# Study of Palaeomagnetism and Some Magnetic and Physical Properties of Some Tertiary Igneous Rocks between Sana'a and Al-Hudyadah Region (Republic of Yemen)

**Jamal Abou-Deeb**

**Department of Geology-Faculty of Sciences-University of Damascus-Syria**

**Received 12/03/2003**
**Accepted 21/12/2003**

## ABSTRACT

**Palaeomagnetism and some magnetic and physical properties (magnetic susceptibility, intensity of the Natural Remnant Magnetization (NRM), ac current electrical conductivity and density) of 136 samples from 22 sites of the Yemen Volcanic Group TKY (Tertiary and (or) Cretaceous) from igneous rock exposures along the road from Sana'a – west towards Al-Hudyadah were studied. A single population consists of seven Virtual Geomagnetic Poles (VGP), of the Upper Oligocene, was accepted and a mean at 182.81° E, 77.44° N with $\alpha_{95}$= 12.5° was calculated. The different properties were measured in order to use these properties as characteristic factors to discriminate the neighboring igneous flows. The measurement of the in situ magnetic susceptibility of 140 points, distributed on 7 sub-areas, in the region helped to calculate the mean value of the magnetic susceptibility of each sub-area, which might be used in any magnetic interpretation of aeromagnetic or magnetic anomalies. Also, the density of 132 samples were measured and a mean value of the density of each sub-area was calculated in order to be used in any future interpretation of any gravity anomaly in the area.**

**Key Words:** Magnetic susceptibility, palaeomagnetism, NRM = Natural Remnant Magnetization, ac current electrical conductivity, density, Virtual Geomagnetic Poles (VGPs), basalt, ignembrite, welded tuffs, basic porphyrites, agglomerate, Yemen Volcanic Group, Sana'a, Al-Hudyadah, Manakhah.

# دراسة المغنطيسية القديمة وبعض الخصائص المغنطيسية والفيزيائية لبعض الصخور الاندفاعية بين صنعاء ومنطقة الحديدة (الجمهورية اليمنية)

**جمال أبو ديب**

قسم الجيولوجيا ـ كلية العلوم ـ جامعة دمشق

تاريــخ الإيداع 2002/03/12

قبل للنشــر في 2003/12/21

## الملخص

**قيست المغنطيسية القديمة، وبعض الخصائص المغنطيسية والفيزيائية: المتأثرية المغنطيسية، والشدة المغنطيسية الأولية، والناقلية الكهربائية (بالتيار المتناوب) والكثافة لـ 136 عينة صخرية مأخوذة مـن 22 موقعاً من مجموعة صخور اليمن الاندفاعية (عائدة للعصر الثلاثي وإلى الكريتاسي)، مـن تكـشفات على جانبي طريق صنعاء-الحديدة. لقد أمكن عزل مجموعة من سبعة أقطاب مغنطيسية (من الأوليغوسين الأعلى) أعطت قيماً وسطية مقدارها 182.81° شرقاً، 77.44° شمالاً $\alpha_{95}$= 12.5° كمـا تـم قيـاس الخصائص الفيزيائية المختلفة لاستخدامها كعوامل مميزة بين صخور الصبات البركانية المتجاورة. وكذلك قيست حقلياً المتأثرية المغنطيسية لصخور المنطقة موضوع الدراسة في 140 موقعاً، موزعـة علـى 7 مناطق جزئية، مما سمح بالحصول على قيمة وسطية للمتأثرية المغنطيسية لكل منها تسهم فـي تفـسير الشواذ المغنطيسية المصادفة في الخريطة المغنطيسية، أو تلك الناتجة عن أي مسح مغنطيسي جـوي أو أرضي في المنطقة. كما تم قياس الكثافة لـ 136 عينة من المنطقة موضـوع الدراسـة، ممـا سـمح بالحصول على قيم متوسطة للكثافة لكل تحت-منطقة، يمكن استخدامها في تفسير الـشذوذات الجاذبيـة المصادفة في خريطة الجاذبية، أو تلك الناتجة عن أي مسح جاذبي في المنطقة.**

**الكلمات المفتاحية:** المتأثرية المغنطيسية، المغنطيسية المتبقية الأوليـة، الناقليـة الكهربائيـة (بالتيار المتناوب)، الكثافة، بازلت، اغنمبريت، طف ملـتحم، بورفيريـت أساسي، أغلوميريت، مجموعة صخور اليمن الاندفاعية، صنعاء، الحديدة، مناخة.

# Introduction

The present study is a part of a palaeomagnetic research project. Sampling was achieved during 1991-1992 and some measurements were achieved during a month-long visit to Yemen during 1998. This project included igneous and sedimentary rocks, but the present study deals with the igneous rock samples, which palaeomagnetic stratigraphy were studied (Abou-Deeb *et al.*, 2002). The study includes paleomagnetism, magnetic susceptibility, natural remnant magnetization (NRM), ac current electrical conductivity and density of 132 rock samples and their knobs of TKY1, TKY4 of the Yemen Volcanic Group. Also the magnetic susceptibility of 140 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 rocks (Henkel, 1976, Saad, 1969). In a previous paper, of this project the auther (Abou-Deeb, 2000) presented a similar study on igneous rocks from Dhamar Region of Yemen.

## Geology of the Yemen Volcanic Group

In a previous paper, of this project the auther (Abou-Deeb, 2000) gave a summary of the geology of Yemen, so in order to avoid repetition only the geology of the Yemen Volcanic Group is presented in this paper.

The Yemen Volcanic Group (TKY) started during an intense volcanic and intrusive activity (Geukens, 1966; Abu Khadra, 1982; El-Anbaawy, 1985) that continued throughout most of the Cenozoic, to cover 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 and continued to the present day (Grolier &.Overstreet, 1983). 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 dark 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.

TKY3 predominantly felsic and tuffaceous.

TKY2 predominantly felsic and tuffaceous.

TKY1 predominantly basaltic, but includes green felsic conglomerate, porphyritic trachyte and pink tuffs and overlies the Tawilah Group sediments (Al-Nakhal, 1988, 1990).

Numerous studies (Civette *et al*., 1978, Capaldi *et al*., 1983, 1987a,b, c, Chiesa *et al*., 1989, Menzies *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. Table 1 gives all the available data about the well documented dated samples from the studied area, while some data were disregarded due to the absence of the coordinates of the sampling location. It is clear from Table 1 that the age of the rock types range in age from 23.20±0.40 Ma to 29.34±0.12 Ma.

**Table 1. Gives all the available information about the dated samples from the studied area.**

| Sample No. & dating method | Rock Type & nearby sites | Lat. ( N ) ° ′ ″ | Long. ( E ) ° ′ ″ | Age Ma. | Ref. |
|---|---|---|---|---|---|
| YN3 K/Ar | Rhyolite Near YH2 | 15 14 00 | 44 00 00 | 24.10±0.40 | Huchon *et al.,* (1991) |
| JB216 $Ar^{40}/Ar^{39}$ | Air fall Tuff Near YH2 | 15 14 02 | 44 00 30 | 29.34±0.12 | Baker *et al.,* (1996) |
| JB221 $Ar^{40}/Ar^{39}$ | Air fall Tuff Near YH2 | 15 14 02 | 44 00 30 | 28.21±0.10 | Baker *et al.,* (1996) |
| JB228-II $Ar^{40}/Ar^{39}$ | Ignimbrite Near YH2 &YH3-4 | 15 15 33 | 43 59 25 | 28.18±0.14 | Baker *et al.,* (1996) |
| JB232 $Ar^{40}/Ar^{39}$ | Rhyolite Near YH3-4 | 15 16 32 | 43 58 57 | 27.75±0.10 | Baker *et al.,* (1996) |
| JB227-II $Ar^{40}/Ar^{39}$ | Ignimbrite Near YH3-4 | 15 16 47 | 43 58 41 | 26.94±0.20 | Baker *et al.,* (1996) |
| YN10 K/Ar | Rhyolite Near YH5-7 | 15 13 00 | 43 59 00 | 23.20±0.40 | Huchon *et al.,* (1991) |

