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PALAEOMAGNETISM OF SOME SYRIAN ARCS IN NORTH SINAI AND EASTERN DESERT EGYPT; TECTONIC IMPLICATIONS

A. M. KAFAFY* and A. L. ABDELDAYEM*

Department of Geology, Faculty of Science, University of Tanta

ABSTRACT

The palaeomagnetic characteristics of rocks from three Syrian arcs in Sinai and north Eastern Desert have been investigated. Rocks of Triassic, Jurassic and Lower Cretaceous ages were collected from Arif El-Naqa (NE Sinai), Maghara (N Sinai) and Shabrawet (north Eastern Desert) anticlines, respectively.

The studied rocks were subjected to AF and/or thermal demagnetization and found carrying a stable secondary magnetization. This magnetization may have been acquired during the late stage of folding in the Upper Cretaceous-Lower Tertiary time. A chemical origin is proposed for the isolated remanent magnetization as a result of recrystallization of the magnetic carriers that might have taken place due to folding forces.

When the isolated characteristic remanent directions were compared to the expected ones for each area they suggest magnetotectonic models for the studied areas. According to these models, both Arif El-Naqa and Maghara anticlines seem to have been dragged to the SE as a result of thrusting. On the other hand, the Shabrawet anticline seem to have a different tectonic attitude where block rotations around vertical axis might be responsible for the resultant deviated palaeomagnetic directions. The proposed models were geologically tested and found feasible and provide a simple explanation for the obtained palaeomagnetic data.

INTRODUCTION

Rocks assigned ages of Triassic, Jurassic and Lower Cretaceous were collected from three major anticlinal structures (Syrian Arcs, KRENKEL 1925) in Sinai and northern Eastern Desert (*Fig. 1*) in an attempt to study their palaeomagnetic characteristics and to understand their palaeomagnetic evolutional history. These arcs are Arif El-Naqa (NE Sinai), Maghara (N Sinai) and Shabrawet (North Eastern Desert). A section of 180 m thickness of sandstones and carbonates of middle Triassic age was collected from the core of Gebel Arif El Naga anticline. A Jurassic section of more than 1900 m thickness was collected from the core of Gebel Maghara anticline, where alternating carbonates and sandstones outcrop. Lower Cretaceous sandstones and carbonates (130 m thick) were sampled from Gebel Shabrawet.

The studied structural elements seem to have played an important role in the development and evolution of the Mesozoic sedimentary basins in Egypt. Furthermore, it is evident that various movements of the microplates in the Tethyan realm have affected the palaeogeographic evolution of the Mediterranean region during the Mesozoic (DIXON and ROBERTSON 1984). Several models have been proposed for the tectonic evolution of these and other Syrian folds (JENKINS 1990), with the

* Tanta, Egypt.

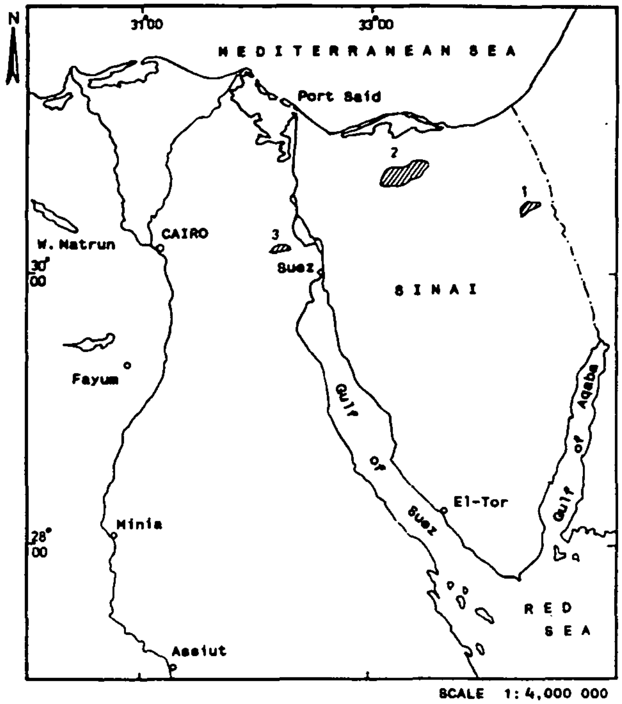

Fig. 1. Location map for the areas under study.
1—G. Arif El Naqa; 2—G. Maghara; 3—G. Shabrawet

main distinction between them is the timing of the initiation and development of the belt:

/1/ The folding was initiated in the Late Paleozoic when the embryonic Gulf of Suez rift was first initiated. Folding was then reactivated throughout the Mesozoic and the deformation climaxed in the Oligocene (for example AGAH 1981).

/2/ The fold system was mainly formed since Cretaceous and was closely related to the compressional stresses created when the Tethys Sea, between the Afro-Arabian and Eurasian land masses, began to close as a result of northerly subduction during the Late Cretaceous (Senonian) period. BARTOV *et al.* (1980), in a detailed study of the stratigraphy and structural history of Gebel Arif El Naga (NE Sinai), postulated that folding started to develop during the Coniacian, continued developing in the Santonian and persisted up to the Late Campanian. MOUSTAFA and KHALIL (1989) attributed the formation of these arcs to a right-lateral convergent wrenching during the Late Cretaceous- Early Tertiary (Laramide orogeny) due to a reactivation of pre-existing deep-seated faults which could have been formed by the late Triassic-Liassic rifting of north Africa-Arabia to form the south margin of the Tethys. On the other hand, RIVA (1986) traced the major tectonic features in Sinai using satellite images and stated that the creation of the Aqaba line due the movement of the Arabian and the African plates, originated stresses that were strongly affected by the oldest structures, so that it rejuvenated old folds and faults. Continued movements along this line is the cause of the dragging of the pre-existing fold axes which show a change from a N 70° to a N 50° trend.

SAMPLING

Sampling was undertaken during several long field trips. Samples were all obtained by drilling to allow precise sampling. No hand samples were taken to avoid introduction of errors due to transference of orientation marks. A total of 388 oriented core samples were collected at 54 sites (averaging 7 cores from each site), where 16 sites were taken from the Triassic rocks at the core of Gebel Arif El Naga, 26 sites from the Jurassic of Gebel Maghara and 12 sites were finally collected from the Lower Cretaceous of Gebel Shabrawet. The majority of samples were oriented in situ using sun compass, while magnetic compass was only used when the Sun was not available. One site (site 6) was taken from the upper weathered basalt sill intruded in the Triassic section. Bedding orientations were measured at each site to enable structural corrections.

Attention was paid to locate sites on both limbs of these folds so that a fold test (GRAHAM 1949) could be applied. This was only possible in the Arif El Naga area where samples could be collected from both sides. In the other two areas the southern parts were inaccessible and quite disturbed and deformed by thrusting which makes them steep and nearly vertical. Consequently, sampling was mainly concentrated in the northern and central parts of the Maghara and Shabrawet folds where beds were not tectonically disturbed and had shallow dips, rarely exceed 20°.

