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PETROGRAPHIC AND ANISOTROPY OF MAGNETIC SUSCEPTIBILITY (AMS) STUDIES OF SOME IGNEOUS ROCKS AT ABU-SHIHAT AREA, NORTHERN EASTERN DESERT, EGYPT

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دراسات صخرية وضعية وتباين خواص المتأثرية المغنطيسية لبعض الصخور النارية بمنطقة أبو شِحات، الصحراء الشرقية الشمالية، مصر

الخلاصة: تتغطى منطقة أبو شحات بصخور القاعدة والتى تعود إلى عصر ما قبل الكمبري. كشفت الدراسات الصخرية الوضعية أن منطقة الدراسة تتكون من صخور الأمفيبوليت، الديوريت، المونزوجرانيت والبيجماتيت. أجريت قياسات معملية (المتأثرية المغنطيسية وتباين خواص المتأثرية المغنطيسية (AMS)) على ١١٤ عينة تم جمعها من صخور منطقة الدراسة، وذلك من أجل وصف سلوك المتأثرية المغنطيسية وتحديد اتجاه تدفق القطر وكذلك تحديد الاتجاه المفضل للتراكيب الجيولوجية السائدة والتي أثرت على مختلف الوحدات الصخرية التي تشكل منطقة الدراسة.

ترجع قيم المتأثرية المغنطيسية لصخور الأمفيبوليت والمونزوجرانيت إلى وجود معادن المجنتيت والإلمينيت ، بينما تعود فى صخور الديوريت والبيجماتيت إلى وجود المعادن البارامغنطيسية. تبين أن النسيج المغنطيسى للديوريت والمونزوجرانيت أولى ومرتبط بعملية التموضع الأصلي من خلال تدفق القطر مع عمليات تبريد وتبلور لاحقة في ظل ظروف ثابتة نسبيًا. أوضحت الدراسة أن الأنسجة المغنطيسية للأمفيبوليت والبيجماتيت ثانوية، تم إكتسابها خلال المراحل التكتونية المتأخرة بعد عمليات التموضع والتبريد. أظهرت إتجاهات تباين خواص المتأثرية المغنطيسية المحددة لأنواع الصخور الأربعة عن أقطاب واضحة المعالم للتورق المغنطيسى. أظهرت الدراسة أن مستويات التورق لهذه الصخور ضحلة إلى متوسطة، مع اتجاهات موازية لإتجاهات إستطالتها في منطقة الدراسة.

ABSTRACT: *Abu-Shihat area is covered by basement rocks of Precambrian age. Petrographic studies revealed that the study area is represented by amphibolites, diorites, monzogranites and pegmatites. Laboratory measurements (magnetic susceptibility and anisotropy of magnetic susceptibility (AMS)) were conducted on 114 samples, gathered from the four rock types in order to describe the behaviour of magnetic susceptibility, determine the direction of magma flow and investigate the preferred orientation of the prevailing structures that affected the different rock units constituting the study area.*

The magnetic susceptibilities of the amphibolites and monzogranites are due to magnetite and/or ilmenite, while for diorites and pegmatites are due to paramagnetic minerals. The magnetic fabrics of diorites and monzogranites are interpreted as being primary related to the original emplacement process through magma flow, with subsequent cooling and crystallization under relatively static conditions. The magnetic fabrics of the amphibolites and pegmatites were interpreted as being secondary, which were acquired during late tectonic stages after emplacement and cooling. The determined AMS directions for the four rock types revealed relatively well-defined poles of magnetic foliation (K_3). The foliation planes for these rocks were shallow to moderate with directions parallel to their elongation trends in the study area.

1. INTRODUCTION

The present study area is situated in the Northern Eastern Desert of Egypt at about 20 km north of Qena-Safaga road, at El-Faroukiya station (85 km from Qena) (Fig. 1). It lies at the intersection of latitude 26° 38' N and longitude 33° 24' E. The area under study is covered by basement rocks of Precambrian age. They are arranged chronologically from the oldest by amphibolites, diorites, monzogranites, and pegmatites (El-Shazly, 1964). These rocks are traversed by Wadis (Dry Valleys), which are filled by Quaternary sediments (Fig. 1).

The study area was selected for this work due to its importance in terms of the discovery of some radiospectrometric anomalies, related to pegmatites. Petrographic studies were conducted in order to determine the main rock units constituting the study area. On the other hand, anisotropy of magnetic susceptibility (AMS) was conducted in order to: 1) Describe the behaviour of magnetic susceptibility in the 4 main rock types forming the study area, since the values of magnetic susceptibilities give the first indication of rock forming magnetic minerals, and 2) Determine the directions of magma flow and investigate the preferred orientations of the prevailing structures affecting the 4 main rock units constituting the study area during or after their original emplacement.