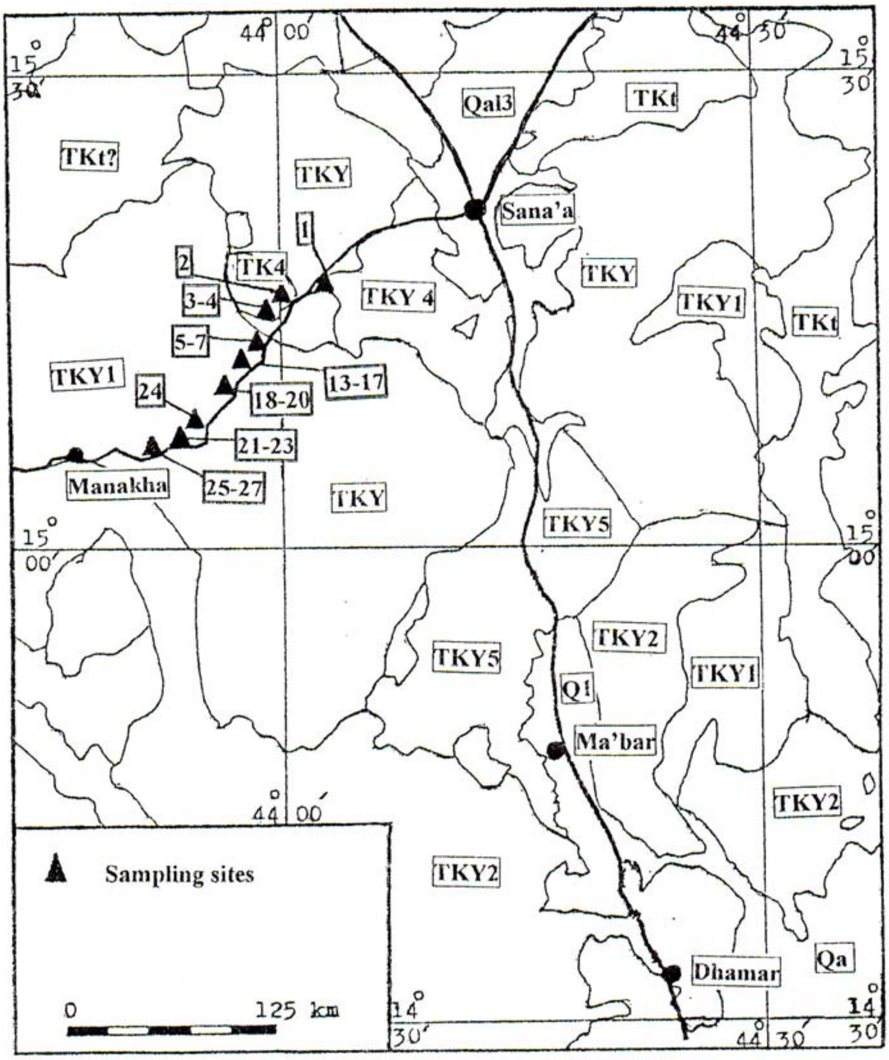


Fig. 1. Geology of the studied area and site locations. Numbers are defined in the text.

## Sampling, measurements and analysis

Sampling was undertaken, using field drill, and orientation by sun compass. The studied samples were sampled from igneous rock exposures from eight different locations along the roadside from Sana'a west towards Al-Hudyadah.

Sites YH1-YH7, YH18-YH20, YH25-YH27 are from basaltic flows, site YH21-YH23, are from welded tuffs, sites YH13-YH14 are from agglomerates, sites YH15-YH17 are from basic porphyrites and site YH24 is from ignembrite (Fig. 1, Table 2):

**Table 2. Gives the sub-area names, rock age, number of sites, sub-area coordinates and number of samples.**

| Sub- Area Number and Name | Age | No. of sites | Latitude (N) ° | ′ | ″ | Longitude (E) ° | ′ | ″ | No. of samples |
|---|---|---|---|---|---|---|---|---|---|
| **1-** Mend Village | TKY4 | YH 1 | 15 | 18 | 00 | 44 | 04 | 00 | 6 |
| **2-** Matna Village | TKY4 | YH 2-YH 4 | 15 | 14 | 00 | 44 | 01 | 00 | 18 |
| **3-** Jabal Al-Manar | TKY1 | YH 5-YH 7 | 15 | 09 | 40 | 43 | 57 | 00 | 19 |
| **4-** 60 km from Sana'a | TKY1 | YH 13-YH 17 | 15 | 08 | 30 | 43 | 56 | 30 | 30 |
| **5-** 65 km from Sana'a | TKY1 | YH 18-YH 20 | 15 | 08 | 00 | 43 | 56 | 00 | 18 |
| **6-** 75 km from Sana'a | TKY1 | YH 21-YH 23 | 15 | 06 | 30 | 43 | 54 | 30 | 20 |
| **7-** 70 km from Sana'a | TKY1 | YH 24 | 15 | 07 | 00 | 43 | 55 | 30 | 6 |
| **8-** 85 km from Sana'a | TKY1 | YH 25-YH 27 | 15 | 06 | 30 | 43 | 53 | 00 | 19 |
| Total Number | | 22 | | | | | | | 136 |

Samples were sliced to provide one standard palaeomagnetic cylinder, 2.5 cm in diameter, 2.1 cm high, from each drill core (Tarling, 1983). The following instruments were used as previously mentioned (Abou-Deeb, 2000) to achieve all the required measurements:

1- Molspin spinner magnetometer (Molyneux, 1971).
2- Low field magnetic susceptibility meter (LFMSM) (Collinson, 1983).
3- Thermal demagnetizer.
4- Rock's physical properties testing system (CTU-2) (SCINTREX, 1981).

Following the measurement of the natural remanent magnetization (NRM) and magnetic susceptibility of the samples, 4 pilot samples (YH1.1, YH7.6, YH14.6 and YH23.2) were subjected to detailed thermal demagnetization (Fig. 2 & 3) 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. Studying the Consistency Range (Tarling & Symons, 1976) 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 by the conventional method that is using a sensitive balance to weigh the sample and its volume was measured by the displacement of water in a calibrated test tube.

The following components were measured:

1. Palaeomagnetism and magnetic susceptibility of the complete samples.
2. Magnetic susceptibility and intensity of the pilot samples.
3. Magnetic susceptibility of the samples' knobs.
4. The ac current electrical conductivity of the samples' knobs.
5. Density of the samples' knobs.
6. In situ 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 specimens.**

| Sample No. | CI | $Range_c$ | $Dec._c$ | $Inc._c$ | da | $range_d$ | $Dec._d$ | $Inc._d$ |
|---|---|---|---|---|---|---|---|---|
| TKY4 | | | | | | | | |
| YH 1.1 | 1.7 | 20-100 | 289.2 | -10.1 | 0.6 | 0-500 | 318.9 | 17.5 |
| TKY1 | | | | | | | | |
| YH7.6 | 2.0 | 20-100 | 5.4 | -0.2 | 6.4 | 50-200 | 12.8 | -1.7 |
| YH14.6 | 5.6 | 200-500 | 55.3 | 34.7 | 5.1 | 100-400 | 49.3 | 57.3 |
| YH23.2 | 2.4 | 20-400 | 19.7 | 13.7 | 4.8 | 50-300 | 354.1 | 6.7 |

# Results

## Palaeomagnetism and magnetic susceptibility of the complete samples

The magnetic susceptibility (Fig. 2) and intensity of magnetization (Fig. 3) of one pilot sample (YH1.1) of TKY4, and three samples (YH7.6, YH14.6 and YH23.2) of TKY1, were studied in order to determine if any thermo-chemical changes had occurred to the magnetic minerals during heating. This will help in the extrapolation of the magnetic mineral that carries the magnetization of the rocks. The normalized magnetic intensity of all samples (Fig. 3) suggests that the main carrier of magnetization is magnetite.

Fig. 2 shows variable changes in the magnetic susceptibility of all samples which indicate the presence of small amounts of other magnetic minerals and started to change, after heating to 150 °C, to other minerals of higher susceptibility (like magnetite). While the decrease in the susceptibility after heating between 500 °C and 600 °C probably due to oxidation of magnetite to haematite.