INITIAL NRM

The initial intensities of the majority of the Triassic samples were generally at least 10 times above the spinner noise level (0.02 mAm/m) with low to fairly moderate values. Only those from the basalt sill from the Triassic outcrop were high, averaging a value of 132.2 mA/m.

The initial intensities of the Jurassic samples showed that 5 of the 26 sites (15, 22, 23, 25, 26) had too low magnetization to be measured using spinner magnetometer and these sites were measured using a cryogenic magnetometer. Three of these sites (22, 23 and 25) were extremely weakly magnetized even for a cryogenic magnetometer with a sensitivity around 0.001 mA/m. Measurements of these three sites were excluded from further analysis. The remaining 21 sites showed inhomogeneous low to fairly moderate intensities with values generally more than ten times that of the spinner sensitivity level, averaging a value of 5.9 mA/m.

The Lower Cretaceous rocks showed inhomogeneous intensities where moderate values were from the lower clastic unit (sites 1 and 2), low values were found in samples from the lower carbonate and upper clastic units, while very low values were from the samples of the upper carbonate unit (sites 11 and 12).

Stability tests

The stability of magnetization was first tested by subjecting a group of selected pilot samples, representing all lithological facies from different outcrops, to demagnetization. Stepwise AF demagnetization was first carried out at steps of 3, 5, 7.5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, and 100 mT.

Most, if not all, of the Triassic samples showed a very high stability. Except for some fluctuations of the intensities due to instrumental effects, no significant changes in either directions or intensities were recorded throughout the treatment.

The majority of the Jurassic samples showed a relatively high stability against AF. However, some samples (e.g. *Fig.* 2) showed a steady decrease of intensity, but the directions remained generally unchanged (within ±10° from the original directions).

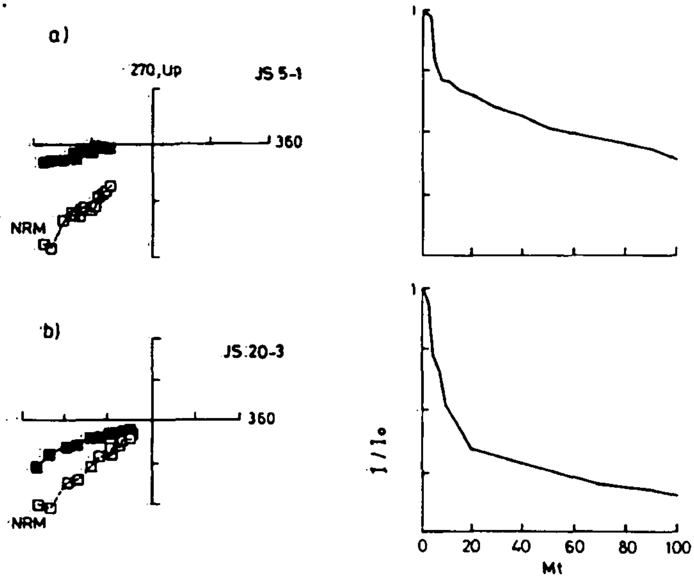

Fig. 2. Directional and intensity changes during progressive A. F. demagnetization of pilot samples from the Jurassic rocks.

Pilot samples from all of the Lower Cretaceous lithologies showed high stability against AF treatment.

As the magnetization of the majority of samples remained virtually constant during AF treatment, another collection of representative samples was selected for thermal treatment using progressive stepwise heating at 12 demagnetization steps incremented up to 680 °C. The bulk susceptibility values were measured at each step in order to monitor any mineralogical changes due to heating.

Unlike the AF method, heating had a clear effect on the magnetization of samples from different lithologies where they showed different behaviours. The magnetization of most of the Triassic samples remained fairly stable up to certain temperatures, with the intensity gradually decreasing as the heating inreased. The sandstone samples (base of the section) all behaved similarly, showing a persistent stability with mostly one component throughout the whole range of treatment (e.g.

Fig. 3). Susceptibility values began to change and showed some increase at ≥550 °C (sample 1.5 in *Fig. 4a*), but there were no significant effects on either the intensity or the direction of the remanence associated with these susceptibility changes. The sample from the basalt sill (*Fig. 3b*) showed one stable direction with

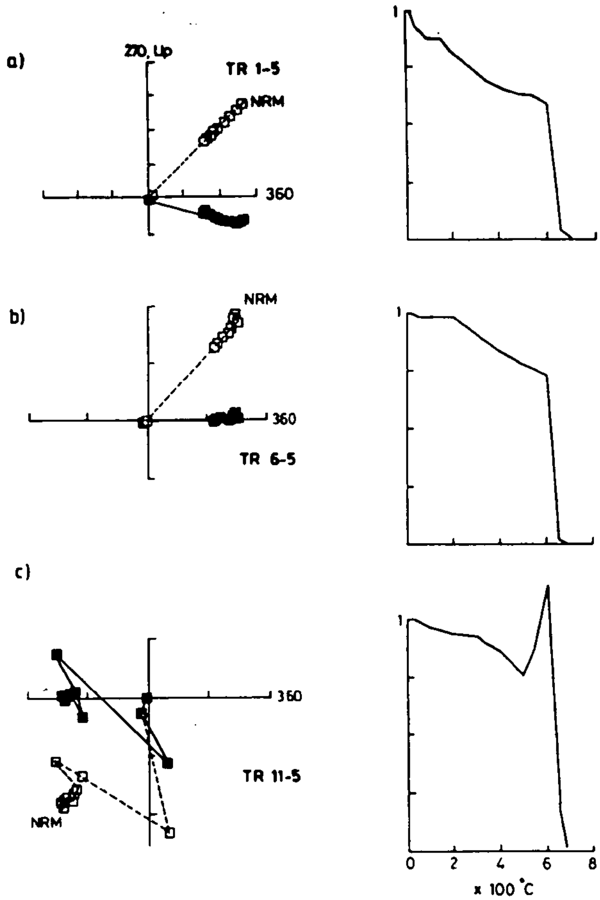

Fig. 3. Directional and intensity changes during stepwise thermal demagnetization of pilot samples from the Triassic rocks.

an intensity gradually decreasing until 600 °C above which the direction began to change, probably due to mineralogical changes associated with the susceptibility increase at ≥500 °C onwards (sample 6.5 in *Fig. 4a*). The remaining samples, mostly carbonates, showed different results, where three samples (representing sites 12, 15 and 16,) lost more than 90% of their magnetization only at 100–150 °C where the intensity dropped to the instrument noise level. Another group of samples from these sites gave similar results. Samples from these three sites were excluded from further analysis in view of their soft and probably viscous magnetization. The remaining Triassic pilot samples showed stable and mostly single magnetic components after the first or second step of heating and up to 400 °C when both the directions and the intensities began to change (e.g. *Fig. 3c*). These