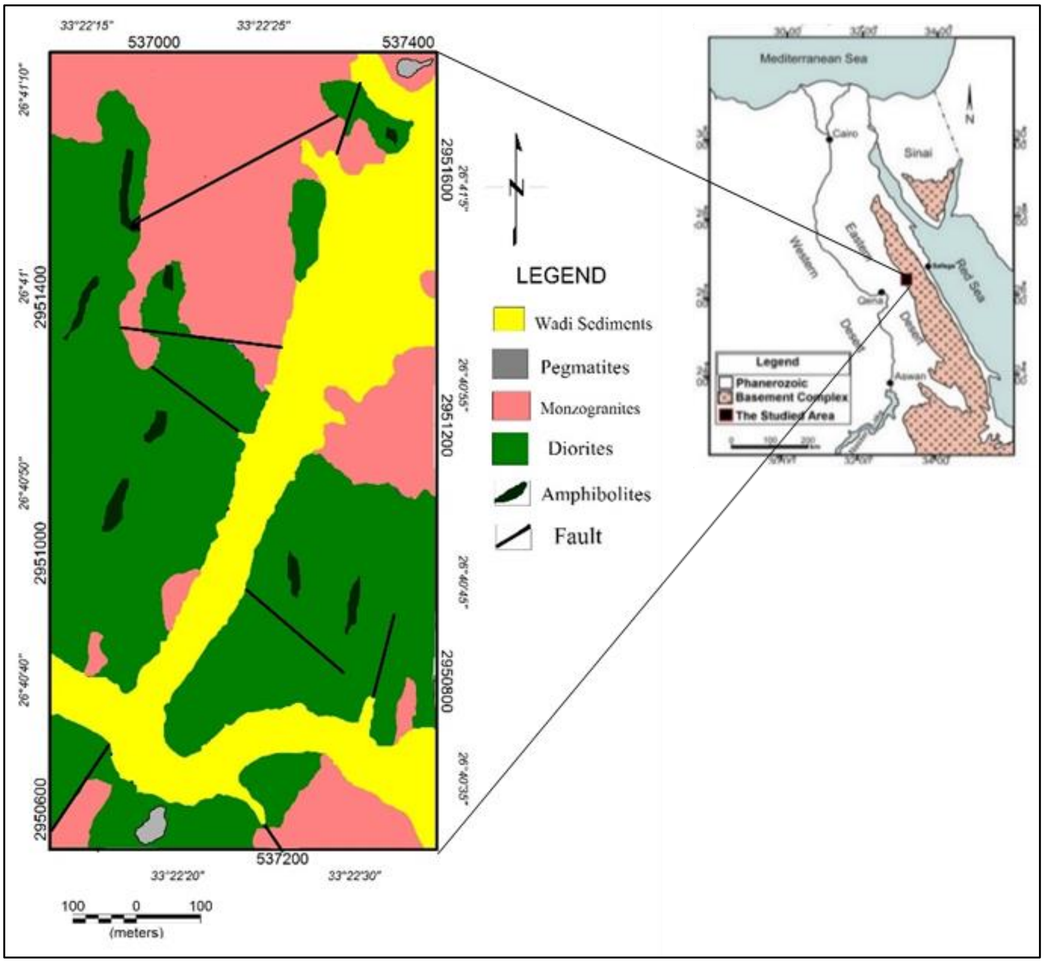

Fig. 1: Location and geological maps of Abu-Shihat area, Northern Eastern Desert, Egypt.

2. PETROGRAPHIC STUDIES

Petrographic investigations were carried out for some thin sections of some representative samples, using a Nikon (optical-pol) polarizing microscope, equipped with a full automatic photomicrograph attachment (Microflex AFX-II). The results of optical examination are illustrated on Figures (2 to 5) and summarized as follows:

2.1. Amphibolites

Amphibolites are present as roof pendants and xenoliths on the diorites and monzogranites. The contacts between amphibolites with both diorites and monzogranites are sharp. They are medium- to coarse-grained rocks, greyish green to whitish green in colour.

Microscopically, they are composed essentially of amphiboles and feldspar, with subordinate quartz and chlorite. Hornblende is the most predominant constituent of mafic minerals. It is present as large plates of green to brownish green anhedral to subhedral crystals, and sometimes occurs as large phenocrysts. Hornblende crystals usually have two sets of cleavage, strongly pleochroic in colour in thin section, varying from pale green to pale brown to yellow. Sometimes, hornblende is associated with fine inclusions of saussuritized plagioclase (Fig. 2a). Plagioclase is a dominant feldspar constituent present as coarse grains, and sometimes forms phenocrysts as elongated laths. Occasionally, plagioclase crystals are altered to kaoline and sometimes to very-fine shreds of saussurite. Chlorite, epidote and saussurite are secondary minerals. The main accessory minerals are iron oxides: magnetite and ilmenite. Iron oxides are mantled by titanite, as an alteration product of ilmenite (Fig. 2b).

2.2. Diorites

The diorites are exposed in the central, and southern parts of the study area. They form elongated mountains of low to moderate elevations, extending in N-S and NNE-SSW directions, parallel to major trends of the regional structures in the whole area (El-Tahir, 1978). These rocks are intruded by pink monzogranites, with sharp contacts.

