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Cenozoic and Mesozoic basalts from Egypt: a preliminary survey with a view to paleointensity

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Numerous phases of igneous activity took place in Egypt during the Mesozoic and the Cenozoic but no paleointensity results have ever been published from these rocks. Therefore a preliminary survey was conducted in the northern part of Egypt and in Sinai to test the suitability of these basalts for paleointensity determinations. Three Oligo–Miocene sites have been sampled north of Cairo: Abu Zaabal, Qatrani, and 6th of October City. In Sinai, we sampled Jurassic basalts in Wadi Budra and Oligo–Miocene rocks from Wadi Nukhul. The main magnetic carriers of these rocks are titanomagnetites with varying Ti content. Large secondary components are present in most middle Jurassic basalts and discrepancies remain in the directional analysis so this sill cannot be used for paleointensity experiments and the associated poles should not be considered for paleomagnetic reconstructions either. Directional analysis of the Oligo–Miocene basalts is very straightforward and updated mean VGPs have been calculated from the Cairo area (68.9°N, 91.3°E; $Kappa = 274$; $A_{95} = 3.7$) and from Wadi Nukhul (72.7°N, 13.4°E; $Kappa = 528$; $A_{95} = 5.4$). Pseudo-paleointensity results obtained as well from stable Egypt as from Sinai are promising, with values lower or similar (between 29 to 58 μT) to present-day field intensity.

Key words: Paleomagnetism, paleointensity, Oligo–Miocene, Jurassic, basalt, Egypt.

1. Introduction

A very good and detailed description of the Geology of Egypt has been published in English by Rushdi Said (1962, book updated in 1990), and a complete list of references for the original papers mainly in Arabic is given. Different phases of igneous activity took place in Egypt during its post Cambrian geological history. Chemical characteristics, size and mode of eruption of the Paleozoic and Mesozoic volcanic rocks are diversified whereas the Cenozoic volcanism is largely basaltic. Paleozoic volcanics are mainly found on the stable shelf that borders the Arabo-Nubian massif, with early Paleozoic (pan-African; 500–550 Ma) and Permo–Triassic (220–250 Ma) ages. The Mesozoic volcanic rocks can generally be related to two main phases of igneous activity in the Late Jurassic–Early Cretaceous (125–155 Ma) and in the Late Cretaceous–Early Tertiary (60–90 Ma). They are located mainly in the Eastern and Western deserts and in Sinai. Several episodes of volcanic activity occurred during the Cenozoic, the earliest of Paleocene age being the continuation of the extensive late Cretaceous igneous activity. Mid Tertiary volcanism is widespread, with successive pulses in the Late Eocene followed by phases related to the opening of the Red Sea and ranging in age from Late Oligocene to Middle Miocene. This volcanism is uniformly basaltic and widely distributed

in the northern part of Egypt and in Sinai. The Quaternary volcanic activity took place mainly in the south Western desert.

However, very few paleomagnetic results are available for the period 0–200 Ma: a few tens of data in the last update of the global paleomagnetic database (GPMDB Version 4.6, compiled by Sergei A. Pisarevsky, The University of Western Australia, 2005). Also no paleointensity results have ever been published from these rocks. Furthermore the analysis of the directional data is not straightforward and ambiguities remain, as well for the Mesozoic than the Tertiary. For example, conflicting paleomagnetic results (Wassif, 1989; Ibrahim *et al.*, 2000) were found for the Jurassic Wadi Budra basalt. Also Tertiary basalts in the areas around Cairo were supposed to define a reliable Early Miocene paleomagnetic pole for the African plate. But surprisingly, Lotfy (1992) and Lotfy *et al.* (1995) found two different groups of paleomagnetic directions. What has been long considered as one single Early Miocene magmatic episode would be in fact two different phases of volcanism? Finally, Tertiary pole positions defined for Sinai (Wassif, 1991; Abdeldayem and Tarling, 1996; Ibrahim *et al.*, 1998; Saleh *et al.*, 2004) are in agreement neither with other Tertiary pole positions for Egypt, nor with South African poles. Let's note here that discrepancies also exist within Africa, between the South and West African cratons, especially in Mesozoic time. In order to avoid an unnecessary complication in our analysis, only results from South Africa (in the general) will be considered here.

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Therefore in order to better understand the relations between Sinai, Egypt and South Africa, a new sampling was planned. Considering the time needed for a paleointensity experiment and the usually low success rate (often less than 20%), a preliminary survey has been conducted in the northern part of Egypt and in Sinai to redefine the paleodirections, and test the suitability of the basalts for paleointensity experiments.

2. Geologic Setting and Sampling

In Sinai, we concentrate on the Abu Zenima area (Fig. 1) and sampled two localities (4 sites, 38 samples): i) Middle Jurassic basalts in Wadi Budra, [28.94°N, 33.30°E]; and ii) Oligo–Miocene rocks from Wadi Nukhul, [29.02°N, 33.16°E]. Different areas have been visited north and west of Cairo and three Oligo–Miocene localities (49 samples) were sampled (Fig. 1): i) Abu Zaabal quarry [30.28°N, 31.35°E]; ii) Qatrani quarry [29.76°N, 30.70°E]; and iii) 6th of October City basalt, [30.04°N, 30.99°E]. All samples were drilled in the field using a gasoline-powered drill and oriented using both magnetic and sun compasses.

The Wadi Budra intrusion, west coast of Sinai, formed a basaltic sheet, 5 to 20 m thick, separating the underlying Ataqa Formation (Kostandi, 1959) of Carboniferous age, recently named Abu Thora Formation (Kora, 1995), from the overlying Budra Formation, also named Quiseb Formation, of Permo-Triassic age (Issawi and Jux, 1982) or Triassic age (Druckman *et al.*, 1970; Beyth, 1981). Whole-rock K–Ar determination (Mousa, 1987) gave a Middle Jurassic age of 182 ± 7 Ma for this basalt. This dating and the presence of a similar basaltic intrusion within the Carboniferous, 7.5 km SE of the locality, indicate that this basaltic rock is a sill rather than a flow (Ibrahim *et al.*, 2000). The Wadi Budra sill is not exposed continuously and five different outcrops have been sampled. Only a global tilt correction could be estimated from the sandstone-like country rock.