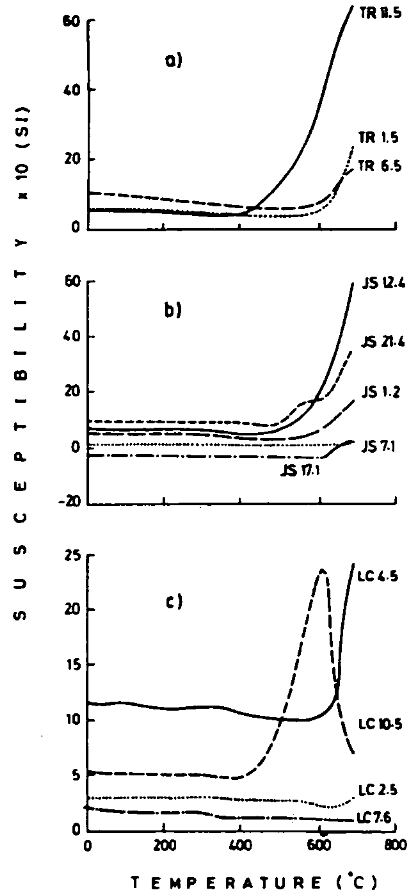

Fig. 4. Bulk susceptibility changes during thermal demagnetization of pilot samples from different localities.
a) Triassic b) Jurassic and c) Lower Cretaceous.

changes could also be attributed to mineralogical changes as indicated by the susceptibility increase at ≥400 °C (e.g. sample 11.5 in *Fig. 4a*).

Stepwise thermal demagnetization applied on a group of Jurassic samples of different lithologies reflected different behaviour. Samples from sites 2, 10 and 24 lost more than 90% of their magnetization by <150 °C and intensities became within the instrument noise. Another group of samples gave similar results, therefore the remaining samples from these sites were excluded from further analysis. Samples from the base of the section (e.g. *Fig. 5a),* after the first heating step, showed a smoothly decaying linear vector up to 500 °C when the intensity began to increase. With continued heating, the intensity decreased again until it dropped rapidly at 680 °C and became unmeasurable. Bulk susceptibility values also began to increase at 500 °C (see sample 1.2 in *Fig. 4b*). The changes in intensity and susceptibility were not accompanied by directional changes of the magnetization. The remaining pilot Jurassic samples gave similar results (*Fig. 5b-e*), except that the intensity and susceptibility values began to increase at higher

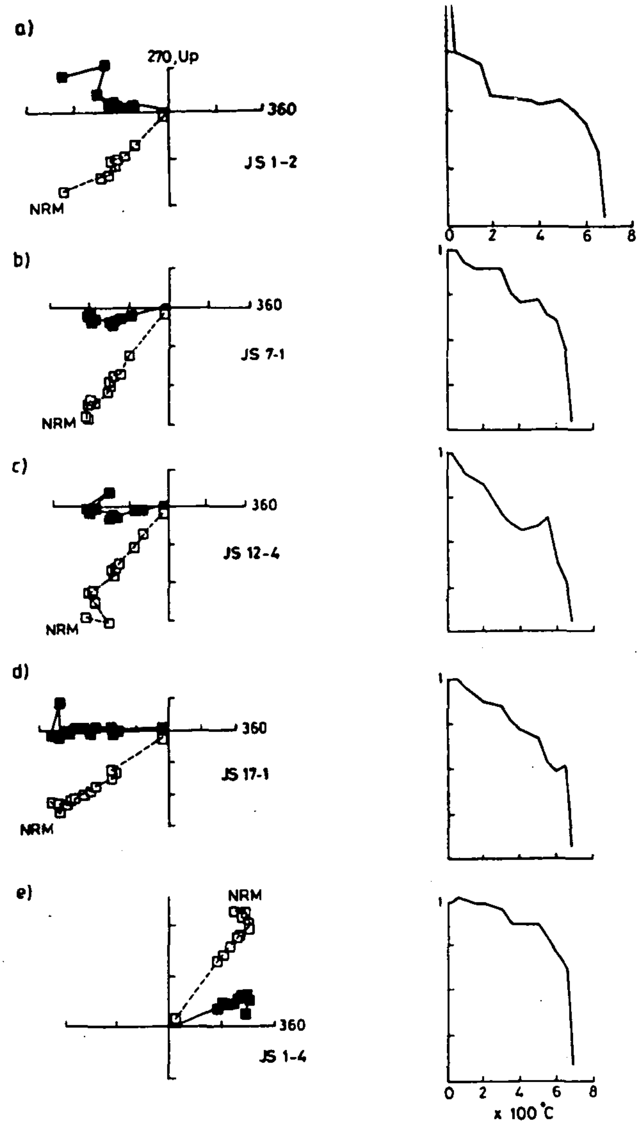

Fig. 5. Directional and intensity changes during stepwise thermal demagnetization of pilot samples from the Jurassic rocks.

temperatures (*Fig. 4a*); these changes led to some directional changes. One sample from the middle of the section (sample 17.1 in *Fig. 4b*) showed a susceptibility change from diamagnetism to paramagnetism at 600 °C.

Stepwise thermal demagnetization on pilot samples from the Lower Cretaceous rocks indicated different behaviour. The intensity of magnetization of a sandstone sample from the base (*Fig. 6a*) remained unchanged up to 200 °C, then began to decrease slowly to 60% at 650 °C and then dropped to 10% of its initial value at 680 °C but without loosing all of its magnetization even when subjected

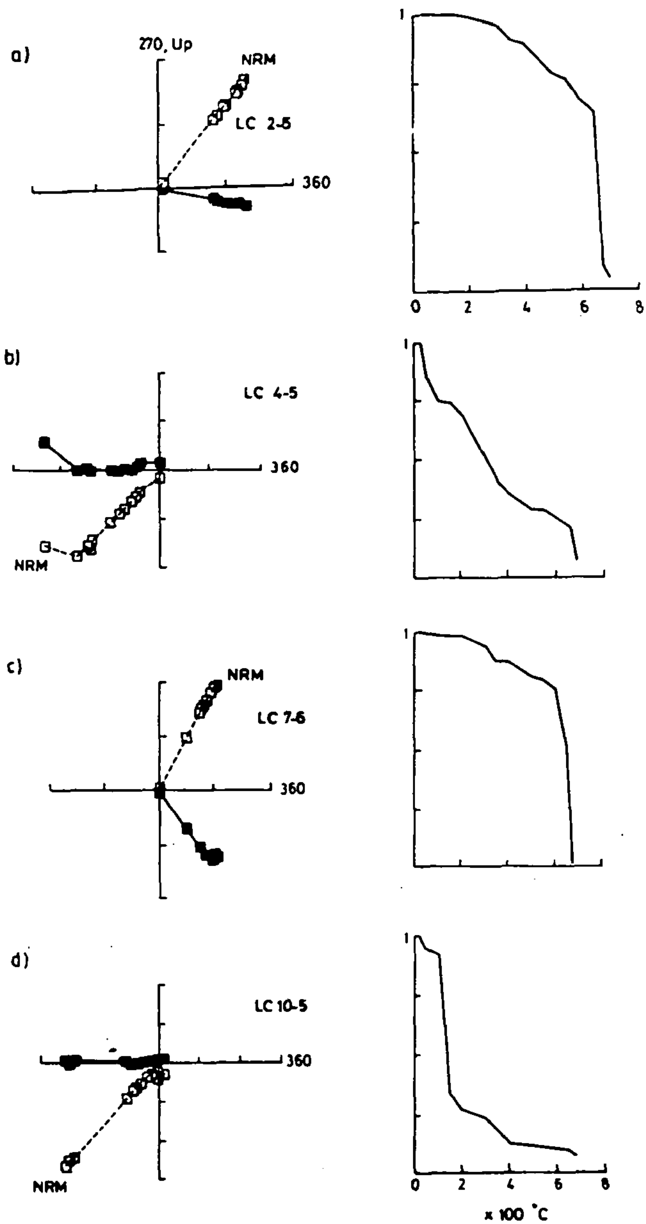

Fig. 6. Directional and intensity changes during stepwise thermal demagnetization of pilot samples from the Lower Cretaceous rocks.

