not suitable for calculating a magnetic direction, it could be used to determine polarity and was used to define the polarity stratigraphy of the section. The demagnetization trajectory of the sample is erratic, and our quality-filtering methods would have excluded it from interpretation. Furthermore, the stable end point is very similar to the modern pole direction, suggesting they document a recent overprint direction. We therefore argue that it is unlikely that a normal polarity interval truly is present in the lower Baynunah Formation.

Our section at Shuwaihat 2 was entirely reversed, while the Shuwaihat section of Hailwood and Whybrow (1999) includes an interval of normal polarity. However, the stratigraphic position of the normal samples of Hailwood and Whybrow (1999) correlate to the interval in which we sampled at high resolution (samples SH02 – SH13, Figure 4.10), which suggests that we were unlikely to have missed a 3-4 m thick N-polarity zone. Furthermore, the demagnetization trajectory of their normal samples (figures 8.3A and 8.4D in Hailwood and Whybrow, 1999) either trend to a stable end point that overlaps with the modern pole direction or have a similar demagnetization trajectory to samples that we identified as reversed and characterized with a great circle (Figure 4.3B and 4.3D). Additionally, Hailwood and Whybrow (1999) note that some samples display an “intermediate direction”, which they interpreted to either represent the sampling of a transitional field during a polarity reversal or disruption of grain structure during sampling. However, as noted above, their demagnetization trajectory was similar to reversed samples that we characterized with a great circle. Therefore, we interpret the normal polarity interval of Hailwood and Whybrow (1999) in the Baynunah Formation at Shuwaihat to be documenting a normal overprint direction from samples that should have been characterized as reversed using a great circle fit.

Our Hamra 5 section, which is from the same location as Hailwood and Whybrow’s ‘Hamra 6’, also differs in some respects. We documented a single normal interval, while they documented two. The normal polarity intervals in the ‘Hamra 6’ section of Hailwood and Whybrow (1999) are both less than 1 m thick and are apparently defined by only one sample each (Table 8.2 in Hailwood and Whybrow,

1999). Based on field notes of A. Hill, the base of our Hamra 5 section began in a similar location to that of the 'Hamra 6' section of Hailwood and Whybrow (1999), and we sampled the same ~5 m interval of interbedded fine sandstone and silty mudstone (Fig. 4.5). Our sampling was at very high resolution (average sample spacing = 29 cm, minimum = 10 cm, maximum = 60 cm; Fig. 4.5, Appendix 1), much greater than Hailwood and Whybrow's (1999 - their Table 8.2), making it extremely unlikely that we missed any normal polarity intervals. Additionally, none of our other sections from the Baynunah document multiple intervals of normal polarity (Fig. 4.11), further suggesting it is unlikely that there are multiple reversals in the Hamra section.

Above our interval of high-resolution sampling is 7.4 m of poorly consolidated fine to coarse grained sandstones and conglomerates, from which we only collected one paleomagnetism sample due to the coarse-grained nature of the bed (Fig. 4.5). Perhaps Hailwood and Whybrow's (1999) section included more samples from these coarse beds, but this is unlikely based on the lithology of that interval and the sample heights indicated in their table 8.2.

It is also possible that one or both of the normal intervals documented by Hailwood and Whybrow (1999) sample overprinted directions. Their sole normal sample figured from Hamra (their figure 8.4A) appears to show a considerable amount of signal retention at their highest temperature step, suggesting that the sample may not have been fully demagnetized, and thus they may not have calculated the characteristic remanence (ChRM) of the sample. Accordingly, we suggest that the lower thin normal polarity zone at Hamra 6 in the section of section of Hailwood and Whybrow (1999) most likely samples a normal overprint.

Finally, Hailwood and Whybrow (1999) used their paleomagnetic pole position to estimate the age of the Baynunah deposits by comparisons to a rudimentary apparent polar wander curve for Arabia. Their estimate of 6 ± 3 Ma is broad, but in line with the biostratigraphic evidence. Updates to the polar wander curve, and variations arising from Neogene global plate kinematics (e.g. Torsvik et al., 2008), however, suggest that stratigraphic methods of correlation to the GPTS are preferable for paleomagnetic age determination of the Baynunah Formation.

Correlation to the Global Polarity Timescale (GPTS)

Within the sampled sections, there is an N-polarity zone at each of Jebel Barakah, Hamra, and Kihal, where both the bottoms and the tops of the N zones were documented. However, because there are no independent geochronological tie-points for the Baynunah Formation, it is not possible to confidently correlate the local polarity stratigraphy uniquely to the GPTS. Biostratigraphic correlations based on the vertebrate fauna suggest an age between ~8 and 6 Ma during which time there are 14 subchrons in the GPTS, from C4n.2n, which begins at 8.108 Ma, to C3r, which ends at 5.235 Ma, according to astronomochronological tuning (Ogg, 2012). Interestingly, at no time during the 8-6 Ma interval of the GPTS are there relatively long durations of R polarity interrupted by a single short-period N subchron, as seen in our composite Baynunah magnetostratigraphy. This may be because: (i) changes in sediment accumulation rates through the section give the appearance of an anomalously short N-polarity zone; (ii) the Baynunah Formation at any given locality might contain one or more disconformities that excised intervals of N polarity and/or R polarity; (iii) all measured sections may be largely complete in temporal representation, but our sampling or data gaps may hide N-polarity zones or short R-polarity zones; (iv) the medial N-polarity zones of our three sections are not isochronous; or (v) the medial N-polarity zones might be synchronous, but represent a subchron of such brief duration that it is not included in the GPTS.

Given these uncertainties, we can only roughly estimate the absolute age range of Baynunah Formation deposition. Assuming option i or ii, within the 8–6 Ma interval that spans the likely biostratigraphic age for Baynunah deposition (see Bibi et al., Ch 19, this volume), there are four intervals of N-polarity generally located within more extensive R-polarity zones of the GPTS (Ogg, 2012). Two of these N-polarity chronos (C3An.2n, C3An.1n) are between ~6.6-5.8 Ma in age and on the order ~200-300 kyr duration each. If either (or both) of these corresponds to our medial N-polarity zone of ~1-5m thickness at Jebel Barakah and Kihal (our two sections with best sampling resolution around the medial N-polarity zone), then we would extrapolate a total exposed interval (~50 m) of Baynunah Formation deposition on the order of 2–15 million years, with an age of around 6 Ma for the central part of the

formation. Obviously, duration estimates longer than 6 myr are impossible, and longer than 2-3 myr unlikely. Furthermore, this correlation would place the upper Baynunah at an age well younger than 6 Ma, which is too young given the biostratigraphic correlations of the assemblage (Bibi et al., Ch. 19, this volume).