The Wadi Nukhul basalt is represented by a wide dyke intruding Eocene limestone that contains chert bands. This dyke lies about 8 km SW of Abu Zenima, west coast of Sinai. It is nearly vertical and uniform in width (~10 m). Close from the contact zone, limestone is baked and shows a black coloration. To the east, this dyke extends as a thin sill, conformable with sedimentary beds. Field observations suggest that the Wadi Nukhul intrusion is related to Mid-Tertiary volcanism. A Miocene age was assigned by Ball (1916) and Hume *et al.* (1920) to this intrusion, while Andrew (1937) and Said (1962) referred it to the Oligocene. The Miocene age seems to be confirmed by one whole-rock K–Ar determination at 22 ± 1 Ma (Steen, 1982). Two sites were sampled, one within the dyke and the other in the sill.

A large quarry is found at Abu Zaabal, northwest of Cairo, formed by a single sheet of basalt exceeding 60 m in thickness. The geology and petrology of this basaltic occurrence, together with several related basalt flows in the Cairo–Suez district, is given in a number of publications (e.g. Andrew, 1937; Said, 1962; El-Hinnawi and Abdel Maksoud, 1968). This basaltic flow overlies Oligocene sands and gravels, and is, in some place, usually unconformably overlain by marine Miocene sediments. The

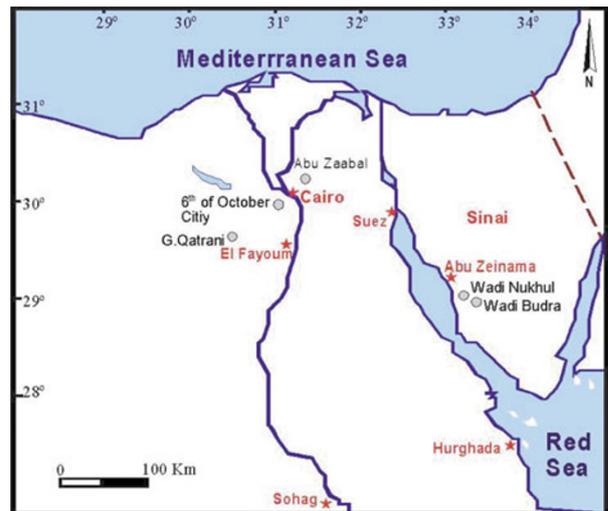


Fig. 1. Schematic map of the studied areas and location of the sampled sites (shaded circles).

stratigraphic and/or petrographic similarity of all Cairo–Suez basalts tends to indicate only one phase of magmatic activity, emplaced along the faults that affected the area during the Oligocene (Said, 1962). The doleritic basalt of Abu Zaabal yielded two whole rock K/Ar ages of 22 and 23 Ma (Meneisy and Kreuzer, 1974). Two sites (27 samples) were sampled: site AZ2 was located about one kilometer to the west of site AZ1. The sheet of basalt is flat-lying, so no tilt correction was necessary. In site AZ1, the lowest exposed part of the flow was too weathered for sampling, so the cores were taken in the upper middle part of the flow; site AZ2 corresponds to the upper part of the flow, close from the top.

The area around 6th of October City, west of Cairo, is underlain by a succession of sedimentary rocks ranging in age from Upper Cretaceous to Quaternary. Basalt, found within the sedimentary sequence, is described as one sheet lying between the Oligocene and the Miocene sands and gravels. It is mineralogically and chemically indistinguishable from the basalt at Gebel Qatrani and Abu Zaabal but quite different from other basalts in Lower and Middle Egypt (Harrell and Bown, 1995). An outcrop found near the city was sampled (oriented bloc) to test the properties of the basalt.

The Qatrani area, North Western desert, is underlain by a succession of fluviomarine and continental sedimentary rocks ranging in age from Middle Eocene to Pleistocene (e.g. Beadnell, 1905; Said, 1962; El-Hinnawi, 1965; El-Hinnawi and Abd El Maksoud, 1968, 1972; Abdel Monem and Heikal, 1981). The name “Gebel Qatrani” was given to a prominent scarp which forms the northwestern rim of the Fayum Depression. Northwest of that scarp, there is an extensive plateau covered by Miocene sands and gravels. Previous workers reported the occurrence of basalt within the sedimentary sequence as one sheet lying between the Oligocene Qatrani Formation and the Miocene sands and gravels, with thickness ranging from 20 to 100 m. However, according to Heikal *et al.* (1983), Gebel Qatrani basalt formed a succession of three distinct sheets (A, B, and C sheets from bottom to top, respectively). Sheets A and C are

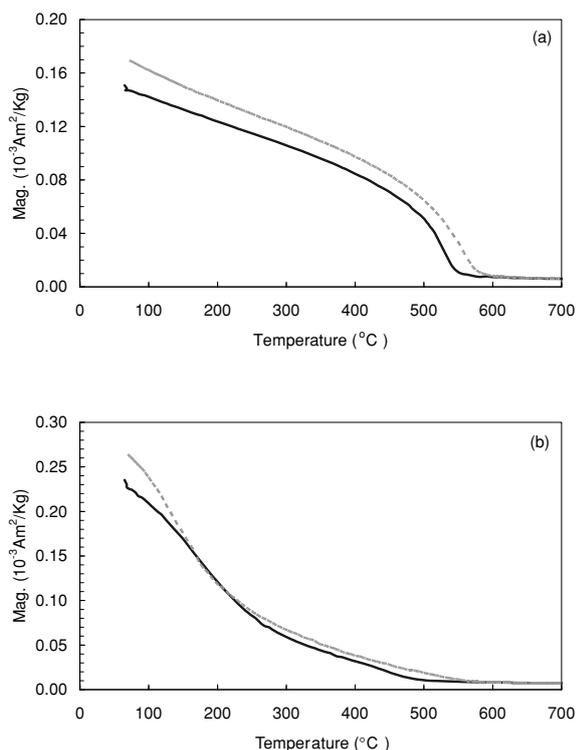


Fig. 2. Characteristic thermomagnetic curves: (a) Abu Zaabal and (b) Wadi Nukhul. Unbroken and dashed lines respectively for heating and cooling cycles.

characteristically amygdaloidal and vesicular, and mostly intensely altered. Sheet B, the most conspicuous sheet in the succession, is massive, fine grained, and mostly fresh, therefore the only one that can be paleomagnetically studied. It is 7 to 10 m thick, and continuous all along the basaltic outcrop, except in its southwestern 3. It forms a noticeable ledge at the top of the Qatrani scarp. The basalt of Gebel Qatrani yielded four whole-rock K-Ar ages ranging between 23 and 27 Ma (Meneisy and Abdel Aal, 1984). Major and trace element studies indicate that the basalt of Qatrani is tholeiitic, formed in a rift environment. Two sites, about 10–15 km apart, were sampled within the flat-lying Qatrani basalt.