to 700 °C! Directions remained unchanged throughout the whole treatment, reflecting a very high stability. Susceptibility values increased slightly after heating at 600 °C (sample 2.5 in *Fig. 4c*). Samples from the lower carbonate unit of the section (e.g. *Fig. 6b*) showed an initial 15% drop of intensity, which was followed by a continual decrease until 680 °C when it became too weak to measure. Directions remained unchanged after the first two heating steps and up to 600 °C, then they began to change. This was accompanied by an increase of the susceptibility (sample 4.5 in *Fig. 4c*) up to a value twice that of the initial value indicating that physico-chemical changes at higher temperatures should have occurred. Sample 7.6 representing the upper clastic unit (*Fig. 6c*) showed a continuous slow decrease of intensity until 600 °C, then it dropped quickly and reached instrumental noise at 680 °C. Directions did not change significantly throughout the treatment. Susceptibility continued to decrease very slowly and reached its lowest value at 680 °C (sample 7.6 in *Fig. 4c*). Finally, the carbonate samples from the top of the section (e.g. *Fig. 6d*) showed a remarkable drop of the intensity, down to 30% of the initial value, then gradually decreased continually up to 550 °C when it began to increase to 650 °C and finally dropped to the instrumental noise at 680 °C. Directions remained unchanged after heating to 100 °C and up to 500 °C when they began to change. This was accompanied by susceptibility changes which began to increase (sample 10.5 in *Fig. 4c*) at 400 °C and reached more than three times that of the initial value at 600 °C when it began to decrease.

Bulk demagnetization

Based on the visual and statistical analysis of the stability characteristics (TARLING and SYMONS 1967; KIRSCHVINK 1980), it was decided to use thermal method to demagnetize the Triassic sandstones (base of the section) as well as the samples from the basalt sill. Steps of 300, 350 and 400 °C were found to be the optimum sequential steps to define linear components in most of the pilot samples. On the other hand, due to previously recorded thermally induced mineralogical changes as well as their low intensities, the carbonate samples (top of the section) were treated using AF. Steps of 30, 40 and 50 mT were used as they were found representing the best AF stability range.

In view of the linear analysis of the demagnetization spectra of the Jurassic pilot samples, it was decided to use thermal method to demagnetize the rest of samples from sites which showed no clear response to the AF (mostly from the middle part of the section). The best linear segments defined from the analysis of the pilot behaviour were found at steps of 250, 300, 350 °C at which temperatures most of the viscous magnetization will be removed and thermal induced changes were unlikely to occur.

The visual and statistical analysis of the stability characteristics of most of the Lower Cretaceous pilot samples revealed that the stable linear components of magnetization were much better defined using thermal demagnetization than AF. Steps of 250, 300 and 350 °C were found, in most of the pilot samples, to be sufficient to remove the soft magnetic components and leave a measurable intensity of magnetization in which the most characteristics and linear segments of magnetizations could be isolated but below the level of any recorded mineralogical changes due to heating. Therefore all the remaining samples were subjected to bulk thermal demagnetization at these three steps. Clastic samples showed better stability than the carbonate ones. The latter showed poorly defined, but comparable, within-sample directions. Samples from site 12 were all excluded as they gave unstable scattered directions due to their very low magnetization.

Directions within each sample were compared where deviant directions were discarded from different calculations. The best estimated site-mean directions (FISHER 1953) were then computed using the most reliable sample-mean direction (Table 1). In most sites the mean directions obtained from bulk demagnetization

Site means cleaned NRM data before and after structural correction

		In situ		Unfolded			
Site	N	Dec. °	Inc. °	Dec. °	Inc. °	K	α_{95}°
1. Triassic							
1	6	9.6	-47.7	24.0	-66.0	304.2	3.9
2	8	179.5	42.0	174.0	58.0	93.3	5.8
3	7	176.6	29.3	164.0	43.0	18.8	14.3
4	7	25.0	-56.9	21.0	-78.0	78.2	6.9
5	7	190.5	10.3	188.0	29.0	100.6	6.1
6	8	1.7	-42.5	358.0	-58.0	276.2	3.3
7	6	198.2	28.9	190.0	58.0	16.6	16.9
8	8	188.3	36.8	171.0	51.0	96.1	5.7
9	8	177.9	36.5	160.0	48.0	21.5	12.2
10	8	193.2	46.5	169.0	62.0	56.7	7.4
11	8	186.9	46.8	162.0	70.0	208.6	3.9
12	7	Unstable and/or viscous magnetization					
13	7	187.9	31.2	178.0	56.0	14.1	16.7
14	7	185.6	35.2	175.0	62.0	126.9	5.4
15	6	Unstable and/or viscous magnetization					
16	7	Unstable and/or viscous magnetization					
Mean	13	187.3	38.0	176.6	57.5		
		α_{95} = 6.8°		α_{95} = 7.3°			
2. Jurassic							
1	5	199.7	43.0	218.0	16.0	18.5	18.3
2		NRM close to the present magnetic field					
3	7	187.3	54.7	221.0	30.0	109.6	5.8
4	7	188.1	34.1	207.0	27.0	11.6	18.5
5	6	192.3	37.7	213.0	27.0	26.4	13.3
6	8	187.8	39.5	211.0	31.0	236.9	3.6
7	9	185.1	50.3	220.0	39.0	172.8	3.9
8	7	186.9	41.5	212.0	32.0	1392.2	1.9
9	6	186.7	23.7	199.0	14.0	82.9	7.4
10		Soft magnetization					
11	6	187.0	35.7	207.0	24.0	26.8	13.2
12	6	180.4	27.3	195.0	18.0	35.2	11.5
13	6	190.6	48.0	218.0	25.0	226.4	4.5
14	7	180.3	41.5	208.0	28.0	824.6	2.1
15	7	1.6	-50.4	36.0	-33.0	106.4	5.9
16	7	190.2	40.9	211.0	24.0	34.7	10.4
17	7	201.1	38.9	217.0	17.0	32.3	10.8
18	8	3.5	-52.1	36.0	-35.0	192.8	4.0

TABLE 1
(continuation)

