J Geophys (1986) 60:47–55

Journal of Geophysics

Magnetic mineralogy of basalts from El-Bahnasa and Tahna, Egypt

Nadia A. Wassif

Department of Geophysics, National Research Centre, Cairo, Egypt

Abstract. The present work gives the magnetic characteristics and opaque mineralogy of 30 porphyritic olivine basalt samples from El-Bahnasa and Tahna (Egypt). Ore microscopic studies, Curie temperature and X-ray diffraction analysis suggest primary titanomagnetites to be the major magnetic mineral present. The Q values and the maximum peak values of Rayleigh loops are largely controlled by magnetic mineralogy, oxidation state and the grain size of the magnetic minerals within the rock sample.

Key words: Rock magnetism – Basalts-Titanomagnetite – Q value

Introduction

Systematic rock magnetic, palaeomagnetic and opaque mineralogical studies were carried out on numerous lava flows in the northern part, especially, of Egypt (Fig. 1). They show close similarity to each other, being characterized by reversed magnetization. The opaque mineralogy of these occurrences indicates: (a) presence of magnetite and ilmenite as subhedral coarse grains indicating slow rate of cooling, (b) the predominance of ilmenite over magnetite, (c) the frequent association of ilmenite and magnetite in intimate intergrowths in the same grain (mainly exsolution, sandwich and granule intergrowths) and also in composite grain and (d) the common alteration of magnetite to martite, the complete oxidation of ulvöspinel to ilmenite and the alteration of ilmenite to rutile-hematite aggregates (El-Rashidi, 1964; El-Sheikh, 1968; Refai and Wassif, 1970; El-Shazly and Krs, 1971; Fahim and Gouda, 1976; Basta et al., 1981).

To the south of the Nile valley, an outcrop of lava flows appears in the neighbourhood of Tahna (Fig. 1). On the opposite side of the Nile, near El-Bahnasa, there are also flows that extend through isolated outcrops from Qaret El-soda near Manfalout of the south-west to Baharia. Ball and Beadnell (1903) reported to similarity of volcanic rocks on the Feshn-Baharyia Desert Road to those occurring west of El-Bahnasa. The volcanic rocks in this area intruded into Eocene limestones, and were described as "hard andesitic basalt". The fluvio-marine series is absent at El-Bahnasa and Tahna. Based on field observations, the basalt flows are considered of Lower Oligocene age.

The primary Fe-Ti oxides which crystallize from basaltic magma above 1000° C are members of magnetite-ulvöspinel and ilmenite-hematite solid solution series. These minerals dominate the bulk magnetic properties (natural remanence, initial susceptibility, Curie point ... etc.) regardless of the subsolidus petrological history. These accessory oxides of both El-Bahnasa and Tahna flows will be described and their magnetic properties will be compared with those of other localities in the northern part of Egypt (Fig. 1). Thirty basaltic samples were collected from three hillocks at El-Bahnasa (sites 700 and 800) and Tahna (site 1,000). The natural remanent magnetization (NRM) and initial susceptibility ($\varkappa$) were measured by an inductometer. The magnetic mineralogy was investigated by reflected-light microscopy, Curie temperature and X-ray analysis.

Microscopic investigations

Petrographically, the rocks are porphyritic olivine basalts consisting of plagioclase, pyroxenes and olivine phenocrysts (25%–30%) embedded in a ground mass of opaque minerals, pyroxenes, plagioclase and exhibit ophitic and subo-

