Study of Palaeomagnetism and Magnetic and Some Physical Properties of Tertiary Igneous Rocks of Sana'a Region (Republic of Yemen).

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ABSTRACT

Palaeomagnetism and some magnetic and physical properties (magnetic susceptibility, intensity of remanent magnetization, ac current electrical conductivity and density) of 115 samples from 18 sites of the Yemen Volcanic Group TKY (Tertiary and (or) Cretaceous) from igneous rock exposures from Sana'a region were studied. One palaeomagnetic pole position was determined and a magneto-strigraphy of the area was suggested. The different properties were measured in order to use them as characteristic factors in discriminating the neighboring igneous flows. The measurement of the in situ magnetic susceptibility of 80 points, distributed on 4 sub-areas, in the area helped to calculate the mean value of the magnetic susceptibility of each sub-area, which may be used in any magnetic interpretation of aeromagnetic or magnetic anomalies. Also, the density of 115 samples were measured and a mean value of the density of each sub-area and an overall mean density of each rock age, were calculated in order to be used in any future interpretation of any gravity anomaly in the area.

Key Words: Magnetic susceptibility, Palaeomagnetism, Magneto-stratigraphy, NRM = Natural Remanent Magnetization,Yemen Volcanic Group.

دراسة المغنطيسية القديمة وبعض الخصائص المغنطيسية والفيزيائية لبعض صخور الدور الثالث الاندفاعية في منطقة صنعاء (الجمهورية اليمنية)

جمال أبوديب

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ملخص

قيست المغنطيسية القديمة وبعض الخصائص المغنطيسية والفيزيائية (المتأثرية المغنطيسية وشـدة المغنطيسية الأولية والناقلية الكهربائية بالتيار المتناوب والكثافة) لـ 115 عينة صخرية مأخوذة من 18 موقعاً من مجموعة صخور اليمن الاندفاعية (عائدة للعصر الثلاثي إلى الكريتاسي) من تكشفات في منطقة صنعاء، لاستخدام هذه الخصائص كعوامل مميزة بين صخور الصبات البركانية المجاورة. تم تعيين قطـب مغنطيسي جديد وتم اقتراح ستراتغرافيا مغنطيسية لصخور المنطقة. كما قيست المتأثرية المغنطيسية فـي الحقل للصخور في 80 موقعاً موزعة على 4 تحت - منطقة في المنطقة المدروسة بهدف الحصول علـى قيمة متوسطة للمتأثرية المغنطيسية لكل تحت - منطقة لاستخدامها في تفسير الشواذ المغنطيسية الواردة في الخريطة المغنطيسية أو تلك الناتجة عن أي مسح مغنطيسي جوي أو أرضي في المنطقـة. وقيـست الكثافة لـ 115 عينة مما سمح بالحصول على قيمة متوسطة لكثافة كل تحت-منطقة وقيمـة متوسـطة لكثافة صخور العمر الجيولوجي الواحد، بحيث يمكن استخدام هذه القيم في تفسير شواذ الجاذبية الواردة في خريطة الجاذبية أو الناتجة عن أي مسح جاذبي في المنطقة.

الكلمات المفتاحية: المتأثرية المغنطيسية، المغنطيسية القديمة، ستراتغرافيا مغنطيسية، المغنطيسية المتبقية الأولية، مجموعة صخور اليمن الاندفاعية.

Introduction

The present study deals with the rock samples, which were used to study their palaeomagnetism (Abou-Deeb 2000, 2004, Abou-Deeb *et al.*, 2002), and their knobs. Magnetic susceptibility, natural remanent magnetization (NRM), ac current electrical conductivity and density of 115 rock samples of TKY?, and TKY4 were studied. Also the in situ magnetic susceptibility of 80 field points were measured in order to use the results in the interpretation of magnetic anomalies in any future study and to distinguish between the different igneous flows (Henkel, 1976, Saad, 1969, Hattom & Abou-Deeb 2001).

Geology of Yemen and the study area:

According to Geukens (1966), Abu Khadra (1982) and El-Anbaawy (1985) the Yemen's PreCambrian - Early Paleozoic gneissic basement has been extensively intruded, metamorphosed and folded. The tectonic movements and associated erosion which took place at the end of the Mesozoic removed most of the Jurassic and Cretaceous sediments from Central Yemen. This was accompanied by an intense volcanic and intrusive activity that continued throughout most of the Cenozoic, leading to the formation of the Yemen Volcanic Group (TKY) that covers some 5000 km^2 and has a maximum thickness of 3000 m (Menzies *et al.*, 1992). This volcanic activity continued during the Paleocene and appears to have waned slightly during the Oligocene and Miocene times, when freshwater deposits intercalated with the volcanics (Grolier & Overstreet, 1983), and continued to the present day. The Yemen Volcanic Group includes bedded alkali flows and pyroclastic rocks (including rhyolite, comendite, pantellerite, trachyte, andesite, basalt and ankermite) (Shukri and Basta, 1955) and was divided into six main units, these are from top to bottom:

TKY6 ark basaltic flows

TKY5 generally leucocratic felsic tuffs with some basaltic flows associated with the formation and collapse of circular volcanic structures.

TKY4 predominantly felsic and tuffaceous, with some basaltic flows, underlies sub-units TKY6 and TKY5.

TKY3 predominantly felsic and tuffaceous, older than TKY4.

TKY2 predominantly felsic and tuffaceous, older than TKY3.

TKY1 predominantly basaltic, but includes green felsic conglomerate, porphyritic trachyte and pink tuffs and overlies the Tawilah Group sediments, the age of which is disputed but contains undisputed Cretaceous and Paleocene sandstones (Al-Nakhal, 1988, 1990).

Numerous studies (Civette *et al*., 1978; Capaldi *et al*., 1983, 1987a,b,c; Chiesa *et al*., 1989; Manzies *et al*., 1990; Manetti *et al*., 1991; Huchon *et al*., 1991; Al-Kadasi , 1994; Baker *et al*. 1996) showed that the radiometric ages for the Yemen Volcanic Group range from 29-20 Ma. According to Civetta *et al*., 1978 and Capaldi *et al*., 1987c, the volcanic sequence of the western part of Yemen was intruded by alkaline granites and both silicic and mafic dikes between 21-23 Ma ago. The volcanic activity continued into the Quaternary, with evidence for basaltic flows in most areas, but particularly in the central part of Yemen.

Italconsult (1972) mapped the Sana'a basin, which shows widespread tectonic activities associated with the creation of the Red Sea Rift, and is composed of the following:

Quaternary: basalt and volcanics,
aluvium
Eocene : chaotic and stratoid rocks
Miocene : stratoid rocks,
Trap basal basalts
Paleocene : Medj-Zir formation (sandstone with interbedded
siltstone and cley).
Cretaceous: Twilah sandstone.
Jurassic : Amran formation (limestone and interbedded shales).
Kohlan formation (Sandstone and shale).

