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Palaeomagnetism of the Mahatta Humaid Group (Cambrian – Early Ordovician, Oman), including a re-interpretation of previous Neoproterozoic palaeomagnetic data

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ABSTRACT

We carried out a palaeomagnetic study in the Al-Huqf region (Sultanate of Oman) on rocks that belong to different units of the Cambrian – Ordovician Mahatta Humaid Group. Thirty-nine samples were systematically collected from a succession ca. 520–495 Ma old. Seventeen samples showed characteristic remanent magnetization components with two antipodal polarities carried by hematite. Evidence suggests that these components have a primary origin. A detailed petrographic analysis revealed syntaxial overgrowths parallel to the easy plane of magnetization of the magnetic carriers that has probably enhanced and reinforced the primary magnetization. A palaeopole computed with the mean direction of the 17 characteristic remanent magnetization components was considered alongside previously published Neoproterozoic – early Palaeozoic palaeomagnetic data, which we placed in an updated chronostratigraphic framework for the Neoproterozoic – Cambrian Huqf Supergroup. Two interpretations were considered: (1) Oman was detached from the Arabian-Nubian craton until ca. 660 Ma, and it became attached (or was nearby) to it by ca. 630 Ma. In this interpretation, an apparent polar wander (APW) path of Arabia is proposed between ca. 630 and 500 Ma. The palaeomagnetic directions of Mirbat obtained by Killner et al. (2005) in rocks 720–660 Ma old are therefore assumed as primary, and taking into account that Oman was an independent block of the Arabian-Nubian craton, the corresponding palaeopole is not considered in the proposed segment of the Arabian APW path. (2) The Neoproterozoic data belong to two different tectonic blocks within the Arabian-Nubian craton and were involved in left-lateral, strike-slip movements along NW-trending faults. One block included the localities of Al Jabal al-Akhdar and Al-Huqf and may have rotated counter-clockwise ca. 45° about a vertical axis between ca. 600 and 500 Ma. The other block included the locality of Mirbat and rotated counter-clockwise ca. 25° about a vertical axis between ca. 600 and 550 Ma. These suggested block rotations may have played a role in generating the underlying fabrics for some of the sedimentary basins in Oman. In the second model, the rocks sampled by Killner et al. (2005) in Mirbat were re-magnetized during the intrusion of dike swarms at ca. 615–600 Ma.

INTRODUCTION

The tectonic setting of the Arabian-Nubian Shield (and the eastern part of the Arabian Plate together forming the Arabian-Nubian craton) during the Neoproterozoic – early Palaeozoic has been discussed by numerous authors (e.g. Husseini, 1989; Husseini and Husseini, 1990; Stern, 1994; Loosveld et al., 1996; Al-Husseini, 2000; Blasband et al., 2000; Meert, 2003). They generally describe a tectonic history that started with the amalgamation of terranes between ca. 800–620 Ma followed by an extensional collapse and post-orogenic magmatism between ca. 620–530 Ma. Other studies, however, suggest refinements to this model (e.g. Koopman et al., 2007), or completely different models including a Proterozoic and/or Early Cambrian collision between an Oman microplate or terranes and the Arabian-Nubian craton (e.g. Immerz et al., 2000).

Palaeomagnetic data are important for constraining the amalgamation of terranes and their later evolution. However, only two palaeomagnetic studies have been done for Arabia, both of which were carried out in Oman on rocks from the Huqf Supergroup that include tillites (Kempf et al., 2000; Kilner et al., 2005). Both palaeomagnetic studies relied on radiometric dating of these glacial units that is now considered to be incorrect and much too young. The palaeomagnetic sampling by Kempf et al. (2000) was from outcrops close to Mirbat with previously estimated ages between 564–513 Ma, whereas the sampling of Kilner et al. (2005) was in Al Jabal al-Akhdar (close to Wadi Bani), the Al-Huqf region (close to Sirab) and Mirbat, with estimated ages of 600–580 Ma (Figure 1). In the updated chronostratigraphic framework (e.g. Rieu et al., 2006, 2007a; Allen, 2007, Rieu and Allen, 2008, and references therein), the age of these glacial units is Cryogenian (older than 635 Ma) and may be as old as 720 Ma (Figure 2).

The objective of this paper is to present new early Palaeozoic palaeomagnetic data obtained in the Al-Huqf region from the Amin, Miqrat and Andam formations of the Mahatta Humaid Group (Haima Supergroup) and to interpret them together with the previously published Neoproterozoic data obtained in three different areas in Oman (Figure 1 and Table 1). The ages of the newly sampled rocks range between ca. 520 Ma (late Early Cambrian) and ca. 495 Ma (Tremadoc, Early Ordovician). We also interpret the palaeomagnetic data from the previously sampled rocks (Kempf et al., 2000; Kilner et al., 2005) in the context of the latest chronostratigraphic framework for Oman (Figure 2) and of the intra-continental extensional tectonics that occurred in Arabia between about 620 and 530 Ma (e.g. Al-Husseini, 2000; Allen, 2007).

We suggest two interpretations. In the first, it is assumed that Oman was detached from the Arabian-Nubian craton before ca. 660 Ma, but that by 630 Ma it was either docking or fully amalgamated to it. For this case, an apparent polar wander (APW) path of Arabia is proposed between ca. 630 and 500 Ma. In this interpretation, the palaeomagnetic directions of Mirbat obtained by Killnet et al. (2005) on rocks 720–660 Ma old are assumed as primary, and considering that Oman formed an independent block of the Arabian-Nubian craton at those ages, the corresponding palaeopole is not considered in the proposed track of the Arabian APW path.

In the second interpretation, it is assumed that the Neoproterozoic data belong to two different tectonic blocks and that the rocks sampled by Killner et al. (2005) in Mirbat were re-magnetized during the intrusion of a dike swarm at ca. 615–600 Ma; we suggest a tectonic model that involves left-lateral, strike-slip along NW-trending faults. In this model, a block that includes the localities of Al Jabal al-Akhdar and Al-Huqf may have rotated counter-clockwise ca. 45° about a vertical axis between ca. 600–500 Ma, whereas another that includes the locality of Mirbat rotated counter-clockwise ca. 25° about a vertical axis between ca. 600–550 Ma. These suggested block rotations may have played a role in generating the underlying fabrics for some of the sedimentary basins in Oman. In this interpretation, the “Infra-Cambrian Sinistral Najd Tectonic Event” (e.g. Husseini, 1989; Loosveld et al., 1995; Al-Husseini, 2000) is considered to have played a controlling role in the rotations of the structural blocks of palaeomagnetic sampled localities in Oman. This tectonic interpretation cannot be extrapolated to the more complex Najd structures that are described further northeast in the Arabian Shield (e.g. Johnson and Kattan, 2001).

GEOLOGICAL SETTING OF THE MAHATTA HUMAID GROUP, AL-HUQF REGION

This section describes the stratigraphic units that were sampled in this palaeomagnetic study on rocks of the Mahatta Humaid Group. The rock units are described in greater detail in Droste (1997) and Sharland et al. (2001). The stratigraphic positions of the Proterozoic units that we re-analyzed and discuss are shown in Figure 2, and further geological information about these units is provided in Kempf et al. (2000) and Kilner et al. (2005). The Mahatta Humaid Group comprises a complex, thick siliciclastic succession of continental deposits of the Amin and Miqrat formations, and a succession of fluvial, shallow-marine sandstones, siltstones and thin limestones within the Andam Formation (Table 1).

The Amin Formation overlies a major unconformity on the Neoproterozoic – Lower Cambrian Huqf Supergroup. The unit comprises a mixed sequence of alluvial fan, fluvial and inland sabkha deposits passing upwards into predominantly aeolian/reworked aeolian strata. In general, the Amin Formation consists of fine- to coarse-grained quartzose sandstones and pebbly lithologies that are unsuitable for palaeomagnetic studies. However, the formation also includes suitable, reddened finer-grained intervals that were sampled for this study.

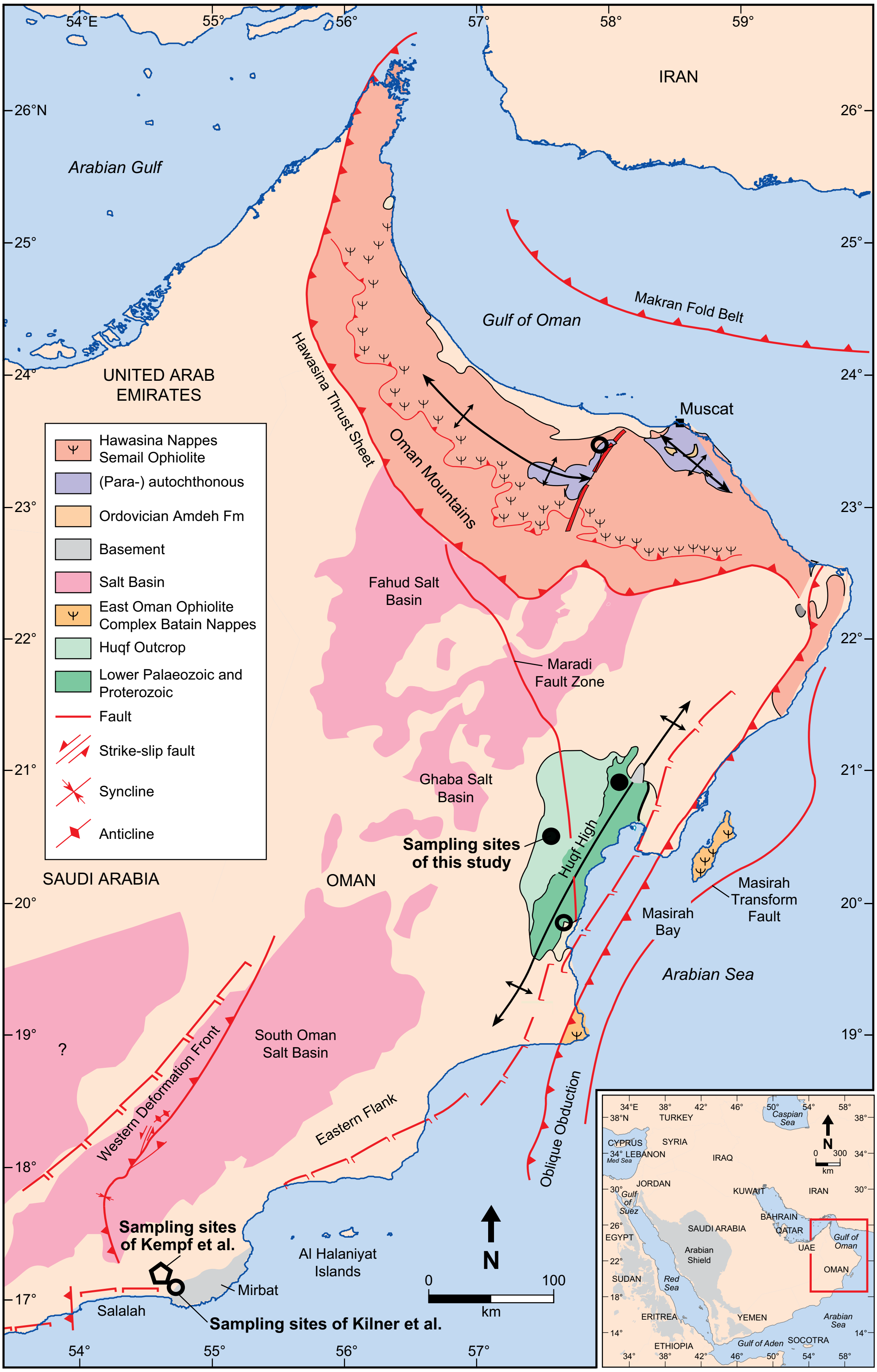


Figure 1: Location map for palaeomagnetic sampling. The map includes sampling sites of previous studies and the sites of the data presented in this paper. Key outcrops and Al-Huqf fold axis are highlighted.

The Miqrat Formation lies above the Amin Formation and comprises red mudstones with thin, laterally extensive, drab-coloured very fine-grained sandstones. These hematite-rich sediments were deposited in a low-relief inland continental (sabkha/playa/fluvial) setting.

Above the Miqrat Formation, the Andam Formation contains the first unambiguous indications of a Cambrian major marine incursion in northern Oman. Marine influences diminish towards the south and the overall section becomes more continental in character. It is composed of three members. The basal Al-Bashair Member comprises parasequence sets of mudrocks, sandstones and thin oolitic limestones deposited in a series of regressive shallowing-upward cycles within an overall sea-level rise. The intermediate Barik Sandstone Member is a sand-dominated unit interpreted as deposits of braided fluvial sandsheets formed during a series of forced regressive cycles within a complex braid plain – coastal setting. Facies information and palaeocurrent data suggest that the main braided Barik system prograded northwards along the axis of the northern Oman sedimentary basins. The lower and upper boundaries of the Barik Sandstone Member are defined lithologically by the appearance and disappearance of sandstone, respectively (Droste, 1997). In the most northerly parts of the basin, the Barik Sandstone Member pinches out and the Al-Bashair Member is overlain directly by mudrocks of the Mabrouk Member.