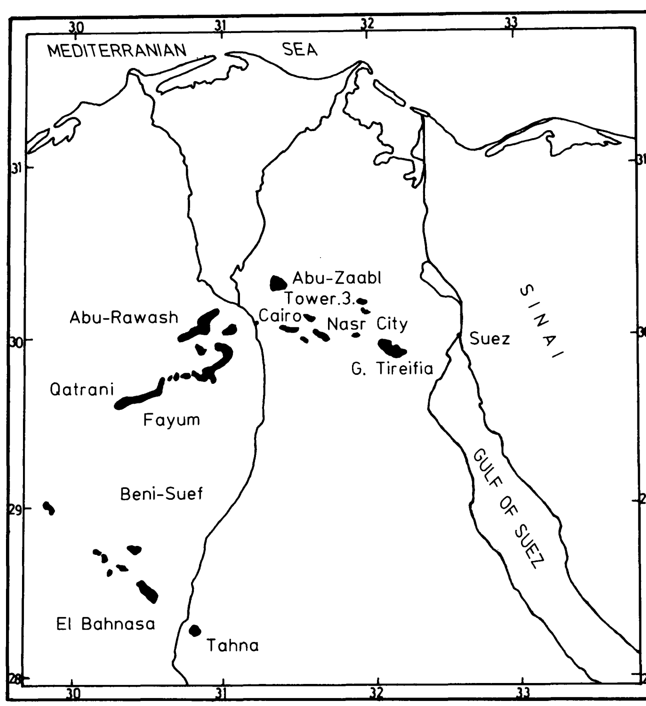
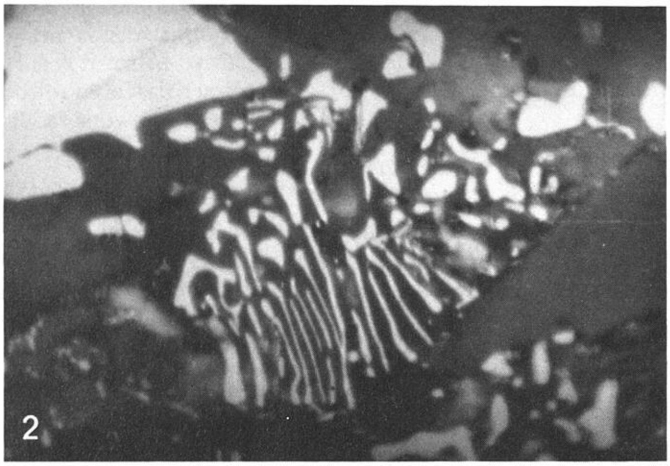
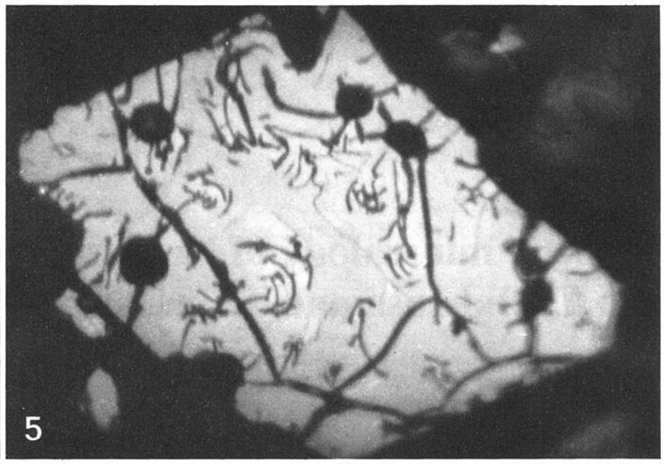
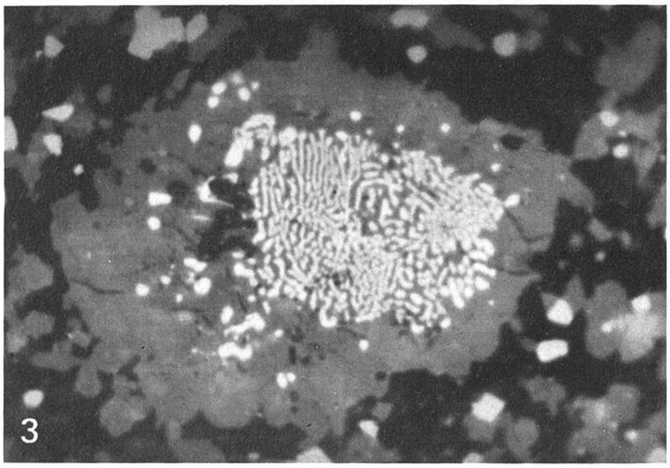
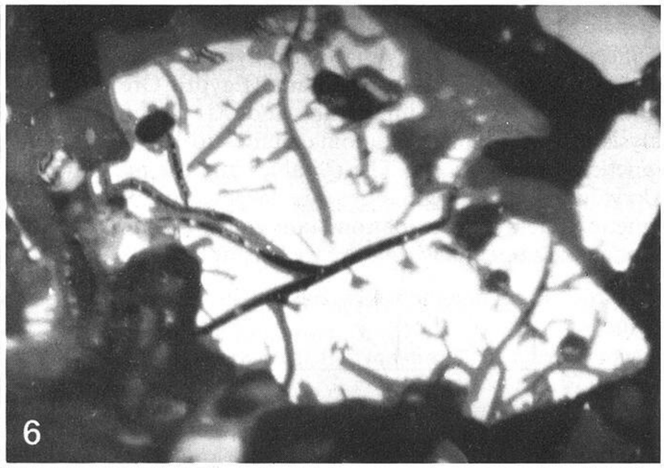


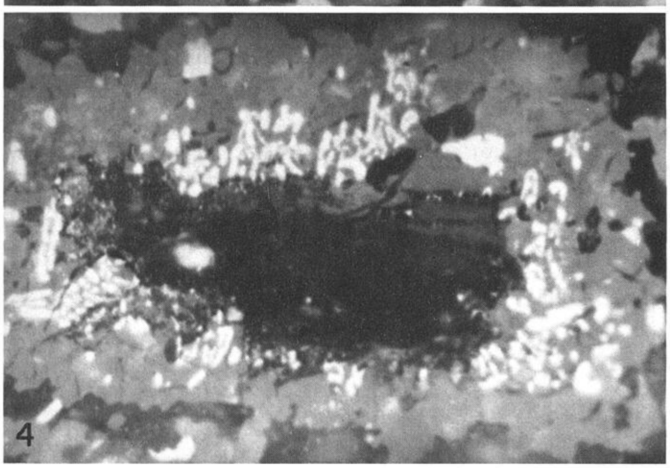
Fig. 1. Key map of the northern and southern basaltic occurrences











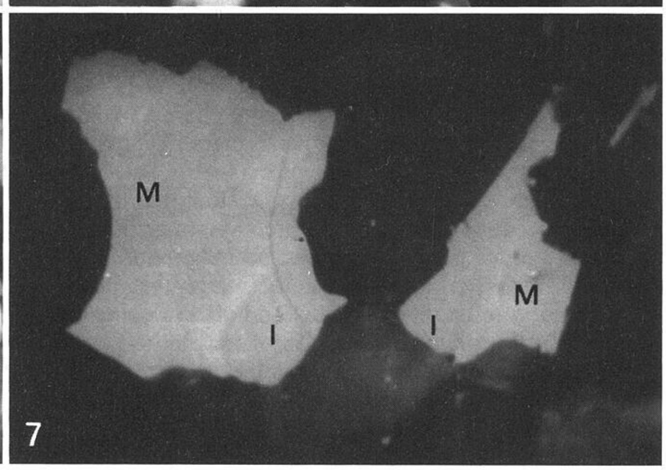


Fig. 2. Myrmikitic intergrowth of secondary magnetite with secondary amphiboles, site 800. Reflected light, oil immersion, × 1,000

Fig. 3. Graphic intergrowth of magnetite in the core of a pyroxene grain, site 700. Reflected light, oil immersion, × 1,000

Fig. 4. Keliphitic rim of magnetite around a pyroxene grain, site 1,000. Reflected light, oil immersion, × 500

Fig. 5. Intensely cracked titanomagnetite (microscopically homogeneous to a magnification × 1,000) with colour heterogeneity around fine cracks where bluish grey patches of maghemite appear, site 700. Reflected light, oil immersion, × 1,000

Fig. 6. Maghemitized magnetite grain with pronounced cracks which are filled by silicates, site 700. Reflected light, oil immersion, × 1,000