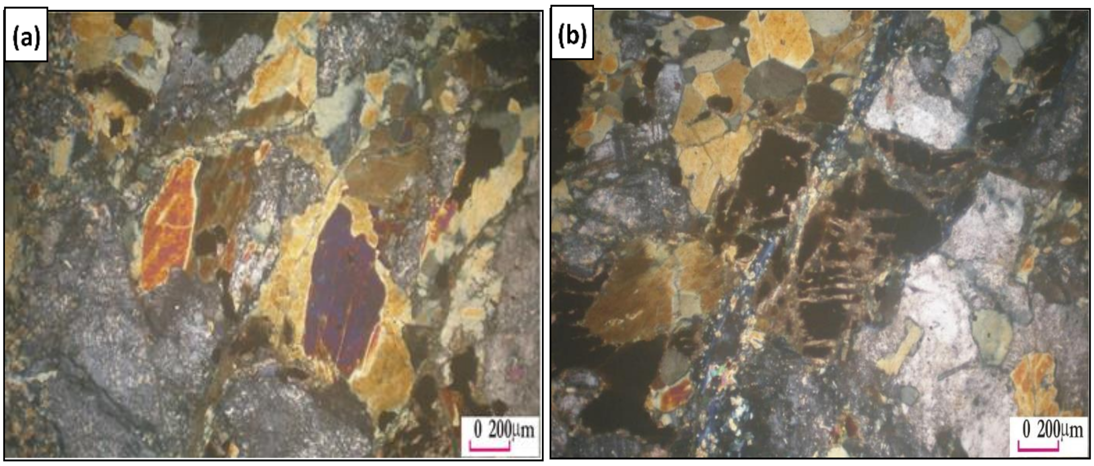

Fig. 2: (a) Hornblende associating saussurited plagioclase and (b) Iron oxides mantled by titanite as an alteration product of ilmenite, Abu-Shihat area, Northern Eastern Desert, Egypt.

Microscopically, the diorites are essentially composed of plagioclase and quartz, with minor amounts of potash feldspar. Hornblende and biotite are common mafic minerals in the diorites, while iron oxides, zircon and opaques represent the accessory constituents. Plagioclase is the most abundant mineral. It forms megacrysts in the porphyritic variety and usually occurs as euhedral to subhedral tabular crystals. Plagioclase crystals commonly contain small inclusions of quartz, opaques and occasionally hornblende (Fig. 3a). In many cases, it is altered to sericite and kaolinite, which mask its lamellar twinning. Quartz is present as medium to coarse grained, anhedral to subhedral crystals. Potash feldspars are represented by few subhedral perthite and microcline crystals and usually fill the interstitial spaces between others. Hornblende crystals are the common mafic constituent, which is usually associated with some biotite flakes. It exhibits yellowish green to brown colours, with strong pleochroism, prismatic in form; sometimes contains small quartz grains as inclusions. Hornblende is associated with oriented fresh and sericitized plagioclase due to the effect of compaction (Fig. 3b).

2.3. Monzogranites

Monzogranites are commonly massive and easily distinguished in the field, from the surrounding country rocks, by their distinctive pink and/or red colours. These rocks are exposed in the northern, and southern parts of the study area. They form discordant outcrops, with sharp intrusive contacts against the surrounding diorites.

Petrographically, these monzogranites are characterized by large phenocrysts of quartz and perthite. They are medium to coarse grained, pink in colour and composed mainly of perthite, quartz, plagioclase and biotite. Potash feldspars are represented by orthoclase perthite. Perthite occurring as subhedral crystals, sometimes may contain inclusions of opaques and quartz. It shows simple twinning and exhibits patchy and flame perthitic intergrowths (Fig. 4a). Quartz is present as fine to medium grains, sometimes as large grains. Plagioclase is present as subhedral to euhedral crystals, highly altered to saussurite and sometimes to kaoline (Fig. 4b). Biotite, which is the dominant mafic mineral, occurs as subhedral to anhedral flakes, variably altered to Fe-chlorite (penninite) and stained by magnetite (Fig. 4c). Some biotite flakes enclose prismatic zircon, apatite and zoned allanite crystals. Secondary minerals are chlorite, saussurite and kaoline, while allanite and titanite are accessory minerals (Figs. 4d and 4e).

2.4. Pegmatites

Pegmatites include most of the radioactive anomalies and mineralizations, compared to the other rock types in the study area (El-Tahir, 1978). They are cutting through all previous rock types, near or in the granite bodies to which they are genetically related. These pegmatites are present as vein-like bodies, mainly lenticular in their shapes.

Petrographically, they are very coarse grained, composed mainly of potash feldspars, quartz, and slight amounts of sodic plagioclase (albite). Potash feldspars are mostly of orthoclase and some microcline. Orthoclase occurs as large anhedral to subhedral crystals. Generally, the feldspars are the most abundant constituents of the whole pegmatite pockets. Quartz is present as large subhedral to anhedral crystals, sometimes form skeletal crystals and make about 25% of the rock (Fig. 5a). Large plates of white mica are present as well as small amounts of biotite (Figs. 5a and 5b). Zoisite and epidote are secondary minerals present as alteration products or veinlets in quartz and feldspar (Figs. 5a and 5b). Columbite and allanite are the main accessory minerals (Figs. 5c and 5d).