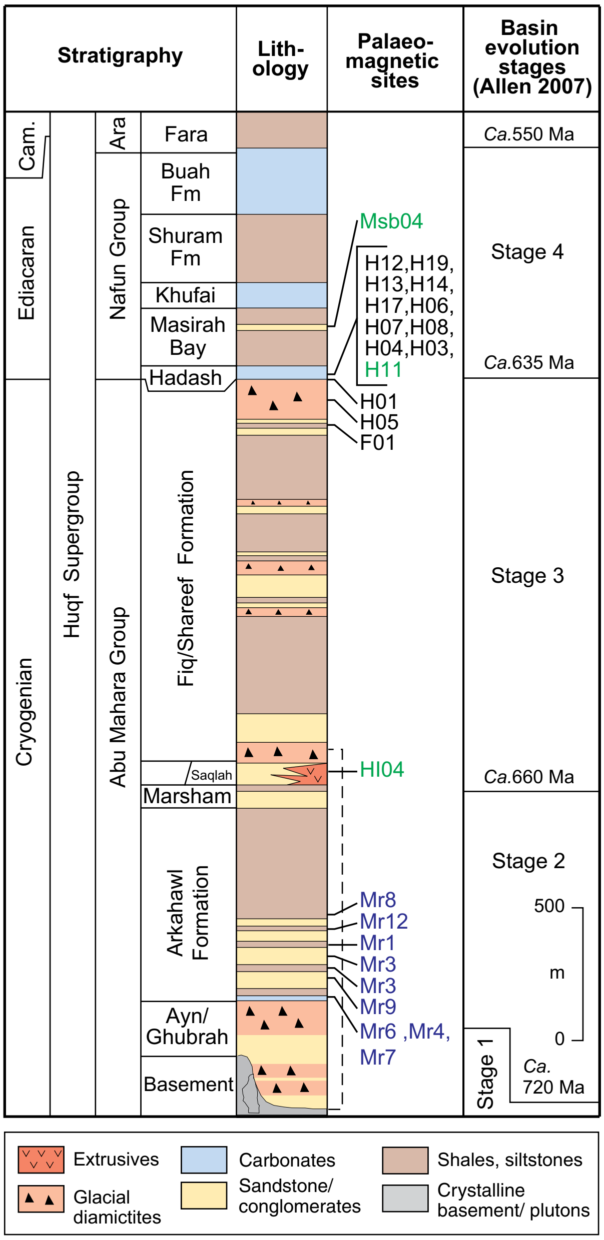


Figure 2: Composite chronostratigraphic column of the Neoproterozoic Huqf Supergroup of Oman based on Rieu et al. (2007a), Allen (2007) and Rieu and Allen (2008). The palaeomagnetic sites of Kilner et al. (2005) were re-located according to this updated stratigraphic framework. Black: sampling sites from Al Jabal al-Akhdar, green: sampling sites from Al-Huqf, and blue: sampling sites from Mirbat.

Age Constraints

The base of the Mahatta Humaid Group has been assumed to be Cambrian, based on limited evidence available from the underlying Huqf Supergroup. Palaeontologically dated lithologies within the mudrock-dominated Al-Bashair and Mabrouk members of the Andam Formation give Middle – Late Cambrian and Tremadoc ages, respectively. Rocks of the succession that crops out in the Al-Huqf region contain the trilobite *Eosaukia* cf. *walcotti*, which indicates a latest Cambrian age (Fortey, 1994; Droste, 1997). A recent magnetostratigraphic study on subsurface rocks (Millson et al., 2008) indicates that from the lower part of the Amin Formation up to the Barik Member, the succession covers a time span from the Early to Late Cambrian, in agreement with the stratigraphic and palaeontological ages. All the data suggest that the age of the sampled rocks studied here is constrained between the Early Cambrian and the Tremadoc (Early Ordovician). The rocks are broadly correlatable with the lower part of the AP2 tectonosequence (Sharland et al., 2001), with its base at 520 Ma and maximum flooding at 494 Ma (named O10 by Sharland et al., 2004).

PALAEOMAGNETIC STUDY OF MAHATTA HUMAID GROUP, AL-HUQF REGION

Palaeomagnetic samples were collected from four outcrop sections, each one representing a formation or member of the Mahatta Humaid Group in the Al-Huqf region. Table 1 shows the sampled units together with the geographic coordinates of the sampling sites. The samples were collected in a stratigraphic sequence on the western flank of a very gentle anticline (a broad surface known as "Al-Huqf") with an optimum vertical spacing of about 5 meters. As the original objective was only to compare palaeomagnetic inclinations of outcropping and subsurface rocks, there are no sites in the conventional palaeomagnetic sense. As the shallowness of the geological dip precluded the use of any statistical fold test, only one flank of the anticline was sampled (Figure 1). Because of the remoteness of the sampling locality and its ecological sensitivity, no drilling was undertaken. The sampling program was developed as part of a broader study of the Haima Supergroup and particularly the magnetostratigraphy of subsurface sections in the Khazzan gas reservoirs (Millson et al., 2008).

A total of 39 hand/block samples were obtained in the surface sampling: seven from the Amin Formation, 15 from the Miqrat Formation and 17 from the Andam Formation (13 from the Al-Bashair Member and 4 from the Barik Member). Each sample was spatially located using GPS and oriented using a combination of a magnetic compass, a sun compass and a GPS electronic compass. All of the hand/block samples were large enough to drill long cores, the upper surfaces of which were discarded so as to avoid weathering effects.

Table 1

Characteristic remanent magnetization (ChRM) directions obtained in different geological units of the Mahatta Humaid Group. All the directions are shown after tilt corrections.

Geological Unit		Sample	Latitude (°N)	Longtitude (°E)	Tilt correction Strike/Dip	Declination (°)	Inclination (°)	MAD (°)
Formation	Member							
Andam	Barik	B 1-1c	21°02´29”	57°55´57”	232/07	290.5	22.4	5
Andam	Al-Bashair	Alb 2-3c	20°59´52”	57°55´58”	182/08	29.3	-56.5	10
Andam	Al-Bashair	Alb 3-3c	20°59´52”	57°55´53”	188/07	72.7	-64.1	4.5
Andam	Al-Bashair	Alb 5-3c	20°59´57”	57°55´40”	172/07	269.6	34.2	17.5
Andam	Al-Bashair	Alb 6-1 c	21°00´05”	57°55´26”	249/10	280.6	54.3	13
Miqrat		M 1-1c	21°02´24”	57°59´54”	243/05	107.2	-51.7	16.4
Miqrat		M 3-2c	21°02´24”	57°59´54”	221/05	54.5	-36.2	12.5
Miqrat		M 4-1c	21°02´24”	57°59´54”	183/02	86.8	-49.7	2.8
Miqrat		M 5-1c	21°02´24”	57°59´54”	183/05	102.4	-54.9	1.7
Miqrat		M 6-3c	21°02´24”	57°59´54”	183/02	96.3	-34.9	5.7
Miqrat		M 9-1c	21°00´51”	57°59´31”	153/07	133.5	-44.7	5.4
Miqrat		M 10-2c	21°00´51”	57°59´31”	270/03	105.6	-52.2	4.8
Miqrat		M 11-1c	20°58´14”	57°55´41”	268/09	247.9	44.8	1.4
Miqrat		M 11-3c	20°58´14”	57°55´41”	268/09	255.5	43.2	4.3
Miqrat		M 12-1c	20°58´14”	57°55´41”	268/09	286.5	22.5	17.1
Miqrat		M 13-1c	20°58´14”	57°55´41”	268/09	93.1	-33.5	2.9
Amin		Am 10-1	20°22´31”	57°39´43”	194/30	309.9	26.4	15.9

Notation as follows: Lat./Long.= latitude and longitude of the sampling site. Declination and Inclination of ChRMs, MAD= minimum angle deviation of principal components analysis, N= number of averaged directions, R and k= statistical parameters of Fisher (1953), α_{95}= 95% confidence level of Fisher (1953). Mean of ChRM directions with upward inclinations: N= 10, Dec.= 89.81°, Inc.= -51.09°, R= 9.39, α_{95}= 13°, k= 14.76. Mean of ChRM directions with downward inclinations: N= 7, Dec.= 278.88°, Inc.= 37.02°, R= 6.59, α_{95}= 16.2°, k= 14.84.
Mean of all ChRM directions: N= 17, Dec.= 94.09°, Inc.= -45.39°, R= 15.84, α_{95}= 9.9°, k= 13.85.

Specimens of fresh rock 2.4 cm in diameter and 2.2 cm long were sliced from each core, and the orientations with respect to north taken in the field were transferred to these specimens. The natural remanent magnetization (NRM) of the specimens was measured with an Agico JR-5A spinner magnetometer. The stability of the NRM was tested by means of progressive thermal demagnetization experiments. Bulk magnetic susceptibility was measured after each thermal step in order to monitor possible magnetic mineral changes.

Magnetic behavior and NRM intensity varied both between and within the geological units. The initial intensities of the whole collection ranged from 0.1–25 mA/m. In 38% of specimens, the patterns of demagnetization were too poor to confidently assign a trend and define a magnetic component; in 18% only a component close to the present-day dipolar direction was defined, and in 44% characteristic remanent magnetization (ChRM) was defined after steps at 400°C (Figures 3 and 4). The unblocking temperature of these components indicates that hematite is the magnetic carrier of the ChRM (Figure 3c).

These ChRM were identified from least-squares analysis on linear segments of the orthogonal vector trajectories (Kirschvink, 1980) and have minimum angle deviations (MAD) < 18° (in general ≤ 10°, see Table 1). The highest number of ChRM belongs to the Miqrat Formation (11), followed by the Al-Bashair Member (5); the other two samples belong respectively to the Amin Formation and the Barik Member (Table 1).

Two different groups of ChRM were recognized (Figure 5a); one group has SW to NW declinations and moderate to low downward inclinations, and the other has NE to SE declinations and moderate upward inclinations. These two groups of directions are probably records of both polarities of the Earth's magnetic field (EMF) in ancient times; this is supported by sedimentological/stratigraphic evidence. Figure 4 shows the upper part of the Miqrat Formation and its contact with the overlying Al-Bashair Member (Andam Formation). The two samples (M11-3c and M13-1c) are separated by a thin transgressive sequence boundary that marks the initial marine flooding associated with the transition to the predominantly marine conditions of the Al-Bashair Member. The two samples show a ChRM of Dec. = 255°, Inc. = 43° (M11-3c) and Dec. = 92°, Inc. = -34° (M13-1c), respectively.

The coincidence of the geomagnetic polarity change and the sequence boundary is consistent with a hiatus. Samples with ChRM components with similar directions but opposite senses, above and below a sequence boundary, indicate a stratigraphic gap in the sequence (involving the absence of a time span that covers at least part of one or two magnetic chrons) without a significant movement

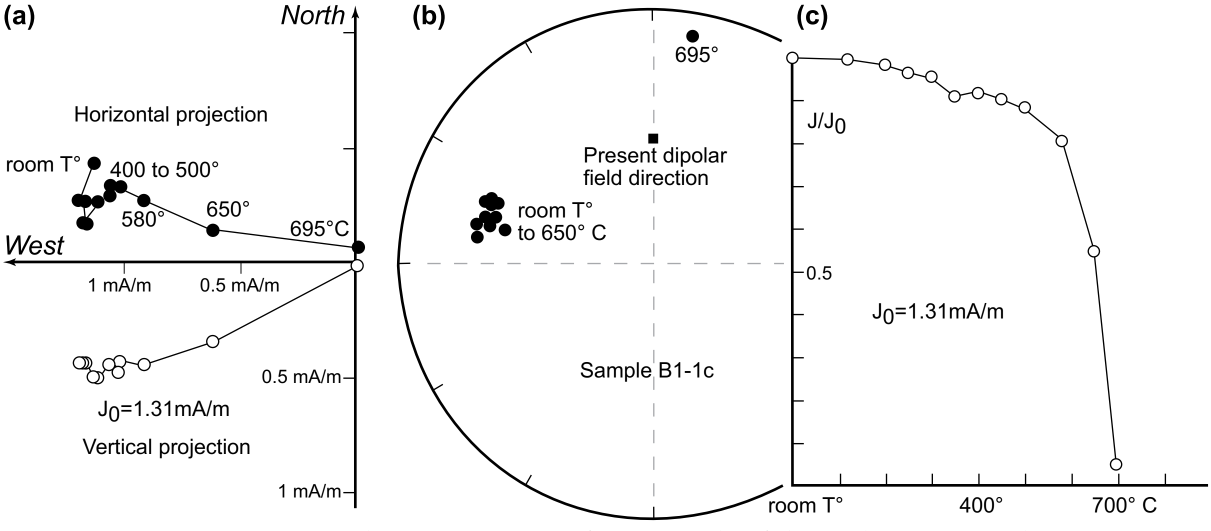


Figure 3: Progressive demagnetization of one sample of the Mahatta Humaid Group. (a) Orthogonal plot; (b) stereographic plot; and (c) normalized demagnetization plot.

of the lithospheric plate. This fact also indicates that the section is not re-magnetized; a pervasive re-magnetization would have printed the same polarity direction above and below the sequence boundary.

When all of the directions of both polarities are analyzed, two mean directions are obtained (Table 1 and Figure 5b) with comparable precision parameters (kappa: k, Fisher 1953). The directions of both polarities share a common mean at the 95% confidence level (McFadden and Lowes, 1981) passing a reversal/antipodal test. Note also that when one of the mean directions is inverted, the 95% confidence (α_{95}) intervals overlap (Figure 5b).