Fig. 7. Ilmenite-magnetite sandwich grain embayed and dissected by the silicates (*black*); notice that ilmenite on both sides has the same colour indicating optical continuity, site 800. Reflected light, oil immersion, × 1,000

Table 1. Summary of ore microscopical results

Site	Opaque minerals % by volume	Magnetite			Ilmenite
		Grain size and texture	Type and intergrowths	Alteration	
700 and 1000	80–100 magnetite 0–20 ilmenite	Few porphyritic grains (400–600 μm) in a very fine ground mass (up to 20 μm)	Mainly titanomagnetite[a]	Partially or severely to maghemite with the development of irregular fine and thick cracks	Minute discrete laths
800	60–70 magnetite 30–40 ilmenite	Fine to medium grains (20–40 μm) with octahedral faces, skeletal crystals and myrmikites (Fig. 2)	Ti-poor[a] magnetite and titanomagnetite in equal amounts. Intergrowths of sandwich (Fig. 7) and granules	Partially to martite and maghemite	Discrete plates (100–150) (10–30) μm

[a] The differentiation between titanomagnetite and Ti-poor magnetite is based on the optical properties as shown under the microscope (particularly colour, reflectivity and presence of weak anomalous anisotropism of titanomagnetite)

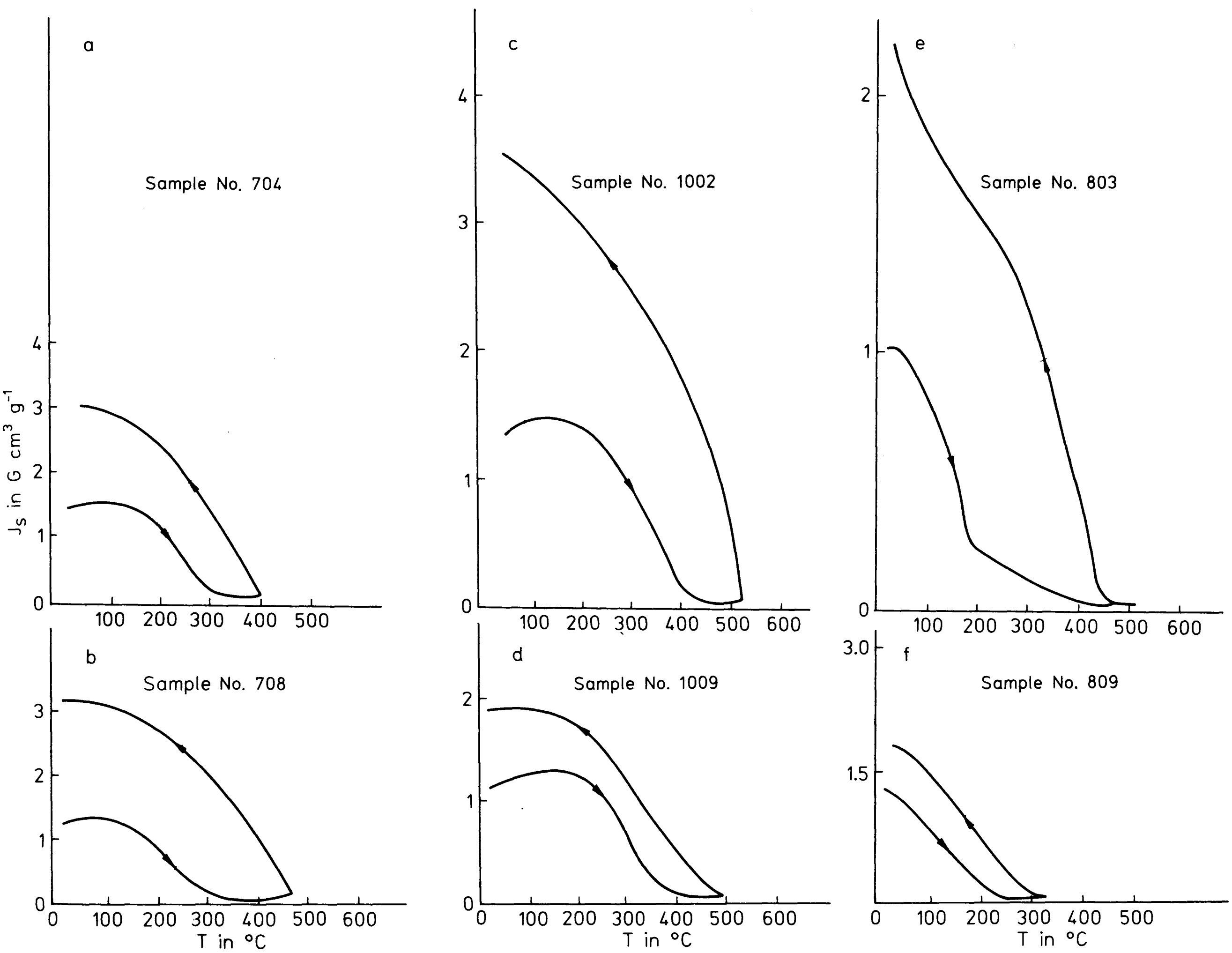


Fig. 8a–f. Representative J_s-T curves for samples from each site. Both heating and cooling cycles are shown and indicated by *arrows*. Note that saturation magnetizations are given in Gcm^3 g^{-1} (=Am^2 kg^{-1})

phitic textures. Although no significant mineral variations among the three sites are observed, the ground mass of sites 700 and 1,000 is finer grained than that of site 800 and contains some glass.

In reflected light, the opaque minerals are abundant, forming about 25% of the total rock; their form testifying to fairly rapid cooling after emplacement at shallow depth. They include magnetite and homogeneous ilmenite, the magnetite being the predominant mineral. It should be emphasized that the terminology used to describe opaque minerals and their intergrowths is that given by Basta (1970). The term titanomagnetite indicates a homogeneous single-phased magnetite containing Ti in solid solution, while titaniferous magnetite is used for magnetite containing at least one exsolved phase of Ti-minerals (ilmenite and/or ulvöspinel).