Another possibility is that our medial N-zone could correlate with the brief N-polarity subchrons between 7.5 and 7.1 Ma in age (C3Bn, C3Br.2n, C3Br.1n), each of which last on the order of 30-70 kyr. The correlations to these chronos depends on the presence of one or more disconformities and/or polarity reversals in the Baynunah section that were not sampled.

In correlation option one, if the Baynunah section is largely complete in temporal resolution and we have not missed any polarity zones due to sampling gaps or disconformities, there are four possible correlations for our local polarity zones A-, B+, C-: (1) chronos C3Br.3r, C3BR.2n, C3BR.2r, (2) chronos C3Br.2r, C3BR.1n, and C3BR.1r, (3) chronos C3Br.1r, C3Bn, C3Ar, or (4) C4n.1r, C4n.1n, C3Br.3r (Fig. 4.11). Based on the duration of the subchrons in the GPTS, the thickness of our local polarity zones, and the sedimentology of the Baynunah Formation, which transitions from fluvial and alluvial to palustrine dominated and thus likely samples a decreasing sediment accumulation rate, we suggest that the first correlation (C3Br.3r, C3BR.2n, C3BR.2r) as the most plausible. In this scenario, if we sampled the full duration of each chron, the maximum duration of deposition for the Baynunah Formation would be 243 kyr. However, given our relatively minimal age constraints for the section, the other three correlations are also possible and would suggest a maximum duration of deposition of 242 kyr (C3Br.2r, C3BR.1n, and C3BR.1r), 518 kyr (C3Br.1r, C3Bn, C3Ar), or 206 kyr (C4n.1r, C4n.1n, C3Br.3r)

Alternatively, in correlation option two, if the Baynunah Formation has one of more disconformities or if we missed zones of polarity reversals due to sampling gaps based on the sedimentology of the outcrops or gaps in magnetization, it is plausible that short subchrons, such as C3Br.1r (42 kyr) and/or C3BR.1n (34 kyr), could be missing. In this scenario, local polarity zone A- would correlate to C3Br.2r and zone C- to C3Ar. Depending on which polarity zone was missing, zone B+ could correlate to (1) C3BN with C3Br.1n and C3BR.1r missing, (2) C3Br.1n and C3Bn, with

C3Br.1r missing, or (3) C3Br.1n with C3Br.1r and C3BN missing. If we sampled the full duration of both reversed chrons, the maximum duration for the Baynunah Formation would be 721 kyr. In a second scenario, the subchrons C3Br.3r (39 kyr) and/or C3Br.2n (35 kyr) could be missing. In this scenario, local polarity zone A- would correlate to C4n.1r and zone C- to zone C3Br.2r. Depending on which polarity zone was missing zone B+ could correlate to (1) C4n.1n with C3Br.3r and C3Br.2n missing or (2) C4n.1n and C3Br.2n with C3Br.3r missing. If we sampled the full duration of both reversed chrons, the maximum duration for deposition would be 410 kyr.

We prefer the first option, a relatively continuous section, because there is no evidence for significant erosional unconformities in the section and sampling gaps were primarily the result of sampling above and below fluvial deposits (coarse cross-bedded sandstones and conglomerates), which are likely to have been deposited quite rapidly (Fig. 4.11). However, we recognize that a short depositional hiatus, relatively minor erosive unconformities, or small sampling gaps could have meant that we missed one or more short lived chrons around the Tortonian-Messinian boundary. Regardless, both options indicate that deposition of the Baynunah Formation would have lasted at most ~725 kyr, and most likely considerably less than that because we are unlikely to have sampled the full duration of the lower and upper reversals in the sequence. Our best estimate, based on the reversal stratigraphy and the biostratigraphy of the fauna, is that the Baynunah Formation is between ~7.7 and ~7.0 Ma in age.

Conclusions

Our revised magnetostratigraphy for the Baynunah Formation documents a series of polarity reversals, which in combination with lithostratigraphy, provides a possible correlation for our sampled sections. Interestingly, these correlations indicate that the micritic limestone layers, which occur in the upper Baynunah Formation, are diachronous, suggesting that their first occurrence may have been climatically driven, but their local position on the landscape may have been affected by local changes in the evolution of the Baynunah fluvial system.

Baynunah fossil localities come from multiple stratigraphic levels and therefore sample slightly different intervals in time, with body fossils mainly coming from the lower R-polarity to the top of the N-polarity intervals, and trackway sites from the upper R-polarity interval, albeit "floating" in that portion of the stratigraphy (Figure 4.11). Our age and duration estimates suggest the maximum time span of the Baynunah is <720 kyr, and most likely a few hundred thousand years at most, which justifies the treatment of the Baynunah fossils assemblage as a single paleo-community.

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Figure Captions

Figure 4.1. Map of Al Gharbia region showing the location of the six sections used in this study from west to east: Jebel Barakah (JBR), Shuwaihat 2 (SHU), Hamra 5 (HMR 5), Kihal 2 (KIH), Mleisa 1 (MLS 1), and Mleisa 2 (MLS 2).

Figure 4.2. Paleomagnetic sampling protocol for the Baynunah Formation. A. The sample was cut in four directions prior to removal using a masonry saw. B. The strike and dip of the upper surface of the cut block was measured using a Brunton Pocket Transit Compass before the sample was removed. C. Samples were removed from the outcrop using a chisel and labeled on the top surface of the sample. D. Samples were wrapped in toilet paper and labeled prior to transport to Yale University where they were prepared for analysis.

Figure 4.3. Representative orthogonal vector demagnetization diagrams and equal area plots for each subset of data. A. Demagnetization trajectory of a reversed sample characterized by a best-fit line (sample P07HN02A). B. Demagnetization trajectory of a reversed sample characterized by a best-fit line that has two components and clustered at a stable end point instead of trending towards the origin (sample P07SH06C). C. Demagnetization trajectory of a normal sample characterized by a best-fit line (sample P07HN08C). D. Demagnetization trajectory of a reversed sample characterized by a great circle (sample P07KH05C). E. Representative sample of erratic demagnetization behavior that was not used for interpretation (sample P07KH30B).