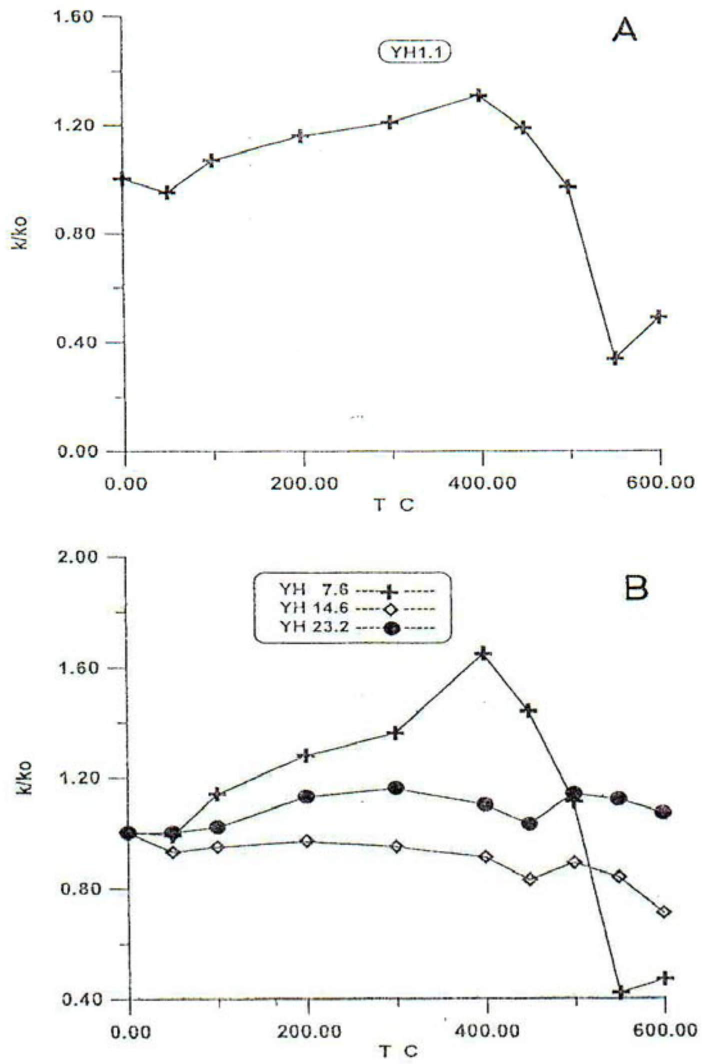


**Fig. 2. Curves of normalized magnetic susceptibility of the pilot samples: A- TKY4 sample, B- TKY1 samples.**

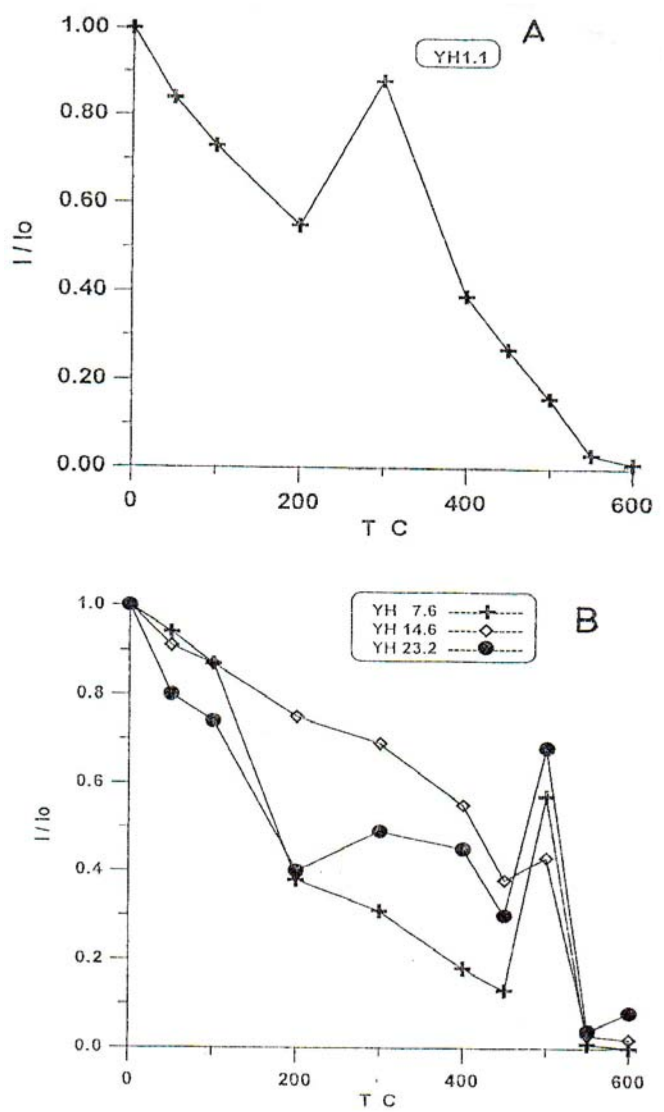


**Fig. 3. Curves of normalized intensity of magnetization of the pilot samples: A- TKY4 sample, B- TKY1 samples.**

The site mean directions of all sites were calculated after demagnetization at 200 °C (Table 4). Sites YH18, YH19, YH25 and

YH27 were excluded, because their directions were highly scattered. The TKY4 sites showed reverse, intermediate normal and intermediate reverse polarity. While the TKY1 sites showed normal and intermediate normal polarity. The TKY1 site mean directions were drawn on an equal area projection (Fig. 4A). Although site YH6 is of normal polarity, but its mean direction is far from the rest of the group, which may be due to some unnoticed local movement of the sampled rock. The intermediate normal (YH5, YH14, YH15, YH17, YH20,YH26) sites were excluded because such sites are regarded to had been magnetized during an excursion movement of the geomagnetic pole or during the transitional period of the geomagnetic field reversal.

**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 declination, Inc. is site mean inclination, k is precision factor and $\alpha_{95}$ 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 | $\alpha_{95}$ | VGP | | Polarity |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Lat. | Long. | |
| TKY4 | | | | | | | | |
| YH1 | 6/6 | 240.0 | 6.4 | 6 | 28.9 | -27.8 | 310.9 | Ri |
| YH2 | 6/6 | 124.8 | 54.7 | 302 | 3.9 | -17.4 | 88.2 | Ri |
| YH3 | 6/6 | 214.0 | -26.2 | 34 | 11.7 | -57.1 | 311.9 | R |
| YH4 | 5/6 | 289.0 | 6.2 | 14 | 21.0 | 19.0 | 312.0 | Ni |
| TKY! | | | | | | | | |
| YH5 | 5/6 | 314.0 | 18.3 | 22 | 16.6 | 44.8 | 312.1 | Ni |
| YH6 | 5/6 | 322.7 | 22.9 | 17 | 19.0 | 53.6 | 313.5 | N |
| YH7 | 5/6 | 9.2 | 11.6 | 18 | 18.6 | 77.0 | 178.9 | N |
| YH13 | 6/6 | 28.4 | 3.9 | 350 | 3.6 | 59.1 | 156.3 | N |
| YH14 | 6/6 | 49.5 | 31.4 | 79 | 7.6 | 42.5 | 124.5 | Ni |
| YH15 | 6/6 | 280.3 | 16.5 | 138 | 5.7 | 12.1 | 319.5 | Ni |
| YH16 | 4/6 | 348.2 | 23.6 | 46 | 13.7 | 78.2 | 301.7 | N |
| YH17 | 6/6 | 302.2 | 5.9 | 67 | 8.3 | 31.8 | 307.9 | Ni |
| YH20 | 5/6 | 132.1 | 32.8 | 8 | 28.4 | -32.4 | 100.7 | Ni |
| YH21 | 4/6 | 15.3 | 5.0 | 21 | 20.0 | 70.3 | 172.7 | N |
| YH22 | 6/6 | 8.2 | 7.8 | 225 | 4.5 | 76.2 | 187.3 | N |
| YH23 | 6/6 | 22.1 | 17.5 | 16 | 17.5 | 67.5 | 147.2 | N |
| YH24 | 5/6 | 345.7 | 4.0 | 98 | 7.8 | 70.8 | 272.4 | N |
| YH26 | 6/6 | 71.8 | -27.2 | 50 | 9.6 | 13.0 | 153.3 | Ni |

The mean site directions of the accepted sites, (YH7, YH13, YH16, YH21-YH24), which are all of normal polarity and of the Upper

Oligocene, are drawn in Fig. 4B, and the calculated overall mean site direction of the accepted sites has Dec.= 8.36°, Inc.= 10.83° with $\alpha_{95}$ =13.3°. The Virtual Geomagnetic Poles (VGPs) of the accepted sites are drawn in Fig. 5. The overall mean of the VGPs is at 182.81°E, 77.44°N, $\alpha_{95}$ =12.5°.