The reflectivity and colour of magnetite suggest the presence of two homogeneous main types; titanomagnetite and a Ti-poor magnetite free of exsolutions. Titaniferous magnetite which contains ilmenite lamellae is completely absent. The titanomagnetite has been formed by very rapid cooling of the parent magma that did not allow the unmixing of its ilmenite or ulvöspinel solid solution. The Ti-poor magnetite is found to be less abundant and occasionally being associated with titanomagnetite. In some instances the titanomagnetite shows some colour variation, possibly due to a variable Ti content or beginning low-temperature oxidation.

Secondary magnetite is sometimes present in the form of myrmikitic intergrowths with secondary amphibole (Fig. 2), graphic intergrowth in the core of pyroxene grain (Fig. 3) and keliphitic rims which are mainly due to deuteric alteration (Fig. 4).

The alteration of magnetite is represented by maghemitization along fine and thick cracks (Figs. 5 and 6) and martitization along grain peripheries. The origin of these alterations is attributed to oxidation, where the titanomagnetite is preferentially altered to maghemite and Ti-free magnetite is usually martitized; late martitization due to weathering is also possible. The transformation of magnetite into maghemite has been considered to be characteristic of low-temperature oxidation (Ozima and Ozima, 1971; Lowrie, 1974; Haggerty, 1976), being more common in submarine basalts (Cockerham and Hall, 1976; Johnson and Hall, 1978). The development of cracks resulted from the defect structure of maghemite. Similar observations were described by Wassif (1983) from the Hefhuf basalts of the Bahariya Oases.

The results of optical examination of sites 700 and 1,000 and site 800 are summarized in Table 1.

Thermomagnetic measurements

For the Curie-point determination, small chips from a basalt sample were ground to a coarse powder and were heated in air in applied magnetic fields of about 3,100 Oe[1] using a horizontal automatic magnetic balance. At least three J_s-T determinations were performed on samples from each site and the results are summarized in the following.

All J_s-T curves are essentially irreversible during heating and cooling. They show a single Curie temperature upon heating around 300°–350° C for site 700 and around 400°–450° C for site 1,000 (Fig. 8a–d). The irreversible behaviour is caused by continual oxidation and/or unmixing of titanomagnetite-maghemite during heating (Ozima and Ozima, 1971). The unstable Curie temperatures and the increase in J_s after heating support the validity of this interpretation. Ore microscopy confirms the presence of titanomagnetite with maghemite-lined cracks (Figs. 5 and 6). The shape of the J_s-T curves and the low Curie temperatures (200°–250° C) at site 800 (Fig. 8e, f) reveal that the magnetic mineral present is an almost unoxidized form of

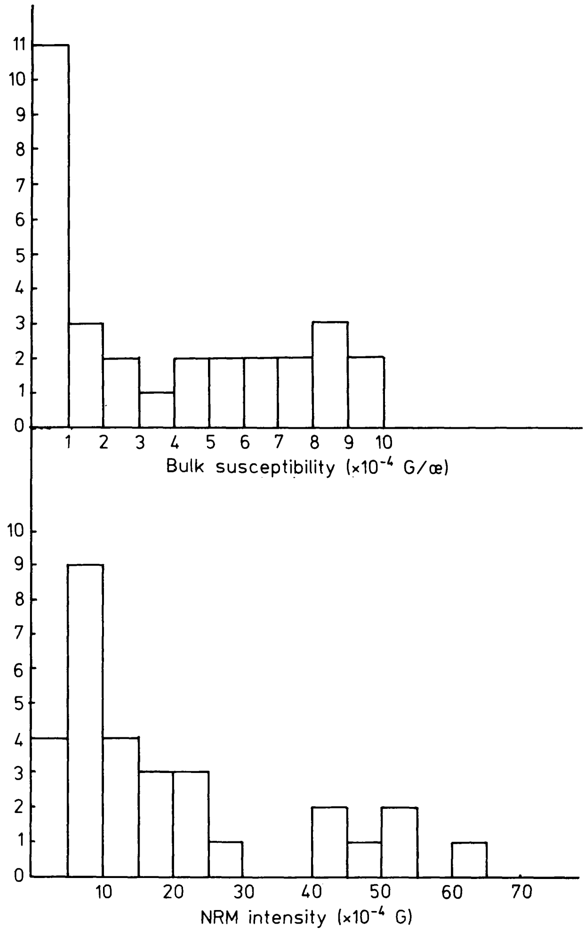


Fig. 9. Histograms of NRM intensities and bulk susceptibilities of 30 basaltic samples

an ulvöspinel-rich (40%–50%) titanomagnetite (Ozima and Larson, 1970). Ore microscopy also supports this interpretation. One sample from this site (Fig. 8e) shows two distinct Curie temperatures, one around 200° C and one around 400°–450° C. This sample, with low initial Curie point, also gave an irreversible thermomagnetic curve with a substantial increase in magnetization but with an increased Curie point higher than 450° C after thermal cycling. This thermomagnetic behaviour can be accounted for by the initial presence of a titanomagnetite or titanomaghemite which separates upon heating to a titanium-rich phase and a titanium-poor phase near to magnetite in composition. On cooling from high temperature, the stronger magnetization of this magnetite appears at a high Curie temperature and increases to its room temperature value (Kent et al., 1978). The subsequent microscopic examination of this sample confirmed the presence of both Ti-poor magnetite and titanomagnetite. Previous studies of unaltered submarine basalts from the Mid-Atlantic Ridge show Curie temperatures of 120° C to 150° C for the original titanomagnetite and Curie points up to a maximum of 400° C for the completely oxidised titanomaghemite (Schaeffer and Schwarz, 1970; Johnson and Atwater, 1977). Although martite was sometimes observed in a microscopic examination of samples from site 800, a thermomagnetic expression was not apparent, presumably due to small amounts of the more weakly magnetic hematite in the presence of mag-