Figure 4.4. Equal area plots of characteristic magnetization directions used in this study. A. Equal area plot of all specimen best-fit lines with a $MAD < 20^\circ$ from all sections. B. Equal area plot of normal and

reversed averaged directions using block samples for each magnetostratigraphic sample and plotted alongside the present dipole field position for Abu Dhabi, the late Miocene direction recalculated from Torsvik et al. (2008), and the antipode of the late Miocene direction. The ellipse around each mean direction represents the 95% confidence cone (Fisher, 1953). C. Mean normal and reversed block sample directions from each section plotted alongside the present dipole field position for Abu Dhabi, the late Miocene direction recalculated from Torsvik et al. (2008), and the antipode of the late Miocene direction. The ellipse around each mean direction represents the 95% confidence cone (Fisher, 1953). HN = Hamra 5, M1 = Mleisa 1, M2 = Mleisa 2, KH = Kihal 2, JB = Jebel Barakah, SH = Shuwaihat 2.

Figure 4.5. Lithostratigraphy and polarity stratigraphy for the Jebel Barakah section. The stratigraphic positions of fossil localities are indicated next to the lithostratigraphic section. Grain size is indicated at the bottom of the section: M = mudstone, ZS = siltstone, SS = sandstone, CG = conglomerate, CB = micritic limestone (carbonate layer). Interpreted polarity for the section is to the right of the virtual geomagnetic polarity figure (black = normal, white = reversed). The reversal boundary was placed at the stratigraphic midpoint between samples of opposing polarity.

Figure 4.6. Lithostratigraphy and polarity stratigraphy for the Shuwaihat 2 section. The stratigraphic positions of fossil localities are indicated next to the lithostratigraphic section. Grain size is indicated at the bottom of the section: M = mudstone, ZS = siltstone, SS = sandstone, CG = conglomerate, CB = micritic limestone (carbonate layer). Interpreted polarity for the section is to the right of the virtual geomagnetic polarity figure (white = reversed).

Figure 4.7. Lithostratigraphy and polarity stratigraphy for the Hamra 5 section. The stratigraphic positions of fossil localities are indicated next to the lithostratigraphic section. Grain size is indicated at the bottom

of the section: M = mudstone, ZS = siltstone, SS = sandstone, CG = conglomerate, CB = micritic limestone (carbonate layer). Interpreted polarity for the section is to the right of the virtual geomagnetic polarity figure (black = normal, white = reversed). The reversal boundary was placed at the stratigraphic midpoint between samples of opposing polarity.

Figure 4.8. Lithostratigraphy and polarity stratigraphy for the Mleisa 1 section. The stratigraphic positions of fossil localities are indicated next to the lithostratigraphic section. Grain size is indicated at the bottom of the section: M = mudstone, ZS = siltstone, SS = sandstone, CG = conglomerate, CB = micritic limestone (carbonate layer). Interpreted polarity for the section is to the right of the virtual geomagnetic polarity figure (white = reversed).

Figure 4.9. Lithostratigraphy and polarity stratigraphy for the Mleisa 2 section. The stratigraphic positions of fossil localities are indicated next to the lithostratigraphic section. Grain size is indicated at the bottom of the section: M = mudstone, ZS = siltstone, SS = sandstone, CG = conglomerate, CB = micritic limestone (carbonate layer). Interpreted polarity for the section is to the right of the virtual geomagnetic polarity figure (white = reversed).

Figure 4.10. Lithostratigraphy and polarity stratigraphy for the Kihal 2 section. The stratigraphic positions of fossil localities are indicated next to the lithostratigraphic section. Grain size is indicated at the bottom of the section: M = mudstone, ZS = siltstone, SS = sandstone, CG = conglomerate, CB = micritic limestone (carbonate layer). Interpreted polarity for the section is to the right of the virtual geomagnetic polarity figure (black = normal, white = reversed). The reversal boundary was placed at the stratigraphic midpoint between samples of opposing polarity.

578 Figure 4.11. A. Correlation figure of all Baynunah Formation magnetostratigraphic sections.
579 Polarity of block samples from each sampling horizon indicated on left of local polarity
580 stratigraphy sections. The correlation between the Jebel Barakah, Hamra 5, and Kihal 2 sections,
581 which is at the base of the normal polarity zone in each section is at used a reference datum and
582 is indicated by a dashed black line. The first occurrence of a prominent micritic limestone bed,
583 which is informally used to designate the transition between the “lower” and “upper” Baynunah
584 Formation, which is based on the first occurrence of micritic limestone beds, is indicated by a
585 dashed red line. The stratigraphic positions of all fossil sites are noted on the local polarity
586 sections. Details about all fossil sites are documented in Bibi et al., Ch. 2, this volume. B.
587 Geomagnetic Polarity Time Scale (GPTS) from Ogg (2012). Red box indicates possibly
588 correlations of local magnetostratigraphy to GPTS. Based on biostratigraphic evidence and
589 sedimentology, the older interpretation for the N-polarity interval in the Baynunah
590 magnetostratigraphy (i.e., sub-chrons C4n.1r through C3Ar) are more likely than the younger
591 interpretation (i.e., sub-chrons C3An.2n – C3An.1n). The text provides a detailed discussion of
592 potential correlations to the GPTS and our rationale for a preferred interpretation.

Table 4.1. Mean paleomagnetic directional data from the Baynunah Formation. n = number of samples used to calculate each average (see text for details); D = declination; I = inclination; k = Fisher's (1953) precision parameter; a₉₅ = radius of 95% confidence cone around mean (Fisher, 1953); Pole = virtual geomagnetic pole (VGP) calculated from block samples; K and A₉₅ = Fisher (1953) statistics of each VGP.

Section	Subset	n	D (°)	I (°)	a ₉₅ (°)	k	n	Pole (N°)	Pole (E°)	A ₉₅ (°)	K
Hamra North	block sample mean normal	8	351.4	36.5	12.3	21.3	8	80.9	303.2	11.9	22.6
Hamra North	block sample mean reversed	10	174	-43.0	10.5	22.0	10	83.4	330.7	28.8	3.8
Mleisa 2	block sample mean reversed	14	181.4	-33.7	12.6	10.9	14	86.8	228.7	12.7	10.8
Mleisa 1	block sample mean reversed	7	182.1	-38.1	16.1	15.0	7	86.4	180.3	17.6	12.7
Jebel Barakah	block sample mean normal	3	259.7	40.3	22.3	31.6	3	89.1	214.7	24.5	26.4
Jebel Barakah	block sample mean reversed	8	162.3	-35.4	24.8	5.9	8	72.5	321.4	25.5	5.7
Kihal	block sample mean normal	2	3.2	40.4	48.2	29.0	2	86.7	160	58.5	20.4
Kihal	block sample mean reversed	24	171.8	-36.2	9.2	11.3	24	81.1	302.6	9.6	10.4
Shuwaihat	block sample mean reversed	22	162.3	-36.5	9.0	12.9	22	74.2	317.6	9.3	12.2
All samples	block sample mean normal	13	352.8	37.9	8.3	22.2	15	82.7	306.6	8.4	21.9
All samples	block sample mean reversed	85	170.7	-36.9	4.9	11.2	82	81.0	311.0	5.1	10.5

n = the number of samples used to calculate the averages (see text for details); D = declination; I = inclination; k = Fisher's (1953) precision parameter; a₉₅ = radius of 95% confidence cone around mean (Fisher, 1953); pole N and E = virtual geomagnetic poles calculated for each line or site mean; K and A₉₅ = Fisher (1953) statistics of paleomagnetic pole direction.