Site	N	In situ Dec. °	Inc. °	Unfolded Dec. °	Inc. °	K	α_{95}°
19	7	19.1	-45.2	39.0	-23.0	139.3	5.1
20	6	164.9	31.3	191.0	33.0	31.8	12.1
21	8	359.2	-56.1	43.0	-38.0	75.8	6.4
22		Very-low magnetization					
23		Very-low magnetization					
24		Soft magnetization					
25		Very-low magnetization					
26	7	191.0	43.6	217.0	21.0	37.5	10.0
Mean	20	187.1	42.1	212.0	27.0		
		α_{95} =4.40 °		α_{95} =4.27°			
3. Lower Cretaceous							
1	9	8.1	-48.3	23.0	35.0	173.1	3.9
2	8	10.1	-46.8	23.0	36.0	586.1	2.3
3	8	180.0	48.6	201.0	-37.0	76.9	6.4
4	8	182.3	46.9	200.0	-39.0	208.5	3.9
5	7	180.4	44.3	196.0	-39.0	123.5	5.5
6	8	4.4	-42.5	16.0	50.0	328.2	3.1
7	9	343.7	-55.4	22.0	31.0	70.4	6.2
8	7	175.2	42.7	195.0	-33.0	194.7	4.3
9	8	181.4	43.9	198.0	-37.0	57.3	7.4
10	8	178.6	55.1	208.0	-29.0	182.6	4.1
11	7	187.2	51.3	209.0	-36.0	40.3	9.6
12	8	Very-low magnetization					
Mean	11	181.3	48.0	201.0	-37.0		
		α_{95} = 3.6°		α_{95} = 3.7°			

N = Number of samples in each site,
Dec. and Inc. = Magnetic declination (E) and inclination in degrees,
K = Precision parameter (FISHER 1953),
α_{95} = Semi-angle cone of confidence in degrees (FISCHER 1953)

were close to those determined for the pilot samples. The bulk demagnetization successfully increased the within-site grouping in the majority of sites. This also led to improvements in the between-site grouping. Site means were mostly deviant from the present Earth's magnetic field in the studied areas (*Fig. 7*). The improvements of the within- and between-site grouping indicate successful removal of the soft magnetization and the isolation of the stable components(s) of magnetization.

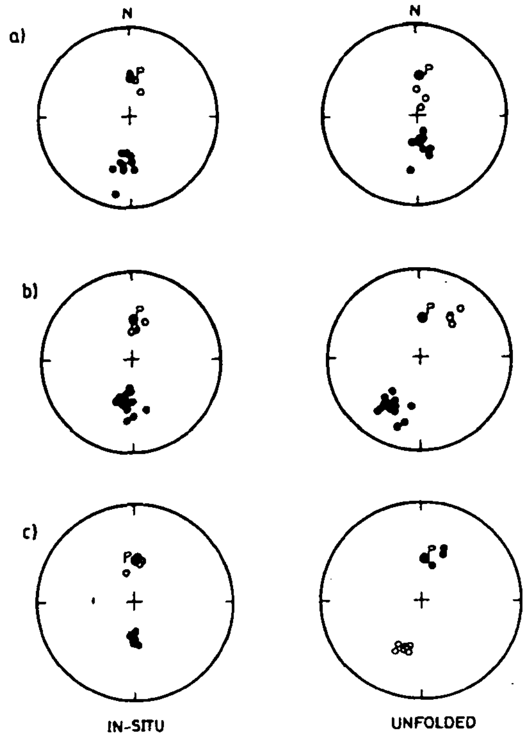

Fig. 7. Equal area stereographic projection of the site mean characteristic NRM of a) Triassic, b) Jurassic and c) Lower Cretaceous rocks before and after structural correction.

FOLD TESTS

In an attempt to date the time of acquisition of magnetization, the Fold Test (GRAHAM 1949, MCFADDEN and JONES 1981, MCFADDEN 1990) was applied on results from each of the studied three folds.

Results of a complete unfolding, i.e. a 100% unplunging and bedding correction on directions from the Triassic of Arif El Naga (Table 2) showed a negative fold test as the correction increased the dispersion of the directions around their mean (*Fig. 7a*, see also values of k and α_{95} in Table 1). Although the results from this test were not statistically reliable, they suggest that magnetization could have been acquired during or after folding.

A proper fold test could not be applied on measurements from Jurassic rocks as sampling was only restricted to the northern limb of the fold (discussed earlier). However plunge and bedding corrections were applied at each site. Using combined geological (JENKINS *et al.* 1982) and mesostructural analysis (EYAL and RECHES 1983), the plunge attitude was considered to be of 250°/20°. Results of a complete correction showed little, and statistically insignificant, improvements in the between-site grouping (Table 1, *Fig. 7b*), but the result had a significant change of directions from N-S to NE-SW. Shallow dipping could be behind the statistical unreliability of the correction. This small improvement of the grouping of directions suggests that magnetization could have been acquired prefolding.

Stepwise unfolding of the studied folds.

Site	In situ		20 %		40 %		60 %		80 %		100 %	
	Dec°	Inc°	Dec°	Inc°	Dec°	Inc°	Dec°	Inc°	Dec°	Inc°	Dec°	Inc°
1. Triassic												
1	190	48	186	54	189	58	193	61	198	64	204	66
2	180	42	173	48	173	50	173	53	174	55	174	58
3	177	29	172	34	170	36	168	39	167	41	164	43
4	205	57	197	65	198	69	198	72	199	75	201	78
5	191	10	189	16	189	20	189	23	188	26	188	29
6	182	43	176	48	177	50	177	53	177	55	178	58
7	198	29	194	39	194	44	193	49	192	54	190	58
8	188	37	181	42	179	45	177	47	174	49	171	51
9	178	37	171	41	169	43	166	45	163	46	160	48
10	193	47	184	54	181	56	178	58	174	60	169	62
11	186	47	177	54	175	58	172	62	168	66	162	70
13	188	31	183	39	182	44	181	48	180	52	178	56
14	186	35	180	44	179	48	178	53	177	57	175	62
Mean	187	38	182	45	181	48	180	51	178	54	177	58
α_{95} °	6.80°		6.73°		6.78°		6.90°		7.09°		7.35°	+
2. Jurassic												
1	200	43	212	27	214	24	216	22	217	19	218	16
3	187	55	210	41	213	38	216	36	218	33	221	30
4	188	34	199	24	201	25	203	26	205	26	207	27
5	192	38	204	26	206	26	208	27	211	27	213	27
6	188	40	201	29	204	30	206	30	209	31	211	31
7	185	50	206	40	209	40	213	40	217	40	220	39
8	187	42	202	31	204	32	207	32	210	32	212	32
9	187	24	194	14	195	14	196	14	198	14	199	14
11	187	36	199	25	201	25	203	25	205	24	207	24
12	180	27	189	19	191	19	192	19	194	18	195	18
13	191	48	208	34	211	32	214	30	216	28	218	25
14	180	42	197	32	200	31	203	30	205	29	208	28
15	181	50	203	39	207	38	210	37	213	35	216	33
16	190	41	204	28	206	27	208	26	209	25	211	24
17	201	39	212	24	213	22	214	21	216	19	217	17
18	184	52	205	40	208	39	211	38	214	36	216	35
19	199	45	212	30	214	28	216	27	217	25	219	23
20	165	31	179	29	181	31	184	32	187	32	191	33
21	179	56	206	45	211	44	215	42	219	40	223	38
26	191	44	206	30	209	28	212	26	214	23	217	21

TABLE 2
(continuation)