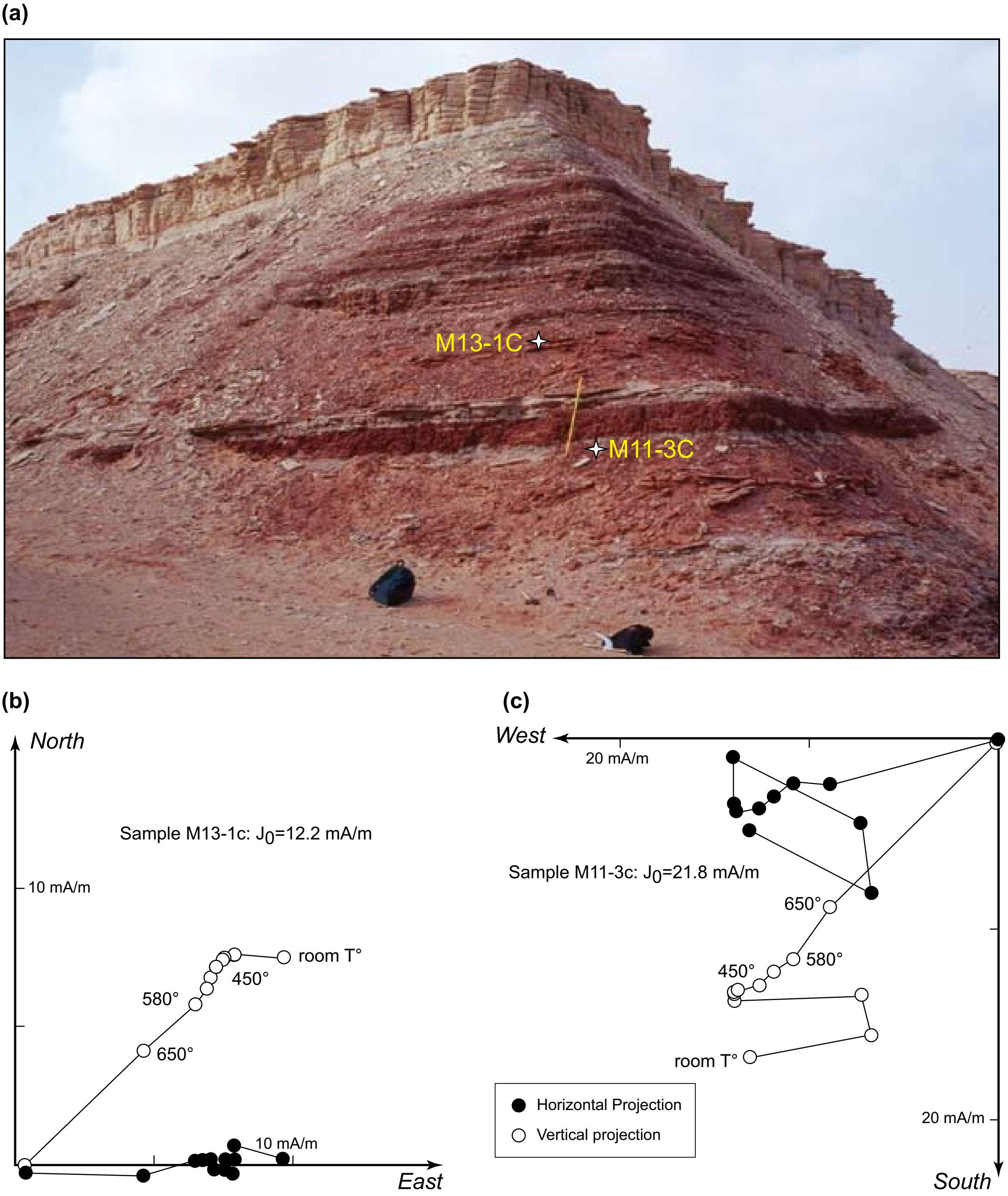


Figure 4: (a) Location of the samples M11-3c and M13-1 of the Miqrat Formation (Mahatta Humaid Group) separated in a stratigraphic section by a sequence boundary. (b) and (c) Orthogonal plots of progressive demagnetization data of both samples.

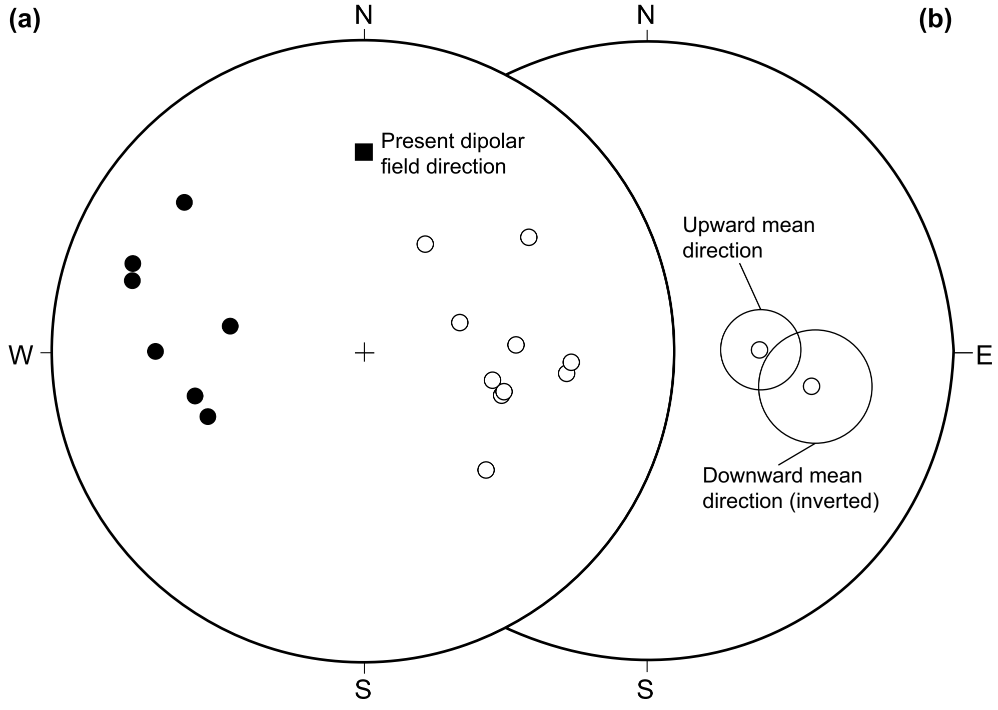


Figure 5: (a) All the characteristic remanent magnetization directions identified in the samples of the Mahatta Humaid Group (represented after tilt corrections). Closed (open) circles belong to downward (upward) palaeomagnetic directions; present dipolar field direction represented with a closed square. (b) Means of downward and upward directions with their 95% confidence intervals (Fisher, 1953).

MINERALOGICAL ANALYSES OF THE MAHATTA HUMAID GROUP, AL-HUQF REGION

To identify any magnetic mineral and its potential contribution to the 17 ChRM recognized in the samples, a large number of polished thin sections were examined using reflected light microscopy to evaluate the iron-titanium (Fe-Ti) oxides and their textural relationships (Figure 6). The mineralogical/petrographic analyses indicate that grains of specular hematite/ilmenohematite are probably the main remanence carriers; this is in agreement with the unblocking temperatures determined by thermal cleaning.

Specular hematite forms as hexagonal, plate-like crystals elongated in the basal {0001} plane. In our study, many of the grains of this mineral show authigenic overgrowths always orientated parallel to the basal {0001} plane (Figure 6), which is the easy plane of magnetization (i.e. Dunlop and Özdemir, 1997). Petrographic analyses indicate a crystallographic continuity between the host grains and the later syntaxial overgrowths parallel to the {0001} plane, suggesting that the overgrowth might inherit the original magnetic directions of the host grains and thereby enhance/reinforce the strength of these magnetizations.

VALIDATION OF PALAEOMAGNETIC DATA FROM THE MAHATTA HUMAID GROUP

The magnetization directions we obtained were in red beds, whose use in palaeomagnetism has been widely debated. The debate centres on the timing of remanence acquisition (Larson and Walker, 1985). Several lines of evidences suggest that the 17 ChRM of the red beds of the Mahatta Humaid Group have a primary origin. (1) These components were recorded as detrital remanent magnetization/post-detrital remanent magnetization carried by hematite/ilmeno-hematite. The formation of diagenetic overgrowth appears to have enhanced rather than destroyed the primary ChRM of these samples because the overgrowths are largely parallel to the easy plane of magnetization in the detrital grains.

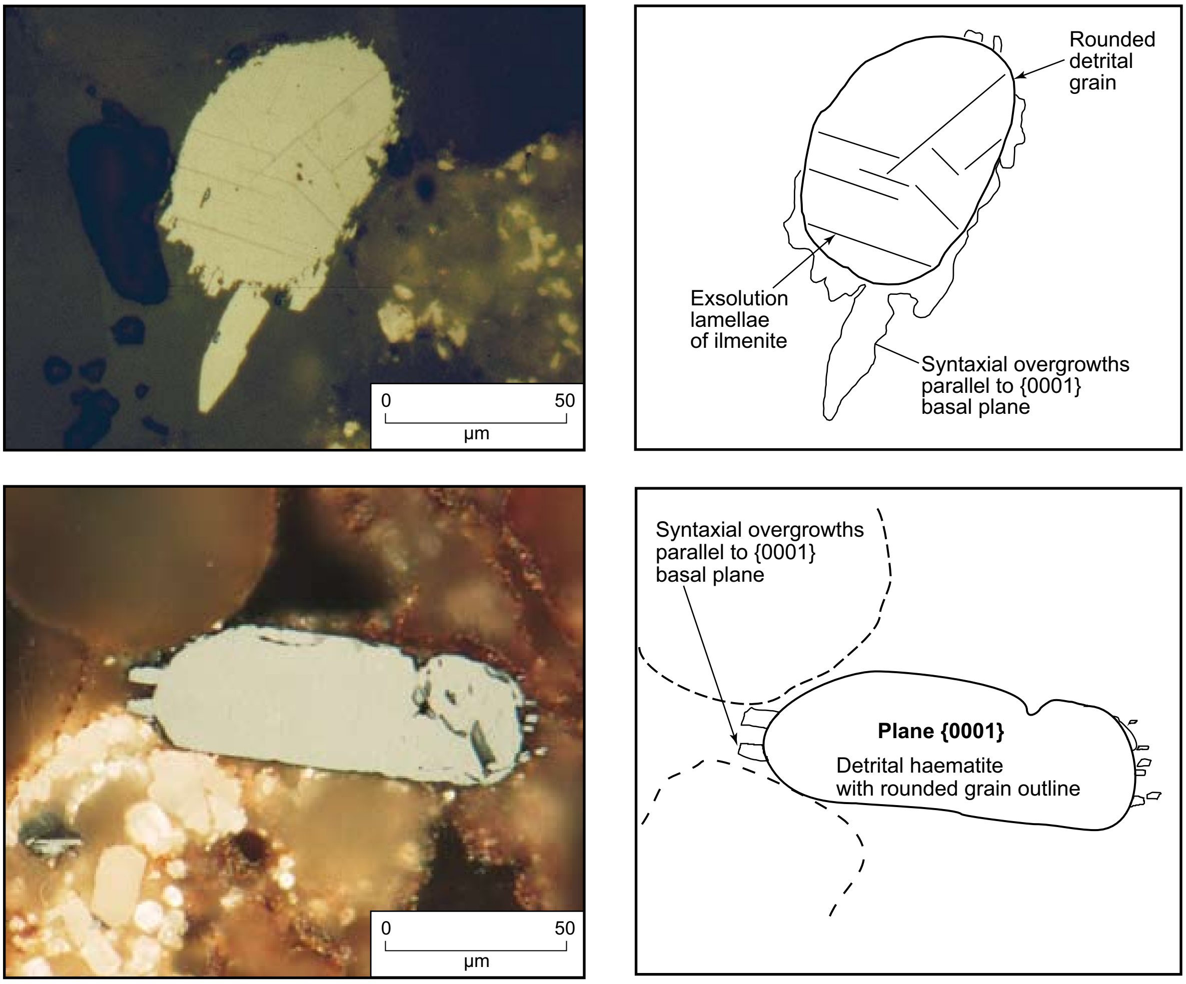


Figure 6: Grains of specular hematite with authigenic overgrowths orientated parallel to the basal {0001} plane, which is the easy plane of magnetization. Note the crystallographic continuity between the host grains and the later syntaxial overgrowths.

(2) Two samples (M11-3c and M13-1c) separated in the stratigraphic section by a sequence boundary recorded two different polarities that are closely anti-parallel, indicating that this section was not remagnetized. (3) Both of these directions also form part of two groups that pass a reversal/antipodal test. In the case of sedimentary rocks, if the specimens collected at various levels have opposite polarity, the ChRM can be reasonably considered to have been recorded not much later than the deposition of the sediments (Butler, 1992; Lanza and Meloni, 2006).

Reversal/Antipodal Test of Characteristic Remanent Magnetizations and the Mahatta Humaid Group Palaeopole

A positive reversal/antipodal test also indicates that the palaeosecular variation of the ancient EMF has been averaged out in the mean direction obtained with the 17 ChRM components, and therefore, it can be useful for tectonic purposes. The mean direction and statistical parameters (Fisher 1953) for the Mahatta Humaid Group (Dec. = 94.1°, Inc. = -45.4°, N = 17 samples, R = 15.8, α_{95} = 10°, k = 13.85) yield a palaeopole for the Al-Huqf region whose geographic coordinates and confidence interval are Latitude = 12.4°N, Longitude = 352.4°E, δp = 8°, δm = 12.4°. The palaeopole was obtained with data from just 17 samples, a number that is small for reliable palaeomagnetic studies; for example, according to Van der Voo (1993), the number of palaeomagnetic samples should exceed 24. However, the precision parameter k (Fisher 1953) for the group of ChRM components in this study is greater than 10 and the angle of confidence is less than 15°, meeting the statistical requirements for a reliable palaeomagnetic study. Note, also, that the Neoproterozoic palaeopole obtained by Kempf et al. (2000) was computed with only 10 samples, which recorded only one polarity, but this has been considered reliable and is used in continental reconstructions (i.e. Meert, 2003; Kilner et al., 2005). As determined by the ages of the sampled units of the Mahatta Humaid Group, the palaeopole presented in this paper for the Al-Huqf region is dated between ca. 520 and 495 Ma.