3. Rock Magnetic Measurements

A set of basic rock magnetic experiments was performed on at least one specimen from each site. These measurements included thermomagnetic curves and hysteresis loops using the variable field translation balance (VFTB) that measured in air, from the Geomagnetic Laboratory of Liverpool. Measurements of the magnetic remanence were conducted using a squid spinner magnetometer.

All samples are characterized by fairly reversible heating and cooling curves during thermomagnetic (J_s - T) cycles indicating titanomagnetite as the main carrier of magnetization in these rocks. Two types of curves have been observed: the first ones, as the example shown from Abu Zaabal (Fig. 2(a)), are characteristic of low Ti titanomagnetite with Curie temperatures between 500°C and 550°C; the rest of the samples display curves characteristic of titanomagnetite richer in Titanium, with Curie points on the

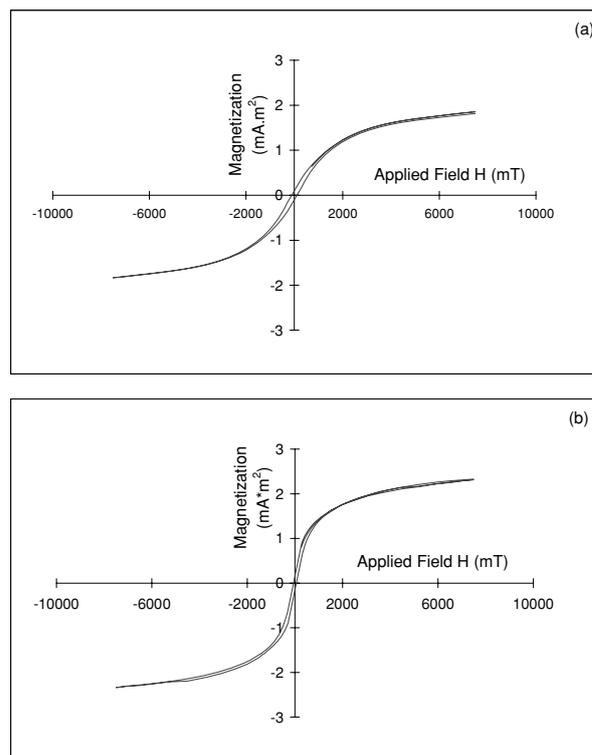


Fig. 3. Characteristic hysteresis loops: a) Abu Zaabal and b) Wadi Nukhul.

order of 300–400°C, as in Wadi Nukhul (Fig. 2(b)).

Typical examples of hysteresis loops of the basaltic rock samples are shown in Fig. 3. The hysteresis parameters B_{cr}/B_c versus M_{rs}/M_s (Fig. 4) cluster within the pseudo single domain (PSD) grain size range on a Day plot (Day *et al.*, 1977). Microscopic investigation under reflecting light, performed on one sample from each site, shows the presence of large magnetite with ilmenite-magnetite intergrowth, indicating a high temperature oxidation of ilmenite lamellae in titanomagnetite (Fig. 5).

4. Paleomagnetic Analysis

All samples were cut into specimens at the University of Montpellier. Few differences were found between readings from magnetic and sun compasses, apart from the mean 2004 magnetic declination which was around 3°E. One half specimen from each core was then stepwise demagnetized using alternating fields (AF) up to 170 mT with the automated degauss system coupled with a 760 Superconducting rock Magnetometer SRM manufactured by 2G enterprises of the Montpellier paleomagnetic laboratory. Mean Characteristic Remanent Magnetizations (ChRM) were calculated by principal component analysis (Kirschvink, 1980), with the upper limit for the Maximum Angular Deviation (MAD) chosen as 5.

4.1 Middle Jurassic basalts

During AF demagnetization, two different components of magnetization were present. The low coercivity components are removed by applying fields between 5 and 20 mT, depending on the samples. The dispersion of the directions associated with these low-field components is very large, almost random. This fact added to a very low Median De-

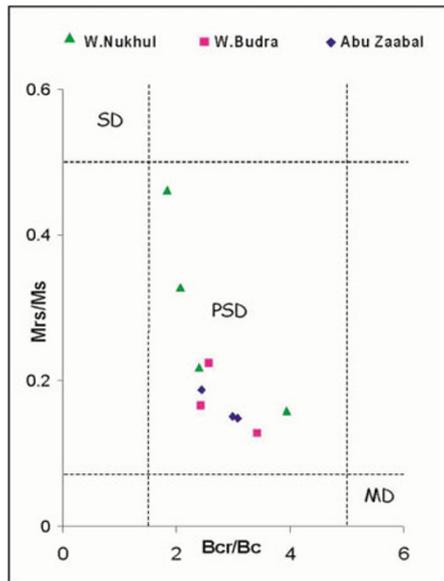


Fig. 4. Day plot for the Egyptian samples.