So the rock exposures in the study area are Meocene diorite (TKY4) in the south and southwest and TKY? basalts (undifferentiated) in the east. While the central and northern part is covered with Quaternary sediments, and the northeastern and northwestern parts are covered with Cretaceous sediments (Fig. 1).

Baker *et al*. (1996) applied the Ar^{40}/Ar^{39} dating method on a number of igneous rock samples from different localities in Yemen including three basaltic samples. The first from the NE of the exposure of sites YM1-YM3, and was found to be 29.23±0.28 Ma old, the second and third samples from the west of the exposure of sites YS1-YS5, and was found to be 29.85±0.18 Ma and 29.65±0.64 Ma old (Table-1).

Table1. Gives all the available information about the dated samples from the studied area.

Sample No. & dating method	Rock Type and nearby sites	Lat. (N) ° ′ ″	Long. (E) ° ′ ″	Age Ma.	Ref.
JB148 Ar^{40}/Ar^{39}	Basalt flow NE of YM1-YM3	15 29 20	44 25 08	29.23±0.28	Baker *et al.*, (1996)
JB279 Ar^{40}/Ar^{39}	Basalt flow West of YS1-YS5	15 24 50	44 05 48	29.85±0.18	Baker *et al.*, (1996)
JB261 Ar^{40}/Ar^{39}	Basalt flow West of YS1-YS5	15 23 16	44 08 07	29.65±0.64	Baker *et al.*, (1996)

***Sampling, measurements and analysis*:**

The present study is a part of a palaeomagnetic research project included Syrian and Yemeni igneous and sedimentary rocks from different ages and different localities (Abou-Deeb *et al.*, 1999, 2002). Sampling (Abou-Deeb, 1997a,b, 1998) was achieved during the academic year 1991-1992 and the measurements of the density and susceptibility of the rocks knobs and the susceptibility of the sampled localities rocks was achieved during a month-long visit to Yemen during the academic year 1997-1998. Sampling was undertaken, using field drill and orientation by sun compass. The studied samples were sampled from igneous rock exposures from four different locations around Sana’a. All sites were in basaltic flows, but ten are of TKY4 and eight are of undifferentiated TKY? (Fig. 1, Table 2).

All samples were sliced to provide one standard palaeomagnetic cylinder, 2.5 cm in diameter, 2.1 cm high, from each drill core (Tarling, 1983). Measurements were achieved in Plymouth (England) University Palaeomagnetic Laboratory and in Damascus University Magnetic and Palaeomagnetic Laboratory.

Following the measurement of their initial magnetization (NRM) and magnetic susceptibility of the samples, 3 pilot samples (YS6.3, YM1.1 and YS1.2) were subjected to detailed thermal demagnetization (Fig. 2) in 9 steps (50, 100, 200, 300, 400, 450, 500, 550, & 600 °C). The remanent magnetization and the low-field susceptibility of these pilot samples were also measured, after each temperature increment to determine whether thermo-chemical changes had occurred to the magnetic mineralogy.

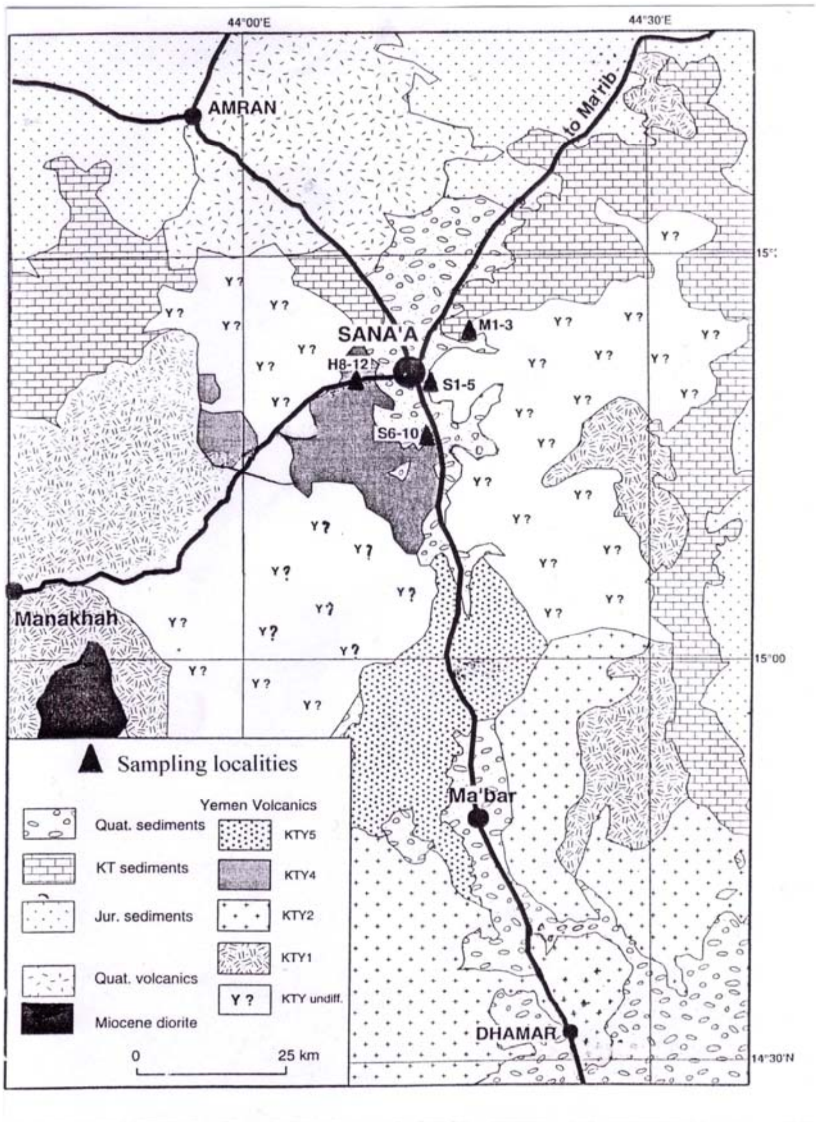

Fig.-1- Geology of the studied area and site locations. Symbols are defined in the text.

Table 2. Gives the rock age, sub-area name, site numbers, sub-areas coordinates and number of samples.

Sub-Area Name	Site No.	Latitude (N) ° ′ ″	Longitude (E) ° ′ ″	No. of samples
TKY4				
Jabal Al-Nahden	YS6-YS10	15 17 00	44 13 30	32
Jabal Asr	YH8-YH12	15 21 00	44 09 00	30
TKY? (undifferentiated)				
Jabal Nuqum	YS1-YS5	15 21 00	44 14 00	35
Sa’awan	YM1-YM3	15 24 35	44 17 15	18
Total number of samples				115

Studying the Consistency Range (Tarling & Symons, 1967) and the Linearity Range (Kirschvink, 1980) (Table 3) suggested that demagnetizing all the samples at 200 °C may be enough to isolate the stable magnetization component.