Comparison of Gondwanan and Mahatta Humaid Group (MHG) Palaeopoles

In order to test if the Mahatta Humaid Group (MHG) palaeopole has an age similar to that proposed above, this pole was compared with the reference apparent polar wander (APW) path for Gondwana of McElhinny and McFadden (2000) in northwestern Africa present geographic coordinates (Figure 7). The MHG pole forms part of a group of poles with ages between 518–443 Ma in northwestern Africa after its restoration using the rotation parameter listed by Meert (2003). In addition, the palaeopole is indistinguishable at 95% confidence from a mean pole between 518–495 Ma (Figure 7), which is in close agreement with the age range proposed above. Note also that the MHG pole does not fit with any younger mean pole of the reference APW path, indicating that the ChRM recorded in the Mahatta Humaid Group were not acquired million of years later as a result of fluid flow within these sedimentary rocks. The fit of the MHG pole with the 518–495 Ma pole for Gondwana reinforces the interpretation that the ChRM recorded in this group are probably primary and that the hematite overgrowths could have inherited the original magnetic directions of the host grains.

The MHG pole is included in new alternative interpretations, in which various groups of Proterozoic palaeomagnetic data have been re-analyzed in light of Allen's comment (2007, p.144): "Currently, the palaeomagnetic data described by Kempf et al. (2000) and Kilner et al. (2005) have not yet been accounted for with a coherent explanation that incorporates the full range of geological observations." Indeed, the palaeomagnetic anomalies seen in their sampling localities may be due to three reasons: (1) Different ages of magnetic records considering that new stratigraphic frameworks indicate that in Al Jabal al-Akhdar, glacigenic rocks crop out that could be younger than the glacigenic rocks cropping out in Mirbat (i.e. Rieu et al., 2006; Allen, 2007); (2) sampling localities associated with discrete different tectonic blocks (i.e. Loosveld et al., 1996; Al-Husseini, 2000); and (3) re-magnetization at different geological times.

AGE OF PALAEOMAGNETIC DATA FROM PREVIOUS STUDIES

The palaeopole of Kilner at al. (2005) was obtained from rocks sampled in three different areas, Al Jabal al-Akhdar (close to Wadi Bani), the Al-Huqf region (close to Sirab) and Mirbat (Figure 1), that were previously dated between 600 and 580 Ma. The palaeopole obtained by Kempf et al. (2000) was based on rock samples cropping out close to Mirbat (Figure 1) that were previously dated between about 564 and 513 Ma. Updated stratigraphic analysis indicates much older ages for the rock samples for both palaeomagnetic studies (Allen, 2007, Figure 2), as discussed below.

Samples from Al Jabal al-Akhdar by Kilner et al. (2005)

In Al Jabal al-Akhdar, rocks of two different glacial epochs crop out; the older is represented in the Ghubrah Formation, above which no carbonate cap has been observed in this locality associated with this glacial event (Allen, 2007), while the younger is represented in the Fiq Formation, and the glacigenic deposits are covered by a carbonate cap (Hadash Formation). This marks the change from the structurally confined Fiq sedimentation to the unconfined, extensive sedimentation of the Nafun Group (Allen, 2007). The Hadash Formation is overlain by the Masirah Bay Formation, composed of siltstones and shales (Allen, 2007). A comparison between the stratigraphic section sampled by Kilner et al. (2005) in Al Jabal al-Akhdar with the updated chronostratigraphic columns (i.e. Rieu et al., 2007a; Allen, 2007) indicates that three of the palaeomagnetic sites belong to the upper part of the Fiq Formation (with glacigenic deposits), and the other 10 to the Nafun Group (probably all of these 10 sites belong to the Hadash Formation, as indicated by Kilner et al., 2005).

There is no doubt about the locations of these palaeomagnetic sites because only in Al Jabal al-Akhdar does a carbonate cap overlie the younger glacial deposits and the lithologies of the different sampled stratigraphic levels are easily recognized in the updated chronostratigraphic columns (Figure 2).

According to Allen (2007), the Fiq glaciation ended after 645 Ma; Le Guerroué et al. (2006) interpolated the approximate ages of formation boundaries of the Nafun Group, suggesting an age younger than 635 Ma and older than 625 Ma for the Hadash Formation (see Figure 6 of Le Guerroué et al., 2006). The ages of the sampled rocks can therefore be considered younger than 645 Ma and older than 625 Ma.

Samples from Al Huqf by Kilner et al. (2005)

Kilner et al. (2005) only reported three reliable palaeomagnetic sites from the Al-Huqf region. The older stratigraphic site is in volcanic rocks interbedded with diamictites, the second site is in a carbonate

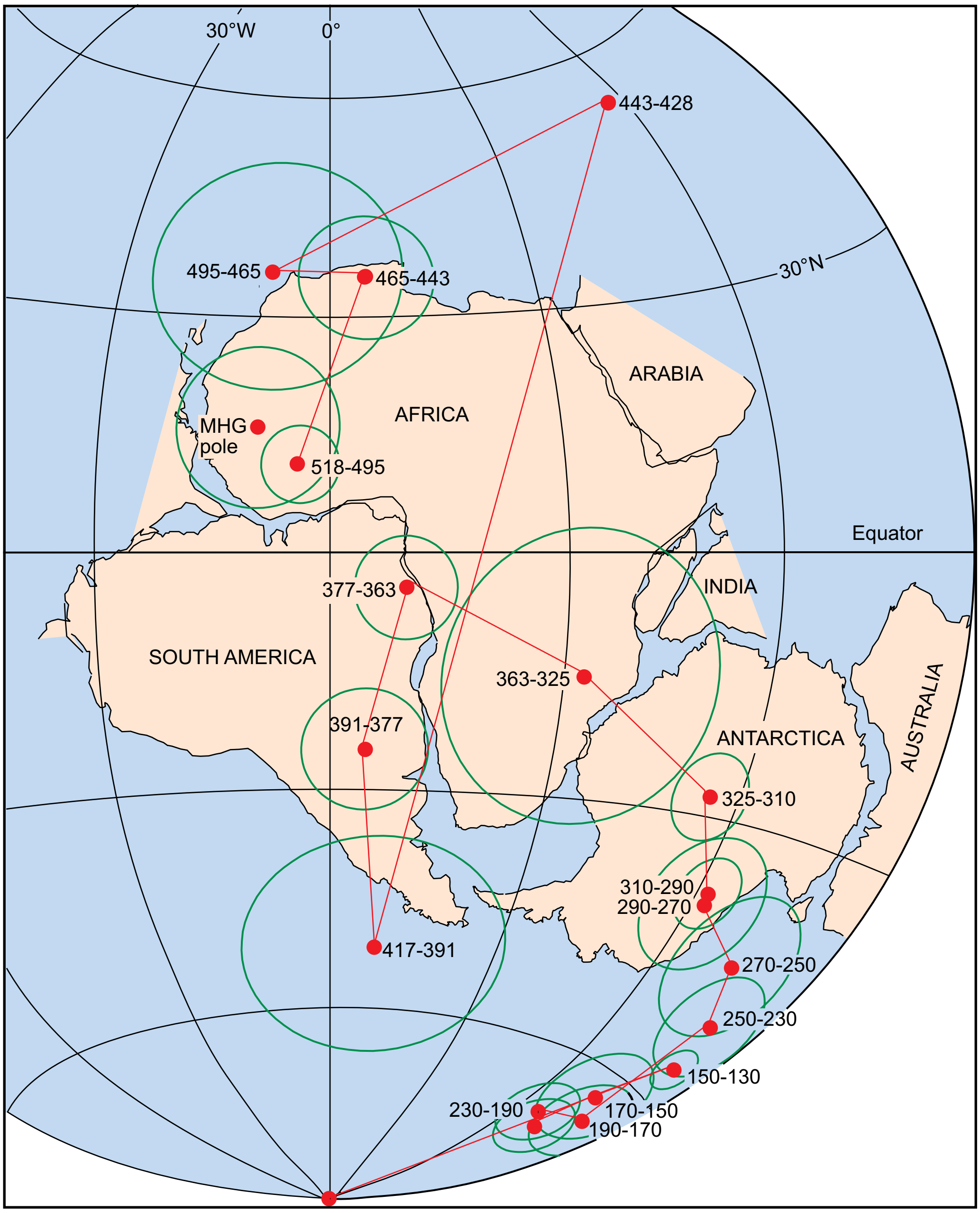


Figure 7: Comparison between Mahatta Humaid Group palaeopole (MHG) and the apparent polar wander path of Gondwana of McElhinny and McFadden (2000) in present Africa geographic coordinates. Notice that the closest pole to the MHG is a mean pole of 518–495 Ma and that there is an overlap of the intervals of confidence of these two poles. This indicates that the age of the magnetic data recorded in the rocks of the Mahatta Humaid Group is about 518–495 Ma, which agrees with the geological age of this stratigraphic unit.

cap above an unconformity that involves a stratigraphic gap, and the site above is in sandstones interbedded with siltstones that follow the cap carbonate without any stratigraphic gap. Various authors did not recognize volcanic rocks in the Neoproterozoic units cropping out in the Al-Huqf area (see Allen, 2007); however if the section sampled by Kilner at al. (2005) is compared with the composite stratigraphic charts of Rieu et al. (2007a) or Allen (2007), the site in the volcanic rocks could belong to the basaltic volcanism represented by the Saqlah Member interbedded between the rocks at the base of the Fiq Formation. Notice that there is no other Neoproterozoic extrusive unit in the Huqf Supergroup. The lithologies of the second and the third palaeomagnetic sites are comparable to the first two units of the Nafun Group (Figure 2). The second palaeomagnetic site was probably in the transgressive Hadash Formation carbonate, and the site above is probably in a bed of sandstones interbedded between siltstones of the Masirah Bay Formation, as indicated by Kilner et al. (2005).

Unfortunately there is no radiometric age for the Saqlah Member, which according to Allen (2007) must have preceded the deposition of the glacigenic diamictites of the Fiq Formation. Allen (2007) proposed an age of ca. 650 Ma for the third stage of basin evolution for the Huqf Supergroup involving the Saqlah Member volcanism. As noted above, the Hadash Formation could be younger than 635 Ma and older than 625 Ma. The Masirah Formation has been suggested to be older than 609 ± 9 Ma and younger than 625 Ma (Le Guerroué et al., 2006; Rieu et al., 2007a). Therefore, the age range of the Neoproterozoic sampled rocks in the Al-Huqf region probably covers a time span between ca. 650 and 610 Ma and contains the age range of the sampling in Al Jabal al-Akhdar.

Samples from Mirbat by Kempf et al. (2000) and Kilner et al. (2005)

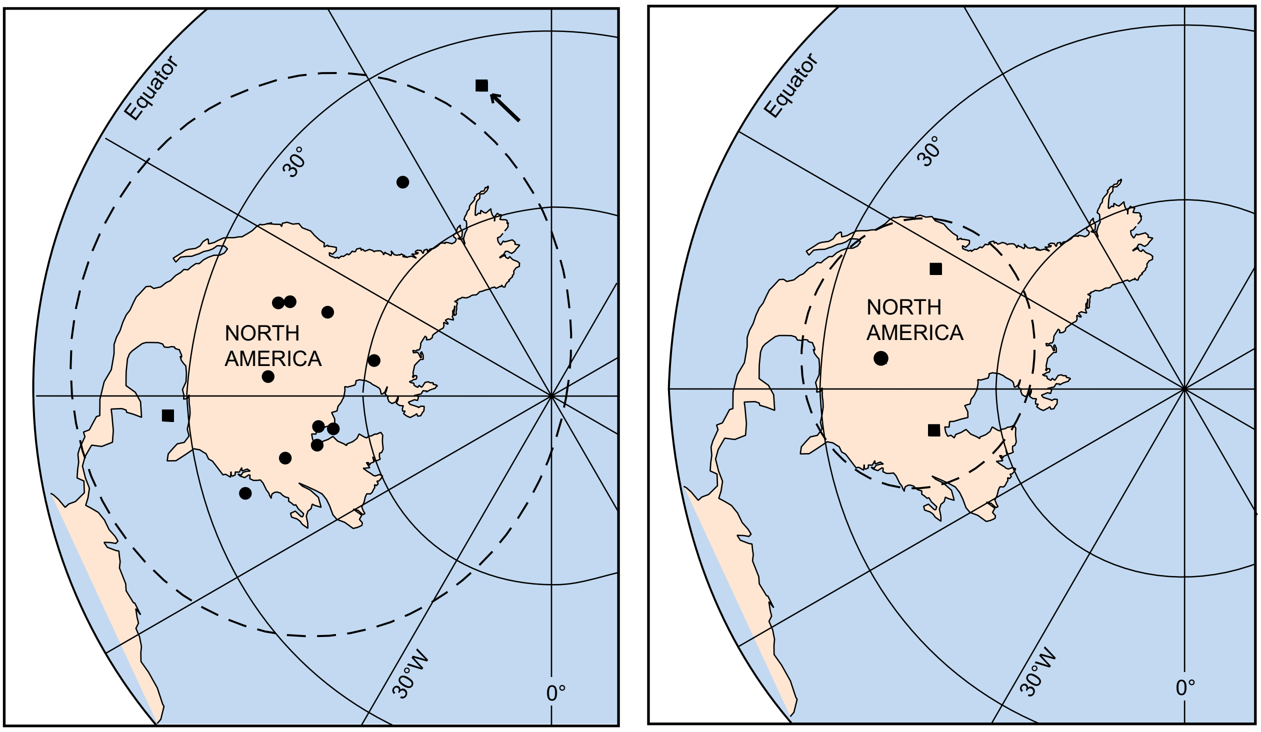
In the Mirbat area, two glacial epochs are represented in the Ayn and Shareef formations (Figure 2; Rieu and Allen, 2008). A cap carbonate overlies the older Ayn Formation, and siltstones with interbedded sandstones overlie this cap in a stratigraphically continuous section. The younger Shareef Formation is less well represented and no cap carbonate has been observed overlying its glacigenic deposits. According to Rieu et al. (2006) and Allen (2007), both of the palaeomagnetic studies reported by Kempf et al. (2000) and Kilner et al. (2005) were done with rock samples from Mirbat belonging to the oldest glacial epoch. Intriguingly, the studies yielded completely different palaeomagnetic poles (see Figure 4 of Kilner et al., 2005), suggesting that at least one of the magnetic records was indeed acquired during a later event as a re-magnetization.