Site	In situ		20 %		40 %		60 %		80 %		100 %	
	Dec°	Inc°	Dec°	Inc°	Dec°	Inc°	Dec°	Inc°	Dec°	Inc°	Dec°	Inc°
Mean	187	42	202	31	205	30	207	29	210	28	212	27
α_{95} °	4.40°		4.27°		4.23°		4.22°		4.25°		4.27° +	
3. Lower Creaceous												
1	188	48	211	12	211	0	211	-12	208	-24	203	-35
2	190	47	211	11	212	-1	211	-13	208	-25	203	-36
3	180	49	206	15	207	2	206	-11	205	-24	201	-37
4	182	47	206	13	206	0	206	-13	204	-26	200	-39
5	180	44	203	11	203	-2	203	-14	200	-27	196	-39
6	184	43	203	7	203	-8	202	-22	200	-36	196	-50
7	164	55	202	26	203	12	204	-3	203	-17	202	-31
8	175	43	199	13	200	2	199	-10	198	-22	195	-33
10	179	55	209	21	209	8	210	-4	209	-17	208	-29
11	187	51	211	14	211	2	211	-11	210	-23	209	-36
Mean	181	48	206	14	206	1	206	-12	204	-24	201	-37
α°	3.65°		3.73°		3.73°		3.69°		3.65°		3.71° +	

As no Lower Cretaceous samples were taken from the southern limb of the Shabrwet anticline, a complete fold test could not also be applied. However plunge and bedding corrections were applied as different sites had different attitudes. Using the plunge of 247°/35° (AL-AHWANI 1982, OMRAN 1989), a complete correction was carried out. Results indicated that the correction changed the directions significantly and even led to a change of polarity in some sites, but with little or statistically insignificant improvements of the between-site grouping (*Fig. 7c*, Table 1). The apparent improvement of the between-site grouping after the correction suggests that magnetization might have been acquired pre-folding.

In order to define whether the magnetization was acquired during or after folding a proportional stepwise unfolding (PERROUD 1983; MCCLELLAND BROWN 1983) was applied. Results at 20% increment intervals (Table 2) showed little changes in α_{95} values suggesting that the populations from the fold limbs attain their tightest grouping when the fold is restored to 20% only. This stepwise unfolding suggests a syn-deformational remanent magnetization acquired probably during the very late stages of the main phase of folding and yields a mean direction of D = 182°, I = 45°, k = 38.9, α_{95}= 6.7° for the magnetization acquired by these Triassic rocks (Table 3). The equivalent overall mean palaeomagnetic pole was then calculated and found to be of Lat. = 32.3 °S, Long = 32.9 °E, and A_{95}= 6.1°.

The tightest grouping of the Jurassic site mean directions was found between 40% and 60% correction (Table 2), which suggests that the magnetization could have been acquired during folding, i.e, syn-deformational magnetization. In consequence, magnetization acquired by these rocks could be of the same age as the folding, i.e Upper Cretaceous-Lower Tertiary (MOUSTAFA and KHALIL 1989). The obtained directions at 60% correction are considered to be the characteristic magnetization acquired by these rocks. Site mean directions (Table 3) yielded an

TABLE 3

Site mean characteristic NRM and the equivalent VGPs for different outcrops.

Site	N	Dec. °	Inc. °	Int.	VGPs	
					Lat. °	Long. °
1. Triassic						
1	6	6.0	-54.0	7.980	24.9	209.0
2	8	173.0	48.0	1.415	-30.2	41.6
3	7	172.0	34.0	1.503	-40.4	44.5
4	7	17.0	-65.0	11.133	11.2	202.7
5	7	189.0	16.0	4.709	-50.5	20.4
6	8	356.0	-48.0	127.512	30.5	218.5
7	6	194.0	39.0	0.450	-35.9	18.4
8	8	181.0	42.0	5.107	-35.4	33.4
9	8	171.0	41.0	7.649	-35.5	44.6
10	8	184.0	54.0	6.732	-25.0	30.8
11	8	177.0	54.0	25.928	-25.1	37.2
13	7	183.0	39.0	15.797	-37.5	31.0
14	7	180.0	44.0	3.486	-33.9	34.5
Mean	13	182.0	45.0		-32.3	32.9
		α_{95} = 6.7 °			A_{95} = 6.1 °	
2. Jurassic						
1	5	216.0	22.0	0.219	-35.5	348.3
3	7	216.0	36.0	3.135	-28.7	354.3
4	7	203.0	26.0	0.559	-40.4	003.4
5	6	208.0	27.0	0.714	-37.6	358.3
6	8	206.0	30.0	1.402	-36.9	001.5
7	9	213.0	40.0	3.864	-27.9	358.7
8	7	207.0	32.0	3.128	-35.4	001.2
9	6	196.0	14.0	34.633	-49.2	008.6
11	6	203.0	25.0	0.480	-40.9	003.1
12	6	192.0	19.0	1.288	-47.9	015.5
13	6	214.0	30.0	1.354	-32.9	353.5
14	7	203.0	30.0	8.912	-38.2	004.8
15	7	030.0	-37.0	0.165	31.1	180.2
16	7	208.0	26.0	6.819	-38.1	357.9
17	7	214.0	21.0	0.648	-37.2	349.8
18	8	031.0	-38.0	25.951	30.1	179.7
19	7	036.0	-27.0	21.052	33.2	170.4
20	6	184.0	32.0	0.291	-41.8	028.2
21	8	035.0	-42.0	0.744	25.7	177.9
26	7	212.0	26.0	0.262	-36.0	353.8

TABLE 3
(continuation)

Site	N	Dec. °	Inc. °	Int.	VGPs Lat. °	VGPs Long. °
Mean	20	207.0	29.0		-36.6	360.0
		α_{95} = 4.22 °			A_{95} = 3.81 °	
3. Lower Cretaceous						
1	9	28.0	24.0	63.067	58.6	150.6
2	8	28.0	25.0	81.672	59.0	149.7
3	8	205.0	-24.0	7.278	-60.9	334.3
4	8	204.0	-26.0	6.016	-62.4	333.9
5	7	200.0	-27.0	1.920	-65.6	338.9
6	8	20.0	36.0	1.399	69.2	147.4
7	9	23.0	17.0	7.548	59.5	162.7
8	7	198.0	-22.0	0.333	-64.8	346.9
9	8	201.0	-25.0	0.297	-64.1	339.2
10	8	209.0	-17.0	1.408	-55.4	334.8
11	7	210.0	-23.0	0.198	-56.8	329.2
Mean	11	204.0	-24.0		-61.6	335.1
		α_{95} = 3.6 °			A_{95} = 2.8 °	

overall mean direction of D = 207°, I = 29°, K = 60.7 and α_{95}=4.2°. The equivalent VGPs (Table 4) suggest an overall mean palaeomagnetic south pole of Lat. = 36.6 °S, Long.= 360.0 °E and A_{95}= 3.8 °.

TABLE 4

Stepwise unthrusting of magnetization of the Triassic and Jurassic rocks.