Table 4.2. Stratigraphic positions of polarity zone boundaries. "Nominal" thickness values prescribe reversal levels precisely at the midpoints between samples of opposing polarity.

Section Name	Magnetic Zone	Lowermost sample in zone	Uppermost sample in zone	Polarity zone thickness (m) min. / nominal / max.
Jebel Barakah	A-	BA02, 1.40m	BA06, 3.90m	$\geq 2.50 / \geq 2.78 / \geq 3.05$
Jebel Barakah	B+	BA07, 4.45m	BA09, 4.90m	0.45 / 1.62 / 2.80
Jebel Barakah	C-	BA10, 6.70m	BA17, 10.95m	$\geq 4.25 / \geq 5.15 / \geq 6.05$
Shuwaihat 2	A-	SH02, 4.50m	SH24, 39.40m	≥ 34.9
Hamra 5	A-	HN01, 1.30m	HN04, 2.40m	$\geq 1.10 / \geq 1.40 / \geq 1.70$
Hamra 5	B+	HN05, 3.00m	HN12, 4.65m	1.65 / 5.35 / 9.05
Hamra 5	C-	HN13, 11.45m	HN25, 23.30m	$\geq 11.85 / \geq 15.85 / \geq 18.65$
Hamra 5	D+ (?)	HN26, 24.50m	HN26, 24.50m	N.A.
Mleisa 1	A-	M102, 0.05m	M110, 9.65m	≥ 9.60
Mleisa 2	A-	M201, 0.00m	M216, 15.00m	≥ 15.00
Kihal	A-	KH01, 0.00m	KH11, 13.80m	$\geq 13.80 / \geq 14.43 / \geq 15.05$
Kihal	B+	KH12, 15.05m	KH13, 16.20m	1.15 / 3.02 / 4.90
Kihal	C-	KH15, 18.70m	KH34, 35.00m	$\geq 16.30 / \geq 17.55 / \geq 18.80$

605 **Appendix 4.1.** Paleomagnetic data of all specimens from the Baynunah Formation. ID: CIR = great circle
606 best-fit. LIN = line best fit. VGP = virtual geomagnetic pole.

Section	Sample	Stratigraphic position	ID	Geographic Declination	Geographic Inclination	Mean angle of deviation	VGP latitude (N°)	VGP longitude (E°)
Jebel Barakah	02A	140	CIR	110.6	-21.3	18.2	-23.2	144.4
Jebel Barakah	02B	140	LIN	121.7	-70.8	13.4	-37.5	194.5
Jebel Barakah	02D	140	CIR	079.1	39.4	13.7	18.3	125.4
Jebel Barakah	03B	295	CIR	095.2	05.5	5.9	-3.6	137.7
Jebel Barakah	04A	325	CIR	235.7	56.7	19.4	-9.4	10.5
Jebel Barakah	04C	325	CIR	084.7	75.1	8.2	23.5	83.0
Jebel Barakah	05A	335	LIN	165.6	-47.8	18.9	-76.2	166.1
Jebel Barakah	05D	335	LIN	161.2	-18.5	13.3	-66.9	106.5
Jebel Barakah	06A	390	LIN	171.2	-07.8	5.7	-68.2	76.6
Jebel Barakah	07A	445	LIN	343.3	29.2	14.0	72.2	297.3
Jebel Barakah	07B	445	LIN	019.5	39.1	12.3	72.0	144.4
Jebel Barakah	07C	445	LIN	018.2	60.7	8.2	66.7	88.4
Jebel Barakah	08A	465	LIN	300.3	64.1	13.5	37.8	2.7
Jebel Barakah	08B	465	LIN	352.2	03.2	15.0	66.4	252.1
Jebel Barakah	08D	465	LIN	350.8	24.1	16.6	75.7	271.3
Jebel Barakah	09A	490	LIN	025.2	41.6	17.3	67.0	137.3
Jebel Barakah	09B	490	LIN	015.1	49.7	13.4	75.1	113.0
Jebel Barakah	09C	490	LIN	027.6	26.3	9.7	62.1	158.5
Jebel Barakah	09D	490	LIN	343.8	46.8	5.1	74.9	341.3
Jebel Barakah	10A	670	CIR	346.7	-20.9	15.8	52.8	254.3
Jebel Barakah	10D	670	LIN	122.4	-49.8	18.3	-38.9	163.2
Jebel Barakah	11D	730	LIN	131.5	-15.6	15.2	-41.0	131.6
Jebel Barakah	12D	790	CIR	086.9	38.9	8.5	11.4	123.2
Jebel Barakah	13C	870	LIN	154.1	-06.4	6.9	-57.5	106.5
Jebel Barakah	14A	900	CIR	144.7	72.7	0.3	-2.8	70.1
Jebel Barakah	14D	900	CIR	156.2	71.2	2.1	-7.7	65.5
Jebel Barakah	15A	965	CIR	226.3	80.8	10.8	11.1	39.2
Jebel Barakah	16D	1000	LIN	206.2	-33.5	13.1	-65.0	330.4
Jebel Barakah	17A	1095	LIN	212.3	-24.7	12.0	-57.5	336.3
Jebel Barakah	17B	1095	LIN	190.9	-51.3	5.8	-77.5	280.2
Shuwaihat 2	01A	35	CIR	094.9	30.6	8.4	2.3	125.3
Shuwaihat 2	02B	450	LIN	152.2	-19.1	3.8	-60.0	118.9
Shuwaihat 2	02C	450	LIN	158.3	-15.7	5.5	-63.8	108.3
Shuwaihat 2	03A	475	LIN	134.9	-15.2	4.5	-43.9	129.3
Shuwaihat 2	03B	475	LIN	128.3	-40.6	7.4	-42.9	152.4
Shuwaihat 2	03C	475	LIN	195.9	-07.3	3.5	-64.5	12.8