The palaeopole of Kempf et al. (2000) was derived from ten samples of only two palaeomagnetic sites, whereas Kilner et al. (2005) reported 9 sites from Mirbat with records of Neoproterozoic palaeomagnetic directions. The older sites sampled by Kilner et al. (2005) are in carbonate caps overlying diamictites, while the younger sites are in siltstones and interbedded sandstones. A comparison between the section sampled by Kilner et al. (2005) in Mirbat and the chronostratigraphic columns (Rieu et al. 2007a; Allen, 2007) indicates that the palaeomagnetic sites are in the Arkahawl Formation (Figure 2), a succession that was likely deposited between ca. 710–650 Ma (Allen, 2007). The palaeomagnetic sampling in Mirbat was done in older rocks than the rocks sampled in Al Jabal al-Akhdar. Indeed, according to Rieu et al. (2006), the magnetostratigraphic correlation made by Kilner et al. (2005) between glacial deposits in southern and northern Oman cannot be used and the inferred equatorial palaeolatitude for the Fiq and Ayn formations based on this correlation must be regarded as speculative.

NEW GROUPING FOR THE SAMPLES

In order to analyze the stratigraphic and tectonic configuration of the palaeomagnetic data reported by Kilner at al. (2005), we refer to them in terms of three geographic groups: (1) Al Jabal al-Akhdar-Kilner, (2) Al-Huqf-Kilner, and (3) Mirbat-Kilner. Because the data samples have different geographic coordinates, the analysis was done by converting the palaeomagnetic directions into virtual geomagnetic poles (VGPs) in order to use the globe as a common reference frame (Figure 8).

A visual inspection of the three groups (Figure 8) suggests that the VGPs for Al Jabal al-Akhdar and Al-Huqf could form a different group from the Mirbat Group. To determine if this is true, we took into account that the palaeomagnetic records belong to different states of the Earth's magnetic field.



(a) Al Jabal al-Akhdar: Kilner et al. group

(b) Al-Huqf: Kilner et al. group

(c) Mirbat: Kilner et al. Group

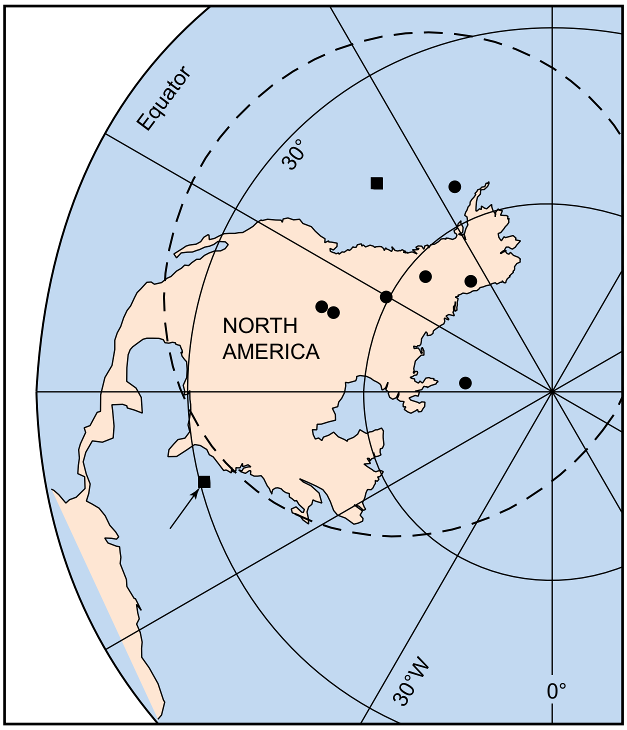


Figure 8: Virtual geomagnetic poles (VGPs) obtained with the directions of Kilner et al. (2005). The VGPs obtained with the downward directions were inverted and are represented in the northern hemisphere by closed squares. The VGPs obtained with the upward directions are represented by closed circles. Dashed lines indicate the cut-off angles calculated with the method of Vandamme (2004). The arrows point out the VGPs that were excluded in our analysis. See the text for further explanations.
(a) VGPs of Al Jabal al-Akhdar locality;
(b) VGPs of Al-Huqf region; and
(c) VGPs of Mirbat locality.

In general, the records belong to stable normal and reverse polarities, and the average of these data is representative of a geocentric axial dipolar field and useful in tectonic studies. However, some records could also belong to transitional states of reversals or excursions of the geomagnetic field (intermediate data between both polarities) and are not useful in tectonic analysis (see Butler, 1992). Because the average of the stable data can be biased by transitional data, they are not considered in the average of the population using a conventionally chosen constant cut-off angle.

Wilson et al. (1972) proposed angles of 35°–40° as cut-offs to divide stable and intermediate poles, on the basis of a study carried out on Tertiary lavas. Vandamme (1994) proposed a method based on the relation between the cut-off angle and the angular standard deviation (ẟ) of the population of VGPs. In this case, the cut-off angle (A) is calculated using the formula: A (°) = 1.8 ẟ (°) + 5°. After iteratively applying this method to the Al Jabal al-Akhdar-Kilner and Mirbat-Kilner groups, the calculated cut-off angles were 42.69° and 40.31°, respectively. In both groups of data, a VGP occurs away from the data enclosed by the respective cut-off angles (Figures 8a and 8c) and they were excluded in the following analysis. These excluded VGPs may be spurious or may have recorded transitional states of the Proterozoic Earth's magnetic field.

After the exclusion of the mentioned palaeomagnetic data and applying the method of McFadden and Lowes (1981), it is demonstrated that statistically the Al Jabal al-Akhdar-Kilner group (mean pole N = 12, statistical parameters of Fisher K = 24.54, R = 11.55) and Al-Huqf-Kilner group (mean pole N = 3, K = 39.7, R = 2.95) are indistinguishable at the 95% confidence level (mean pole of both groups together N = 15, K = 27.87, R = 14.5). In contrast, the Mirbat-Kilner group (mean pole N = 8, K = 34.18, R = 7.79) does not share a common mean at the 95% confidence level with the other groups (mean pole including all Kilner groups: N = 23, K = 20.46, R = 21.92). Therefore, two different groups of VGPs are recognized for the Kilner et al. (2005) data. One of them belongs to a region that includes Al Jabal al-Akhdar and Al-Huqf, and the other belongs to Mirbat. It is noteworthy that Kilner et al. (2005) considered that the palaeomagnetic data of the three localities formed only one group and that their palaeopole was representative of the whole of Arabia for 600–580 Ma. In the present study, we computed two different palaeopoles for the Al Jabal al-Akhadar/Al-Huqf region (Latitude = 48.1°N, Longitude = 264.6° E, A_{95}= 7.4°) and the Mirbat region (Latitude = 60.1°N, Longitude = 232.4° E, A_{95} = 9.6°).

As this new analysis yields two different groups of palaeomagnetic data for stratigraphic sequences of different geological ages cropping out in what are probably two different tectonic blocks, it is necessary to constrain the ages of both magnetic records. Figures 9a and 9b show the directions of the Al Jabal al-Akhdar/Al-Huqf-Kilner group *in situ* and bedding-corrected without the direction that yields the excluded VGP. They pass a fold test (Enkin 2003), which indicates a pre-folding magnetization. Figures 10a and 10b show the directions of the Mirbat-Kilner group *in situ*, bedding-corrected and without the excluded VGP direction noted previously. In this case, the fold test (Enkin 2003) is inconclusive; statistically there is no significant difference between the mean *in situ* and the

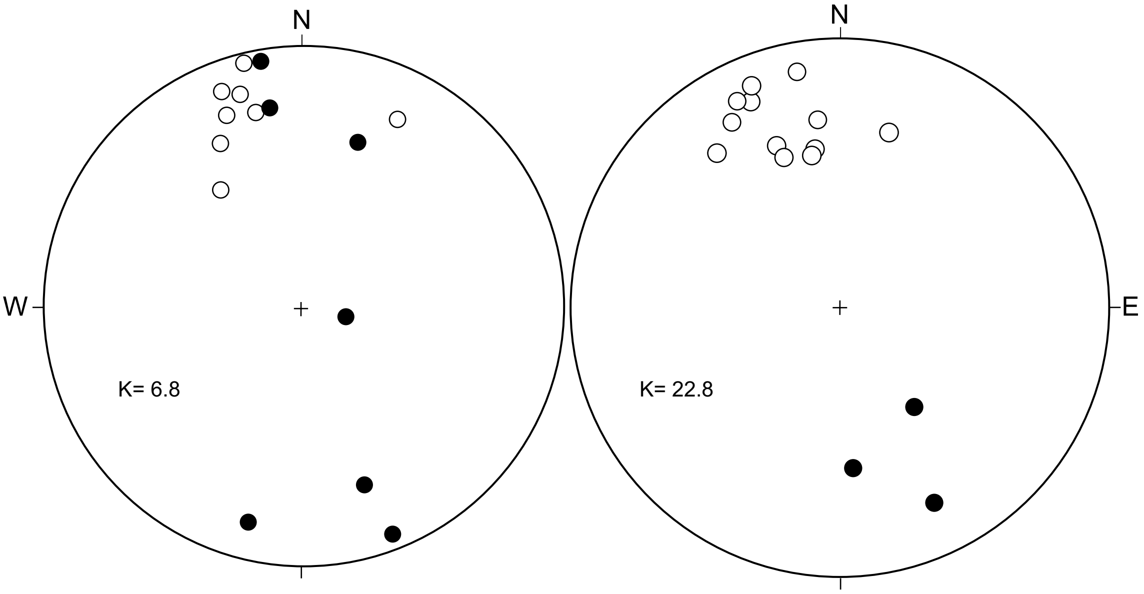


Figure 9. Characteristic remanent magnetizations of "Al Jabal al-Akhadar/Al-Huqf : Kilner et al. groups" without the direction which VGP was excluded after applying the method of Vandamme (1994); (a) directions *in situ* and (b) before bedding corrections. Notice that after bedding corrections, the value of K is higher, which indicates a positive structural test ("fold test").

mean bedding-corrected directions (see the values of k in Figure 10). Therefore, the palaeomagnetic directions could have been recorded before or after the deformation. Notice also that the VGPs computed with *in situ* and bedding corrected directions of Mirbat share a common mean at 95% confidence.

The results indicate that the palaeomagnetic records of the Al Jabal al-Akhdar/Al-Huqf-Kilner group were acquired prior to deformation of the strata. We note that the bedding-corrected directions of the Al Jabal al-Akhdar/Al-Huqf-Kilner group also pass a reversal test, indicating that this palaeomagnetic record was acquired not long after deposition of the sediments. Both tests together indicate that the magnetic records in Al Jabal al-Akhdar/Al-Huqf are probably primary. It is noteworthy that most of the palaeomagnetic sites are concentrated above and below the boundary of Basin Stages 3 and 4 of Allen (2007) (see Figure 2). Only one palaeomagnetic site belongs to the Saqlah Member of about 650 Ma (Allen, 2007). Moreover, from the 15 palaeomagnetic sites that are concentrated close to the boundary of Stages 3 and 4, 11 belong to the Hadash Formation (Figure 2), which, according to Le Guerroué et al. (2006), may be younger than 635 Ma and older than 625 Ma. In this case, the mean palaeomagnetic direction is conditioned by most of the sampling sites in the Hadash Formation, and therefore an age of ca. 630 Ma is assumed for the calculated palaeopole.

In the case of the directions of the Mirbat-Kilner group, there is only one direction with a polarity opposite to the others, which precludes any meaningful reversal test, and the palaeomagnetic directions could have been recorded before or after deformation. In this case, there is no conclusive palaeomagnetic test to confirm if the palaeomagnetic data are primary or acquired in younger times as re-magnetizations. If they are primary, as the sampling sites are in the lower part of the Arkahawl Formation (Figure 2), the age of magnetization would be ca. 700 Ma (see Allen, 2007). On the other hand, the locality of Mirbat was intruded by two sets of dikes. The older set gave an age of about 700 Ma while the younger gave ages of about 615–600 Ma (Worthing, 2005). If the magnetization was recorded thermally during the intrusion of the first set of dikes, it would be as a primary magnetization. In any case, as there is no conclusive palaeomagnetic test to confirm this possibility, we cannot rule out another alternative and consider that the data of Mirbat are a re-magnetization recorded thermally during the intrusion of the younger set of dikes at about 615–600 Ma.