The density of the samples’ knobs was measured using the conventional method using a sensitive balance to weigh the sample and its volume was measured by displacement of water in a calibrated test tube.

In summary the following components were measured:

1. Magnetic susceptibility and NRM intensity of the complete samples.
2. Magnetic susceptibility and intensity of the demagnetized complete samples.
3. Magnetic susceptibility and intensity of the pilot samples.
4. Magnetic susceptibility of the samples’ knobs.
5. The ac current electrical conductivity of the samples’ knobs.
6. Density of the samples’ knobs.
7. Magnetic susceptibility of the rocks of the sampled field localities.

Table 3. Gives Consistency Index, consistency range and magnetization declination and inclination (Tarling & Simons, 1967) and diagonal angle, Linearity range and magnetization declination and inclination (Kirschvink, 1980) of the pilot samples.

Sample No.	CI	$Range_c$	$Dec._c$	$Inc._c$	da	$Range_d$	$Dec._d$	$Inc._d$
TKY4								
YS6.3	4.9	20-200	55.5	9.1	4.8	20-400	56.4	7.1
TKY?(undifferentiated)								
YM1.1	1.9	20-100	206.8	-27.5	7.8	400-500	230.4	70.5
YS1.2	3.0	100-300	182.7	-7.1	6.3	100-300	1.8	-62.0

Results

Palaeomagnetism of the complete samples:

The magnetic susceptibility (Fig. 2-A) and intensity of magnetization (Fig. 2-B) of one pilot sample (YS6.3) of TKY4 and two samples (YM1.1 and YS1.2) of TKY? were studied in order to determine if any thermo-chemical changes had occurred to the magnetic minerals during heating and to extrapolate the magnetic mineral that carries the magnetization of the rocks. The normalized magnetic intensity (Fig. 2-B) shows that the main carrier of magnetization is magnetite.

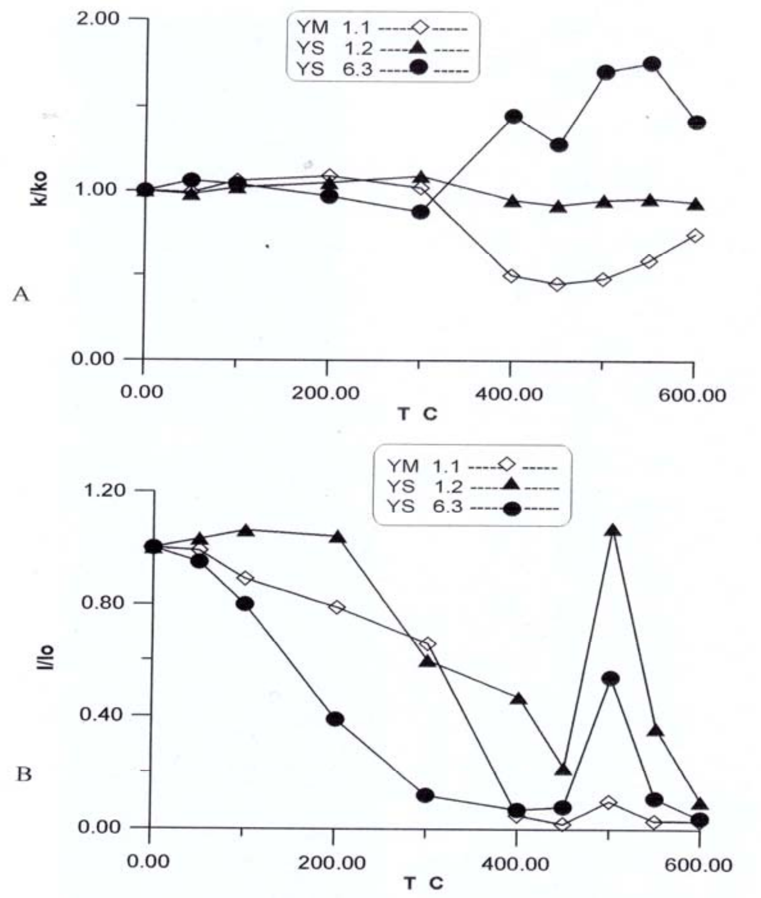

Fig. 2. A- Normalized magnetic susceptibility of the pilot samples.
B-Normalized intensity of magnetization of the pilot samples.

The changes in the magnetic susceptibility and intensity are indication of the presence of amounts of other magnetic minerals, which started to change to another mineral that is usually haematite.

The site mean directions of all sites were calculated after demagnetization at 200°C (Table 4). The TKY4 sites showed reverse, intermediate normal and intermediate reverse polarity. Site YS8 was excluded, because its directions were highly scattered while all the other sites were excluded because they are widely scatterd, which maybe due to local tectonic movements.

Table 4. Gives the site mean direction after demagnetization at 200°C. N is the number of the accepted samples, n is total number of samples, Dec. is site mean direction, Inc. is site mean inclination, k is precision factor and α_{95} is the cone angle which is characterized by 95% probability that the true direction is located inside the cone. N = Normal, R = Reverse, Ni = Intermediate Normal and Ri =Intermediate Reverse.

Site No.	N/n	Dec.	Inc.	k	α_{95}	VGP		Polarity
						Lat.	Long.	
TKY4								
YS6	6/6	44.8	14.3	73.9	7.8	45.4	139.4	Ni
YS7	6/6	14.4	7.0	152.6	5.4	71.6	172.5	N
YS8	HIGHLY SCATTERED							
YS9	5/7	6.9	- 9.9	19.9	15.4	68.6	205.1	N
YS10	5/7	71.0	30.8	31.1	13.9	22.1	122.2	Ni
YH8	5/6	324.8	-50.9	274.7	4.6	32.1	259.6	Ni
YH9	6/6	135.0	-23.2	89.1	7.1	-46.2	135.7	Ri
YH10	5/6	153.0	4.7	80.0	8.6	-57.9	102.9	R
YH11	5/6	193.5	31.0	29.5	14.3	-55.2	21.1	R
YH12	5/6	233.3	10.0	26.1	15.2	-33.4	331.1	Ri
TKY?								
YS1	4/7	164.8	-13.1	23.7	19.3	-72.7	105.4	R
YS2	7/7	177.4	- 5.6	578.5	2.8	-77.1	56.0	R
YS3	7/7	194.2	- 1.0	677.5	2.6	-69.5	359.6	R
YS4	6/7	183.5	- 2.5	39.4	9.7	-75.4	30.2	R
YS5	6/7	160.2	- 6.7	122.6	5.5	-67.1	104.5	R
YM1	4/6	184.3	-16.8	83.4	10.1	-82.0	12.1	R
YM2	4/6	155.1	- 1.7	31.6	16.6	-61.4	106.0	R
YM3	6/6	172.1	- 5.8	35.8	11.4	-75.3	77.0	R

All the eight TKY? sites showed reverse polarity and their site mean directions were drawn on an equal area projection (Fig. 3, Tables 4, 5). They are well grouped (Mean site Dec=173.93°, Inc=-6.80°, k=32, α_{95}=10° and the Virtual Geomagnetic Pole (VGP) Long=71.33°, Lat=-76.63°, k=35, α_{95}= 9.4°) (Fig.4).