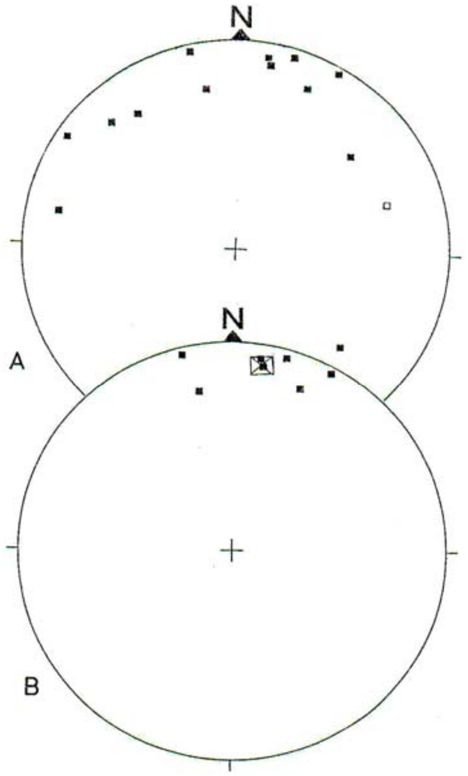


**Fig. 4. TKY1 site mean directions after demagnetization at 200 °C on an equal area projection. Positive (downward) inclinations are shown with solid squares and negative (upward) inclinations are shown with hollow squares.**
**A- All TKY1 sites. B-The accepted sites. The centre of the hollow rectangle is the overall mean site direction of the accepted sites.**

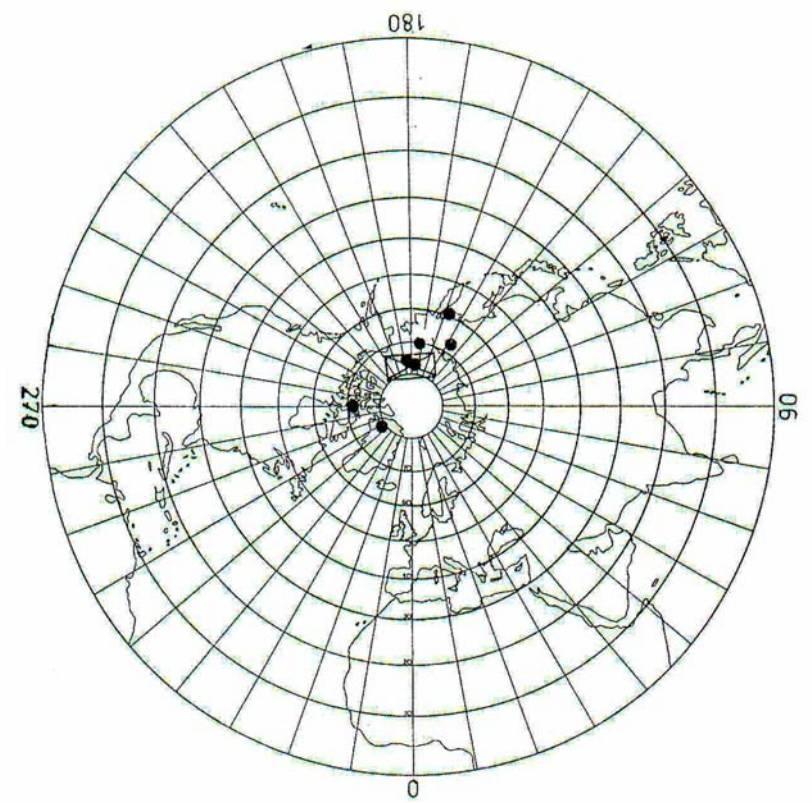


**Fig. 5. Virtual Geomagnetic Poles derived from site mean directions plotted in Fig. 4. The overall mean of the VGPs is represented by the centre of the hollow rectangle.**

The susceptibility of the 24 TKY4 basaltic rock samples (Fig. 6A) of sub-areas (1 & 2) ranges between 3014 mSI and 3988 mSI with a mean of 3449 ± 288 mSI, and their NRM intensity range between 942 mA/m and 2213 mA/m (Table 5).

The susceptibility of the TKY1 rock samples was measured in six sub-areas (3-8) (Fig. 6B). Table 5 gives the minimum, maximum and the mean magnetic suscebtibility of the complete samples.

Apart from the basic porphyrite there is a direct proportionality between the magnetic susceptibility and the NRM (Fig. 7A&7B).

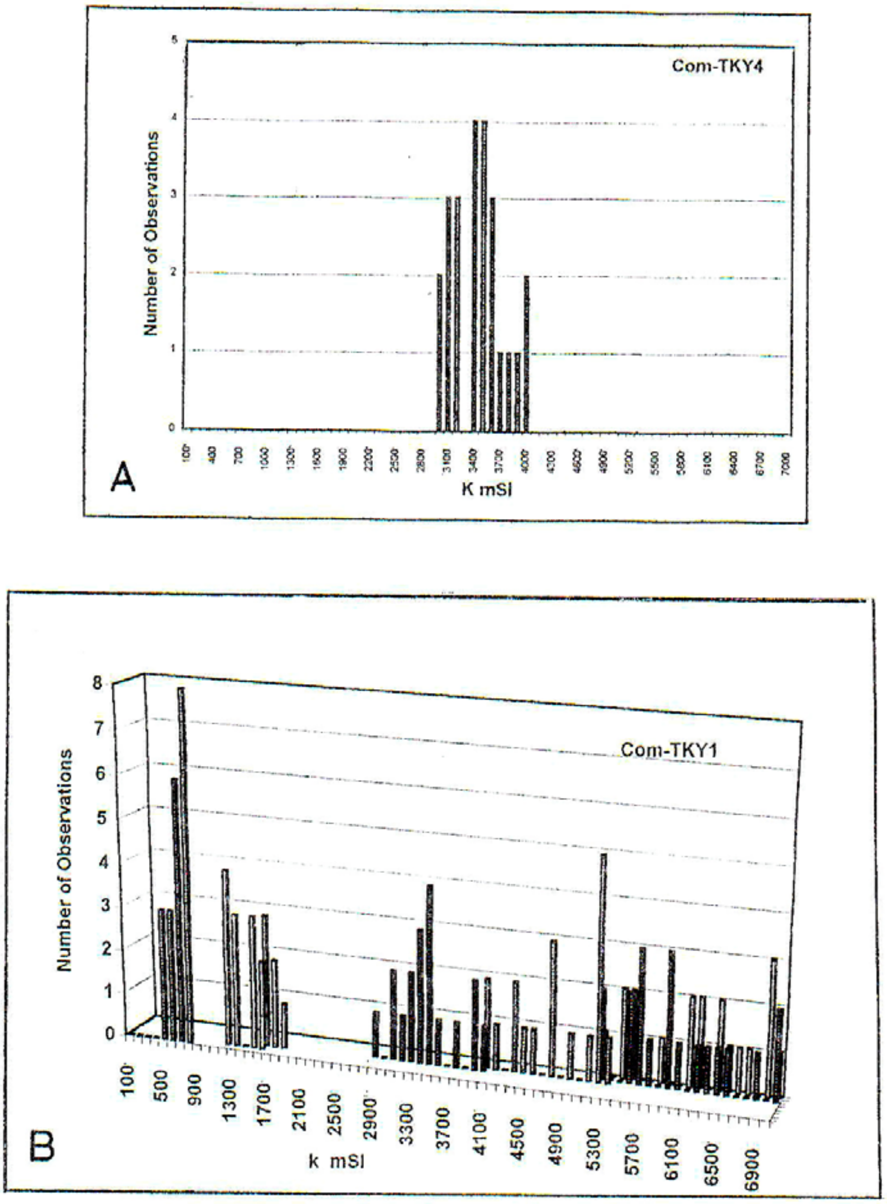


**Fig. 6. Histogram shows the distribution of magnetic susceptibility of the complete samples. A-TKY4 samples, B-TKY1 samples.**