[1] 1 Oe ≃ 80 Am⁻¹

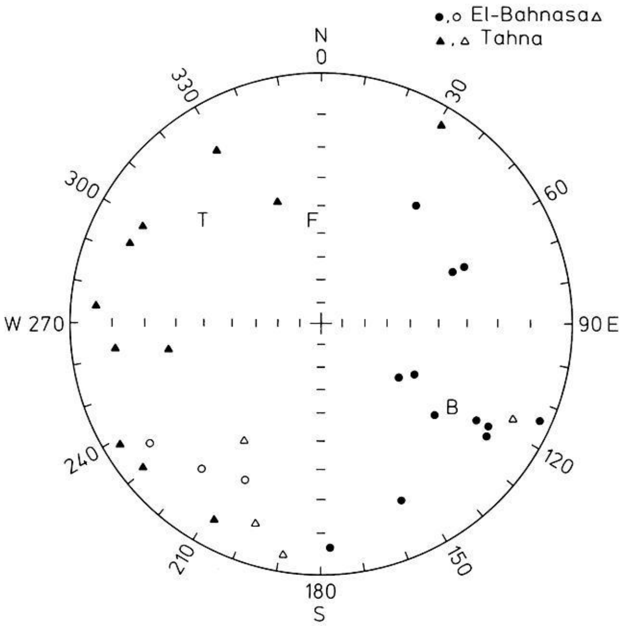


Fig. 10. Stereo plot showing the NRM directions for all samples. *Full* (*open*) symbols = positive (negative) inclinations. *F*: present field direction and B(T) are site mean directions for El-Bahnasa (Tahna) areas

netite which was volumetrically and magnetically dominant in most samples.

X-ray diffraction analysis (XRD)

XRD data for magnetically separated opaques confirmed the microscopic determinations, where the patterns of titanomagnetite and maghemite in site 800 are present together with a strong pattern of ilmenite. In sites 700 and 1,000, the titanomagnetite and maghemite patterns are more distinct, while ilmenite is absent or very weak.

NRM and susceptibility

The remanent magnetization vectors and low field susceptibilities were measured by an inductometer (Thellier, 1938). Histograms of natural remanent magnetization (NRM) intensities J_{NRM} and bulk susceptibilities χ for all the 30 samples are shown in Fig. 9. The remanence intensities vary between 1.21×10^{-4} G and 65.01×10^{-4} G[2], while the initial susceptibilities range from 0.18×10^{-4} G/Oe to 10.01×10^{-4} G/Oe[3]. The Koenigsberger ratio Q_n is a measure of the relative contribution of remanent to induced magnetization in a sample and is calculated as $Q_n = J_{NRM}/\chi \cdot F$ where F is the geomagnetic field intensity at the studied area ($F = 0.42$ Oe). The calculated Koenigsberger values of all samples are much greater than unity (from 2 to 136). Therefore, remanent magnetization dominates the total magnetization of all these basalts in the Earth's magnetic field.

It is clear from the results that a large variation in magnetization (NRM and suceptibility) as well as opaque mineralogy content is observed in specimens taken from a single sample. Similar fluctuations were noted by Kent et al. (1978) and Johnson and Hall (1978). They suggest that the rocks are not very homogeneously magnetized even on a hand-sample scale, as a result of different local concentrations of magnetic minerals.

Because viscous components of remanent magnetization affect the measurements, the collection was measured again after 1 month in order to obtain a rough qualitative estimate of the stability of magnetization. Samples from El-Bahnasa yielded more stable NRM directions, while those from Tahna showed varying consistency between measurements. NRM directions are widely scattered (Fig. 10). Mean directions of each site, together with statistical parameters, are reported in Table 2. Occasionally, samples collected from one and the same spot (from Tahna area) yield totally different directions. Strong viscous components of magnetization varying rapidly with time made the measurements unreliable and those samples were discarded as unreliable for further palaeomagnetic studies.

The ratio between the magnetic moment per unit mass (otherwise termed magnetization) and the applied field has been used successfully to obtain a representative set of loops. Long uniform cylindrical polished samples were prepared and by using Gough's method (1889) the changes in susceptibility with applied field (up to 25 Oe) were measured. The rocks under investigation did not saturate because of the limitation on the peak magnetic field obtainable. The results of 12 representative samples (Table 3) clearly showed Rayleigh loops (1887) that could be classified into two groups. The first group (Fig. 11a–d) has high peak susceptibility values (K) between 14×10^{-3} and 25×10^{-3} G/Oe and clearly shows irreversible behaviour. The rayleigh loops of the second group are nearly reversible (Fig. 11e and f) and characterized by a lower peak at the same applied field.

Table 2. NRM mean directions from the three sites, with precision parameters

Site	N	D (°)	I (°)	α_{95} (°)	R	K	R_0
700	8	148	+24	16	7.452	12.77	4.48
800	7	149	+32	38	5.265	8.16	4.18
El-Bahnasa	2	148	+28	25	1.990	100	
Tahna (1000)	15	313	+24	39	7.748	2.24	6.19

N, number of samples; D, I, declination, inclination; α_{95}, R, K and R_0, precision parameters (Fisher, 1953) and (Watson, 1956)

Discussion and conclusions

Correlation between magnetic data and opaque mineralogy

Table 3 shows that, for opaque minerals (frequency, species and intergrowths), the maximum peak values K and Q values of sites 700 and 1,000 are very similar, while site 800 shows different opaque constituents being characterized by lower K and Q values. These data may possibly be interpreted by the following: (a) coarser grain size of site 800, despite the presence of few porphyritic crystals in samples from sites 700 and 1,000 (see Table 1); (b) the composition and alteration of magnetite at site 800 is characterized by

[2] 1 G = 10^3 Am^{-1}
[3] 1 G/Oe = 4π SI units (m^3 m^{-3})