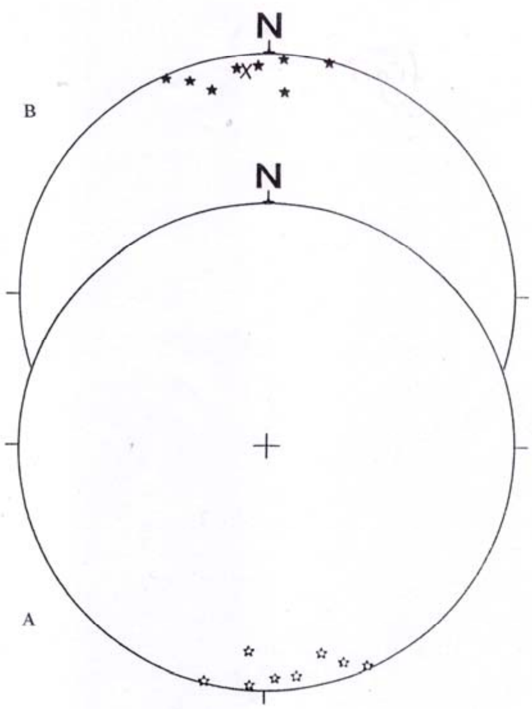

Fig. 3. TKY? site mean directions after demagnetization at 200°C on an equal area projection.
A- The negative (upward) inclinations of all the TKY? sites.
B- The positive (downward) inclinations of all the TKY? sites after rotating them 180° through the center.

If this mean is rotated 180° through the center it will be Dec=353.93°, Inc=6.80° and their VGP is at 251.33°E, 76.63°N.

Table 5. Gives the mean site direction of the accepted sites after demagnetisation at 200 C°. Dec. sites mean declination, Inc. sites mean inclination, k is precision factor and α_{95} cone angle which is characterized by 95% probability that the true direction is located inside the cone.

Mean site direction of the accepted sites					
Site No.	**Dec.**	**Inc.**	**k**	**α_{95}**	**Polarity**
YS1, YS2, YS3, YS4, YS5, YM1, YM2, YM3	73.9	-6.8	32	10	Reverse
Virtual Geomagnetic Pole					
Site No.	Long.	Lat.	k	α_{95}	Polarity
YS1, YS2, YS3, YS4, YS5, YM1, YM2, YM3	71.3	-76.6	35	9.4	Reverse

This direction is very close to that of the mean of the seven TKY1 sites of Al-Hudyadah region (Abou-Deeb, 2004), which are all of normal polarity and of the Upper Oligocene, and their calculated overall mean site direction has Dec.= 8.36°, Inc.= 10.83°, k=22, $\propto_{95}$=13.3° and their overall mean of the VGPs is at 182.81°E, 77.44°N, k=24, $\propto_{95}$=12.5°.

The overall mean direction of the seven TKY1 sites and the rotated eight TKY? sites is Dec= 0.58°, Inc= 8.74°, k= 23, $\propto_{95}$= 8.2° and the VGP Long= 221.07°, Lat= 79.18°, k=25, $\propto_{95}$= 7.8°).

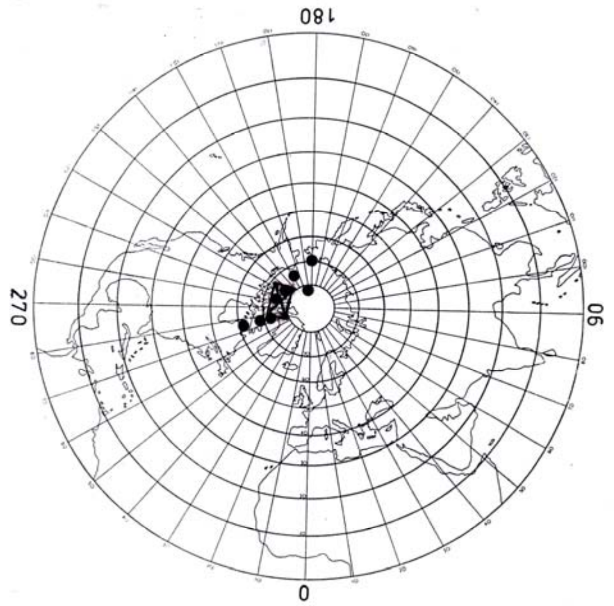

Fig. 4. Virtual Geomagnetic Poles derived from site mean directions plotted in Fig. 3. The overall mean of the VGPs is represented by the centre of the hollow rectangle.

Magneto-stratigraphy of the igneous rocks of Sana'a region:

The undifferentiated rocks (TKY?) of Sana'a region overlie the Palaeocene Tawilah Group Sediments and were dated by Baker *et al.* (1996). His dating ages suggest that the onset of the Yemen volcanics occurred during chron C11r.1r some 29 Ma ago, and that the first Yemen volcanic unit persisted through the normal C10n chron, and that eruption persisted for some 3 to 4 Myr, probably terminating during chron C8, some 26 Ma ago (Abou-Deeb *et al.*, 2002). Because the three basaltic flow samples (JB148, JB279 and JB261) were dated as 29.23±0.28, 29.85±0.18 and 29.65±0.64 Ma respectively. The former one is NE of YM1-YM3, while the later two are west of YS1-YS5. The first sample can be correlated to the reversed period C10r between chron C10n.2n and chron C11n.1n (Cande and Kent, 1992) (Fig.5) and the third sample to the reversed period C11n.1r between chron C11n.1n and chron C11n.2n, while the age of the second sample is during the normal polarity chron C11n.2n. According to the mentioned radiometric ages and the clossness of the palaeomagnetic directions of the TKY1 sites and the TKY?, as shown in the previous section, it seems possible to refer the undifferentiated TKY? basaltic flows of Sana'a region to the base of TKY1 and that the basaltic flow of YS1-YS5 were erupted during the reversed polarity period between chron C11n.1n and chron C11n.2n, while that of YM1-YM3 were erupted during the reversed polarity period between chron C10n.2n and chron C11n.1n. These were followed by the eruption of the normally polarized TKY1 lavas (Abou-Deeb, 2004) during the normal polarity chrons C10n.2n, C10n.1n or even during C9n**.**

Magnetic susceptibility and intensity of NRM of the complete samples

The magnetic susceptibility (Fig. 6A, Table 6) of the TKY4 complete samples of sites YS6-YS10 ranged between 2834 mSI and 4198 mSI, with a mean of 3479±327 mSI, and that of YH8-YH12 ranged between 2033 mSI and 3379 mSI, with a mean of 2725±388 mSI. While the magnetic susceptibility (Fig. 6B, Tables 6) of the TKY? complete samples of sites YS1-YS5 ranged between 2777 mSI and 4167 mSI, with a mean of 3455±346 mSI, and that of YM1-YM3 ranged between 2652 mSI and 3814 mSI, with a mean of 3098±481 mSI. It is clear that the magnetic susceptibility ranges of the complete samples are close to each other.