We note that the Al Jabal al-Akhdar/Al-Huqf-Kilner and Mirbat-Kilner groups are statistically different; however, they both yield poles whose dipolar palaeocolatitudes have 95% intervals of confidence that overlap (Figure 11a), which means that they are statistically indistinguishable. Given

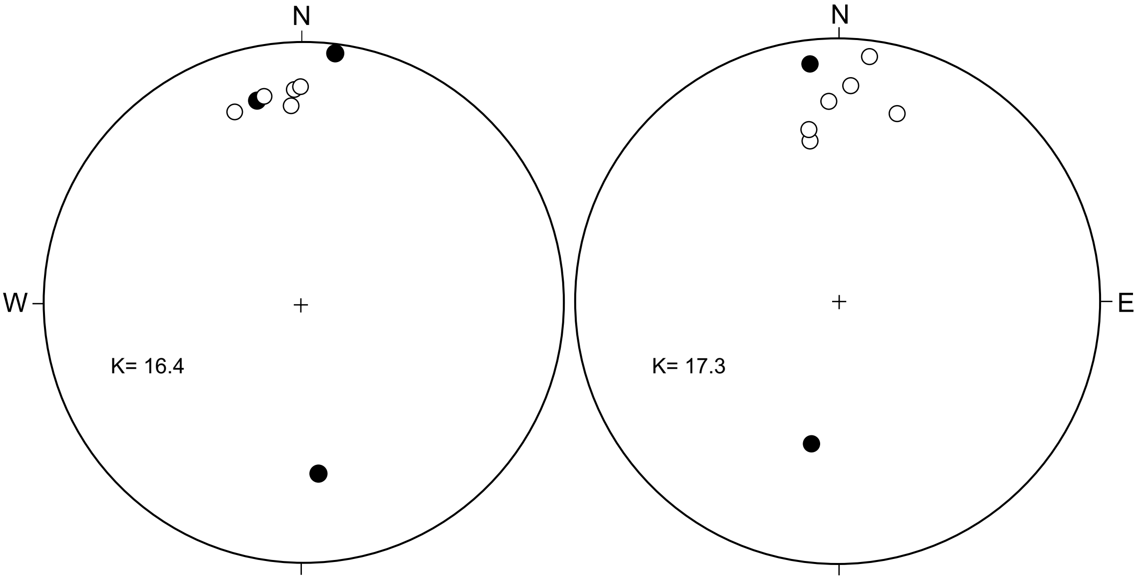


Figure 10: Characteristic remanent magnetizations of "Mirbat : Kilner et al. groups" without the direction which VGP was excluded after applying the method of Vandamme (1994); (a) directions *in situ* and (b) before bedding corrections.

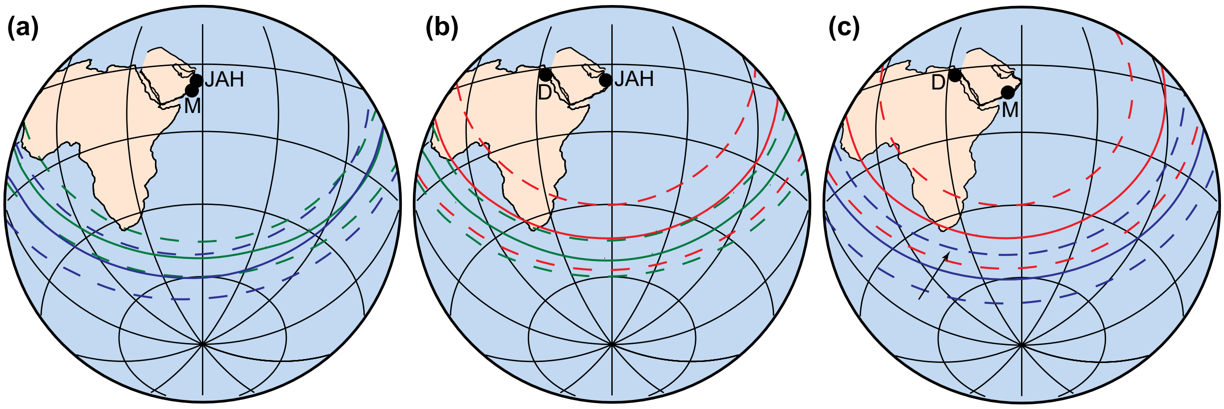


Figure 11: Comparison between dipolar palaeocolatitudes of the palaeomagnetic poles of Al Jabal al-Akhdar/Al-Huqf, Mirbat and Dokhan Volcanics. The 95% confidence levels are represented with dashed lines. JAH: sampling site of Al Jabal al-Akhadar/Al-Huqf; M: sampling site of Mirbat; D: sampling site of Dokhan Volcanics

a) Dipolar palaeocolatitudes of Al Jabal al-Akhadar/Al-Huqf (in green) and Mirbat (in blue) refer to their sampling sites.

b) Dipolar palaeocolatitudes of Al Jabal al-Akhdar/Al-Huqf (in green) and Dokhan Volcanics (in red) refer to Al Jabal al-Akhadar/Al-Huqf sampling sites.

c) Dipolar palaeocolatitudes of Mirbat (in blue) and Dokhan Volcanics (in red) refer to the Mirbat sampling site. The arrow points out the overlap of the levels of confidence of Mirbat and the Dokhan Volcanics dipolar palaeocolatitudes. The overlap of the confidence levels of all of these palaeocolatitudes indicates that their magnetic remanences could have been probably recorded at about the same time.

the chronostratigraphic ages indicated by Allen (2007, among others), and the dates of the magnetic records discussed above for the rocks sampled by Kilner et al. (2005), there are three possibilities to explain this situation: (1) Oman did not experience any latitudinal movement from ca. 700 to 630 Ma (a time span of about 70 My); (2) southern Oman was in low latitudes at ca. 700 Ma and experienced similar palaeolatitudes at ca. 630 Ma; or (3) both palaeomagnetic groups were recorded during a shorter time span and the older sequence was re-magnetized at an age close to that of the younger Al Jabal al-Akhadar/Al-Huqf group. There is no other reliable palaeomagnetic pole of about 700 Ma for the Arabian-Nubian Shield or neighbouring cratons to compare the palaeopoles from Oman and test the first two possibilities. There is only a “possible” remanent magnetization for the Arabian Shield that has been obtained with relative precision from aeromagnetic data (Galdeano et al., 2001) but not from conventional palaeomagnetic studies. The recovered magnetic direction is vertical, indicating a polar position for Arabia. The age of this magnetization is a major problem. In fact, as the deep rocks in particular appear to be magnetized vertically, it is difficult to acquire a firm date (Galdeano et al., 2001). Evidently this record must be from a time that is different from the record times of the data published by Kilner et al. (2005).

On the other hand, the same rocks of the locality of Mirbat yielded completely different palaeomagnetic poles. According to Thover et al. (2006), the pole of Kempf et al. (2000) was obtained with data from re-magnetized rocks. Moreover, this latter palaeopole was calculated with 10 directions with the same polarity as only two palaeomagnetic sampling sites. In the rest of the sampling sites, only records of the recent geomagnetic field in Oman were found.

APPARENT POLAR WANDER (APW) PATHS OF THE GONDWANA AND OMAN PALAEOPOLES

APW paths for Gondwana together with James Hutton´s Principle of Uniformitarianism can help us as an approach to continue our analysis. Figure 7 shows the Phanerozoic track of the APW path developed with palaeomagnetic data of the continents that formed Gondwana. In general, there are no periods of about 70 My (or longer) with latitudinal stability, which brings back the first possibility pointed out in the previous section.

Figure 12 shows that the palaeomagnetic record of the Mirbat-Kilner group could be older than 550 Ma, but it does not resolve whether the directions are primary or younger re-magnetizations. Notice also in this Figure that the pole of Mirbat obtained by Kempf et al. (2000) is contained within the 95% confidence level of a mean pole of 550 Ma. The mean pole (N = 4, Latitude = 22.12°S, Longitude = 333.73°E, K = 35.8, A_{95}= 15.6° in Arabian geographic coordinates) was calculated with the four poles of about 550 Ma from Gondwana cratons (Sinyai Dolerite, Lower Arumbera, Brachina Formation, Bhander-Rewa poles) listed by Meert (2003). The overlap between the levels of confidence of both poles indicates that the data reported by Kempf et al. (2000) are probably of this age. Therefore, these data likely represent a re-magnetization, probably related to the period of plutonism and felsic volcanism that affected the crust from Arabia to Madagascar from 550 to 530 Ma (i.e. Allen, 2007, p. 153).

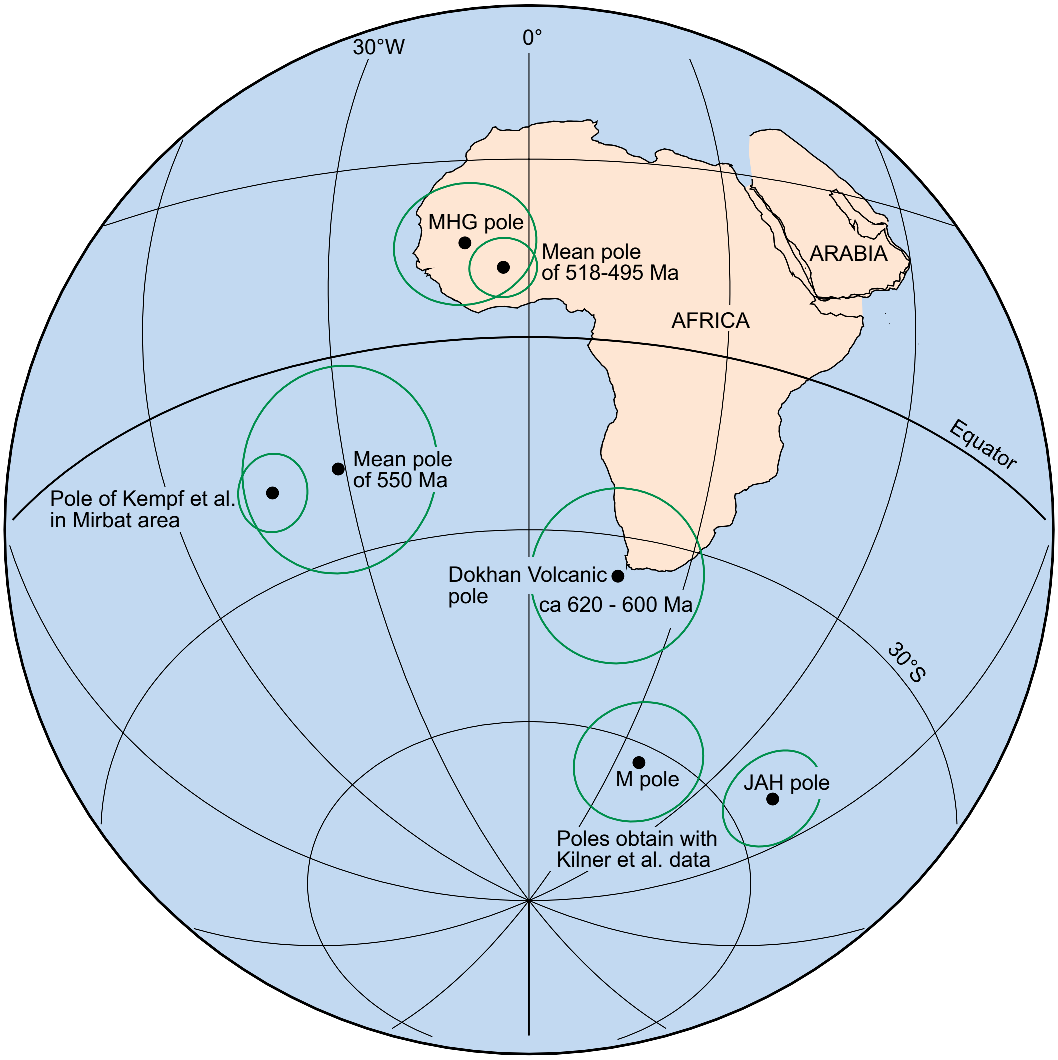


Figure 12: Comparison of the palaeomagnetic poles of Oman with reference poles. Notice that the JAH pole (from Al Jabal al-Akhdar/Al-Huqf) and M pole (from Mirbat) do not fit with the reference pole of ca. 600 Ma (from the Dokhan Volcanics). Notice that the pole of Mirbat obtained by Kempf et al. is contained by the 95% confidence level of a mean pole of 550 Ma, which indicates that the magnetic remanences reported by Kempf et al. are probably of this age. The fit between the poles of the Mahatta Humaid Group (MHG) with a mean pole of 518–495 Ma indicates that the magnetic remanences recorded in rocks of Mahatta Humaid are probably of this age.