Table 3. Correlation between magnetic data and ore microscopical results

Site	Sample no.	Opaque minerals % by volume	Textures and mode of occurrence of ore minerals	Magnetite				Composite grains sandwich, mass and juxta position inter-growths	Ilmenite	Max. peak values of K (10^{-3} G/Oe)	$Q_n = J/\chi \cdot F$	Curie Temp. (°C)	J_s (G/g)
				Ti-free magnetite	Titano-magnetite	Degree of martiti-zation	Degree of maghemi-tization		Normal and homogeneous				
Site	701	< 20	Porphyritic, intensely cracked	–	XXXX	–	XXXX	–	–	25.91	104.23		
700	704(a)	< 20	Porphyritic, slightly cracked	–	XXXX	–	XX	–	–	15.20	116.48	325	1.4–3
	705	> 20	Fine to medium grains	XX	X	XX	X	X	XX	5.05	36.25		
	708(b)	< 20	Porphyritic-myrmikitic	X	XX	X	X	–	–	16.90	134.50	325	1.2–3.2
Site	1002(c)	< 20	Porphyritic-fine cracks	–	XXXX	–	XX	–	–	25.95	82.47	425	1.3–3.5
1000	1005	> 20	Porphyritic-fine cracks	–	XXX	–	XX	–	–	10.42	97.28		
	1007	< 20	Porphyritic-keliphetic rims	–	XXXX	–	XXX	–	–	15.02	136.73		
	1009(d)	< 20	Porphyritic-fine cracks	–	XXX	–	XX	–	X	20.59	96.28	400	1.25–2
	1012	< 20	Porphyritic-thick cracks	X	XXX	XX	XX	–	X	14.10	45.87		
Site 800	803(e)	15–20	Fine to medium grains, skeletal crystals	XXX	XX	XX	X	XXX	XXX	6.93	36.03	200 425	1–2.2
	805	15–20	Fine to medium grains, very initial skeletals	XX	XX	XX	X	XX	XXX	3.66	21.52		
	809(f)	15–20	Fine to medium grains	XX	XX	X	X	XX	XX	8.24	16.01	250	1.4–1.6

– = absent; X = rare; XX = fairly common; XXX = common; XXXX = predominant

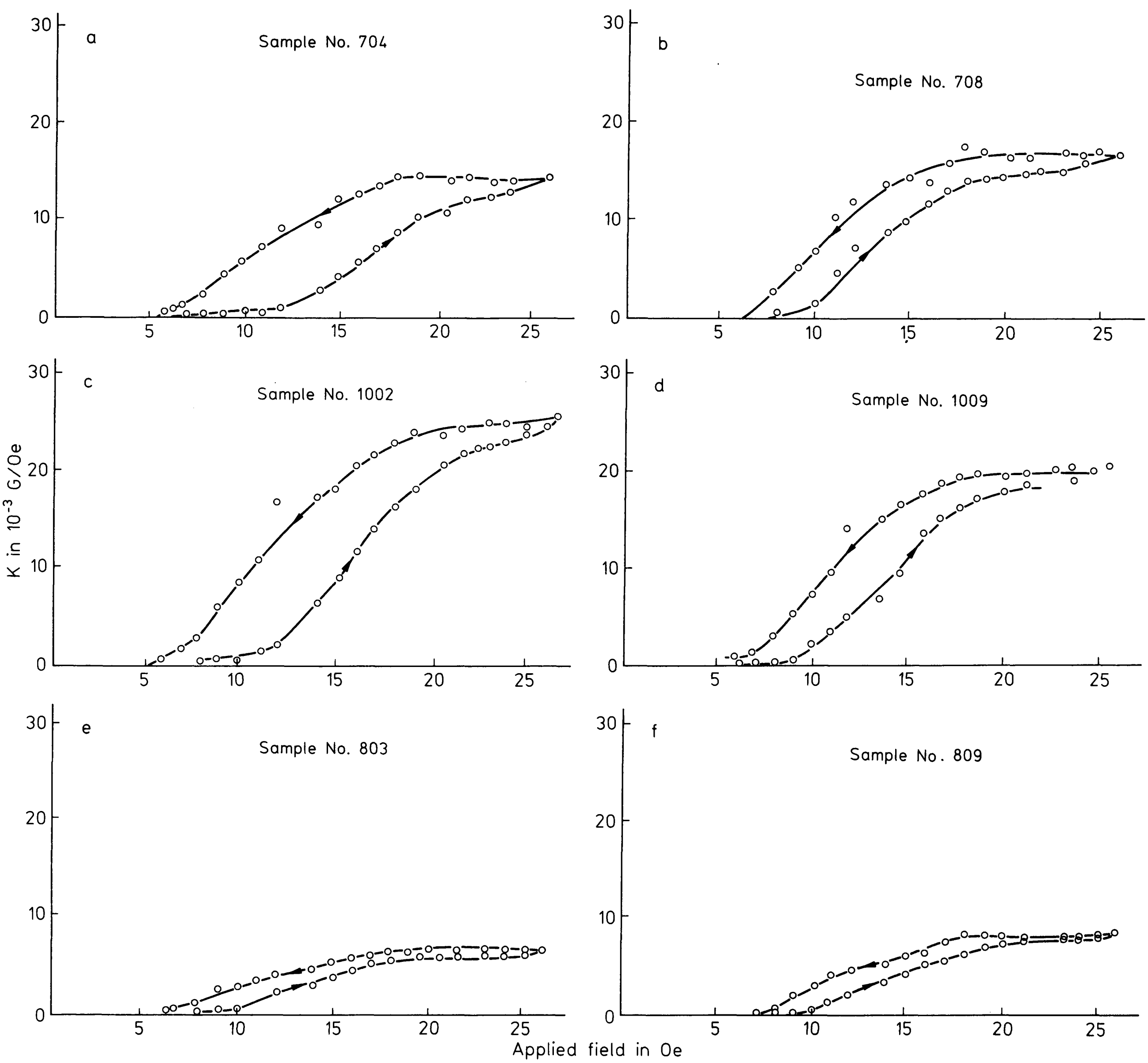


Fig. 11a–f. The dependence of susceptibility on the applied magnetic field. The upper parts **a–d** refer to high K(G/œ) peak values with irreversible behaviour, while **e** and **f** are characterized by lower peak values

the presence of almost equal amounts of Ti-poor and Ti-rich varieties which are altered into martite and maghemite (as for sites 700 and 1,000, titanomagnetite predominates, being altered to maghemite); (c) common presence of ilmenite-magnetite sandwich and granule intergrowths as well as discrete ilmenite at site 800.