Shuwaihat 2	04A	500	LIN	146.6	-04.9	6.0	-51.2	113.7
Shuwaihat 2	04C	500	LIN	145.8	-05.4	8.7	-50.7	114.7
Shuwaihat 2	05B	525	LIN	119.6	-28.7	9.3	-32.9	145.5
Shuwaihat 2	05C	525	LIN	153.1	-26.6	7.5	-62.8	125.8
Shuwaihat 2	06B	855	LIN	175.6	-41.1	8.4	-86.0	137.0
Shuwaihat 2	06C	855	LIN	158.0	-49.7	5.8	-69.4	165.6
Shuwaihat 2	07A	960	LIN	128.5	-24.1	9.5	-40.1	138.7
Shuwaihat 2	07B	960	LIN	197.6	-39.3	11.3	-73.7	324.9
Shuwaihat 2	07C	960	LIN	126.9	-33.9	11.1	-40.5	146.8
Shuwaihat 2	08A	990	LIN	166.0	-18.6	8.5	-70.3	97.4
Shuwaihat 2	08B	990	LIN	164.6	-58.2	6.6	90.0	0.0
Shuwaihat 2	08C	990	LIN	139.0	-15.4	6.1	-47.6	126.9
Shuwaihat 2	10A	1080	LIN	132.6	-53.6	10.4	-47.7	167.4
Shuwaihat 2	10B	1080	LIN	168.0	-35.5	8.9	-78.0	123.2
Shuwaihat 2	10C	1080	LIN	199.3	-48.9	2.0	-71.9	299.4
Shuwaihat 2	11A	1145	LIN	167.2	-49.9	13.6	-76.8	175.6
Shuwaihat 2	11B	1145	LIN	133.5	-31.2	9.9	-46.0	142.0
Shuwaihat 2	11C	1145	LIN	132.0	-22.2	4.5	-42.9	135.7
Shuwaihat 2	12A	1185	LIN	224.8	-42.8	5.4	-49.4	311.5
Shuwaihat 2	12B	1185	LIN	150.1	-23.6	14.3	-59.4	125.2
Shuwaihat 2	12C	1185	LIN	187.9	-30.0	14.3	-79.2	7.7
Shuwaihat 2	13A	1195	LIN	136.2	-18.3	5.1	-45.8	130.7
Shuwaihat 2	13B	1195	LIN	132.9	-48.0	15.6	-47.8	159.8
Shuwaihat 2	14A	2150	LIN	130.2	-58.5	6.3	-45.6	174.6
Shuwaihat 2	15C	2500	LIN	173.4	-54.6	10.8	-77.5	206.6
Shuwaihat 2	15D	2500	LIN	220.0	-60.3	8.1	90.0	0.0
Shuwaihat 2	16B	2575	LIN	207.9	-45.8	8.3	-64.7	309.4
Shuwaihat 2	16C	2575	LIN	181.7	-20.1	15.0	-76.2	45.5
Shuwaihat 2	17A	2590	LIN	159.0	-75.8	6.5	-48.5	218.4
Shuwaihat 2	17B	2590	LIN	200.4	-21.5	9.4	-66.7	352.7
Shuwaihat 2	17C	2590	LIN	129.3	-16.1	15.6	-39.1	133.2
Shuwaihat 2	18A	2665	LIN	223.5	-66.6	15.3	-47.9	274.7
Shuwaihat 2	19A	2815	LIN	160.3	-23.7	18.6	-68.0	113.9
Shuwaihat 2	19B	2815	CIR	076.0	37.9	12.5	20.7	127.7
Shuwaihat 2	20A	3400	LIN	166.6	-16.2	-17.1	-69.6	93.7
Shuwaihat 2	20B	3400	LIN	134.3	-29.0	10.5	-46.3	139.9
Shuwaihat 2	20C	3400	LIN	205.4	-18.5	13.7	-61.7	349.2
Shuwaihat 2	21B	3700	LIN	179.7	-16.4	18.5	-74.3	53.6
Shuwaihat 2	22B	3730	LIN	178.8	-47.5	14.6	-85.4	219.4
Shuwaihat 2	23A	3910	LIN	140.6	-28.8	17.3	-52.0	136.7
Shuwaihat 2	24A	3940	LIN	189.3	-22.1	7.0	-74.6	15.9
Hamra 5	01D	130	LIN	152.7	-49.9	10.2	-65.0	163.8
Hamra 5	02A	185	LIN	166.2	-40.2	2.9	-77.3	139.9

Hamra 5	02B	185	LIN	159.3	-37.2	9.1	-70.6	136.8
Hamra 5	02C	185	LIN	159.6	-36.1	5.5	-70.7	134.4
Hamra 5	03A	200	LIN	164.6	-39.0	4.5	-75.7	137.3
Hamra 5	03B	200	LIN	165.8	-33.8	5.4	-75.6	122.3
Hamra 5	03C	200	LIN	165.7	-33.9	8.5	-75.6	122.7
Hamra 5	04A	240	LIN	171.5	-45.4	19.4	-81.8	164.3
Hamra 5	04B	240	LIN	159.1	-40.2	6.5	-70.8	143.2
Hamra 5	04C	240	LIN	170.6	-42.2	9.1	-81.4	146.4
Hamra 5	05A	300	LIN	005.1	40.6	13.3	85.2	152.4
Hamra 5	05B	300	LIN	007.9	36.4	14.1	81.7	168.8
Hamra 5	05C	300	LIN	358.0	35.4	10.9	85.1	255.1
Hamra 5	06A	330	LIN	008.3	39.7	16.9	82.2	152.4
Hamra 5	06C	330	LIN	332.8	44.8	17.0	65.3	333.6
Hamra 5	06D	330	LIN	001.9	37.7	14.5	86.5	201.6
Hamra 5	07B	340	LIN	346.5	39.0	13.3	77.4	315.8
Hamra 5	07C	340	LIN	012.8	26.2	11.4	74.1	180.6
Hamra 5	07D	340	LIN	334.3	11.1	9.7	59.1	289.8
Hamra 5	08C	350	LIN	346.0	48.2	15.4	76.5	347.8
Hamra 5	09A	375	LIN	347.3	22.6	17.0	72.8	279.0
Hamra 5	09B	375	LIN	354.1	38.5	12.3	84.1	299.7
Hamra 5	09C	375	LIN	009.9	44.3	19.6	80.8	128.4
Hamra 5	10A	400	LIN	340.7	24.7	8.6	68.6	294.5
Hamra 5	10B	400	LIN	306.0	42.0	9.7	41.1	334.4
Hamra 5	10D	400	LIN	293.9	50.7	10.9	90.0	0.0
Hamra 5	11A	440	LIN	341.0	39.9	9.4	72.5	321.7
Hamra 5	11B	440	LIN	343.6	42.1	17.3	75.0	326.7
Hamra 5	12A	465	LIN	343.7	07.1	5.0	64.1	272.5
Hamra 5	12B	465	LIN	349.0	26.9	7.2	75.7	280.9
Hamra 5	13B	1145	LIN	192.8	-46.0	15.6	-78.0	303.9
Hamra 5	16B	1630	LIN	164.5	-31.8	15.4	-74.0	120.0
Hamra 5	16C	1630	LIN	192.9	-69.6	19.0	-59.2	247.6
Hamra 5	19A	1740	LIN	201.4	-47.9	8.2	-70.3	303.6
Hamra 5	19B	1740	LIN	150.2	-42.3	11.3	-62.9	149.5
Hamra 5	19D	1740	LIN	178.8	-70.5	11.3	-59.4	231.1
Hamra 5	21B	1775	CIR	202.1	-12.8	12.6	-62.4	358.6
Hamra 5	22C	1790	CIR	246.4	-55.6	6.7	-32.4	293.7
Hamra 5	23B	1810	LIN	211.8	-54.6	15.3	-60.4	293.2
Hamra 5	23C	1810	CIR	168.6	15.9	4.9	-55.9	72.9
Hamra 5	25B	2330	LIN	159.3	-30.2	8.9	-69.1	124.3
Hamra 5	25C	2330	LIN	169.2	-15.4	9.9	-70.7	86.7
Hamra 5	26A	2450	LIN	012.2	11.8	4.5	68.4	197.7
Mleisa 1	02B	5	LIN	222.6	-42.6	17.2	-51.4	312.5
Mleisa 1	02C	5	CIR	127.3	-00.8	18.7	-33.8	125.6