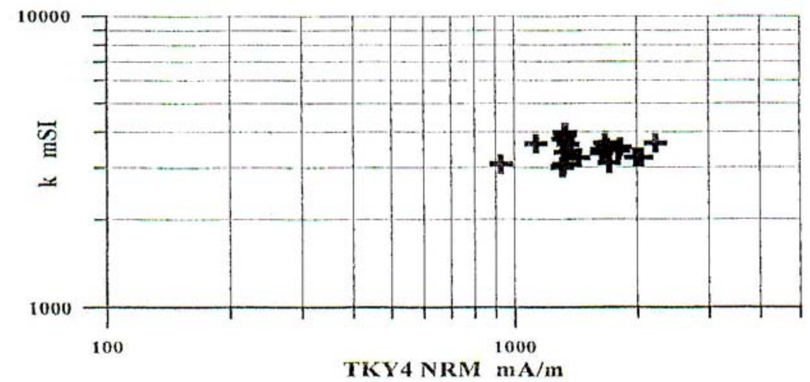


**Fig. 7A. Distribution of the magnetic susceptibility versus intensity of NRM of the complete TKY4 samples.**

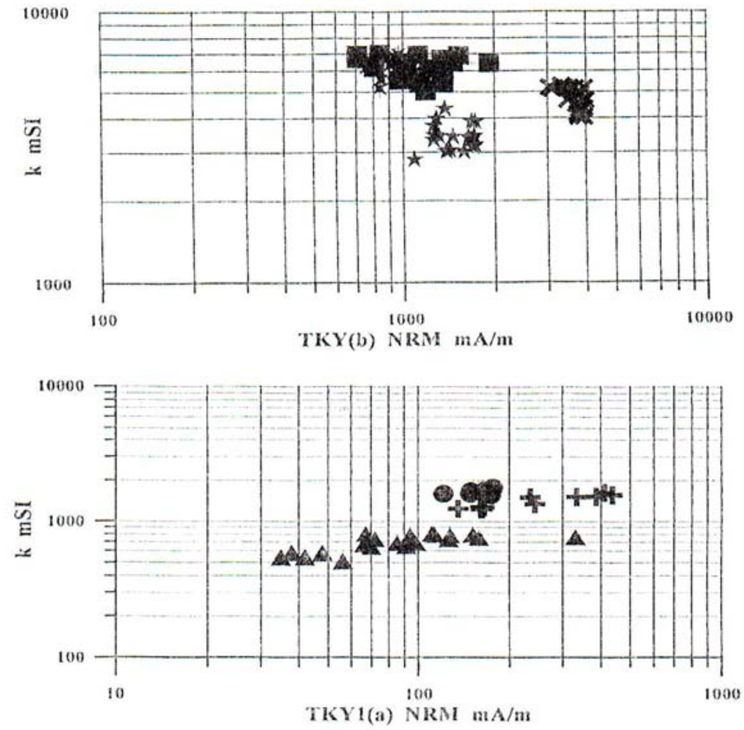


**Fig. 7B. Distribution of the magnetic susceptibility versus intensity of NRM of the complete TKY1 samples.**

**(a)- ▲ - Welded tuffs, ● - ignembrite, + - agglomerate. (b)- ■ - Basalt (sub-area 3), ★basalt(sub-area 5), ✖ -basalt (sub-area 8), x - basic porphyrites.**

### Magnetic susceptibility of the samples knobs:

The magnetic susceptibilities of the 136 sample knobs (Fig. 8A, 8B) were measured to compare them with the magnetic susceptibility of the complete samples. The susceptibility of the 24 TKY4 basaltic rock knobs of sub-areas (1 & 2) (Fig. 8A) ranges between 3025 mSI and 3955 mSI with a mean of 3418 ± 325 mSI (Table 5).

The susceptibility of the TKY1 rock knobs was measured in six sub-areas (3-8) (Fig. 8B). Table 5 gives the minimum, maximum and the mean magnetic susceptibility of the samples knops.

**Table 5. Gives the minimum, maximum and the mean magnetic susceptibility of the complete samples and their knobs, the density of the samples' knobs and the Standard Deviation of each mean.**

| **Measured component** | **TKY4** | **TKY1** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | YH1-4 | YH5-7 | YH13-14 | YH15-17 | YH18-20 | YH21-23 | YH24 | YH25-27 |
| Minimum NRM intensity of the complete samples | 942 | 704 | 135 | 3031 | 1084 | 35 | 121 | 757 |
| Maximum NRM intensity of the complete samples | 2213 | 1916 | 435 | 3971 | 1721 | 328 | 176 | 1312 |
| Minimum susceptibility of the complete samples | 3014 | 5033 | 1230 | 4040 | 2826 | 507 | 1573 | 5158 |
| Maximum susceptibility of the complete samples | 3988 | 6977 | 1637 | 5270 | 3985 | 801 | 1777 | 6988 |
| Susceptibility Of complete samples | 3449± 288 | 6187± 598 | 1381± 156 | 4715± 442 | 3387± 322 | 689± 96 | 1650± 77 | 5995± 558 |
| Minimum susceptibility of the samples knobs | 3025 | 5270 | 1255 | 4080 | 2933 | 553 | 1596 | 5015 |
| Maximum susceptibility of the samples knobs | 3955 | 6730 | 1620 | 5440 | 4335 | 889 | 1785 | 5910 |
| Susceptibility Of samples knobs | 3418± 325 | 6245± 371 | 1409± 149 | 4670± 414 | 3318± 395 | 666± 108 | 1676± 71 | 5528± 349 |
| Density | 2.87± 0.05 | 2.95± 0.04 | 2.21± 0.04 | 3.19± 0.04 | 3.05± 0.04 | 2.26± 0.04 | 2.47± 0.03 | 2.89± 0.06 |

The comparison of Figure 6 and Figure 8 and the values of the means of the magnetic susceptibility of the complete samples and their knobs (Table 5) confirms the validity of the means of the magnetic susceptibiliy of these rocks and the reliability of any future use of these means.

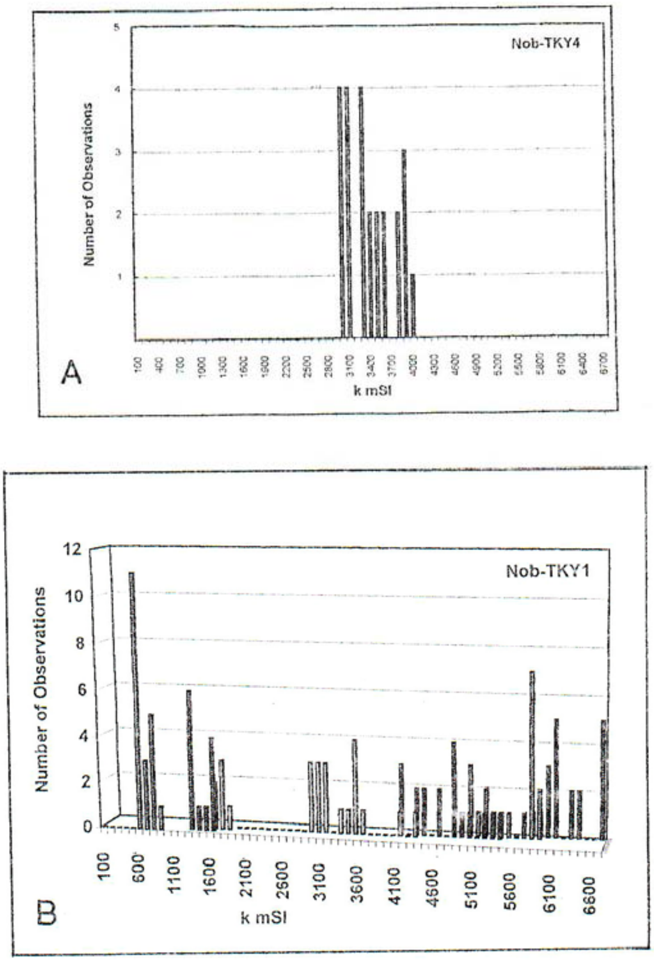


**Fig. 8. Histogram shows the distribution of magnetic susceptibility of the samples' knobs. A- TKY4 samples, B- TKY1 samples.**

In a recent study Hattom & Abou-Deeb (2001) used the magnetic suscebtibility to discriminate between different types of basalts (Hattom & Abou-Deeb, 2001(Table-3)), but it is hard to corrolate the Yemeni igneous rocks to the Syrian basalts due to the difference in age, locality and lithology.