The intensity of the NRM of the same samples was measured by the Molspin magnetometer of Plymouth Palaeomagnetic Laboratory and found (Table 6) that TKY4 samples of sites YS6-YS10 ranged between 942 mA/m and 2213 mA/m, and that of YH8-YH12 ranged between 704 mA/m and 1916 mA/m. While the intensity of the NRM (Table 6) of the TKY? of sites YS1-YS5 ranged between 135 mA/m and 435 mA/m, and that of YM1-YM3 ranged between 3031 mA/m and 3971 mA/m.

The low values of the intensity of the NRM (Table 6) of the TKY? of sites YS1-YS5 is difficult to explain because of their high magnetic susceptibility, except that is because of a low intensity of the geomagnetic field at the time of the cooling of these rocks.

Figure 7 shows the distribution of magnetic susceptibility versus intensity of NRM of the complete samples in order to see if the increase of susceptibility is due to the increase in the geomagnetic field at the time of cooling the rocks.

Magnetic susceptibility of the samples knobs:

The magnetic susceptibility (Fig. 8A, Table 6) of the TKY4 samples knobs of sites YS6-YS10 ranged between 3060 mSI and 4420 mSI, with a mean of 3628±351 mSI, and that of YH8-YH12 ranged between 2040 mSI and 3388 mSI, with a mean of 2556±340 mSI. While the magnetic susceptibility (Fig. 8B, Tables 6) of the TKY samples knobs of sites YS1-YS5 ranged between 2953 mSI and 3995 mSI, with a mean of 3394±303 mSI, and that of YM1-YM3 ranged between 2678 mSI and 3750 mSI, with a mean of 3193±316 mSI.

The similarity between the ranges of the complete samples and the ranges of the sample knobs , for both the TKY4 and TKY? samples, confirms the validity of the results.

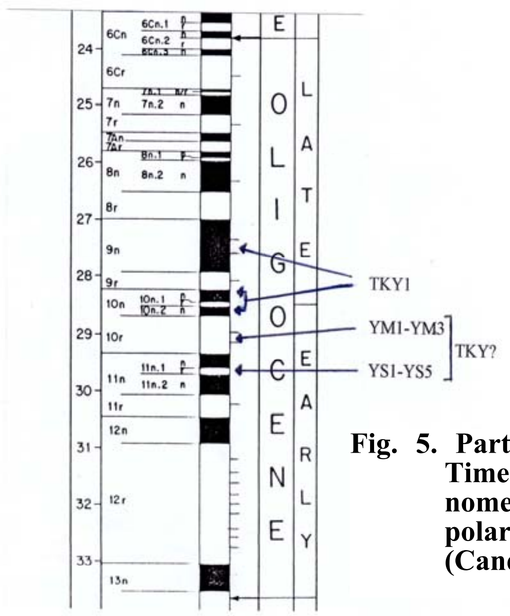

Fig. 5. Part of the geomagnetic Polarity Time Scale showing the nomenclature of chrons and polarity events the Oligocene (Cande and Kent, 1992).

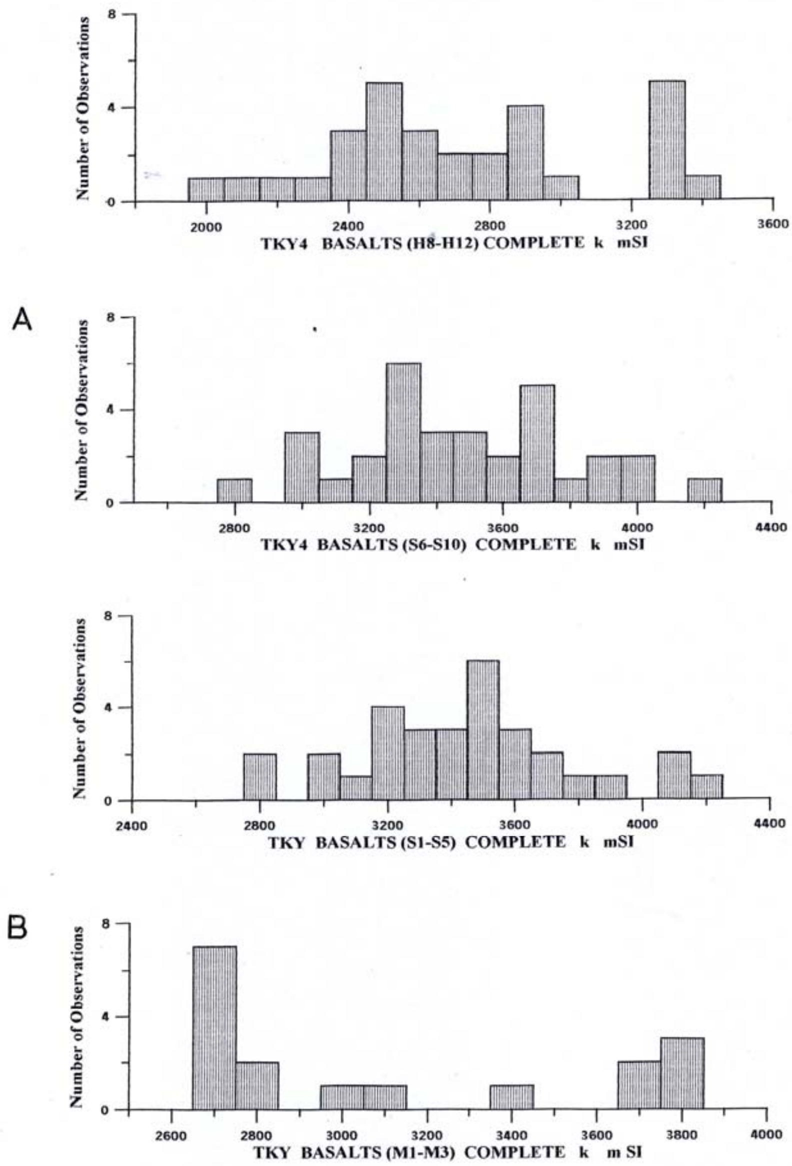

Fig. 6. Histogram showing the distribution of magnetic susceptibility of the complete samples.
A = TKY4 samples. B = TKY? Samples.