Mleisa 1	03A	30	CIR	075.4	37.2	9.6	21.1	128.4
Mleisa 1	04A	60	LIN	121.7	-26.2	15.9	-34.3	143.2
Mleisa 1	04B	60	LIN	193.7	-13.2	13.6	-68.2	13.2
Mleisa 1	04C	60	LIN	133.8	-07.2	5.5	-41.0	125.2
Mleisa 1	05C	140	LIN	175.1	-41.5	15.1	-85.5	140.5
Mleisa 1	06B.1	200	CIR	086.2	20.6	4.8	7.8	134.3
Mleisa 1	07A	785	LIN	152.6	-29.0	7.2	-62.9	129.1
Mleisa 1	07B	785	LIN	213.9	-40.8	19.7	-59.0	316.9
Mleisa 1	07C	785	LIN	183.7	-32.2	5.4	-82.5	24.2
Mleisa 1	08A	795	LIN	205.0	-42.1	5.6	-67.2	316.8
Mleisa 1	09B	895	LIN	206.1	-20.2	11.5	-61.7	346.8
Mleisa 1	09C	895	LIN	137.3	-59.8	9.7	-50.8	178.0
Mleisa 1	09D	895	LIN	182.4	-07.6	19.3	-69.6	45.6
Mleisa 1	10A	965	LIN	124.3	-29.3	9.4	-37.3	144.3
Mleisa 1	10B	965	LIN	215.2	-31.4	11.9	-56.4	328.0
Mleisa 2	01B	0	LIN	122.2	-73.4	6.9	-36.9	199.7
Mleisa 2	02A	10	LIN	204.0	-17.2	10.5	-62.4	352.2
Mleisa 2	03B	155	CIR	121.2	09.4	5.9	-25.9	123.9
Mleisa 2	03D	155	LIN	169.2	-18.4	15.0	-72.1	89.4
Mleisa 2	04A	255	LIN	203.4	-17.8	13.7	-63.1	352.4
Mleisa 2	04C	255	LIN	144.4	-47.8	11.8	-57.9	158.9
Mleisa 2	04D	255	LIN	181.6	-47.0	13.4	-85.7	251.5
Mleisa 2	05C	325	CIR	150.9	44.6	8.0	-32.3	83.6
Mleisa 2	05D	325	LIN	174.3	-03.6	10.0	90.0	0.0
Mleisa 2	06D	375	LIN	212.3	-25.2	8.7	-57.6	336.1
Mleisa 2	07A	495	CIR	089.8	-40.2	9.0	-9.0	163.6
Mleisa 2	07C	495	LIN	186.1	-25.0	12.6	-77.6	23.6
Mleisa 2	08B	510	LIN	220.4	-25.9	5.3	-50.5	330.2
Mleisa 2	08C	510	LIN	201.8	-30.9	16.7	-68.3	338.3
Mleisa 2	08D	510	LIN	183.4	-23.7	11.5	-77.8	36.4
Mleisa 2	09B	550	LIN	175.9	-11.1	10.1	-71.1	65.1
Mleisa 2	09C	550	LIN	225.4	-32.7	7.6	-47.3	321.9
Mleisa 2	09D	550	CIR	093.4	-35.4	17.2	-10.8	159.1
Mleisa 2	10C	590	LIN	157.1	-35.5	3.5	-68.3	135.0
Mleisa 2	12A	860	LIN	182.6	-21.5	9.4	-76.8	41.2
Mleisa 2	12B	860	LIN	184.6	-25.6	10.4	-78.5	29.3
Mleisa 2	12C	860	LIN	175.8	-21.4	15.2	-76.4	70.2
Mleisa 2	12D	860	LIN	167.0	-35.4	12.4	-77.1	124.3
Mleisa 2	14D	1235	LIN	155.2	-29.9	10.5	-65.4	127.9
Mleisa 2	15B	1360	LIN	183.4	-64.5	12.7	-67.6	238.6
Mleisa 2	16B	1500	LIN	194.8	-49.0	8.5	-75.6	295.4
Mleisa 2	16C	1500	LIN	157.8	-29.9	12.0	-67.7	125.4
Mleisa 2	16D	1500	LIN	161.4	-48.9	11.6	-72.5	165.5