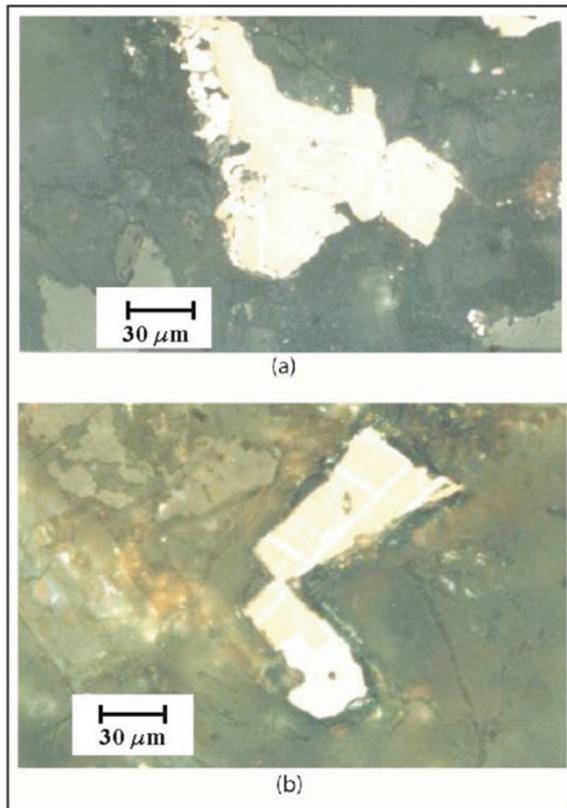


Fig. 5. Photo Micrographs in reflected light: (a) Qatrani basalt and (b) Abu Zaabal basalt.

structive Field (half of the Natural Remanent Magnetization NRM is removed by 5–10 mT) points to an isothermal process for the acquisition of these secondary components, likely during lightning strikes. However, at higher fields, characteristic directions of magnetization can be isolated, usually between 20 and 70 mT. These directions are well defined (Table 1; Fig. 6) with MAD between 0.7 and 4.3 and a good grouping at the site level ($\kappa=157$; $\alpha_{95}=3^\circ$).

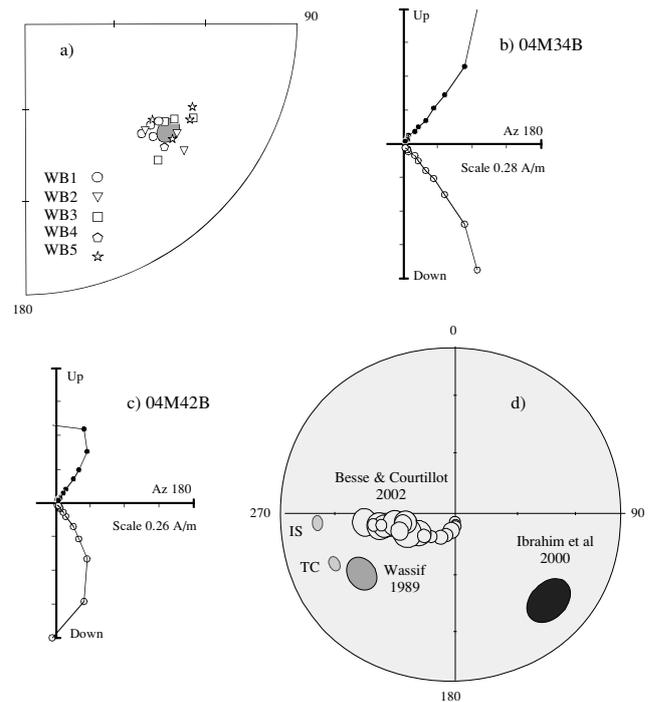


Fig. 6. Paleomagnetic analysis of the middle Jurassic basalts: (a) equal-area plot with individual ChRM directions and α_{95} confidence circle of the mean site direction; (b) and (c) orthogonal diagrams with open/close circles for horizontal/vertical projections respectively; and (d) polar equal-area projection for Jurassic VGPs. IS and TC are respectively our in situ and tilt corrected mean directions. (Besse and Courtillot, 2002): South Africa synthetic apparent polar wander path for the past 200 Ma calculated for a 10 Ma sliding window every 5 Ma.

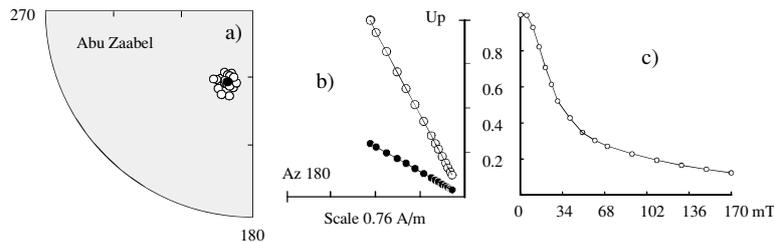
This new study was expected to decide in favor of one of the two conflicting paleomagnetic results (Wassif, 1989; Ibrahim *et al.*, 2000) obtained for the Wadi Budra basalt. However, as can be seen from Table 1 and Fig. 6(d), there are amazingly large differences between the three sets of Virtual Geomagnetic Poles (VGP). Wassif's VGP is much closer to our results but still differ by an angle of respectively 14 and 30° , depending on the reference frame we used for our data (tilt corrected TC or in situ IS). The angular difference becomes very large when comparing Ibrahim *et al.*'s result to our TC and IS data (respectively 100 and 116°). Furthermore all three poles are significantly different from the Master Polar Wander Path (Besse and Courtillot, 2002) for South Africa as also shown in Fig. 6(d). Ibrahim *et al.* (2000) considered different parameters to try to explain the discrepancy between their data and Wassif's results. Among them, they mentioned local tectonic movements, global tectonics and secular variation. It is obvious that even though secular variation is clearly not averaged out in such a sill, it cannot account for differences on the order of 100° . It is exactly the same for global tectonic movements between South Africa, Egypt and the Sinai Peninsula which could account for a few tens of degrees but unlikely for that kind of angles. In this new analysis, we tried to estimate the influence of local tectonics in the discrepancy. As said before, the Wadi Budra sill is not exposed continuously and therefore bloc rotation from one outcrop to the other could explain dispersion of the directions. However,

Table 1. Published paleomagnetic data from Wadi Budra, West coast of Sinai (Middle Jurassic; 182 ± 7 Ma). N/N_0 : Number of samples used in the calculation/Total number of samples.

Site		N/N_0	Direction				VGP		Reference
Lat °N	Long °E		Dec	Inc	k	α_{95}	Lat	Long	
28°55'	33°20'	29	63.3	8.0		10.2°	25°N	133°E	Ibrahim <i>et al.</i> (2000)
28°57'	33°19'	4	159.0	39.6	150	7.5°	35°N	237°E	Wassif (1989)
28°56'	33°18'	16/19	127.5	35.9	157	3.0°	20°N	266°E	This study—In situ
28°56'	33°18'	16/19	145	47	157	3.0°	24°N	247°E	This study—Tilt corrected

Table 2. Comparison of previously published paleomagnetic data with the Oligo–Miocene data derived from the present study B : number of sites; N/N_0 : Number of samples used in the calculation/Total number of samples; *for recalculated VGPs. Symbols used in Fig. 10 and explained in text. In italic, not used for mean calculation.