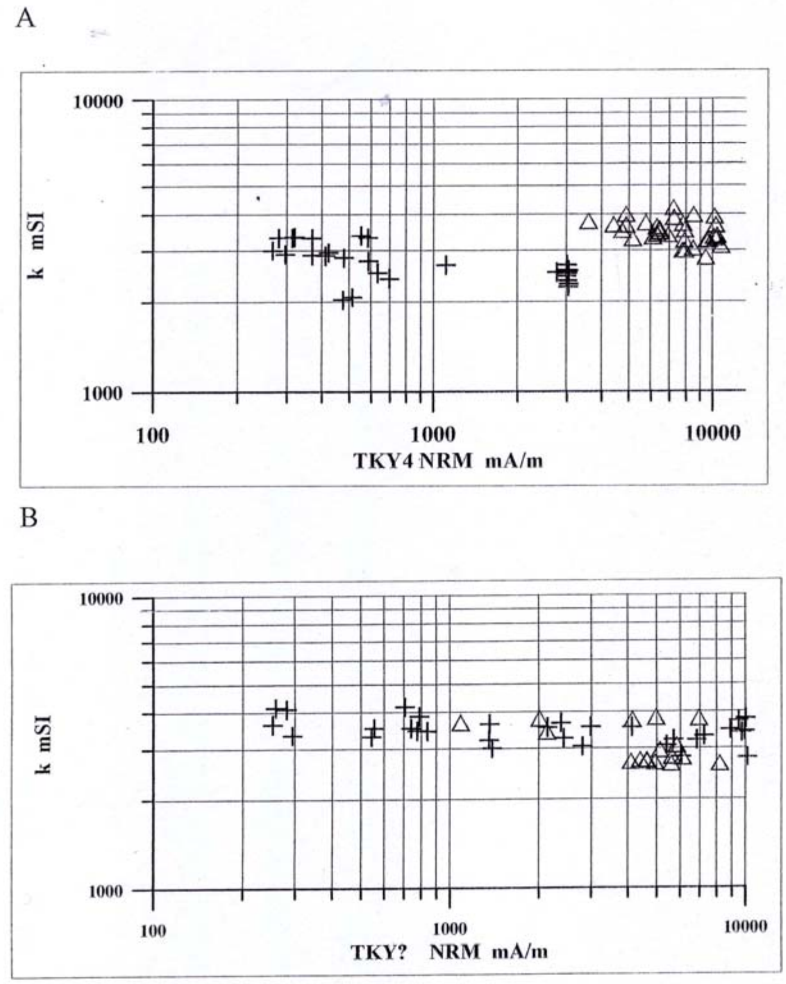

Fig. 7. Distribution of the magnetic susceptibility versus intensity of NRM of the complete samples.
A = TKY4 samples. B = TKY? Samples.

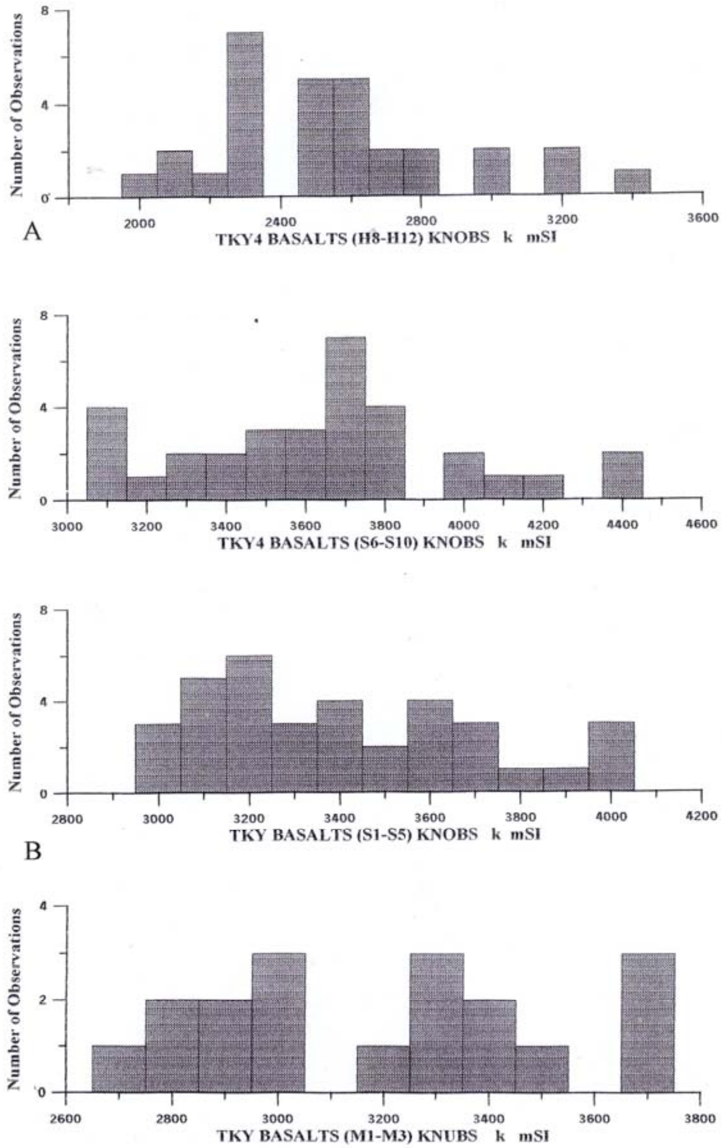

Fig. 8. Histogram showing the distribution of magnetic susceptibility of the samples' knobs.
A = TKY4 samples. B = TKY? Samples

Table 6. Gives the minimum, maximum NRM intensity of the complete samples and the minimum, maximum and the mean magnetic susceptibility of the complete samples and their knobs, and the Standard Deviation of each mean.

Measured component	TKY4		TKY?	
	YS6-YS10	**YH8-YH12**	**YS1-YS5**	**YM1-YM3**
Minimum NRM intensity of the complete samples	942	704	135	3031
Maximum NRM intensity of the complete samples	2213	1916	435	3971
Minimum susceptibility of the complete samples	2834	2033	2777	2652
Maximum susceptibility of the complete samples	4198	3379	4167	3814
Susceptibility Of complete samples	3479± 327	2725± 388	3455± 346	3098± 481
Minimum susceptibility of the samples knobs	3060	2040	2953	2678
Maximum susceptibility of the samples knobs	4420	3388	3995	3750
Susceptibility Of samples knobs	3628± 351	2556± 340	3394± 303	3193± 316

The ac current electrical conductivity of the samples knobs:

The ac current electrical conductivity of the 115 samples knobs was measured and found to be less than 1 mhos/m. This result differs to some extent from the results of the Syrian rocks (Abou-Deeb, 1997a,b,1998), where some of the rocks showed higher values of the electrical conductivity.