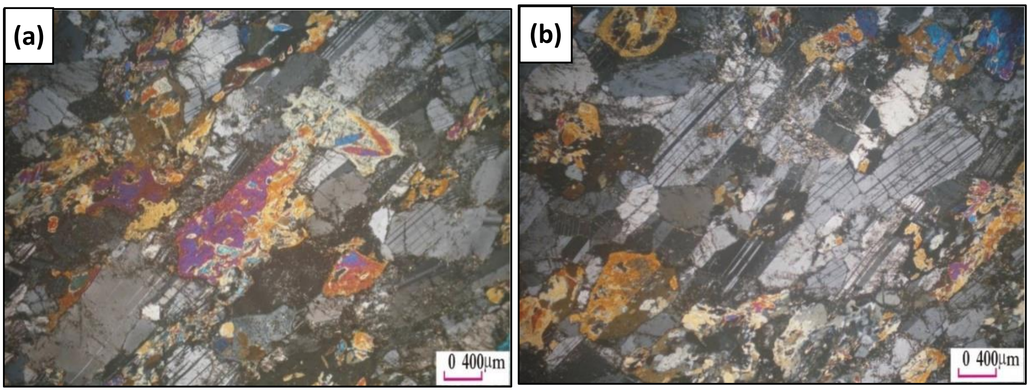

Fig. 3: (a) Plagioclase crystals enclosing small inclusions of quartz, opaques and occasionally hornblende and (b) Hornblende associated with oriented fresh and sericitized plagioclase due to the effect of compaction, Abu-Shihat area, Northern Eastern Desert, Egypt.

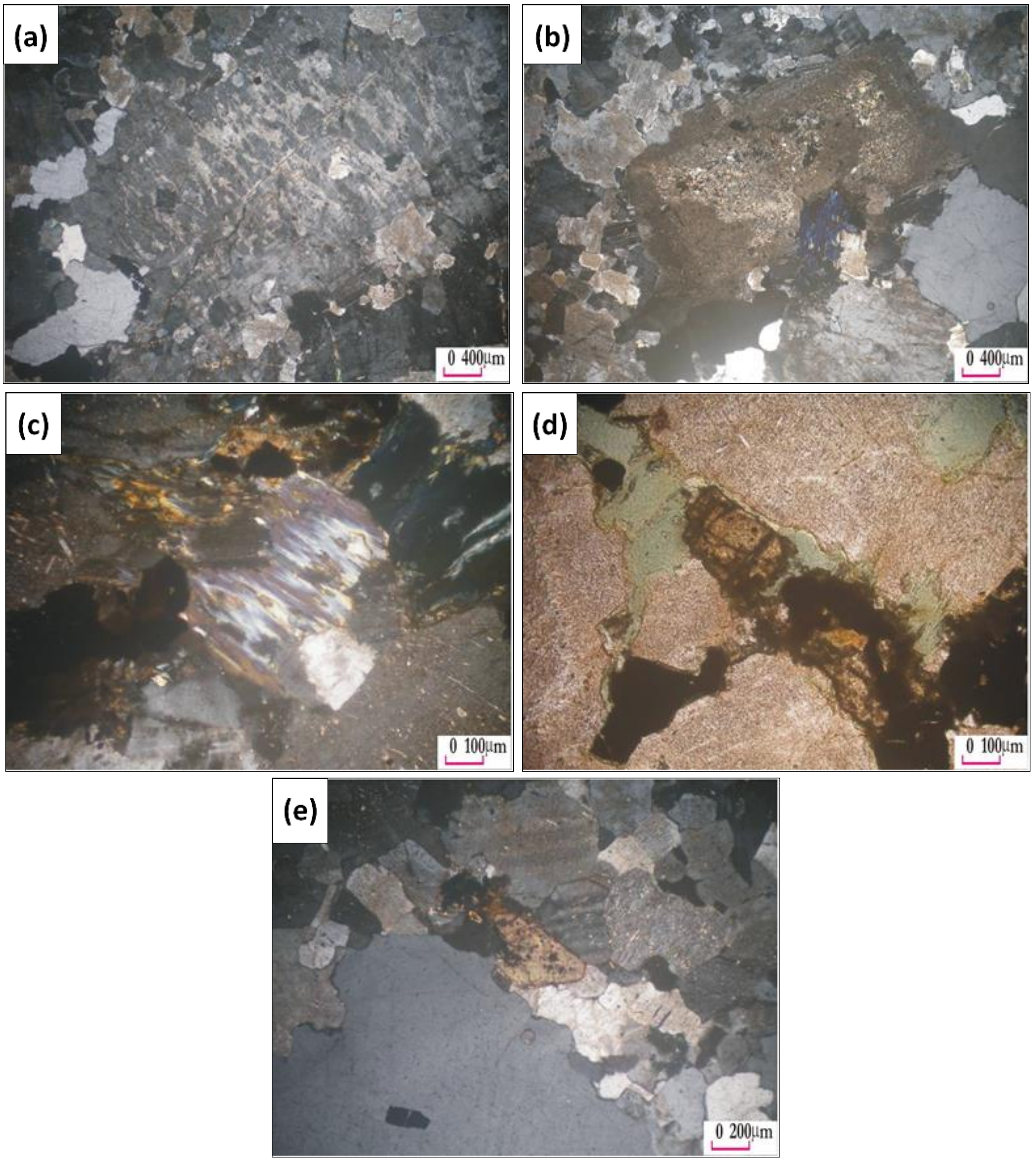

Fig. 4: (a) Subhedral crystal of patchy perthite surrounded by fine plagioclase and quartz crystals, (b) Zoned plagioclase crystal completely altered to saussurite, (c) Biotite altered completely to chlorite (penninite-Fechlorite), (d) Allanite crystal associating chlorite and opaques and (e) Plagioclase and quartz enclosing titanite crystals, Abu-Shihat area, Northern Eastern Desert, Egypt.