Area	Site	Age	Site				In situ				VGP		Reference	
			Symbol	Lat °N	Long °E	B	N/N_0	Dec	Inc	k	α_{95}	Lat		Long
Northeast Cairo	Abu Zabel	22–23 Ma	azp	30.28°	31.36°	2	26/27	200.3	−60	673	1.1°	70°N	83°E	This study
			azl	30.18°	31.11°	4	132	202	−58		8°	70N*	90E*	Lofty (1992)
Southwest Cairo	Qatrani	23–27 Ma	qp	29.71°	30.65°	2	17/21	207.3	−58.5	249	2.3°	66°N	90°E	This study
			ql	29.42°	30.40°	11		203	−59		7°	68°N	87°E	Lofty (1992)
			qa	29.6	30.6	2	15	207	−55	271	—	67	98	Abdeldayem (1999)
			qh	29.67	30.50		15	209.2	−60.2	472	1.0	64	87	Hussain <i>et al.</i> (1980)
North Cairo	East West	Early Miocene	<i>ecl</i>	<i>30.08°</i>	<i>31.52°</i>	<i>11</i>	<i>132</i>	<i>198</i>	<i>−24</i>	<i>417</i>	<i>3</i>	<i>66</i>	<i>164*</i>	Lofty <i>et al.</i> (1995)
			wcl	30°	31°	18	216	197	−51	270	3	76	111	
West coast of Sinai	Wadi Nukhul	22±1 Ma	wnp	29.02°	33.16°		10/18	168.7	−63.6	76	5.6°	71°N	7°E	This study
			wnw	29°00'	33°15'			173.5	−60.7	47	8.2°	76°N	13°E	Wassif (1991)
			wns	29.02°	33.16°		47	174	−65	103	12°	71°N	20°E	Saleh <i>et al.</i> (2004)

Fig. 7. Paleomagnetic analysis of Oligo–Miocene basalts from Abu Zaabal: (a) equal-area plot with ChRM directions and mean α_{95} confidence circle; (b) orthogonal diagram; and (c) demagnetization curve.

no significant differences could be found between results obtained from the five different outcrops (WB1 to WB5) we sampled as can be seen from Fig. 6(a). New analysis is still needed to try to solve the Wadi Budra ambiguity and, for the moment, these poles cannot be used for paleomagnetic reconstructions, or for paleointensity experiments.

4.2 Oligo–Miocene basalts

The magnetic behavior of all samples from the 22–23 Ma Abu Zaabal quarry, north of Cairo, is very simple, with only one component of magnetization likely of primary origin (Fig. 7(b)). Despite the fact that both sites sampled different parts of the flow, the magnetic properties of the samples are very similar (NRM intensities, coercivities, and thermomagnetic behavior). About 20% of the magnetization being left after demagnetization at 170 mT, hematite is likely a carrier of magnetization. All best fits have been estimated between room temperature and 170 mT with MAD between 0.3 and 0.6. ChRM directions are identical for both sites, with an Abu Zaabal mean direction {azp} extremely well defined ($\alpha_{95} = 1.1$; $kappa = 673$; see Table 2 and Fig. 7(a)).

The magnetization of the samples from the flat-lying 23–

27 Ma Qatrani basalt, west of Cairo, is also mainly univectorial (MAD between 0.4 and 1.6), apart from a soft viscous component removed by 5–10 mT (Fig. 8(b)). However the magnetic properties of samples from both sites are fairly different. All samples from Q2, as well as one sample from Q1, have low coercivities (e.g. Fig. 8(d) and (e)) while all other samples from Q1 are much harder with about 20% of the magnetization left after 170 mT (e.g. Fig. 8(b) and (c)). Anyway, there is no systematic directional difference between both sites (Fig. 8(a)) and the mean site direction {qp} is well defined ($\alpha_{95} = 2.3$; $kappa = 249$; see Table 2 and Fig. 8(a)).

Unfortunately the analysis of the lower Miocene Wadi Nukhul samples, southwestern coast of Sinai, is not so straightforward. Secondary components of magnetization are present in most samples up to 10–30 mT, with very scattered directions. For reasons already given for Wadi Budra, these components are likely related to lightning strikes. After removal of the secondary components, ChRMs can be isolated for the majority of the samples (MAD between 0.3 and 1.9). Most samples have a magnetic behavior sim-

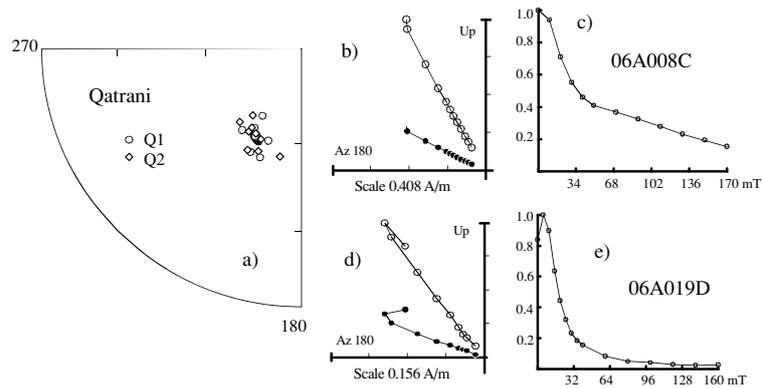


Fig. 8. Paleomagnetic analysis of Oligo–Miocene basalts from Qatrani: (a) equal-area plot with ChRM directions and mean α_{95} confidence circle; (b)–(c) and (d)–(e) orthogonal diagram and demagnetization curve for Q1 and Q2 type samples respectively.