### The ac current electrical conductivity of the samples knobs

The ac current electrical conductivity of all the samples knobs were measured and it was found that the conductivity of all the samples is less than 1 mhos/m. This is similar to the electrical conductivity of the Dhamar samples knobs (Abou-Deeb, 2000), but slightly differs from the results of the Syrian rocks (Abou-Deeb, 1997a, b, 1998) where some of the rocks showed higher electrical conductivity.

### Density of the samples knobs

The density of 136 sample knobs was measured (Fig. 9A,B,C, Table 6) in order to distinguish between the different igneous rocks 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 each rock type seems to be well grouped as shown in Figs. 9A, 9B and 9C and by the low Standard Deviation, which ranges between ± 0.03 g/cm³ and ± 0.06 g/cm³.

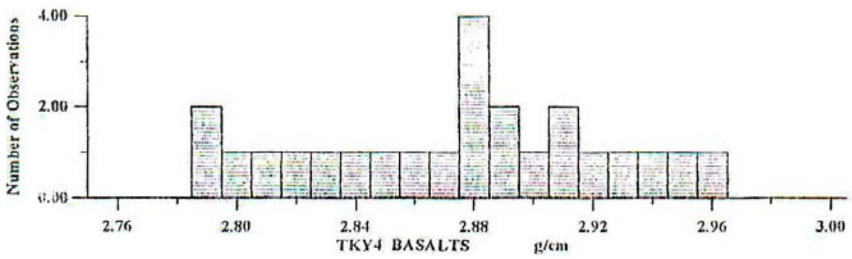


**Fig. 9A. Distribution of density of TKY4 samples' knobs.**

The mean density of the 24 TKY4 basaltic rock knobs of sub-areas (1 & 2) is 2.87 ± 0.05 g/cm³ (Fig. 9A) (Table 5).

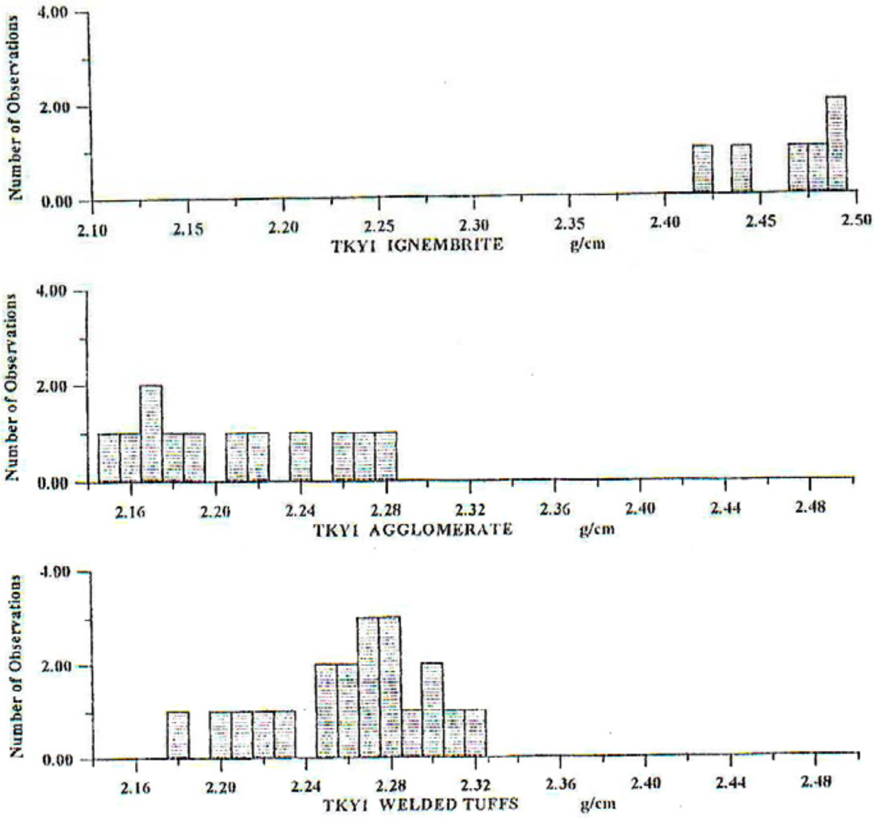


**Fig. 9B. Distribution of density of TKY1 samples' knobs. The low range of density values.**

The density of the TKY1 rocks was measured in six sub-areas (3-8). (Figs. 9B and 9C) The mean density of the basaltic rocks in sub-areas (3, 5 & 8) is 2.95 ± 0.04 g/cm³ (19 knobs), 3.05 ± 0.04 g/cm³ (18 knobs) and 2.89 ± 0.06 g/cm³(19 knobs) consequently. The mean density of the agglomerate knobs of sub-area (4) is 2.21 ± 0.04 g/cm³ (12 knobs). While the mean density of the basic porphyrite knobs of sub-area (4) is 3.19 ± 0.04 g/cm³ (18 knobs). The mean density of the welded tuff knobs of sub-area (6) is 2.26 ± 0.04 g/cm³ (20 knobs). And the mean density of the ignembrite knobs of sub-area (7) is 2.47 ± 0.03 g/cm³ (6 knobs) (Table 5).