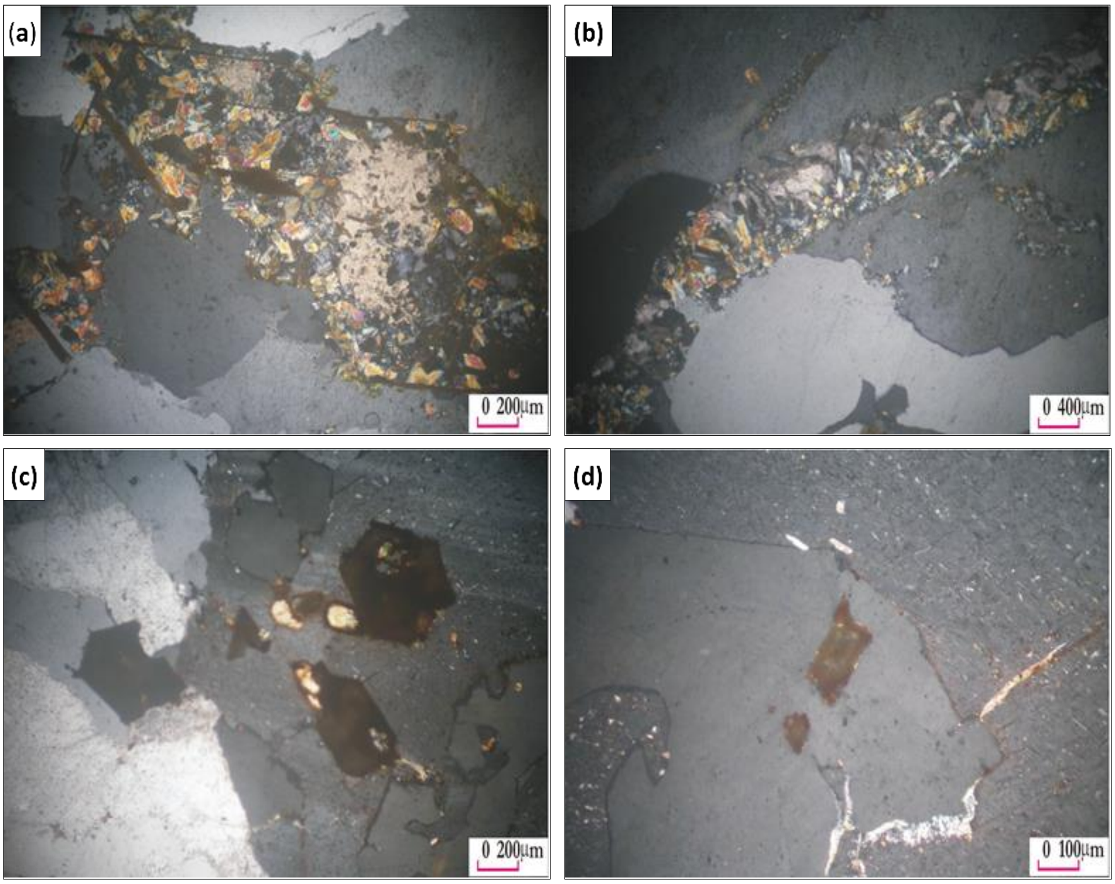

Fig. 5: (a) Skeletal crystals of quartz and epidote associating megacrysts of albite, (b) Veinlet filled with zoisite and epidote cutting feldspar and quartz megacrysts, (c) Reddish brown to black columbite crystals included in feldspars and (d) Quartz enclosing well-formed allanite crystals, Abu-Shihat area, Northern Eastern Desert, Egypt.

3. ANISOTROPY OF MAGNETIC SUSEPTIBILTY (AMS) STUDIES

Sources of magnetic susceptibility and their anisotropy provide the most fundamental data for the interpretation of geophysical magnetic surveying (Clark et al., 1992). Rock magnetic studies are useful in the analysis of rock fabrics, the determination of preferred grain orientations in rocks, the definition of current directions, the specifications of magmatic flow paths and strain histories by relating magnetic anisotropy to mineral-grain-shape alignments and crystallographic preferred orientations (e.g., Fuller, 1963; Stephenson et al., 1986; Clark et al., 1988; Jackson, 1991; Rochette et al., 1992).

The AMS of rocks, which investigates the preferred orientations of magnetic minerals, contains information about both the grain susceptibilities and their orientation-distribution. A preferential orientation-distribution of mineral grains is developed during various geological processes, such as water flow in sediments, magma flow in igneous rocks or ductile deformation in metamorphic rocks (Sagnotti et al., 2011).