Kihal	01A	0	LIN	147.4	-26.3	10.2	-57.6	130.0
Kihal	02A	135	LIN	163.8	-31.4	11.2	-73.3	120.3
Kihal	02B	135	LIN	169.7	-31.9	9.8	-78.2	109.1
Kihal	02C	135	LIN	189.0	-43.8	11.2	-81.7	310.0
Kihal	04A	335	LIN	138.4	-61.5	9.9	-51.1	181.3
Kihal	04B	335	LIN	160.5	-28.8	10.0	-69.7	120.5
Kihal	05B	425	LIN	223.5	-39.1	12.6	-50.1	316.2
Kihal	05C	425	CIR	218.2	06.5	9.0	-43.9	353.5
Kihal	06A	550	LIN	200.9	-29.3	6.9	-68.7	341.8
Kihal	06C	550	LIN	166.0	-21.6	11.6	-71.5	100.7
Kihal	07B	760	LIN	166.1	-16.7	3.7	-69.5	95.2
Kihal	08C	890	LIN	124.4	-40.4	10.4	-39.4	153.2
Kihal	09B	1265	LIN	140.9	-45.1	14.0	-54.7	155.0
Kihal	10C	1325	LIN	202.1	-25.6	13.9	-66.6	345.4
Kihal	11C	1380	LIN	158.8	-40.7	9.8	-70.6	144.3
Kihal	12B	1505	LIN	046.0	55.3	18.9	48.9	114.8
Kihal	12C	1505	LIN	360.0	23.2	13.8	78.0	232.4
Kihal	13A	1620	LIN	356.7	21.1	6.3	76.5	246.4
Kihal	13B	1620	LIN	339.1	53.9	11.3	69.1	356.8
Kihal	15C	1870	LIN	194.5	-51.1	15.5	-75.1	288.2
Kihal	15C	1870	LIN	151.0	-21.0	16.3	-59.4	121.8
Kihal	17B	1945	LIN	194.9	-35.6	9.5	-75.5	337.2
Kihal	17C	1945	LIN	184.2	-27.4	3.8	-79.6	29.2
Kihal	18A	2015	LIN	187.1	-19.9	10.7	-74.6	25.1
Kihal	18B	2015	LIN	179.6	-23.4	8.2	-78.1	54.3
Kihal	20A	2060	LIN	205.9	-07.6	7.2	-57.8	357.4
Kihal	21B	2185	LIN	198.8	-41.4	18.0	-72.8	319.6
Kihal	24A	2295	LIN	131.9	-44.4	19.8	-46.6	155.6
Kihal	25A	2385	LIN	177.8	-05.1	11.3	-68.4	58.4
Kihal	25B	2385	LIN	158.3	-33.8	11.5	-69.1	131.1
Kihal	25C	2385	LIN	194.3	-16.8	14.7	-69.3	8.6
Kihal	27A	2555	CIR	189.3	07.6	15.2	-60.7	33.2
Kihal	27C	2555	LIN	191.8	-06.8	6.8	-66.4	21.8
Kihal	29A	3050	LIN	170.8	-41.0	13.2	-81.6	140.1
Kihal	30A	3290	LIN	121.8	-30.7	10.1	-35.3	146.2
Kihal	31A	3325	LIN	107.3	-49.3	18.4	-26.1	165.6
Kihal	31B	3325	LIN	186.6	-50.4	16.8	-80.8	270.6
Kihal	31C	3325	LIN	151.1	-25.8	11.4	-60.8	126.6
Kihal	32A	3400	LIN	184.0	-75.2	12.4	-51.9	235.4
Kihal	32C	3400	LIN	219.5	-29.2	5.0	-52.0	327.8
Kihal	32E	3400	LIN	154.2	-09.3	3.5	-58.5	108.5
Kihal	33A	3445	LIN	176.5	-14.7	9.1	-73.0	64.4
Kihal	33B	3445	LIN	154.5	-75.2	8.1	-48.2	214.8

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Kihal	34A	3500	LIN	175.9	-45.2	8.6	-85.5	178.6
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Appendix 4.2. Mean direction of all block samples. N = number of specimens used in block sample calculations. Only best fit lines in Appendix 1 were used to make mean block sample calculations. VGP = virtual geomagnetic pole.

Site	Sample	Stratigraphic position	Declination	Inclination	Mean angle of deviation	n	VGP latitude	VGP longitude
Jebel Barakah	02	140	121.7	-70.8	13.4	1	-37.5	194.5
Jebel Barakah	05	335	163.0	-33.2	69.4	2	-73.1	125.2
Jebel Barakah	06	390	171.2	-07.8	5.7	1	-68.2	76.6
Jebel Barakah	07	445	004.5	44.3	35.3	3	85.5	115.1
Jebel Barakah	08	465	342.7	31.7	62.5	3	72.4	302.6
Jebel Barakah	09	490	014.5	42.4	20.9	4	76.8	137.0
Jebel Barakah	10	670	122.4	-49.8	18.3	1	-38.9	163.2
Jebel Barakah	11	730	131.5	-15.6	15.2	1	-41.0	131.6
Jebel Barakah	13	870	154.1	-06.4	6.9	1	-57.5	106.5
Jebel Barakah	16	1000	206.2	-33.5	13.1	1	-65.0	330.4
Jebel Barakah	17	1095	203.6	-38.5	74.3	2	-68.2	323.6
Shuwaihat 2	02	450	155.3	-17.4	14.7	2	-62.0	113.9
Shuwaihat 2	03	475	154.4	-24.0	66.7	3	-63.2	121.6
Shuwaihat 2	04	500	146.2	-05.2	2.1	2	-51.0	114.2
Shuwaihat 2	05	525	136.5	-28.7	69.8	2	-48.3	138.6
Shuwaihat 2	06	855	167.5	-45.7	33.3	2	-78.3	160.5
Shuwaihat 2	07	960	147.6	-36.8	55.3	3	-59.9	142.1
Shuwaihat 2	08	990	155.1	-31.1	44.0	3	-65.6	129.8
Shuwaihat 2	10	1080	167.9	-49.0	37.1	3	-77.7	173.7
Shuwaihat 2	11	1145	141.7	-35.4	32.6	3	-54.2	142.8
Shuwaihat 2	12	1185	184.7	-35.9	52.9	3	-84.0	4.4
Shuwaihat 2	13	1195	134.8	-33.2	70.2	2	-47.6	143.2
Shuwaihat 2	14	2150	130.2	-58.5	6.3	1	-45.6	174.6
Shuwaihat 2	15	2500	194.8	-59.6	57.8	2	-69.4	265.8
Shuwaihat 2	16	2575	192.8	-33.6	80.9	2	-76.8	345.0
Shuwaihat 2	17	2590	163.5	-42.1	81.9	3	-74.9	147.0
Shuwaihat 2	18	2665	223.5	-66.6	15.3	1	-47.8	274.4
Shuwaihat 2	19	2815	160.3	-23.7	18.6	1	-68.0	113.9
Shuwaihat 2	20	3400	169.6	-23.9	55.1	3	-74.8	94.7
Shuwaihat 2	21	3700	179.7	-16.4	18.5	1	-74.4	53.4
Shuwaihat 2	22	3730	178.8	-47.5	14.6	1	-85.3	219.5
Shuwaihat 2	23	3910	140.6	-28.8	17.3	1	-52.0	136.6
Shuwaihat 2	24	3940	189.3	-22.1	7.0	1	-74.7	15.5