Fold Axis Strike/Dip	Direction Dec. °	Direction Inc. °	Pole Lat ° (S)	Pole Long ° (E)	Rotation R (°)	Rotation P(°)
1. Triassic						
In situ	182.0	45.0	-33.1	32.3	7.1±7.2	-30.4±6.7
065/10	178.4	35.9	-39.7	36.4	3.9±7.0	-23.7±6.7
065/20	176.1	26.7	-45.4	39.9	1.0±6.8	-17.9±6.7
065/30	174.7	17.3	-50.5	42.7	0.0±6.7	-12.6±6.7
065/40	173.9	7.9	-55.2	45.2	0.9±6.7	-07.8±6.7
2. Jurassic						
In situ	207.0	29.0	-36.6	360.0	33.2±5.1	-19.7±5.0
250/10	203.6	22.8	-42.2	001.4	29.3±5.1	-15.7±5.0
250/20	201.4	14.6	-46.7	001.5	27.1±5.1	-11.7±5.0
250/30	200.1	07.0	-50.8	000.5	25.8±5.1	-07.7±5.0
250/40	199.8	-00.7	-54.3	357.8	25.6±5.1	-03.9±5.0

The tightest site-mean grouping of directions from the Lower Cretaceous rocks was found when the fold was restored to 80% (Table 2). This suggests that the magnetization could have been acquired during folding, i.e during Upper Cretaceous-Lower Tertiary which is the time proposed for the age of folding. Therefore directions obtained at 80% correction have been considered to be the characteristic magnetization carried by the Shabrawet Lower Cretaceous rocks. The site-mean directions and the corresponding VGPs (Table 3) yield an overall mean site direction, giving unit weight to each site, of D = 204°, I = -24° with α_{95}= 3.6° and a corresponding palaeomagnetic south pole of Lat.= 66.1°S, Long.= 335.1°E with A_{95}= 2.8°.

DISCUSSION AND TECTONIC IMPLICATIONS

Although the fold test results were not strongly significant at a 95% statistical confidence level in directions from the three folds, which could be attributed to the shallow dipping of the beds, they still suggest that the remanence is most likely to be of secondary origin. Stepwise unfolding also indicates that magnetization was probably acquired during the very latest stage of the main phase of folding in the Upper Cretaceous-Lower Tertiary (BARTOV *et al.* 1980; ALLAM and KHALIL 1988; MOUSTAFA and KHALIL 1989). The magnetization could, therefore, have been acquired due to recrystallization of haematite as a result of chemical changes probably associated folding.

The overall palaeomagentic pole computed from site mean directions from each of the three folds was compared with the pole expected for the area under study, assuming it to be a part of stable Africa during the Upper Cretaceous-Early Tertiary times (as a proposed age of magnetization). The 80 my average palaeomagnetic pole of 63.0°S Lat, 46°E Long with A_{95}= 4.3° was chosen (IRVING and IRVING 1982; PIPER 1987, 1988; BESSE and COURTILLOT 1988, 1991) as the reference pole representing the time of acquisition of the magnetization. Using the method of BECK (1980), corrected by DEMAREST (1983), rotation and flattening were then calculated for each of the three folds.

The comparison of directions from the Triassic rocks with the chosen reference pole yielded 7.1°±7.2° for the rotation about the vertical axis, i.e insignificant rotation. They also yielded -30.4°±6.7° for the rotation about the horizontal axis, which indicates substantial palaeopoleward translation.

The comparison of the overall palaeomagnetic pole computed from the Jurassic site mean directions with the reference pole yielded a significant rotation of 37.3°±5.2° about the vertical axis and -22.2°±5.1° rotation about a horizontal axis. The latter suggests a substantial south poleward translation.

When the palaeomagnetic pole from the Lower Cretaceous rocks was compared to the reference pole it yielded a significant rotation of 28°±4.6° around the vertical axis and an insignificant rotation of 1.9°±4.5° along the horizontal axis. This indicates that, unlike the results from Arif El Naga (Triassic) and Maghara (Jurassic), this result does not suggest a palaeopole translation component and the rotation around vertical axis is the only significant.

The resultant southward poleward translation of 30° for the Triassic rocks and 22° for the Jurassic rocks cannot be accommodated but due to local tectonic effects. This is due to the fact that the tectonic history of these areas, as a part from the stable north Sinai province, gives no evidence whatsoever to support the idea that the region has translated either to the north or to the south as a separate microplate. This is also evident from the fact that there is a continuity of geological formations, since early Mesozoic age and onwards, extending from Sinai to southern Israel into Lebanon and Syria, with no clear tectonic disruption reported.

It has been known that pole translation can be interpreted as a result of normal, or reverse, faulting, which could lead to a change in the magnetic inclination (RON *et al.* 1986). This gives a clue that this component could be related to the effect of the thrusting which affected the two areas at their southern borders. The thrusting which was contemporaneously with, or soon after, the main folding (BARTOV *et al.* 1980; MOUSTAFA and KHALIL 1989), could have pulled these folds rigid blocks, towards the SE. Consequently, the beds attitude has changed from, presumably, fairly steep and symmetric on both sides of the fold to shallow, <20°, in the north and very steep or overturned in the south, close to the thrust.

An attempt to test this model for the restoration of these folds to a pre-thrusting attitude was made by applying a stepwise conventional bedding correction to the magnetization resulted from rocks of the two folds using their axes directions and proposed angles to pull the folds back to the NW. The proposed model appears to be applicable as the pole translation component becomes insignificant at an angle of 40° for the Triassic rocks and 30° for the Jurassic rocks (Table 4) when both anticlines are pulled back to the NW.

The geological applicability of the proposed model has also been tested by applying the same bedding correction used previously for the magnetization to two in-situ field readings for bedding on both sides of the Arif El Naga fold. The reading from the northern flank had an attitude of 120°/10° while the other from the southern flank had an attitude of 075°/80°. Results of the suggested stepwise unthrusting (Table 5) suggest that the Arif El Naga fold, and Maghara by implication, could have been a symmetrical anticline before thrusting with the beds on the limbs dipping between 40° and 45°.

TABLE 5

Stepwise unthrusting of the Arif El Naga anticline.

Fold limb	In situ	Fold axis attitude 065°/10°	065°/20°	065°/30°	065°/40°
Northern	120/10	093/18	083/27	079/37	076/46
Southern	075/80	076/70	076/60	078/51	080/41

The presence of faulting and folding (MOUSTAFA and KHALIL 1989) as well as the large scale of the Maghara fold (1500 km^2), could have led to a rotation about an inclined axis which in turn might have resulted in the combined rotation around both the horizontal and vertical axes. This might account for the remaining significant angle of rotation of 25.6°±5.1° around the vertical axis. The area, like most of the North Sinai province, is highly deformed by sets of E-W trending strike-slip faults. It has long been recognized that fault blocks in strike-slip tectonic domains must progressively rotate on vertical axes as the overall strike-slip motion continues (FREUND 1974, RON *et al.* 1984, GARFUNKEL and RON 1985).

The remaining clockwise rotation of 26° around a vertical axis of the Maghara fold could, therefore, only be related to the effect of the strike-slip faults recognized in the area. These faults could have created separate fault domains, in each of which the rocks should rotate in the same way, but rocks in different domains rotate in different ways.