The magnetic and mineralogical properties studied here have been found in rocks carrying normal as well as reversed remanent magnetization directions. These properties have no bearing on the polarity of the natural magnetization of the rocks.

Comparison with results from northern egypt

Table 4 reveals that the directions of magnetization of the northern volcanic rocks (Fig. 1) are reversed, i.e. the inclinations are always negative. The declinations were also found to be quite consistent, pointing to SSW. The directions of El-Bahnasa and Tahna are grossly different, with low positive inclinations. Semiangle circles of confidence (α_{95}) are very large. The initial susceptibility values for both the northern and southern volcanics indicate that they range from very low values to rather high values. But the magnetic intensities for El-Bahnasa and Tahna are about three times higher than the northern localities and the Q_n values are ten times those of the northern sites.

The magnetic properties of the completely oxidised Fe-Ti oxides are distinctly different from the unoxidized or little oxidized. Hematite has a weak ferromagnetism with a saturation magnetization about 200 times less than that of magnetite and a Curie temperature of 670° C, while rutile and pseudobrookite are dia- or paramagnetic at room temperature. Therefore, the highly oxidized lava flows (northern lavas) are characterized by low intensity of magnetization on the one hand and high stability of remanence on the other hand (see Table 4) since hematite is able to carry

Table 4. Magnetic and mineralogical results from the northern and southern lava flows

Locality	N	D_m (°)	I_m (°)	α_{95} (°)	R	K	Mean values J_{NRM} (10^{-4} G)	χ (10^{-4} G/Oe)	Q_n	Mineralogical results
Abu Rawash (Refai and Wassif, 1970)	20	193	−57	3	19.80	190	6.40	2.66	5.68	Total opaque % by volume (6–12) coarse grained, highly oxidized Fe−Ti oxides
Abu Zaabal (El-Rashidi, 1964)	33	208	−58	4	31.92	29	3.90	2.77	3.30	
Cairo-Zuez Road (*T 3*) (Fahim et al., 1971)	9	210	−59	5	8.93	114	3.63	1.63	3.10	
East of Cairo (*Nasr City*) (El-Sheikh, 1968)	9	200	−59	4	8.96	197	2.39	1.47	3.70	
Qatrani-Fayum (Basta et al., 1981)	22	191	−55	3	21.83	123				
	21	195	−63	3	20.84	129	4.5	3.21	3.04	
	9	204	−57	5	8.89	76				
El-Bahnasa Present work	8	148	+24	16	7.45	13	16.25	3.65	40	Total opaque % by volume (20–25). Fine grain unoxidized or little oxidized Fe−Ti oxides
	7	149	+32	38	5.26	8				
Tahna Present work	15	313	+24	39	7.74	2	18.5	4.15	48.53	

Fig. 12. Some pillowed basalts from Tahna area

a very stable remanent magnetization. The slow rate of cooling is the most important controlling factor in the determination of grain size. This would again encourage exsolution lamellae of ilmenite (northern lava) to divide the more magnetic fraction, essentially magnetite, into very small portions of the order of 0.01 µm of linear dimensions. It is very likely that some of these subdivisions (0.01 µm) reach single-domain particle dimension and are probably the source of a hard component of magnetization (Stott, 1971).

In a magma body which behaves as a closed system, and cools very rapidly, the composition of the primary ore minerals is frozen in (Hargraves and Petersen 1971). Rocks originating in such an environment are extremely vulnerable to oxidation by air or water, leading to substantial changes in mineralogy and magnetic properties. If the oxidation of the primary Fe−Ti oxides has not been completed at high temperatures but goes on at temperatures below 600° C, a metastable cation-deficient spinel phase titanomaghemite may be formed. It seems that the subaqueous environment which is rich in water appears to favour the particular oxidation into maghemite or low-temperature oxidation (Ozima and Ozima, 1971). As a result of rapid cooling, the size of ore grains is relatively small, from submicroscopic to a few tens of microns (southern lavas); they therefore possess high coercivities and low Curie points. This is reflected in the high values of their Q_n factors as reported, for example, by Ade-Hall (1965), Stacey (1967) as well as Hargraves and Petersen (1971).

The mechanism of Tertiary volcanicity in Egypt has been discussed by Rittman (1954). He raised the question of whether the eruptions happened on land or beneath a shallow sea. He stated that this will be difficult to decide because the characteristic surface features of the Tertiary volcanics of Egypt were removed by erosion during Pliocene and Pleistocene times. The absence of pillow lavas presents an argument in favour of subaerial origin of the flows; an argument which, however, is not absolutely cogent. According to Abdel Maksoud (1968), the eruptions of Tahna and El-Bahnasa were certainly partly erupted beneath shallow waters. The data presented in the foregoing, together with the occasional presence of pillowed basalts in a matrix of clays and carbonates (Fig. 12) in Tahna, might suggest that at least a portion of these basalts were formed in a subaqueous environment (e.g. lakes). However, quantitative correlations of the cooling history and accurate age determinations are still lacking.

Finally, it is concluded that the ore microscopic observations can help a great deal towards the understanding of the magnetic data. Titanomagnetite was found to be the major opaque mineral in all the basalts, a feature that is corroborated by the J_s-T curves. Although titanomagnetite is the dominant phase, variations in the magnetic characteristics were observed. Such differences are attributed to variation in grain size, amount of magnetic minerals, degree and type of magnetite alteration and frequency of ilmenite present as a coexisting phase. This is clear when comparing the magnetic and opaque characteristics of the three investigated sites. Furthermore, the directions of magnetization at the two sites of El-Bahnasa are almost similar. However, the above-mentioned mineralogical differences are behind the variation in the other magnetic properties.