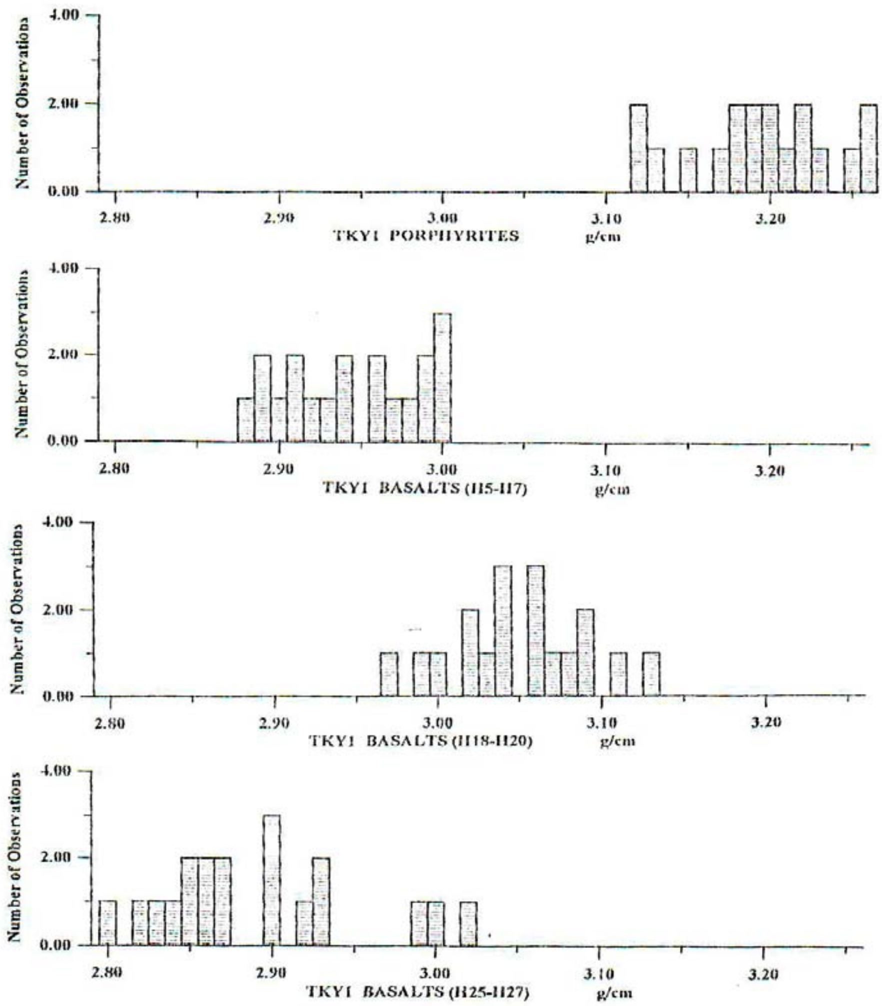


**Fig. 9C. Distribution of density of TKY1 samples' knobs. The high range of density values.**

The relation between the density and the magnetic susceptibility is given in Fig. 10A and Fig. 10B, which show large increase in the magnetic susceptibility with the increase of density. Fig. 11A shows the mean density of the TKY1 sample knobs versus the mean of the magnetic susceptibility of the complete samples of each rock type. And Fig. 11B shows the mean density of the TKY1 sample knobs versus the mean of the magnetic susceptibility of the sample's knobs of each rock type. Both figures show a direct proportionality relationship between the density and the magnetic susceptibility as indicated by the straight lines (A-A in Fig. 11A) (B-B in Fig. 11B).

**Table 6. Age, type of rock, site number, site mean density, number of samples, sub-area's mean density and the Standard Deviation of each mean density.**

| Age<br>Rock type | Site number and the mean density of each site g / cm$^3$ | | No. of Samples | Mean of each sub- area |
|---|---|---|---|---|
| TKY4<br>Basalt | YH1 = 2.90<br>YH2 = 2.82 | YH3 = 2.92<br>YH4 = 2.86 | 24 | 2.87± 0.05 |
| TKY1<br>Basalt | YH5 = 2.92<br>YH6 = 2.94 | YH7 = 2.98 | 19 | 2.95± 0.04 |
| TKY1<br>Agglomerates | YH13 = 2.23<br>YH14 = 2.18 | | 12 | 2.21± 0.04 |
| TKY1<br>Basic<br>Porphyrites | YH15 = 3.16<br>YH16 = 3.20 | YH17 = 3.22 | 18 | 3.19 ± 0.04 |
| TKY1<br>Basalt | YH18 = 3.04<br>YH19 = 3.06 | YH20 = 3.05 | 18 | 3.05 ± 0.04 |
| TKY1<br>Welded tuffs | YH21 = 2.25<br>YH22 = 2.27 | YH23 = 2.26 | 20 | 2.26 ± 0.04 |
| TKY1<br>Ignembrite | YH24 = 2.47 | | 6 | 2.47 ± 0.03 |
| TKY1<br>Basalt | YH25 = 2.95<br>YH26 = 2.87 | YH27 = 2.84 | 19 | 2.89 ± 0.06 |

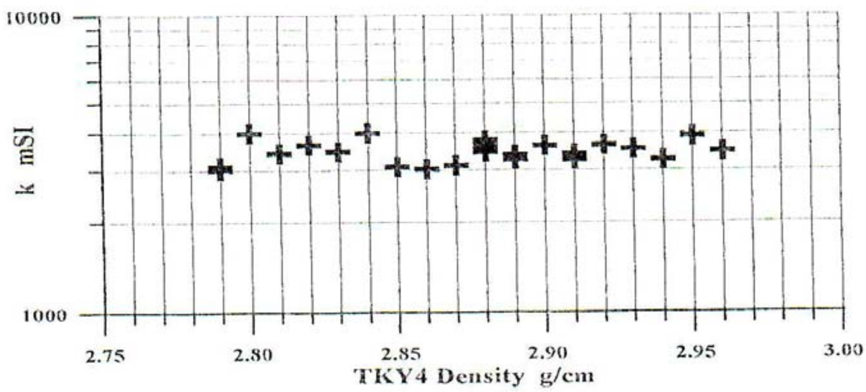


**Fig. 10A. Distribution of the magnetic susceptibility versus density of TKY4 samples' knobs. (Symbols as in Fig. 7A).**

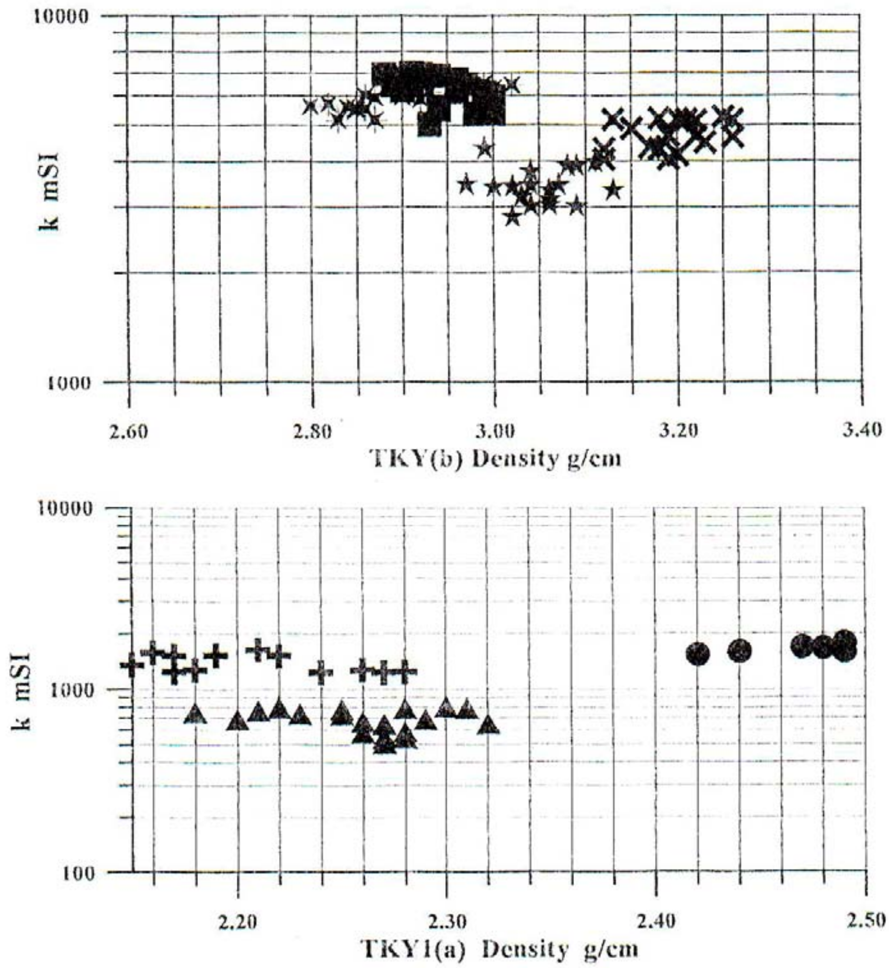


**Fig. 10B. Distribution of the magnetic susceptibility versus density of TKY1 samples' knobs. (Symbols as in Fig. 7B).**