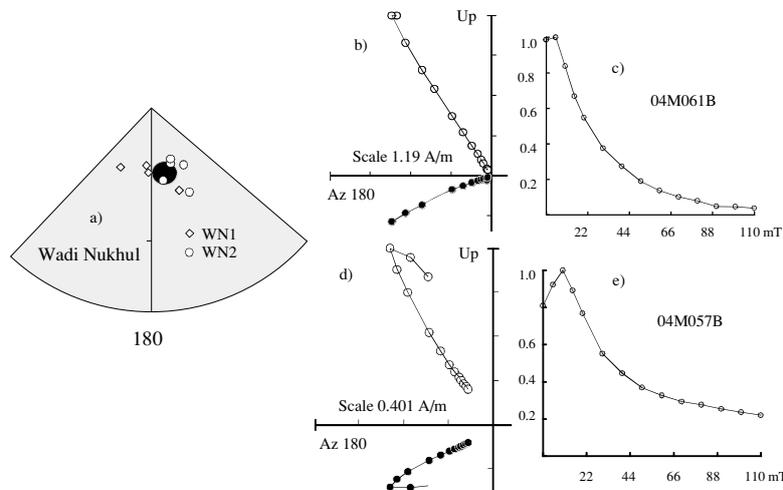


Fig. 9. Paleomagnetic analysis of Oligo–Miocene basalts from Wadi Nukhul: (a) equal-area plot with ChRM directions and mean α_{95} confidence circle; (b)–(c) and (d)–(e) orthogonal diagram and demagnetization curve for the two types of samples.

ilar to 04M61B (Fig. 9(b) and (c)), with a few looking like 04M057B (Fig. 9(d) and (e)). The ChRM directions are much more scattered with a significant difference between WN1 and WN2 (Fig. 9(a)). Slight differential rotations within the dyke could explain the difference, but no evidence was noticed in the field. More likely the difference is related to a slightly different timing in the acquisition of the magnetization and recording of secular variation. The mean site direction {wnp} ($\alpha_{95} = 5.6$; $\kappa = 76$) is given in Table 2.

Oligo–Miocene virtual geomagnetic poles are shown in Fig. 10, together with results previously obtained from the same areas. Results obtained in this study from the Cairo area (Abu Zaabel {azp} and Qatrani {qp}) are in excellent agreement with most previously published results (Lofty, 1992 {azl} and {ql}; Abdeldayem, 1999 {qa}; Hussain *et al.*, 1980 {qh}; Table 2). However, about ten years ago, Lofty proposed the existence of two distinctive non-overlapping components in the Oligo–Miocene volcanism north of Cairo (Lofty *et al.*, 1995; Components {ecl} and {wcl}, Table 2). No directions close to their {ecl} component has been found in this study, while their {wcl} component is comparable to all other directions. It is worth noting that, while the sites giving a {wcl} direction covered a

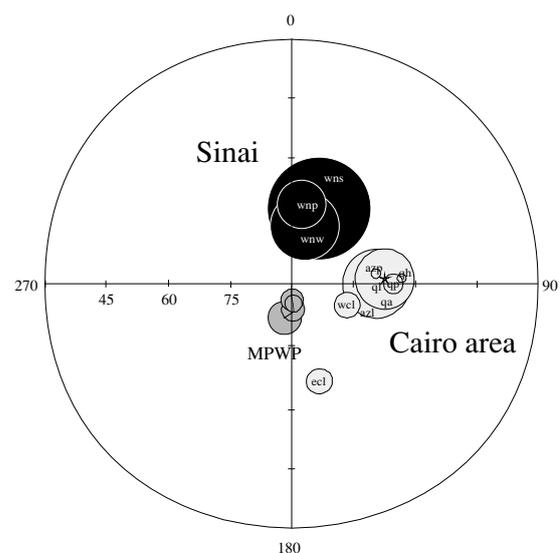


Fig. 10. Truncated ($30\text{--}90^\circ$) polar equal-area projection for Oligo–Miocene VGPs. Symbols as in Table 2. MPWP is the Master Polar Wander Path for South Africa corresponding to the past 40 Ma calculated for a 10 Ma sliding window every 5 Ma (Besse and Courtillot, 2002).

fairly large geographic extent, all sites giving the {ecl} direction come from the same volcanic body. Local tilt can then not be excluded to explain the 27° difference (only in inclination, see Table 2) between their two directions. Excluding Lofty's {ecl} component, a mean Oligo–Miocene (22–27 Ma) VGP was calculated ($N = 7$; Lat = 68.9°N; Long = 91.3°E; Kappa = 274; $A_{95} = 3.7$) for the Cairo area. As all results are coming from volcanic rocks, one may wonder about secular variation. The geographic extent of the sampling (hundreds of km²) and the age difference between both units (22–23 Ma and 23–27 Ma respectively) are arguments against an instant recording of the magnetization throughout the sampling area. Paleosecular variation was estimated as the angular standard deviation (ASD = 11.0° with 95% confidence limit +5.2°/–2.7°) of the VGPs (McFadden *et al.*, 1991). This value is slightly lower than the value (~17°) predicted by the PSV model of McFadden *et al.* (1991) for the time period and the paleolatitude, suggesting that secular variation has not been completely averaged out from this pole position.

Along the west coast of Sinai, besides our results {wnp}, two other analyses have been carried out on the Wadi Nukhul dyke (Wassif, 1991 {wnw}; Saleh *et al.*, 2004 {wns}). Even though all three analyses have α_{95} larger than for the Cairo area (see Fig. 10), the overlapping of the A_{95} confidence circles is very good and an updated mean Wadi Nukhul VGP can be proposed ($N = 3$, Lat = 72.7°N, Long = 13.4°E, Kappa = 528, $A_{95} = 5.4$).

The mean Oligo–Miocene VGP for the Cairo area is 24° apart from the Wadi Nukhul pole, and both are respectively 23 and 24° apart from the 20–30 Ma Master Poles for South Africa (Besse and Courtillot, 2002). Even though secular variation is probably not completely averaged out from these poles, it can unlikely account alone for that kind of differences and the tectonic relations between Sinai, stable Egypt and South Africa will have to be closer investigated with a more extensive paleomagnetic sampling.

5. Pseudo-Thellier Experiments

The primary goal of this analysis was to test the suitability of the Egyptian basalts for paleointensity experiments. Secondary components present in all Jurassic samples were too large for paleointensity purpose, but most Oligo–Miocene basalts were tested. Pseudo-Thellier (Perrin, 1998) and Thellier/Coe (Thellier and Thellier, 1959; Coe, 1967) experiments have been carried out with a controlled atmosphere vibrating thermo-magnetometer (Cat VTM; see Poidras *et al.*, this issue), on all samples carrying only one component of magnetization (apart from a small viscous component).