The output of AMS measurements is an ellipsoid of magnetic susceptibility (AMS ellipsoid) defined as the length and orientation of its hree principal axes, $K_1 \geq K_2 \geq K_3$ the three eigenvectors of the susceptibility tensor (Rochette et al., 1992). K_1 defines the maximum susceptibility (K_{max}) or the direction where most of the magnetic grains are aligned. K_2 is defined as the intermediate (K_{int}) and K_3 as the minimum susceptibility (K_{min}).

When measured, each AMS eigenvector is determined with two uncertainty angles, which define the regions where each principal susceptibility direction lies with a probability of 95 %. AMS ellipsoid shapes are classified according to the relationships between the magnetic susceptibility eigenvalues, as seen on Figure (6).

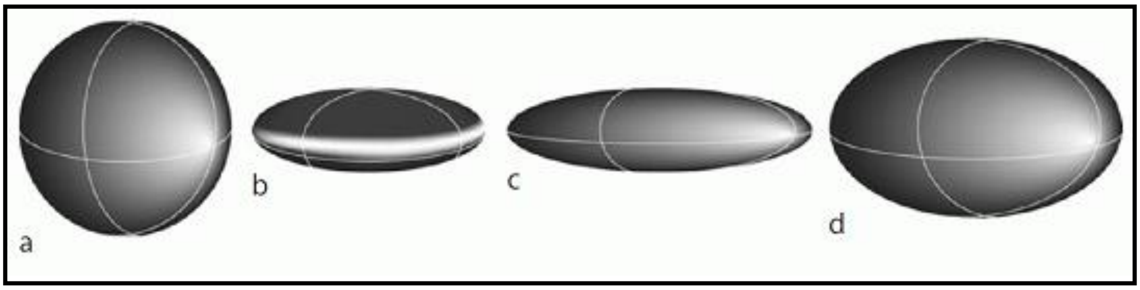

Fig. 6: Shapes of AMS ellipsoids: (a) Kmax≈ Kint≈ Kmin; isotropic susceptibility, the AMS ellipsoid is a sphere; (b) Kmax≈ Kint > Kmin; the AMS ellipsoid is an oblate shape; (c) Kmax≈ Kint <Kmin; the AMS ellipsoid has a prolate shape; (d) Kmax> Kint> Kmin; the AMS ellipsoid is triaxial (Sagnotti et al., 2011).

3.1. Sampling and Measurements

Abu-Shihat area, Northern Eastern Desert, Egypt, was sampled at 20 sites, covering amphibolites, diorites, monzogranites and pegmatites (Fig. 1). Oriented block samples, only, were collected from all sites, whereas drilled core samples were not accessible. These samples were oriented in situ, while still attached to the outcrops, using a solar compass (Tarling, 1971). The block samples were subsequently reoriented in the laboratory, where cylindrical samples of 2.5 cm diameter were drilled. Generally, three to five core samples were drilled from each block sample. Each core sample was then sliced into one to three standard core specimens of 2.2 cm length. This sampling scheme produced a total of 114 core samples. The coordinates of sampling sites were accurately determined in the field, using a GPS instrument.

The equipment used in this study is the Minisip susceptibility meter. It is a computer-controlled instrument and provides a mean of measuring both the bulk susceptibility and the AMS of a rock sample, with a sensitivity of 10^{-7} Gauss/Oersted. Bulk susceptibility measurement occurs within 4 seconds. It depends on a balanced air-core transformer, having a mechanism that allows a rock sample to be introduced into a section of a core, thus, unbalancing it. The degree of unbalance is a measure of the bulk susceptibility along the cylindrical axis (Molspin Ltd., UK, 1998).

For the present study, five parameters were calculated; 1) mean susceptibility (Nagata, 1961), 2) Anisotropy degree (Jelink, 1981), 3) Magnetic lineation (Blasely & Buddington, 1960), 4) Magnetic foliation (Stacey et al., 1960) and 5) Ellipsoid shape (Jelink, 1981).

Table (1) illustrates the calculated AMS parameters for each site.

Measurements of the magnetic susceptibilities and AMS parameters were carried out for a total of 31, 29, 26 and 28 core samples collected from amphibolites, diorites, monzogranites and pegmatites, respectively (Table 1).

3.2. Results

3.2.1. Amphibolites

Magnetic susceptibility measurements revealed high values, with an average of 3620 x 10^{-5} S.I. units. The anisotropy degree, P_J, showed also high values, with an average of 1.15 (Table 1). The relation between the anisotropy degree and magnetic susceptibility (Fig. 7a) reveals the existence of a general increase of magnetic susceptibilities with increasing anisotropies. The magnetic lineation, P_1, is low and homogeneous, with an average of 1.070, while the magnetic foliation, P_3, is higher than, P_1, in all sites, with an average of 1.152, reflecting the predominance of magnetic foliation (oblate ellipsoid) over lineation (Table 1). The ellipsoid shape change in the sampling area is further presented by the P_3 versus P_1 plot (Fig. 7b), which resemble the Flinn deformational plot used by structural geologists (Flinn, 1962). The line of unit slope, which passes through the origin, separates the oblate ellipsoids ($P_3 > P_1$) from the prolate ones ($P_1 > P_3$). Another diagram for describing the ellipsoid shape of the AMS parameters is shown on Figure (7c), in which the region above the horizontal axis represents an oblate ellipsoid and the region below represents a prolate ellipsoid.