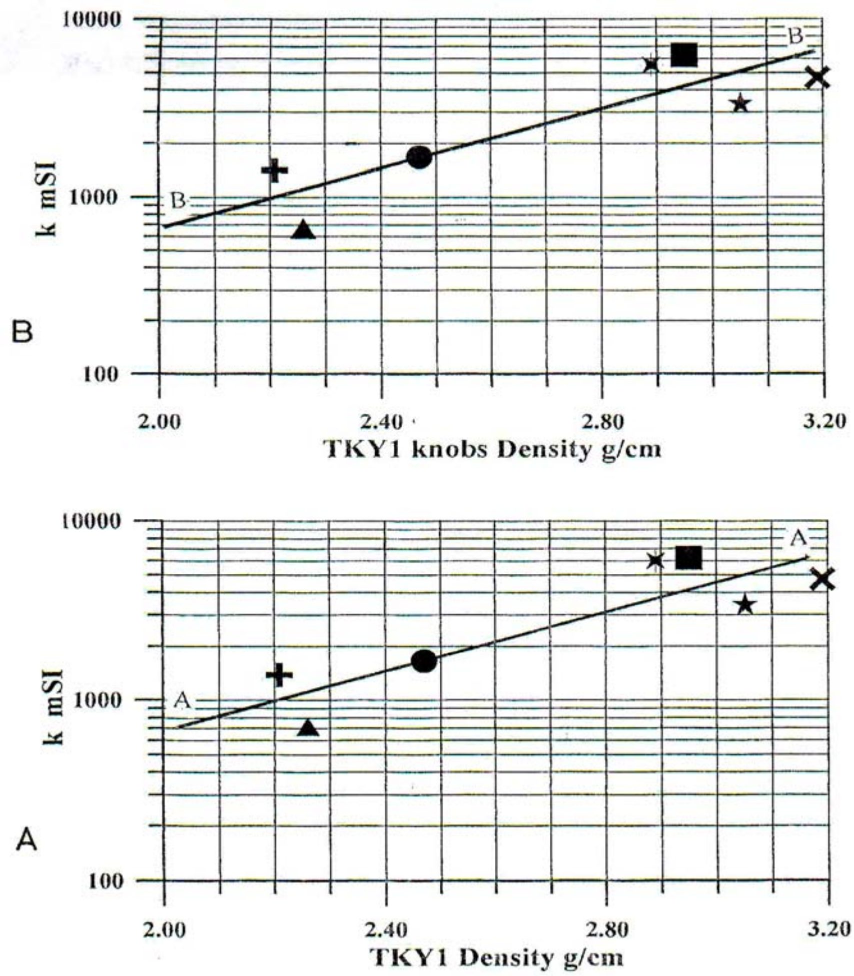


**Fig. 11. Shows the mean density of the TKY1 sample knobs versus.**
A- The mean of the magnetic susceptibility of the complete samples of each rock type. Line A-A represents the median.
B- The mean of the magnetic susceptibility of the sample's knobs of each rock type. Line B-B represents the median. (Symbols as in Fig. 7B).

## Magnetic susceptibility of the rocks of the sampled field localities

In order to determine the mean 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 in situ magnetic susceptibility of the rocks of the sampled sub-areas was measured (Table 7) in 20 different points (the susceptibility of each point is the mean of three different measurements).

The susceptibility of the TKY4 basaltic rocks was measured in two sub-areas (1 & 2). The mean susceptibility is 3423 ± 474 mSI and 3328 ± 173 mSI consequently (Table 7).

The susceptibility of the TKY1 rocks was measured in five sub-areas (3-6 & 8). The mean susceptibility of the basaltic rocks in sub-areas (3, 5 & 8) is 6448 ± 1102 mSI, 6508 ± 1077 mSI and 7335 ± 1345 mSI consequently. While the mean susceptibility of the agglomeratic rocks of sub-area (4) is 2895 ± 645 mSI and the mean susceptibility of the welded tuff rocks of sub-area (6) is 714 ± 60 mSI (Table 7).

**Table 7. The magnetic susceptibility values of the sampled field sub-areas, the mean of each sub-areas and the Standard Deviation of each mean value.**

| Sub-ar Nan<br>Point No. | YH1<br>(1) | YH2<br>(2) | YH5-7<br>(3) | YH13-14<br>(4) | YH18-20<br>(5) | YH21-23<br>(6) | YH25-27<br>(8) |
|---|---|---|---|---|---|---|---|
| 1 | 2900 | 3050 | 6300 | 2150 | 7700 | 773 | 5700 |
| 2 | 3200 | 3150 | 7300 | 2700 | 6900 | 663 | 5700 |
| 3 | 4300 | 3400 | 5200 | 2600 | 6900 | 643 | 5700 |
| 4 | 3100 | 3400 | 6300 | 3450 | 5950 | 643 | 8900 |
| 5 | 3550 | 3250 | 5200 | 2700 | 4700 | 623 | 8900 |
| 6 | 4100 | 3150 | 5200 | 3950 | 7700 | 723 | 8900 |
| 7 | 3550 | 3675 | 7300 | 3300 | 7900 | 773 | 5700 |
| 8 | 3450 | 3150 | 7300 | 2150 | 7300 | 723 | 5700 |
| 9 | 3450 | 3400 | 7900 | 2900 | 6900 | 693 | 5700 |
| 10 | 2950 | 3400 | 4100 | 2050 | 7300 | 813 | 5700 |
| 11 | 3000 | 3200 | 4850 | 2200 | 4550 | 763 | 7700 |
| 12 | 3550 | 3300 | 7300 | 2950 | 7100 | 723 | 6900 |
| 13 | 3550 | 3150 | 5200 | 2200 | 6300 | 763 | 7500 |
| 14 | 4200 | 3400 | 7300 | 3550 | 7100 | 663 | 7900 |
| 15 | 3700 | 3300 | 7300 | 3950 | 7300 | 713 | 8900 |
| 16 | 3550 | 3775 | 7300 | 2800 | 5050 | 723 | 7700 |
| 17 | 2700 | 3450 | 6700 | 3700 | 5050 | 613 | 8900 |
| 18 | 2550 | 3250 | 6300 | 3700 | 5050 | 673 | 7700 |
| 19 | 3300 | 3300 | 7300 | 2700 | 7100 | 773 | 8450 |
| 20 | 3800 | 3400 | 7300 | 2200 | 6300 | 793 | 8450 |
| Mean of sub-Area | 3423±474 | 3328±173 | 6448±1102 | 2895±645 | 6508±1077 | 714±60 | 7335±1345 |

## 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 seven sites of normal polarity has a Dec.= 8.36°, Inc.= 10.83° with $\alpha_{95}$ =13.3°.

2- An overall Virtual Geomagnetic Poles (VGPs) of the accepted sites, of the Upper Oligocene, is at 182.81° E, 77.44° N, $\alpha_{95}$ =12.5°.

3- Magnetite is the main magnetic mineral of the rocks with small amounts of other magnetic minerals.

4- The magnetic susceptibility of the TKY4 samples showed a medium value (3449 ± 288 mSI for the complete samples and 3418 ± 325 mSI for the sample's knobs). While the magnetic susceptibility of the TKY1 samples increased from the welded tuffs to agglomerites to ignembrite to the basalt of locality (5) to the basic porphyrites to the basalt of locality (8) and finally to the basalt of locality (3).

5- The intensity of the NRM showed high interference among the different types of rocks, which is expected because of the variable history of their magnetization.

6- The ac current electrical conductivity is low.

7- The calculated means of the density of the rocks can be used in the interpretation of any gravity study. The overall mean of the TKY4 basalt is 2.87 ± 0.05 g/cm³. While the overall mean of the TKY1 increased from 2.21 ± 0.04 g/cm³ (agglomerates) to 2.26 ± 0.04 g/cm³ (welded tuffs) to 2.47 ± 0.03 g/cm³ (ignembrite) to 2.89 ± 0.06 g/cm³ (sub-area 8 basalt) to 2.95 ± 0.04 g/cm³ (sub-area 3 basalt) to 3.05 ± 0.04 g/cm³ (sub-area 5 basalt) to 3.19 ± 0.04 g/cm³ (basic porphyrites).

8- There is a clear direct proportionality between the density and the magnetic susceptibility of all rock types.

9- The magnetic susceptibility of the in situ rocks of the sampled localities can be used in the interpretation of any magnetic or aeromagnetic study of the different sub-areas. The overall mean of the TKY4 rocks of the area around site YH1 is 3423 ± 475 mSI, while that of the area around site YH2 is 3328 ± 173 mSI. The overall mean of the magnetic susceptibility of the TKY1 rocks increased from 714±60 mSI for sub-area (6) to 2895 ± 645 mSI for sub-area (4) to 6448 ± 1102 mSI for sub-area (3) to 6508 ± 1077 mSI for sub-area (5) to 7335 ± 1345 mSI for sub-area (8)

**Acknowledgments**

The author is grateful for the financial support given by the British Council Branches at Sana'a (Yemen) and Damascus (Syria). Thanks are due to Prof. D. H. Tarling of the Department of Geological Sciences of Plymouth University, England, for his continuous help that made the whole project a reality. Thanks are also due to the officials in Damascus and Sana'a Universities for their financial support. Dr. Ali Seif Gamel of the Geology Dept. of Sana'a University was invaluable during the fieldwork.

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