Acknowledgements. I am grateful to Professor Dr. Maher A. Takla for valuable discussions and critically reading the manuscript. Also, I am thankful to Professor Dr. Bahga H. Mawaid for generous help in various stages of the work and Professor Dr. Gamel S. Saleeb for providing facilities during collection of the oriented sample.

References

Abdel Maksoud, M.A.: Petrographical, geochemical and physical properties of Egyptian basaltic rocks with special references to Abu-Zaabal. M.Sc. Thesis, Cairo University, 1968

Ade-Hall, J.M.: The magnetic properties of some submarine oceanic lavas. J. Geophys. **9**, 85–94, 1965

Ball, J., Beadnell, H.J.L.: Baharia oasis, its topography and geology. Egypt Survey Dept., Cairo, 84, 1903

Basta, E.Z.: Different types of ilmenite-magnetite intergrowths and their origin. Bull. Fac. Sci., Cairo University, **44**, 195–212, 1970

Basta, E.Z., Refai, E., Wassif, N.A.: Correlation between magnetic and mineralogical properties of some Tertiary basaltic rocks from Qatrani-Fayum Area, Egypt. Pageoph. **119**, 357–372, 1981

Cockerham, R.S., Hall, J.W.: Magnetic properties and paleomagnetism of some DSDP, Leg. 33, basalts and sediment and their tectonic implications. J. Geophys. Res. **81**, 4207–4222, 1976

El-Rashidi, Y.M.: Study of the magnetic properties of some Egyptian rocks and their relation to the Earth's magnetic field. M.Sc. Thesis, Cairo University, 1964

El-Shazly, E.M., Krs, M.: Magnetism and paleomagnetism of oligocene basalts from Abu-Zaabal and Qatrani, Northern Egypt. Travaux Inst. Geophys. Acad. Tchécosl. Sci. No. 356, Geofysikalni Sbommik, 1971

El-Sheikh, M.E.: Magnetic survey in the area East of Cairo. M.Sc. Thesis, Cairo University, 1968

Fahim, M., Gouda, H.: Magnetization and paleomagnetism of Abu-Zaabal and Abu-Rawash basalts. Egypt, Helwan Institute of Astronomy and Geophysics, Bull. No. 134, 1976

Fahim, M., Basta, E.Z., El-Rashidi, Y.M.: A paleomagnetic study on some Tertiary basalts from Egypt. IAGA, XV IUGG, General Assembly, Moscow, 1971

Fisher, R.A.: Dispersion on a sphere. Proc. R. Soc. London, A **217**, 295–305, 1953

Gough, L.G.: Compt. Rend. **109**, 935, 1889

Haggerty, S.E.: Opaque mineral oxides in terrestrial igneous rocks. In: Oxide minerals, Rumble, D. (ed.) Mineralogical Society of America short course notes, 3: pp 101–140. Blackburg, Virginia, USA: Southern Printing Company, 1976

Hargraves, R.B., Petersen, N.: Notes on the correlation between petrology and magnetic properties of basaltic rocks. Z. Geophys. **37**, 367–382, 1971

Johnson, H.P., Atwater, T.: A magnetic study of the basalts from the Mid-Atlantic Ridge at 37°N. Bull. Geol. Soc. Am. **88**, 637–647, 1977

Johnson, H.P., Hall, J.M.: A detailed rock magnetic and opaque mineralogy study of the basalts from the Nazca Plate. Geophys. J.R. Astron. Soc. **52**, 45–64, 1978

Kent, D.V., Honnorez, B.M., Opdyke, N.D., Fox, P.J.: Magnetic properties of dredged oceanic gabbros and the source of marine magnetic anomalies. Geophys. J.R. Astron. Soc. **55**, 513–537, 1978

Lowrie, W.: Oceanic basalt magnetic properties and the Vine and Matthews hypothesis. J. Geophys. **40**, 513–536, 1974

Ozima, M., Larson, E.E.: Low- and high-temperature oxidation of titanomagnetite in relation to irreversible changes in the magnetic properties of submarine basalts. J. Geophys. Res. **75**, 1003–1018, 1970

Ozima, M., Ozima, M.: Characteristic thermomagnetic curve in submarine basalts. J. Geophys. Res. **76**, 2051–2056, 1971

Rayleigh, L.: Notes on electricity and magnetism. III-on the behaviour of iron and steel under the operation of feeble magnetic forces. Phil. Mag. **23**, 225, 1887

Refai, E., Wassif, N.A.: Studies on the magnetism of Abu-Rawash basalts. Bull. Fac. Sci., Cairo University, **44**, 219–230, 1970

Rittman, A.: Remarks on the eruptive mechanism of the Tertiary volcanoes in Egypt. Bull. Volcanologique, **XV**, 109, 1954

Schaeffer, R.M., Schwarz, E.J.: The Mid-Atlantic Ridge near 45°N. IX. Thermomagnetics of dredged samples of igneous rocks. Can. J. Earth Sci. **7**, 268–273, 1970

Stacey, F.D.: The Koenigsberger ratio and the nature of thermoremanence in igneous rocks. Earth Planet. Sci. Lett. **2**, 67–68, 1967

Stott, P.M.: The stability of magnetization in basic igneous rocks. BMR Bull. **129**, Australia, 1971

Thellier, E.: Sur l'aimantation de terres cuites et ses application en géophysique. Thése, Paris, 1938

Wassif, N.A.: Opaque mineralogy and magnetic investigation of basaltic rocks from the Bahariya area, Egypt. J. Univ. Kuwait (Sci) **10**, 111–123, 1983

Watson, G.S.: Analysis of dispersion on a sphere. Roy. Astron. Soc. Geophys. Suppl. **7**, 153, 1956

Received October 18, 1984;
revised versions December 23, 1985, and June 2, 1986
Accepted June 12, 1986