The P_3 versus P_1 plot refers that all sites fall within the flattening field (Fig. 7b). This is also evident from both the calculated positive values of T parameter (Table 1).

3.2.2. Diorites

Magnetic susceptibility (K) measurements displayed very low values, with an average of 26.167 x 10^{-5} S.I. units. The anisotropy degree, P_J, showed low values, with an average of 1.028 (Table 1). No relation between the anisotropy degree (P_J) and magnetic susceptibility (K) could be found (Fig. 8a). The magnetic lineation (P_1) values are weak, with an average of 1.009. The magnetic foliation (P_3) is higher than (P_1), with an average of 1.024. The ellipsoid shapes are oblate, expect for one site which is prolate (Fig. 8b). This is also reflected in the values of T parameter that ranges from -0.03 to 0.65 (Table 1).

Table 1: Site-mean magnetic susceptibilities and AMS parameters for the amphibolites (Am), diorites (D), monzogranites (MG) and pegmatites (PG), Abu-Shihat area, Northern Eastern Desert, Egypt.

Site	N	$K \times 10^{-5}$	P_J	T	P_1	P_3
Am.1	10	4805	1.253	0.331	1.077	1.159
Am.2	5	3800	1.142	0.223	1.083	1.140
Am.3	6	2794	1.101	0.235	1.088	1.121
Am.4	5	4200	1.176	0.325	١,٠٥5	1.130
Am.5	5	2500	1.090	0.320	1.043	1.210
Mean	---	3620	1.150	----	1.070	1.152
D.1	4	28.790	1.040	0.650	1.010	1.040
D.2	7	23.700	1.028	0.423	1.008	1.019
D.3	7	24.229	1.004	-0.030	1.006	1.005
D.4	6	26.200	1.03	0.630	1.010	1.010
D.5	5	25.300	1.022	0.600	1.007	1.020
Mean	---	26.167	1.028	---	1.009	1.024
MG.1	6	261.80	1.075	0.083	1.033	1.039
MG.2	4	25.43	1.017	0.083	1.005	1.011
MG.3	5	188.90	1.061	0.376	1.027	1.033
MG.4	6	210.20	1.053	0.230	1.003	1.020
MG.5	5	195.95	1.020	0.19	1.010	1.030
Mean	---	176.4	1.045	---	1.016	1.026
PG.1	6	23.580	1.30	0.468	1.070	1.201
PG.2	6	30.007	1.139	-0.194	1.083	1.048
PG.3	5	27.830	1.215	0.390	1.035	1.099
PG.4	6	35.487	1.15	0.350	1.045	1.100
PG.5	5	34.000	1.29	0.420	1.063	1.150
Mean	---	30.1	1.218	---	1.059	1.119

N: Number of measured core samples in each site.
K: Volume magnetic susceptibility, in S.I. units.
P_J & T: Magnitude of anisotropy and ellipsoid shape, respectively (Jelinek, 1981).
P_1 & P_3: Lineation (Balsley & Buddington, 1960) and foliation (Stacey et al., 1960), respectively.

Directions of the three principal magnetic susceptibility axes for all sites, represented on the stereographic projection, are shown on Figure (8d). The magnetic foliation plane (plane containing K_1 (magnetic lineation) and K_2 axes) are stringing within a relatively shallow foliation plane, trending mainly in a NNE-SSW direction, with a subordinate N-S direction (Fig. 8d). The K_3 axes (magnetic foliation poles) are scattered along ENE direction, with moderate to steep inclinations and trending in an ENE-WSW direction, with a subordinate E-W trend.

3.2.3. Monzogranites

These rocks show relatively moderate magnetic susceptibility values, with an average of 176.4 x 10^{-5} S.I. units. The anisotropy degree, P_J, showed low values, with an average of 1.045 (Table 1). There is a general direct relation between the anisotropy degree and magnetic susceptibility (Fig. 9a). The magnetic lineation, P_1, is low and heterogeneous, with an average of 1.016, while the magnetic foliation, P_3, is slightly higher than P_1, with an average of 1.026 (Table 1). This reflects clear predominance of magnetic foliation (oblate ellipsoid) over lineation. This is also evident from both the calculated positive values of T parameter (Table 1) and the P_3 versus P_1 plot, where values from all sites plot well within the flattening field (Fig. 9b). The flattening of oblate-shaped ellipsoids generally increase with the increase of anisotropy degree P_J (Fig. 9c).