Density of the samples knobs:

The density of 115 sample knobs was measured (Fig. 9, Table 7) in order to distinguish between the different basaltic flows and to calculate the mean density of the rocks in order to be used in any future gravity interpretation of the area. The density of the TKY4 samples knobs of sites YS6-YS10 ranged between 2.48 g/cm^3 and 2.90 g/cm^3 with a mean 2.64±0.13 g/cm^3, and that of YH8-YH12 ranged between 2.71 g/cm^3 and 2.91 g/cm^3 with a mean 2.80±0.06 g/cm^3, and the mean of all the TKY4 is 2.72±0.14 g/cm^3, while the density of the TKY? samples knobs of sites YS1-YS5 ranged between 2.82 g/cm^3 and 2.99 g/cm^3 with a mean 2.90±.

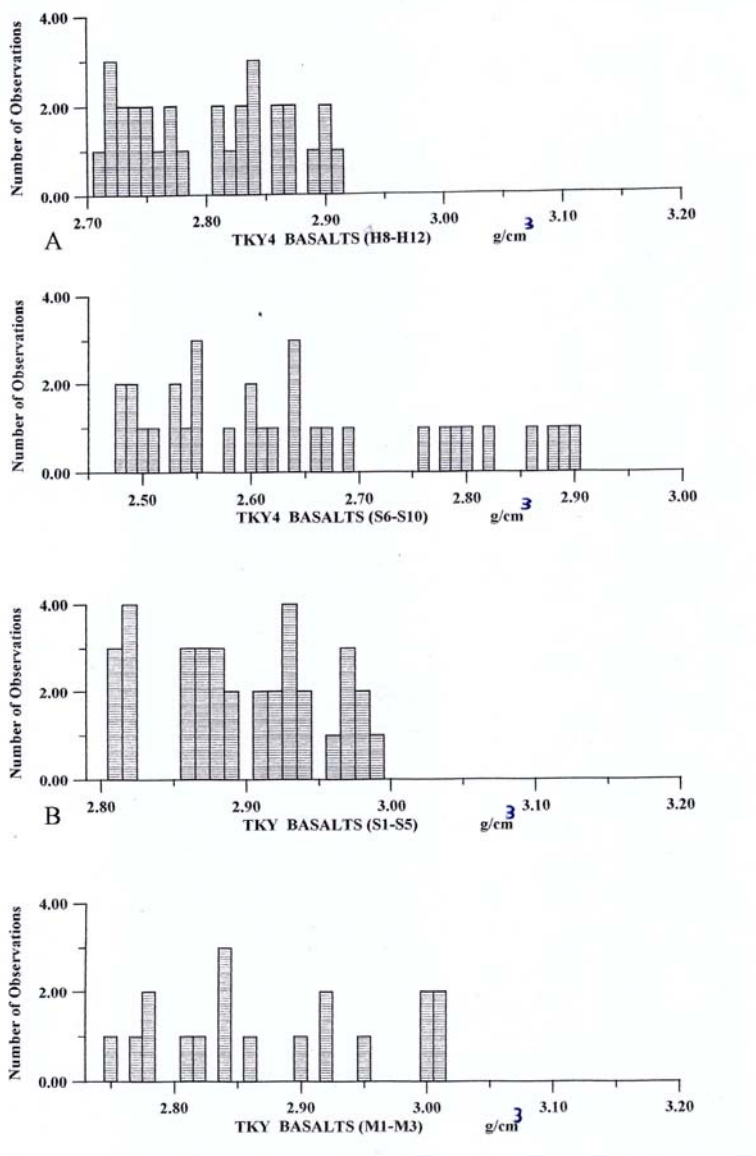

Fig. 9. Distribution of density of: A- TKY4 samples' knobs.
B- TKY? samples' knobs.

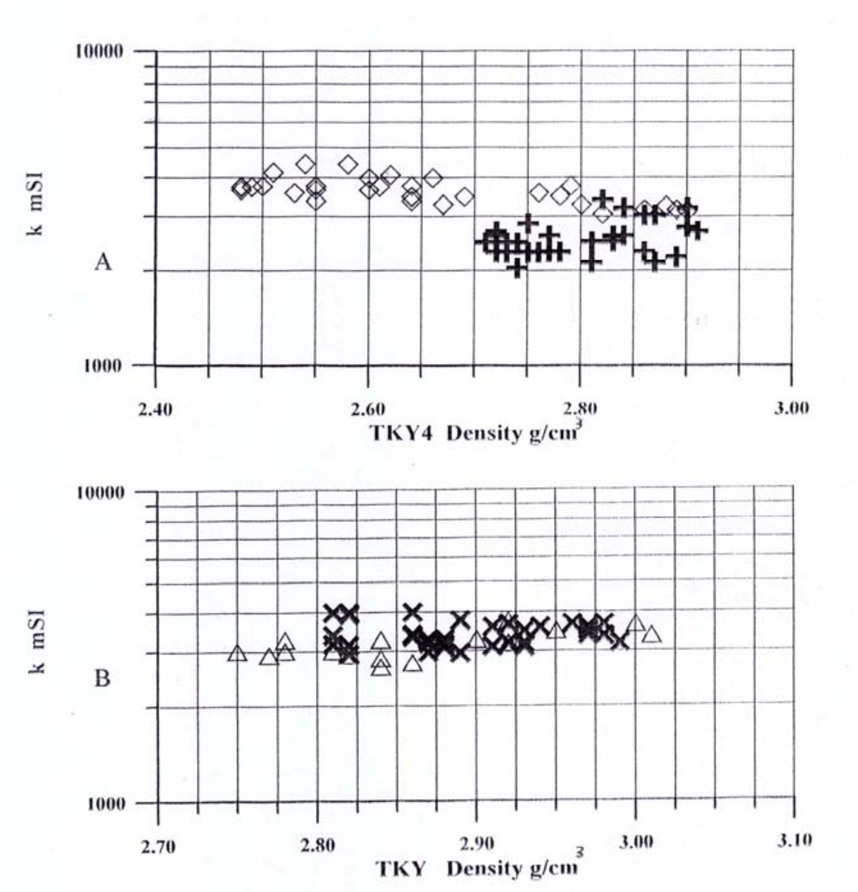

Fig.10. Distribution of the magnetic susceptibility versus density of: A- TKY4 samples' knobs. B- TKY? samples' knobs.