ALTERNATIVE INTERPRETATIONS

Taking into account the scarcity of reliable Neoproterozoic palaeomagnetic data from the Arabian-Nubian Shield and our previous analysis, we propose two alternative interpretations. Both interpretations are also based on three assumptions: (1) The palaeomagnetic data reported by Kempf et al. (2000) are considered to be re-magnetizations recorded at about 550 Ma. (2) Oman could have undergone latitudinal movements over time spans of about 70 My. (3) Oman was attached to the eastern part of the Arabian Plate (Ar-Rayn terrane), which, according to Allen (2007), became amalgamated together with other terranes to the Arabian-Nubian Shield at about 640 Ma. It should also be noted that sources for 600–640 Ma detrital zircons found in the Neoproterozoic Nafun Group of Oman can readily be identified in the Arabian-Nubian Shield, suggesting that Oman had long been sutured to this shield by this time (Allen, 2007). Moreover, a possible correlation between the Nafun Group of Oman and the J'Balah Group of northern Arabia (Nicholson et al., 2007) implies that the Arabian-Nubian Shield and Oman formed part of the same continental crust during the Ediacaran Period (632-543 Ma).

In both interpretations, we consider a pole from the Arabian-Nubian Shield obtained on the Dokhan Volcanics (Davies et al., 1980) with ages of ca. 620 Ma by whole rock Rb-Sr (Abdel-Rahman and Doig, 1987; see also Eliwa et al., 2006) and ca. 600 Ma by SHRIMP U-Pb zircon (Wilde and Yossef, 2000). The 95% confidence level of a palaeomagnetic pole from the localities of Mangbai/Balché (Congo craton) with an age of 580 ± 20 Ma (Ponte-Neto, 2001) overlaps the 95% confidence level of the Dokhan Volcanics pole, indicating that the Congo craton was attached to the Arabian-Nubian Shield at about 600 Ma (Tohver et al., 2006). This constraint excludes the possibility of any large-scale, strike-slip motion within these African cratons since the late Neoproterozoic. The Dokhan Volcanic pole is therefore useful for constructing an APW path or as a reference pole to compare other ones.

First Interpretation: A Track of the Arabian APW Path from ca. 630 to 500 Ma

In this interpretation, the magnetic remanences of the Mirbat-Kilner group are assumed to be primary with an age of ca. 700 Ma. Considering that at that time Oman was not attached to the Arabian-Nubian craton (i.e. Allen, 2007), the calculated pole is not considered in the proposed segment of the Arabian APW path. There is no reliable palaeomagnetic information to suggest a hypothetical palaeogeographic model of this block together with other terranes and continental blocks at ca. 700 Ma. The palaeomagnetic data of the Mirbat-Kilner group yield a palaeolatitude of 13° (+8°/-7°) for the locality of Mirbat, which would be its latitude when the Ayn Formation glacigenic rocks were deposited. This would also be the latitude during the deposition of the cap carbonate, sandstones, shales and siltstones of the Arkahawl Formation. Therefore, both glacial and cap carbonate were deposited at tropical latitudes, supporting the model proposed by Rieu et al. (2007b). This model suggests intermittent climatic ameliorations during the Cryogenian "snowball Earth" events (Hoffman et al., 1998).

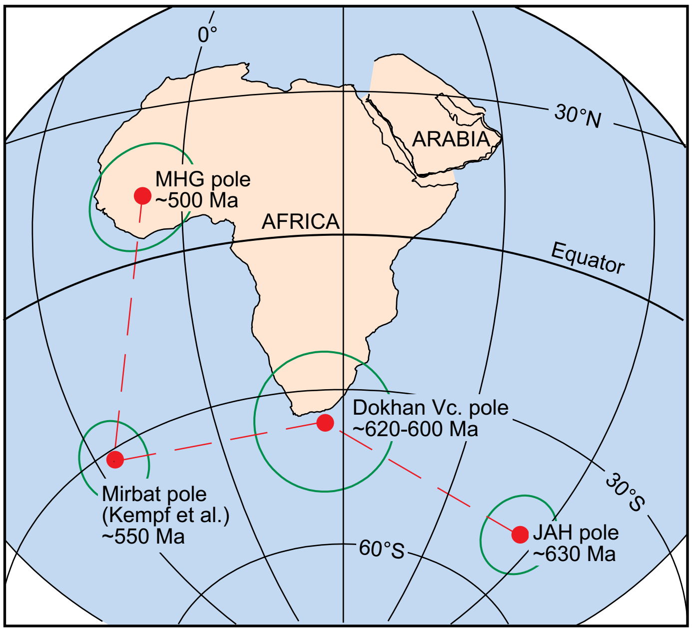


Figure 13: Track of the apparent polar wander path of Arabia from ca. 630 until ca. 500 Ma. MHG (Mahatta Humaid Group) pole, JAH (Al Jabal al-Akhadar/Al-Huqf) pole.

Figure 13 shows the proposed track of the Arabian APW path from ca. 630 to 500 Ma. The track was constructed using the 630 Ma pole of Al Jabal al-Akhdar/Al-Huqf Kilner group, the

620–600 Ma Dokhan Volcanic pole (in present Arabian geographic coordinates), the 550 Ma "re-magnetized" pole of Kempf et al. (2000) and the 500 Ma MHG pole. APW paths constrain the palaeo-latitude of a continent but not its palaeo-longitude. Accordingly, the latitudinal drift of Arabia was calculated from ca. 630 to 500 Ma on the basis of the palaeopoles and their intervals of confidence considered in our track. The proposed segment of the APW path of Arabia involves a latitudinal drift of c. 3 cm/year (with a lower drift of 1.5 cm/year) between 630 and 600 Ma considering the SHRIMP U-Pb ages obtained for the Dokhan Volcanics; or a faster drift of 9 cm/year (with a lower drift of 4.4 cm/year) between 630 and 620 Ma considering the whole rock Rb-Sr ages. This segment also involves a latitudinal drift for this plate of c. 7 cm/year (with a lower drift of 3.5 cm/year) between 600 and 550 Ma, and a latitudinal drift of c. 7 cm/year (with a lower drift of 4.7 cm/year) between 550 and 500 Ma. The velocity calculated considering the whole rock Rb-Sr age for the Dokhan Volcanics is relatively high; but not unreasonable when compared to that of India, which was nearly twice this velocity during its journey from Gondwana to Laurasia (Patriat and Achache, 1984). The lower velocity calculated on the basis of SHRIMP U-Pb age suggests that this radiometric age may be a much better geochronologic estimate.

The palaeolatitudes calculated with the poles of this APW path for the locality of Al-Huqf (our original palaeomagnetic sampling area for the Mahatta Humaid Group) are respectively 17° (+6°/ -6°) for 630 Ma, 25° (+12°/ -10°) for 620–600 Ma, 6° (+5° / -5°) for 550 Ma and 27° (+9° / -7°) for 500 Ma. The tropical latitude for 630 Ma was obtained with palaeomagnetic data recorded mainly in a glacial diamictite and a cap carbonate (Figure 2). Therefore, these data again support the model of Rieu et al. (2007b), indicating that Oman underwent climatic cycles during the "snowball" glacial epochs throughout late Cryogenian time.

Second Interpretation: Block Tectonic Rotations in Oman and the Najd Fault System

In this interpretation, the palaeomagnetic data of the Mirbat-Kilner group are considered to have been recorded during a re-magnetization that occurred at a time younger than the age of the rocks that carry the remanence. As indicated by the Gondwana Phanerozoic APW path (Figure 7), a continent can remain in a stable position for intervals of about 30 My (i.e. the Early Ordovician interval). The second interpretation makes a similar assumption, with the Arabian-Nubian standing still from 630 to 600 Ma (or 620 Ma, according to the different ages obtained for the Dokhan Volcanics). As shown above, the pole from the Dokhan Volcanics can be used as a reference to compare the poles of Al Jabal al-Akhdar/Al-Huqf-Kilner and Mirbat-Kilner groups. Both poles are different from the Dokhan Volcanics pole (Figure 12); however the confidence intervals of their dipolar palaeocolatitudes overlap (undistinguishable at 95% confidence, Figure 11), which probably indicates that the palaeomagnetic data of these Proterozoic rocks from Oman were recorded close to ca. 620–600 Ma. The age of the glacigenic sequence of Al Jabal al-Akhdar is relatively close to the ages of the Dokhan Volcanics, which again indicates that the magnetic directions of this sequence were probably recorded not very far from their deposition. The magnetic remanences of the Mirbat-Kilner group could be a re-magnetization, perhaps recorded during a phase of dike intrusion in Mirbat at about 615–600 Ma (Worthing, 2005). As mentioned above, the Mirbat palaeopole reported by Kempf et al. (2000), which fits with a mean pole of 550 Ma (Figure 12), could represent a younger re-magnetization, probably related to the period of plutonism and felsic volcanism that affected the crust from Arabia to Madagascar from 550 to 530 Ma (i.e. Allen, 2007, p. 153).

As previously mentioned, the poles of Al Jabal al-Akhdar/Al-Huqf-Kilner, Mirbat-Kilner and the Dokhan Volcanics are different, although the 95% confidence levels of their dipolar palaeocolatitudes overlap (Figure 11). The greater differences between these data could therefore be related to the declinations of their mean directions but not to their inclinations. To test this possibility, we compared data from the Al Jabal al-Akhdar/Al-Huqf and Mirbat-Kilner groups with those of the Dokhan Volcanics (in Arabian present geographic coordinates) using the method of Beck (1989). Table 2 shows the results of our analysis; declination differences of about 45° and 25° can be assured, respectively, for the Al Jabal al-Akhdar/Al-Huqf and Mirbat-Kilner groups compared to the Dokhan Volcanic data. Figure 14 shows the poles of both groups before and after clockwise rotations around a vertical axis in the sampling localities, which agree with the calculated anomalies. Note the overlapping of the 95% levels of confidence of the restored poles and the ca. 620–600 Ma Dokhan Volcanic pole.

Table 2
Tectonic motions calculated for the JAH and M blocks at different geological times.

Age of Palaeomagnetic data	Structural block	Pole name or geological unit	Motion calculated respect to	Apparent rotation (R ± ∆R)	Apparent Poleward displacement (P ± ∆P)
Circa 630 - 600 Ma	JAH block	Huqf Supergroup	Dokhan Volcanics	46.5° ± 12.3°	08.6° ± 11.3°
Circa 600 Ma (*)	M block	Huqf Supergroup	Dokhan Volcanics	26° ± 13.6°	17.4° ± 12.2°
Circa 550 Ma (**)	M block	Mirbat SS	Mean of 4 poles (***)	02.1° ± 12.2°	-10.9° ± 12.2°
Circa 500 Ma	JAH block	Mahatta Humaid Group	Mean pole of 518-495 Ma (****)	12.7° ± 8.6°	5.8° ± 7.6°

(*) Age of a re-magnetization according to the second interpretation. (**) Age of a re-magnetization according to this paper. (***) the mean of 4 poles with ages of about 550 Ma listed by Meert (2003). These poles are: Sinyai Dolerite, Lower Arumbera, Brachina Formation, Bhander-Rewa. (****) Mean pole of McFadden and McElhinny (2000).

In contrast, the pole obtained by Kempf et al. (2000) in Mirbat is, according to those authors, in good agreement with published poles from Gondwana with ages of about 550 Ma. Using the method of Beck (1989), we compared the pole of Mirbat in Arabian geographic coordinates with the mean pole previously calculated with the four poles of about 550 Ma from Gondwanan cratons listed by Meert (2003). The comparison indicates that there is no significant difference between the pole of Mirbat and the mean reference pole (Table 2 and Figure 12). Notice that the calculated intervals of confidence include any difference between these poles.

The palaeomagnetic pole of the Mahatta Humaid Group (MHG) presented in this paper was also compared using the method of Beck (1989) considering as a reference the pole of 518–495 Ma of McElhinny and McFadden (2000). The difference between the geographic positions of the poles is negligible and their intervals of confidence overlap (Figure 12), indicating that there is no significant difference (Table 2). As such, the higher palaeomagnetic differences are restricted to the poles of Oman with older ages.

The palaeomagnetic evidence can be interpreted in tectonic terms (Figure 15). The sampling localities in the Al Jabal al-Akhdar and Al-Huqf areas whose Neoproterozoic palaeomagnetic data statistically form one group can be interpreted as belonging to a structural block (JAH block) rotated by about 45° counterclockwise along a vertical axis after ca. 620–600 Ma (according to the declination anomaly previously determined), and before 520–495 Ma (since the pole of the MHG does not show this anomaly). The sampling locality in Mirbat may belong to a structural block that rotated about 25° counterclockwise after ca. 620–600 Ma and before ca. 550 Ma (given that the re-magnetization pole of ca. 550 Ma of Kempf et al. fits with a mean Gondwana pole of this age).

The timings of these tectonic rotations are in general agreement with the onset of the movement of the Najd Fault System further northwest in the Arabian-Nubian Shield (Hadley, 1972; Loosveld et al., 1996; Blasband et al., 2000; Al-Husseini, 2000; Johnson and Kattan, 2001). The NW-trending Najd Fault System dislocated the Arabian Shield left-laterally by about 300 km (i.e. Husseini and Husseini, 1990). This left-lateral sense of movement also agrees with the counterclockwise sense of movement of structural blocks indicated by our palaeomagnetic analysis in Oman. Loosveld et al. (1995) and Al-Husseini (2000) associated the Najd Fault System of the Arabian-Nubian Shield with Oman rift basins. Our interpretation of the palaeomagnetic anomalies of about 600 Ma also indicates an association between these geological features. Loosveld et al. (1996) considered dextral strike-slip along the borders of NE rifts related to the left-lateral movements of the NW Najd Faults (their Figure 4). The counter-clockwise rotation of the JAH block is compatible with left-lateral, strike-slip along NW faults and with dextral strike-slip along the borders of a NE rift.