The Cat VTM allows continuous measurement of both remanent and induced magnetizations by translating the sample (up to 12 mm in length and up to 10 mm in diameter) between two identical detection coils connected in opposition in order to cancel ambient field fluctuations, in an Argon atmosphere. The magnetic moment is measured with a precision of 2×10^{-9} A m². Two μ metal screens surround the entire device in order to cancel most of the ambient field at the center of the magnetometer, the remaining residual field in the measurement zone being dynamically

compensated to zero. Samples can be subjected to automatic heating-cooling cycles from room temperature up to 700°C throughout the whole experiment, applying or not a field between 0 and 150 μ T.

In the Pseudo-Thellier experiments (Perrin, 1998), samples are subjected to heating-cooling cycles, using the Cat VTM. Heatings are performed in zero field, and coolings with an applied field along the measurement axis. Let's start (Fig. 11) with the natural remanent magnetization of the sample ($\text{NRM}_{\text{RT}-T_c}$)_{RT} (RT: room temperature, T_c : Curie point). After heating in zero field up to 100°C, the remaining NRM is carried by grains having unblocking temperatures above 100°C, which is NRM_{100-T_c} measured at 100°C (NRM_{100-T_c})₁₀₀. The field is switched on and the sample is cooled to room temperature, thus acquiring a pTRM (TRM_{100-RT}). The field is switched off, and NRM_{100-T_c} is estimated again, but this time at room temperature, (NRM_{100-T_c})_{RT} plus TRM_{100-RT} . The difference between this measurement and the previous one correspond to TRM_{100-RT} , assuming that NRM_{100-T_c} is the same when measured at 100°C than at room temperature. The above assumption is of course not correct because of the reversible variation of J_S with temperature, and for natural rocks, $[\text{NRM}_{100-T_c}]_T$ will usually be lower than $[\text{NRM}_{100-T_c}]_{RT}$ by a ratio that is equal to J_S/J_{S0} , the effect being larger closer to the Curie point (Figs. 12(a2)–(a4), (b2)–(b4)). If the small specimen used for VTM measurements are drilled along the characteristic NRM direction, which was the case in our experiments, then NRM_{100-T_c} and TRM_{100-RT} can be used to construct the NRM-TRM diagram, and another cycle can be done at higher temperature.

To further assess the soundness of the pseudo-Thellier procedure as a selection tool, most tested samples were in addition submitted to Thellier/Coe experiments, also using the Cat VTM. In this case, an additional cycle is added to the process. After heating the sample to a given temperature, we first cool the sample in a zero field and measure the remnant NRM at room temperature before heating again to the same temperature and cooling with an applied field to acquire the pTRM. Additional cycles were also performed for pTRM checks at 200, 300, and 400°C. A 50 μ T laboratory field was used as well for pseudoThellier as for Thellier/Coe experiments.

Both techniques are in excellent agreement as well in the favorable cases showing only one slope (Fig. 12(a)) as in the more complicated two slopes cases (Fig. 12(b)), and the paleointensity estimates are very close, except for the low temperature component of the two slope case where a much higher field is estimated from Thellier/Coe than from pseudo-Thellier experiments. So the pseudo-Thellier procedure, which is at least twice as fast as the Cat VTM Thellier/Coe experiments, is perfectly well suited as a selection criterion. However, as long as the Cat VTM will measure the magnetization only along one axis, none of them can replace conventional Thellier experiments satisfactorily. Also experimental errors can be expected to be slightly larger with the Cat VTM techniques as the samples have to be drilled along the direction of the characteristic magnetization (error usually less than 5°).

Even though the linearity of the pseudo-paleointensity re-

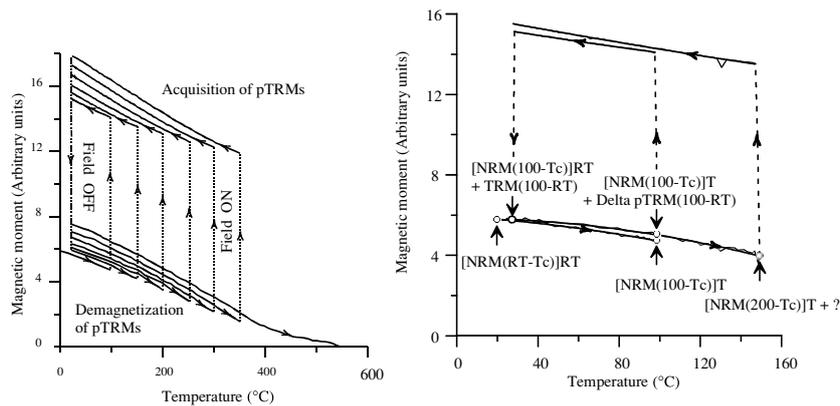


Fig. 11. Pseudo-Thellier procedure (reprint from Perrin, 1998). See text for details.