0.06 g/cm³, and that of YM1-YM3 ranged between 2.75 g/cm³ and 3.01 g/cm³ with a mean 2.88±0.09 g/cm³ and the mean of all the TKY? is 2.89±0.07 g/cm³. The Jabal Nahden samples showed low densities with a mean 2.64 ±0.13 g/cm³ and in general the TKY4 samples showed lower densities than the TKY? densities, inspite of the overlap of the ranges of all four sub-areas.

The relation between the density and the magnetic susceptibility is given in Figure 10A (TKY4) and Figure 10B (TKY?), which do not show remarkable changes in the magnetic susceptibility with the increase of density.

Table. 7. Sub-Area names, site numbers, site mean density, number of samples, sub-area mean density, overall mean density of TKY4 and TKY? sites and the Standard Deviation of each mean density.

Sub-Area Name	Site number and the mean density of each site g/cm^3	No. of Samples	Mean of each Sub-Area	Mean of each rock age
Jabal Nahden	YS6= 2.86 YS7= 2.71 YS8= 2.59 YS9= 2.58 YS10= 2.52	32	2.64 ± 0.13	TKY4
Jabal Asr	YH8= 2.83 YH9= 2.85 YH10= 2.75 YH11= 2.74 YH12= 2.85	30	2.80 ± 0.06	2.72 ± 0.14
Jabal Nuqum	YS1= 2.93 YS2= 2.85 YS3= 2.90 YS4= 2.96 YS5= 2.85	35	2.90 ± 0.06	TKY?
Sa'awan	YM1= 2.95 YM2= 2.85 YM3= 2.83	18	2.88 ± 0.09	2.89 ± 0.07
Number of samples		115		

Magnetic susceptibility of the rocks of the sampled field localities:

The magnetic susceptibility of the in situ rocks of the sampled areas was measured in order to determine the magnetic susceptibility of the different rocks in the studied areas to be used in the interpretation of any future magnetic study or the magnetic anomalies of the aeromagnetic map of the area. The susceptibility of the rocks of each sub-area was measured in 20 different points (the susceptibility of each point is the mean of three different measurements).

The magnetic susceptibility of the TKY4 rocks of Jabal Al-Nahden (Table 8) has a mean of 2410±225 mSI, and that of Jabal Asr has a mean of 2525±226 mSI. While the magnetic susceptibility of the TKY? rocks of Jabal-Nuqum has a mean of 1398±245 mSI, and that of Sa'awan has a mean of 1419±211 mSI.

It is clear that the field magnetic susceptibilities are in general lower than those of the complete and knobs of the samples, but the differences between them are larger for TKY? than for TKY4, which is difficult to explain.

Table. 8. The magnetic susceptibility values of the sampled field localities, the mean of each point in the four localities with the overall mean of each locality and the Standard Deviation of each locality mean value.

Age	TKY4		TKY?	
Site Number / Point No.	YS6-YS10	YH8-YH12	YS1-YS5	YM1-YM3
1	2350	2350	1675	1200
2	2300	2400	1300	1300
3	2650	2350	1575	1150
4	2650	2400	1300	1200
5	2350	2400	1300	1300
6	2200	2550	1100	1400
7	2200	2350	1100	1675
8	2350	2550	1825	1675
9	2350	2550	1100	1400
10	2050	2800	1875	1675
11	2650	2850	1150	1675
12	2800	2400	1575	1100
13	2700	2200	1150	1350
14	2100	2200	1575	1150
15	2350	2850	1400	1300
16	2650	2850	1575	1675
17	2200	2800	1400	1675
18	2450	2400	1575	1400
19	2650	2400	1200	1400
20	2200	2850	1200	1675
Mean of Area	2410± 225	2525± 226	1398± 245	1419± 211

Conclusion

The results of this study could be summarized as follows:

1- Demagnetisation of the complete rock samples led to the isolation of a stable magnetic component. The overall Site Mean Direction of eight sites of reverse polarity has a Dec=173.93°, Inc=-6.80°, k=32, $\propto_{95}$=10°.

2- An overall Virtual Geomagnetic Pole (VGPs) of the accepted sites, of the Upper Oligocene, is at Long=71.33°, Lat=-76.63°, k=35, $\propto_{95}$= 9.4°).

3- An overall mean direction of the seven TKY1 sites (Abou-Deeb, 2004) and the eight TKY? sites of the Upper Oligocene is calculated at Dec= 0.58°, Inc= 8.74°, with k= 23, $\propto_{95}$= 8.2° and the VGP is calculated at Long= 221.07°, Lat= 79.18°, with k=25, $\propto_{95}$= 7.8°), which could be regarded as a new palaeomagnetic pole of the Upper Oligocene.

4- It is most probable that the magnetic mineral of the basaltic rocks is magnetite with small amounts of other magnetic minerals.

5- The magneto-stratigrahy of the studied area is summarized as followes:
The Tawilah Group Sediments of the Cretaceous and Paleocene age was followed by the TKY? igneous activity which started in Sana'a region by the Jabal Nuqum volcanic activity during the reverse chron C11n.1r (30.071-29.633 My ago) then followed by the Sa'awan volcanic activity during the reverse chron C10r (29.008-28.995 My ago) then followed by TKY1 igneous activity which probably started during the normal chron C10n (28.716-28.255 My ago) or C9n (27.946-27.004 My age) in Al-Hudyadah region.

6- The ac current electrical conductivity is low.

7-The calculated means of the density of the rocks could be used in the interpretation of any future gravity study of the different areas. The density of the TKY4 rocks of Jabal Al-Nahden has a mean of 2.64±0.13 g/cm³, and that of Jabal Asr has a mean of 2.80±0.06 g/cm³, and the mean of all TKY4 is 2.72±0.14 g/cm³, while the density of the TKY? rocks of Jabal Nuqum has a mean 2.90± 0.06 g/cm³, and that of Sa'awan with a mean 2.88± 0.09 g/cm³ and the mean of all TKY? is 2.89±0.07 g/cm³.

8-The magnetic susceptibility of the rocks of the sampled field localities could be used in the interpretation of any future magnetic or aeromagnetic study of the different areas. The magnetic susceptibility (Table 8) of the TKY4 rocks of sites YS6-YS10 area ranged between 2050 mSI and 2650 mSI, with a mean of 2410±225 mSI, and that of sites YH8-YH12 area ranged between 2200 mSI and 2850 mSI, with a mean of 2525±226 mSI. While the magnetic susceptibility of the TKY? rocks of sites YS1-YS5 area ranged between 1100 mSI and 1825 mSI, with a mean of 1398±245 mSI, and that of sites YM1-YM3 area ranged between 1100 mSI and 1675 mSI, with a mean of 1419±211 mSI.

It is clear that the field magnetic susceptibilities are in general lower than those of the complete and knobs of the samples, but the differences between them are larger for TKY? than for TKY4, which is difficult to explain.

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