Hamra 5	01	130	152.7	-49.9	10.2	1	-64.9	163.8
Hamra 5	02	185	161.6	-37.9	5.7	3	-72.8	136.7
Hamra 5	03	200	165.4	-35.6	4.6	3	-75.8	127.4
Hamra 5	04	240	166.9	-42.7	8.8	3	-78.1	148.8
Hamra 5	05	300	003.6	37.5	7.5	3	85.5	183.3
Hamra 5	06	330	355.1	41.7	22.3	3	85.5	323.8
Hamra 5	07	340	350.8	26.4	36.0	3	76.7	274.8
Hamra 5	08	350	346.0	48.2	15.4	1	76.5	348.0
Hamra 5	09	375	356.2	35.5	22.5	3	84.4	272.3
Hamra 5	10	400	316.3	41.0	36.6	3	50.2	330.7
Hamra 5	11	440	342.3	41.0	6.4	2	73.8	324.1
Hamra 5	12	465	346.2	17.0	46.1	2	69.8	275.3
Hamra 5	13	1145	192.8	-46.0	15.6	1	-78.0	303.3
Hamra 5	16	1630	172.7	-51.4	106.6	2	-79.7	195.3
Hamra 5	19	1740	175.4	-55.8	34.9	3	-77.1	215.3
Hamra 5	23	1810	211.8	-54.6	15.3	1	-60.3	292.9
Hamra 5	25	2330	164.5	-22.9	38.8	2	-71.0	105.6
Hamra 5	26	2450	012.2	11.8	4.5	1	68.5	197.3
Mleisa 1	02	5	222.6	-42.6	17.2	1	-51.3	312.2
Mleisa 1	04	60	149.3	-18.0	65.0	3	-57.2	120.8
Mleisa 1	05	140	175.1	-41.5	15.1	1	-85.5	141.5
Mleisa 1	07	785	181.9	-36.6	40.9	3	-86.0	26.2
Mleisa 1	08	795	205.0	-42.1	5.6	1	-67.2	316.3
Mleisa 1	09	895	182.9	-31.3	64.0	3	-82.4	30.5
Mleisa 1	10	965	169.1	-39.8	>180	2	-79.9	136.8
Mleisa 2	01	0	122.2	-73.4	6.9	1	-36.8	199.5
Mleisa 2	02	10	204.0	-17.2	10.5	1	-62.5	351.8
Mleisa 2	03	155	169.2	-18.4	15.0	1	-72.2	89.4
Mleisa 2	04	255	180.2	-40.2	46.5	3	-88.9	44.1
Mleisa 2	05	325	174.3	-03.6	10.0	1	-67.1	67.1
Mleisa 2	06	375	212.3	-25.2	8.7	1	-57.7	335.9
Mleisa 2	07	495	186.1	-25.0	12.6	1	-77.7	23.3
Mleisa 2	08	510	201.8	-27.7	26.4	3	-67.5	342.8
Mleisa 2	09	550	198.6	-23.9	168.5	2	-68.9	352.2
Mleisa 2	10	590	157.1	-35.5	3.5	1	-68.3	135.1
Mleisa 2	12	860	177.8	-26.1	10.9	4	-79.6	64.2
Mleisa 2	14	1235	155.2	-29.9	10.5	1	-65.4	128.0
Mleisa 2	15	1360	183.4	-64.5	12.7	1	-67.5	238.4
Mleisa 2	16	1500	169.8	-43.8	28.4	3	-80.6	154.3
Kihal	01	0	147.4	-26.3	10.2	1	-57.6	130.1
Kihal	02	135	173.3	-36.1	19.3	3	-82.7	111.1
Kihal	04	335	152.7	-45.6	88.2	2	-65.3	155.3
Kihal	05	425	223.5	-39.1	12.6	1	-50.1	316.0

Kihal	06	550	182.9	-26.5	77.4	2	-79.6	36.6
Kihal	07	760	166.1	-16.7	3.7	1	-69.6	95.3
Kihal	08	890	124.4	-40.4	10.4	1	-39.4	153.2
Kihal	09	1265	140.9	-45.1	14.0	1	-54.7	155.1
Kihal	10	1325	202.1	-25.6	13.9	1	-66.6	345.1
Kihal	11	1380	158.8	-40.7	9.8	1	-70.6	144.5
Kihal	12	1505	017.3	41.5	133.3	2	74.2	139.4
Kihal	13	1620	349.9	37.8	86.9	2	80.3	307.6
Kihal	15	1870	168.3	-38.0	125.7	2	-78.9	130.8
Kihal	17	1945	189.3	-31.6	27.0	2	-78.9	358.9
Kihal	18	2015	183.4	-21.7	17.1	2	-76.8	37.5
Kihal	20	2060	205.9	-07.6	7.2	1	-57.9	357.2
Kihal	21	2185	198.8	-41.4	18.0	1	-72.8	319.2
Kihal	24	2295	131.9	-44.4	19.8	1	-46.6	155.6
Kihal	25	2385	177.7	-19.1	34.6	3	-75.7	61.6
Kihal	27	2555	191.8	-06.8	6.8	1	-66.5	21.5
Kihal	29	3050	170.8	-41.0	13.2	1	-81.6	140.7
Kihal	30	3290	121.8	-30.7	10.1	1	-35.3	146.1
Kihal	31	3325	148.6	-46.1	49.3	3	-61.6	156.0
Kihal	32	3400	184.5	-41.6	78.7	3	-85.9	322.6
Kihal	33	3445	172.0	-45.3	>180	2	-82.2	165.1
Kihal	34	3500	175.9	-45.2	8.6	1	-85.4	179.5

A **B** **C** **D** **E**

- ★ Expected direction ◻ Step not used
- ☆ Antipode to expected direction ◻ Upper hemisphere
- * Present dipole field ■ Lower hemisphere

Y Root traces	■ Block sample
○ Ostracods	direction
⌀ Vertebrate coprolite	○ Specimen - line
⌀ Invertebrates	× Specimen - circle