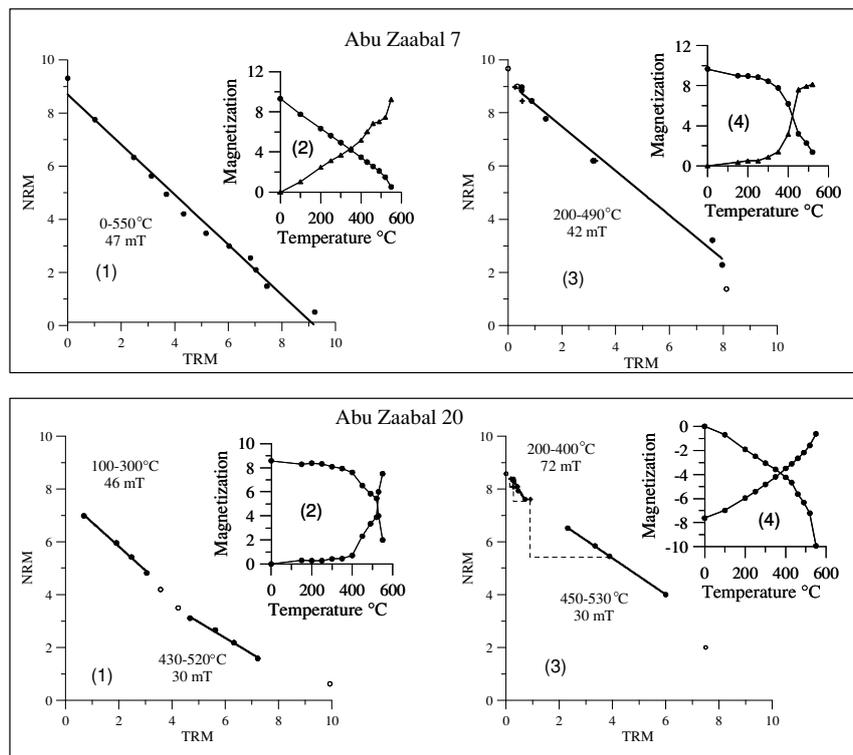


Fig. 12. Comparison of Pseudo-Thellier (PTE) and Thellier/Coe (TCE) paleointensity experiments, obtained from Abu Zaabal samples 7 (upper group of plots) and 20 (lower group of plots). Plots 1 and 3 are respectively NRM-TRM plots for PTE and TCE. Plots 2 and 4 are respectively demagnetization/remagnetization curves for PTE and TCE.

sults obtained from the Cairo area is not perfect (Figs. 12 and 13), about half of the samples gave very coherent values (between 34 and 58 μT), similar or slightly lower than the present-day 50 μT dipole field. A few Sinai samples gave also acceptable results (Fig. 13) with even lower estimates (between 29 and 37 μT). Because of their simple directional analysis, their favorable magnetic properties and the consistency of their Pseudo-Thellier estimates, we think that these Oligo–Miocene basalts from Egypt are good candidates for an extensive paleointensity analysis.

6. Conclusion

After removal of secondary components, likely related to lightning strikes, paleomagnetic analysis of the middle Jurassic (182 ± 7 Ma) Wadi Budra basalts is easy, with

well defined characteristic directions of magnetization and a good grouping at the site level ($\alpha_{95} = 3.0^\circ$). However, there is an amazingly large difference with a previously published result (Ibrahim *et al.*, 2000), and a noteworthy difference with another pole (Wassif, 1989) also obtained from Wadi Budra sill. Furthermore all poles are significantly apart from the Master Apparent Polar Wander Path (Besse and Courtillot, 2002) for South Africa. Tectonic movements between South Africa, Egypt and the Sinai Peninsula could account for a few tens of degrees but unlikely for angles on the order of 30–116°. An extensive sampling as well on the stable part of Egypt as in Sinai will be needed to understand this discrepancy. In the meantime, none of the Wadi Budra poles should be used for paleomagnetic reconstruction. About paleointensity, the secondary components present in

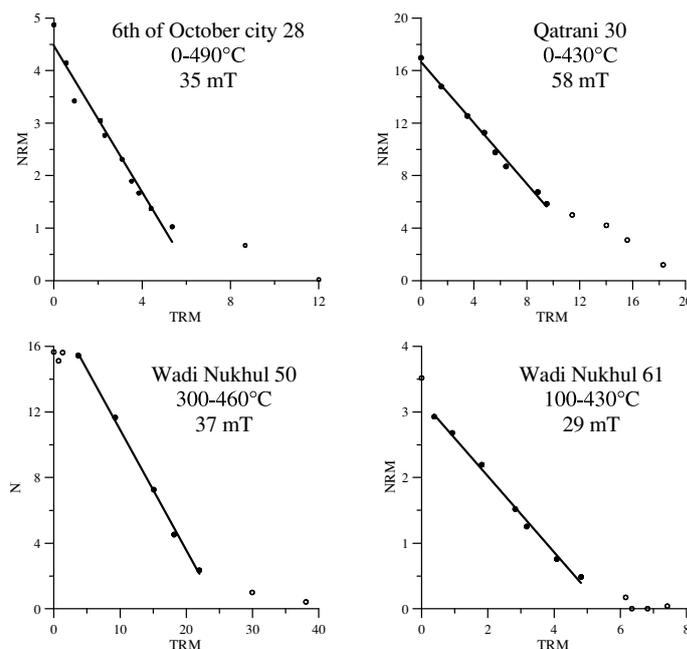


Fig. 13. NRM-TRM plots of Pseudo-Thellier paleointensity experiments for the other sites.

all samples are too large, and no further test was attempted. Other Jurassic localities will have to be tested.

The directional analysis of Oligo–Miocene basalts is very straightforward and updated mean VGPs have been calculated from the Cairo area ($N = 7$; Lat = 68.9°N ; Long = 91.3°E ; Kappa = 274; $A_{95} = 3.7$) and for Sinai ($N = 3$; Lat = 72.7°N ; Long = 13.4°E ; Kappa = 528; $A_{95} = 5.4$). A 24° angular difference exists between the Cairo and the Wadi Nukhul mean VGPs, and both are respectively 23 and 24° apart from the 20–30 Ma Master Poles for South Africa (Besse and Courtillot, 2002). Secular variation can unlikely account alone for that kind of differences and a more extensive paleomagnetic sampling will be needed to better constrain movements between South Africa, Egypt and the Sinai Peninsula during the Oligo–Miocene.

Considering the time needed for a classic paleointensity experiment, the lack of physical grounds for most natural samples (PSD grains) and therefore the high failure rate (often up to 80%), selection of sample favorable for that type of analysis has always been a goal in the community. Bulk rock magnetic parameters often failed to successfully select samples as they not necessarily describe the magnetic properties of the phase carrying the NRM. The pseudo-Thellier experiments used here mimic true Thellier experiments but, as they are fully automated, they are much faster and much easier to use for selection of the reliable samples. However, they cannot replace true Thellier experiments.

Even though the technical quality of the pseudo-paleointensity results obtained as well from the North Cairo area as from Sinai is not perfect, the consistency of the results is promising, with values between 35 to 58 μT for the Cairo area and between 29–37 μT for Sinai. Therefore this preliminary survey emphasizes clearly the need of a detailed sampling of Jurassic and Cenozoic basalts from Egypt, as well for directional as paleointensity purposes. Considering both directional results and pseudo-Thellier,

results should be obtained first from the Oligo–Miocene of stable Egypt.

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