The available limited picture of tectonic setting of the Shabrawet area (SAID 1962, AL-AHWANI 1982, OMRAN 1989), on the other hand, does not support rigid block rotation, instead the area is highly dissected by faults dominated by two main sets of high angle normal faults, the older ENE—WSW which affected the Cretaceous rocks and younger trending NW—SE and exposed the Eocene rocks. The latter were rejuvenated in the late Miocene due to the opening of the Gulf of Suez (AL-AHWANI 1982). This might have risen the local stresses and deformation of the area as it becomes a part of the plate marigin between the Arabian plate and the Sinai microplate separated by the Gulf of Suez. Consequently, in order to accommodate these stress strike slip movements, probably of left lateral sense, could have occurred along the old NW—SE faults. This new movements would create separate fault domains which would cause rocks to rotate in the same sense within each of these domains and probably in different sense in the other domains. The obtained 28°±4.6° degree of rotation could therefore represent the average value of the different movements. At the moment and with the available limited structural field observations it is difficult to depict a clear tectonic setting of the area in a satisfactory way. Therefore more palaeomagnetic and field observational data are essentially required for further analysis.

SUMMARY

The studied rocks were found carrying a stable secondary magnetization, probably acquired during the late stages of the folding in the Upper Cretaceous-Lower Tertiary time. Palaeomagnetic results from the different areas suggest a chemical origin for the magnetic minerals carrying the magnetization as a result of recrystallization which could have taken place due to the folding forces. The results also throw some more light on the origin and development of these anticlines, suggesting that the folds were dragged to the SE as a result of the thrusting and that this probably took place during or soon after folding. The proposed models have been found geologically feasible and provides a simple explanation of the palaeomagnetic observations.

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REFERENCES

AGAH A. 1981. Structural map and plate reconstruction of the Gulf of Suez-Sinai area. Rep., Conoco Oil Co., Houston, Texas, USA.

AL-AHWANI M. M. 1982. Geological and sedimentological studies of Gebel Shabrawet area, Suez Canal district. Egypt. Ann. Geol. Surv. Egypt. **12**, 305—381.

ALLAM A. M. and KHALIL H. M. 1988. Geology and stratigraphy of the Arif El-Naqa area, Sinai, Egypt. Egypt J. Geol. **32**, 199—218.

BARTOV Y., LEWY Z., STEINITZ G. and ZAK I. 1980. Mesozoic and Tertiary stratigraphy, paleogeography and structural history of the Gebel Arif en Naga area, eastern Sinai. Isr. J. Earth Sci. **29**, 114—139.

BECK M. E. JR. 1980. Paleomagnetic record of plate margin tectonic processes along the western edge of North America. J. Geophys. Res. 85, 7115—7131.
BESSE J. and COURTILLOT V. 1988. Paleogeographic maps of the continents bordering the Indian Ocean since the Early Jurassic. J. Geophys. Res. 93, 11,791—11,808.
BESSE J. and COURTILLOT V. 1991. Revised and synthetic apparent polar wander paths of the African, Eurasian, North American and Indian plates, and true polar wander since 200 Ma. J. Geophys.. Res. 96, 4029—4050.
DEMAREST Jr. H. H. 1983. Error analysis for the determination of tectonic rotation from paleomagnetic data. J. Geophys. Res. 88, 4321—4328.
DIXON J. E. and ROBERTSON A. H. F. (eds) 1984. The gelogical evolution of the eastern Mediterranean. Blackwell Sci. Publish. Oxford, 824 p.
EYAL Y. and RECHES Z. 1983. Tectonic analysis of the Dead Sea rift region since the late Cretaceous based on mesostructures. Tectonics. 2, 167—185.
FISHER R. A. 1953. Dispersion on a sphere. Proc. R. Soc. Lond. A217, 295—305.
FREUND R. 1974. Kinematics of transform and transcurrent faults. Tectonophys. 21, 93—134.
GARFUNKEL Z. and RON H. 1985. Block rotation and deformation by strike-slip faults 2.The properties of a type of macroscopic discontinous deformation. J. Geophys. Res. 90, 8589—8602.
GRAHAM J.W. 1949. The stability and significance of magnetism in sedimentary rocks. J. Geophys. Res. 54, 131—167.
IRVING E. and IRVING G. A. 1982. Apparent polar wander paths Carboniferous through Cenozoic and the assembly of Gondwana. Geophys. Surv. 5, 141—188.
JENKINS D. A. 1990. North and Central Sinai. *In:* SAID R. (eds) The geology of Egypt. Rotterdam and Boston, Balkema, 361—380.
JENKINS D. A., HARMS J. C. and OESLEBY T. W. 1982. Mesozoic sediments of Gebel Maghara, north Sinai. Sixth E.G.P.C. Explor. Seminar Cairo. 1, 130—158.
KIRSCHVINK J. L. 1980. The least-squares line and plane and the analysis of palaeomagnetic data. Geophys. J.R. astr. Soc. 62, 699—718.
KRENKEL E. 1925. Geologie Afrikeas. Brontraeger, Berlin. 1, 461p.
MCCLELLAND BROWN E. 1983. Palaeomagnetic studies of fold development and propagation in the Pembrokeshire Old Red sandstone. Tectonophys. 98, 131—149.
MCFADDEN P. L. 1990. A new fold test for palaeomagnetic studies. Geophys. J. Int. 103, 163—169.
MCFADDEN P. L. and JONES D. L. 1981. The fold test in palaeomagnetism. Geophys. J. R. astr. Soc. 67, 53—58.
MOUSTAFA A. R. and KHALIL M. H. 1989. North Sinai: Structures and tectonic evolution. M.E.R.C. Ain Shams Univ. Earth Sci. Ser. 3, 215—231.
OMRAN M. A. 1989. Geological studies in Shabrawet area. Suez Canal, Egypt. M.Sc. Thesis, Suez Canal Univ. 234 p.
PERROUD H. 1983. Palaeomagnetism of Palaeozoic rocks from the Cabo de Penas, Asturia, Spain. Gephys. J. R. astr. Soc. 75, 201—215.
PIPER J. D. A. 1987. Palaeomagnetism and the continental crust. Open Univ. Press, Milton Keynes, 434 p.
PIPER J. D. A. 1988. Palaeomagnetic database. Open Univ. Press, Milton Keynes, 304 p.
RIVA E. T. 1986. Compressive features and wrench tectonics in western central Sinai. Eighth Explor. Sem. Cairo, November 1986.
RON H., FREUND R., GARFUNKEL Z. and NUR A. 1984. Block rotation of strike-slip faulting: structural and paleomagnetic evidence. J. Geophys. Res. 89, 6256—6270.
RON H., AYDIN A. and NUR A. 1986. Strike-slip faulting and block rotation in the Lake Mead fault system. Geology. 14, 1020—1023.
SAID R. 1962. The geology of Egypt. Elsev. Publish. Co. Amster., 377 p.
TARLING D. H. and SYMOND D. T. A. 1967. A stability index of remanence in palaeomagnetism. Geophys. J. R. astr. Soc. 12, 443—448.

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