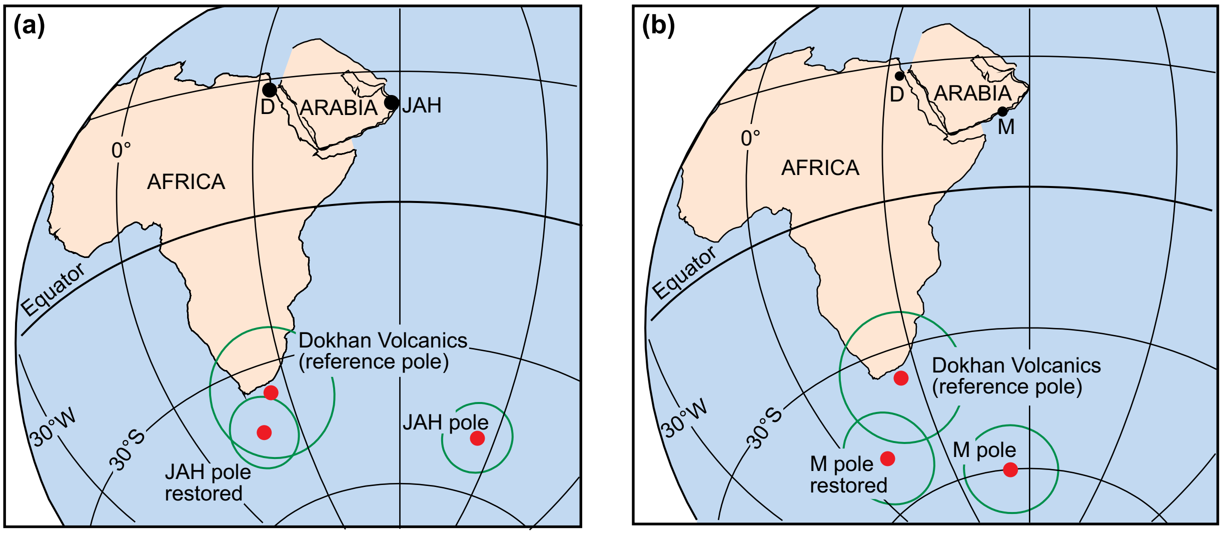


Figure 14: Comparison of the poles of Al Jabal al-Akhadar/Al-Huqf and Mirbat with the pole of the Dokhan Volcanics before and after the restoration of the poles from Oman applying clockwise rotations around a vertical axis in their sampling sites and considering the apparent rotation angles of Table 2.

This tectonic interpretation is supported by experimental models for the opening of sedimentary basins during finite transcurrent shear (Soula, 1984, his Figure 4). For that reason we considered two possible NW-trending faults with left-lateral, strike-slip delimiting the JAH block and a NE-trending rift with dextral strike-slip along its borders (Figure 15b). Although our tectonic proposal is conceptual, one of our possible faults could have a geographic trend parallel to the Abu Jifan Fault (Al-Husseini, 2000, his Figure 1). The suggested northern fault could have an orientation like the possible fault perpendicular to the Dibba Rift and the Oman Rift considered by Al-Husseini (2000) in his Figure 6. However, this author suggests a right-lateral movement along this fault (like the Zagros Fault farther north) opposite to our interpretation.

In contrast, the M block is located between possible major left-lateral, strike-slip faults proposed by Loosveld et al. (1996, their Figure 1) represented schematically as projections of Najd Faults recognized properly in the Arabian-Nubian Shield. The locality with the palaeomagnetic anomaly is in a block intruded by two sets of dikes. The older set gave an age of about 700 Ma whilst the younger gave ages of about 615–600 Ma (Worthing, 2005). The dikes were intruded along conjugate faults that developed in response to major NW-trending sinistral transtensional faulting (Worthing, 2005), which agrees with the tectonic rotation suggested by our palaeomagnetic analysis. We note that further northwest, where the rocks of the Arabian Shield crop out, the geometry of dike swarms implies extensional tectonics between 635–550 Ma that was also accommodated by NW-trending left-lateral faults (Nehlig et al., 2002).

Figure 15b shows the trends of the "Najd-type" faults drawn schematically rectilinear as in Al-Husseini (2000). We agree that further northwest where the rocks of the Arabian-Nubia Shield crop out, the faults of this system are anastomosing shear zones as shown by Johnson and Kattan (2001). In this context, the 6,000 km-long late Proterozoic Tibesti lineament in Africa is practically parallel to the Najd Faults (Guiraud et al., 2000, p. 899). Its projection to Madagascar in a reconstruction of Gondwana could be correlated with a virgation zone developed by left-lateral, strike-slip at about 560 Ma (Nédélec et al., 2000). Therefore, rectilinear systems of long faults with left-lateral, strike-slip movement could have been common during the late Neoproterozoic – early Palaeozoic, like the faults drawn in Figure 15b and in the tectonic map compiled by Johnson (1998).

The second interpretation suggests that the NW-trending Najd Fault System, which dislocated the Arabian-Nubian Shield, also played a role in the development of rift basins in Oman, as suggested by Loosveld et al. (1996) and Al-Husseini (2000).

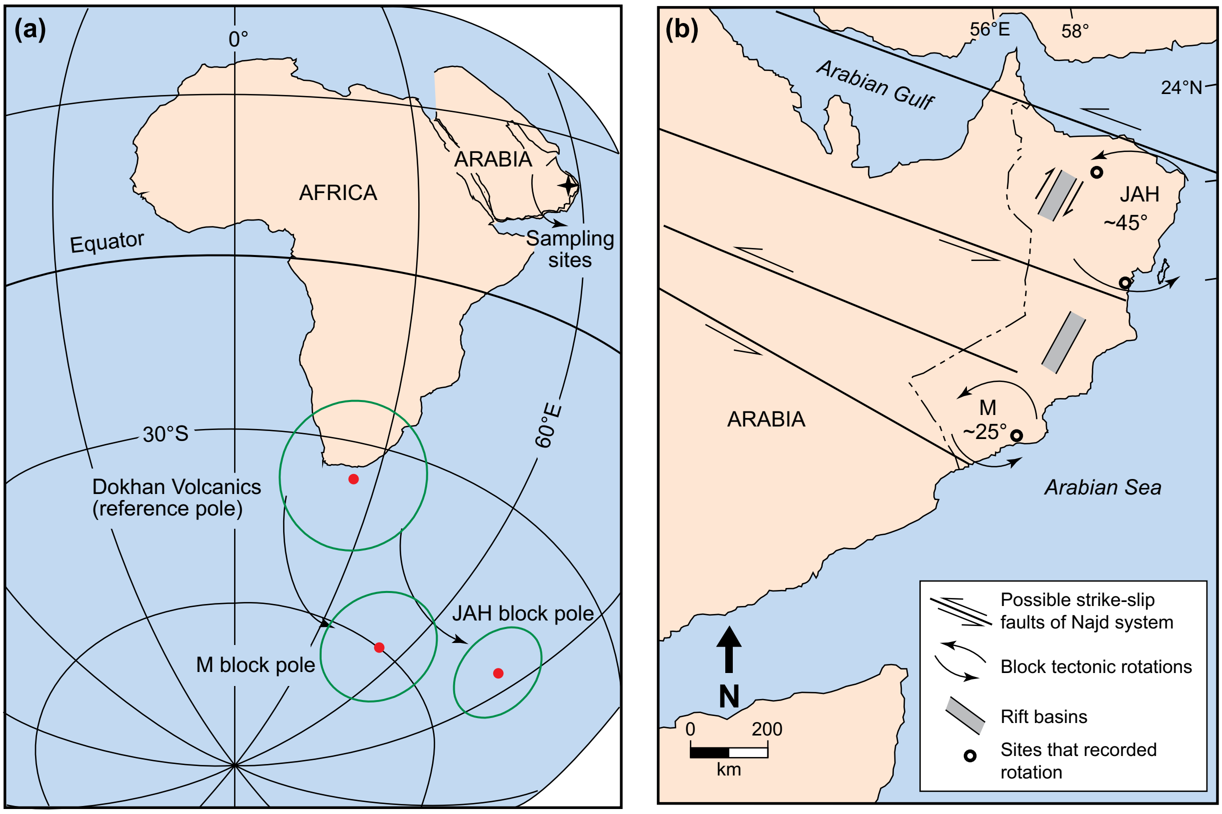


Figure 15: (a) Palaeopoles calculated for the Al Jabal al-Akhdar-Al-Huqf block (JAH block) and the Mirbat block (M block) and the Dokhan Volcanics palaeopole (used as a reference pole). Note that the palaeopoles of both the JAH and the M blocks are rotated counterclockwise with respect to the Dokhan Volcanic palaeopole. (b) Tectonic interpretation considering counterclockwise rotations of both the JAH block and the Mirbat block of about 45° and 25°, respectively (Table 2).

CONCLUSIONS

We carried out a palaeomagnetic study in the Al-Huqf region (Sultanate of Oman), systematically taking 39 samples from different units of the Cambrian – Ordovician Mahatta Humaid Group (MHG) with an age of ca. 520–495 Ma. Seventeen samples from different units showed ChRM components whose origin is probably primary. Petrographic analysis of these samples indicates a crystallographic continuity between the host grains and their later syntaxial overgrowths parallel to the {0001} plane, suggesting that the overgrowth inherited the original magnetic directions of the host grains and thereby enhanced/reinforced the strength of the primary magnetizations. The mean direction of the ChRM components averaged out the palaeosecular variation, and a palaeopole was computed for the Mahatta Humaid Group. The geographic coordinates of this palaeopole and its 95% interval of confidence are: Latitude = 12.4° N, Longitude = 352.4° E, $\delta p = 8°$, $\delta m = 12.4°$.

Two alternative interpretations are proposed using this new palaeopole and previously published palaeomagnetic data. In the first, the new palaeopole forms part of a hitherto undocumented track of the Arabian APW path. In the second interpretation this palaeopole was useful in helping to constrain the age of the rotation of one structural block.

In both interpretations, we reanalyzed palaeomagnetic data obtained by Kempf et al. (2000) and Kilner et al. (2005) in light of an updated chronostratigraphic framework for the Neoproterozoic Huqf Supergroup (Allen, 2007; among others) and the belief that the palaeomagnetic localities could belong to tectonic blocks delimited by continental faults defined as the Najd Fault System, and that they could extend with a NW trend from the Arabian-Nubian Shield into Oman (Al-Husseini 2000, among others). For these reasons, the palaeomagnetic data of Kilner et al. (2005) were analyzed by dividing them into three different groups belonging to three different localities: Al Jabal al-Akhdar, Al-Huqf and Mirbat. We recognized two groups of palaeomagnetic data: (1) the Al Jabal al-Akhdar/Al-Huqf-Kilner group and (2) the Mirbat-Kilner group. In both interpretations, the palaeomagnetic data of the first group are considered primary (they pass "fold/reversal tests"), while in the case of the Mirbat-Kilner group, there is no conclusive palaeomagnetic test to confirm if the palaeomagnetic data are primary or acquired in younger times as re-magnetizations. For that reason, the first interpretation considers these palaeomagnetic data as primary and recorded at about 700 Ma, while in the second interpretation, the data of the Mirbat-Kilner group are considered as the record of a re-magnetization that occurred during the intrusion of ca. 615-600 Ma dikes.

The other data from Mirbat reported by Kempf et al. (2000) are considered in both interpretations as the record of a younger re-magnetization that occurred during a period of plutonism and felsic volcanism that affected the crust from Arabia to Madagascar from 550 until 530 Ma.

In the first interpretation, we propose a track of the Arabian APW path for ca. 630–500 Ma. The track is composed of the 630 Ma pole of Al Jabal al-Akhdar/Al-Huqf, the 620–600 Ma Dokhan Volcanic pole (in Arabian geographic coordinates), the 550 Ma "re-magnetized" pole of Kempf et al. (2000) and the 500 Ma MHG pole.

In the second interpretation, we interpreted the palaeomagnetic data in tectonic terms considering two structural blocks: the Al Jabal al-Akhdar/Al-Huqf (JAH) block and the Mirbat (M) block. This tectonic interpretation suggests that the JAH block and the M block underwent counterclockwise tectonic rotations about vertical axes of ca. 45° and 25°, respectively, after ca. 620–600 Ma due to left-lateral, strike-slip movement on Najd Faults. The rotation of the JAH block is constrained to be older than ca. 500 Ma because the pole of the MHG presented here agrees with a reference mean pole of about this age. Meanwhile, the age of the rotation of the M block is palaeomagnetically constrained to be older than ca. 550 Ma because the pole of Kempf et al. (2000) agrees with a reference mean pole of about this age. According to this interpretation, any palaeocurrent direction measured on stratified rocks older than 620–600 Ma cropping out in the JAH and the M blocks should be corrected according to the proposed rotations about vertical axes.

If the second interpretation is the valid one, new palaeomagnetic studies are necessary to better determine the dimensions of the studied blocks and to define other blocks that could also have rotated because of left-lateral, strike-slip on the Najd Faults.

The interpretation of block tectonic rotations about vertical axes agrees with the suggestion that the NW-trending Najd Fault System that dislocated the Arabian-Nubian Shield could have also played a role in the development of NE rift basins in Oman (e.g. Al-Husseini, 2000).

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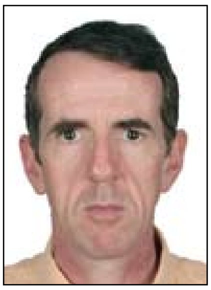

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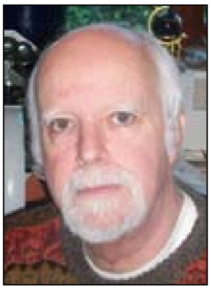

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