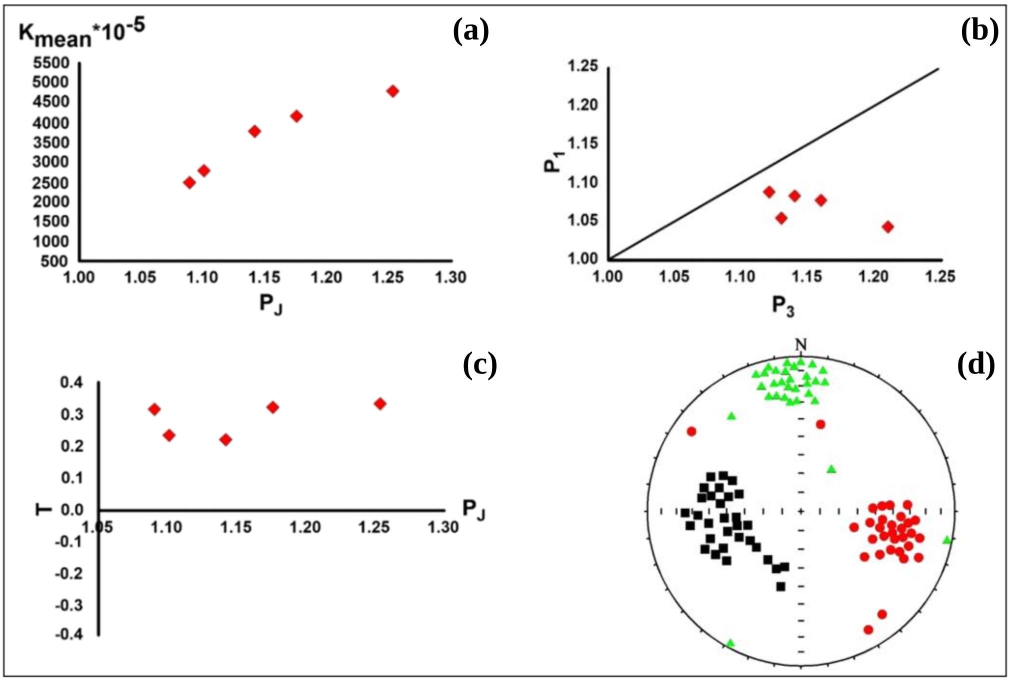

Fig. 7: (a) Anisotropy degree (P_J) and magnetic susceptibility (K), (b) Foliation (P_3) versus lineation (P_1) (c) anisotropy degree (P_J) and ellipsoid shape (T) and (d) Equal-area lower hemisphere stereographic projections of site-mean directions of the principal magnetic susceptibility axes for the amphibolites (Am), Abu-Shihat area, Northern Eastern Desert, Egypt.

■ Maximum axes (K_1). ▲ Intermediate axes (K_2). ● Minimum axes (K_3).

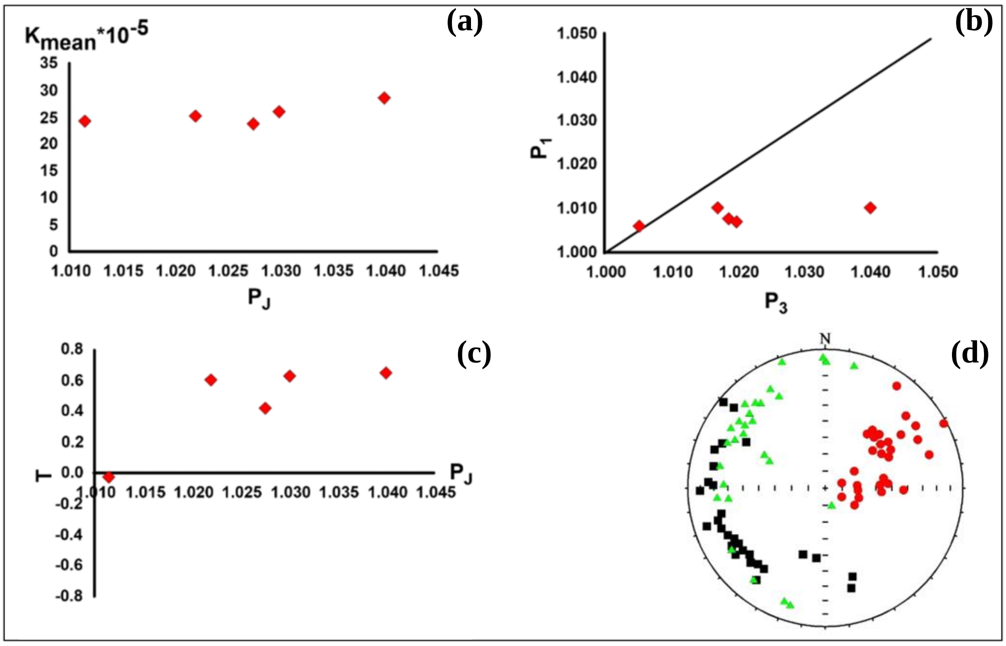

Fig. 8: (a) Anisotropy degree (P_J) and magnetic susceptibility (K), (b) Foliation (P_3) versus lineation (P_1) (c) anisotropy degree (P_J) and ellipsoid shape (T) and (d) Equal-area lower hemisphere stereographic projections of site-mean directions of the principal magnetic susceptibility axes for the diorites (D), Abu-Shihat area, Northern Eastern Desert, Egypt.

■ Maximum axes (K_1). ▲ Intermediate axes (K_2). ● Minimum axes (K_3).

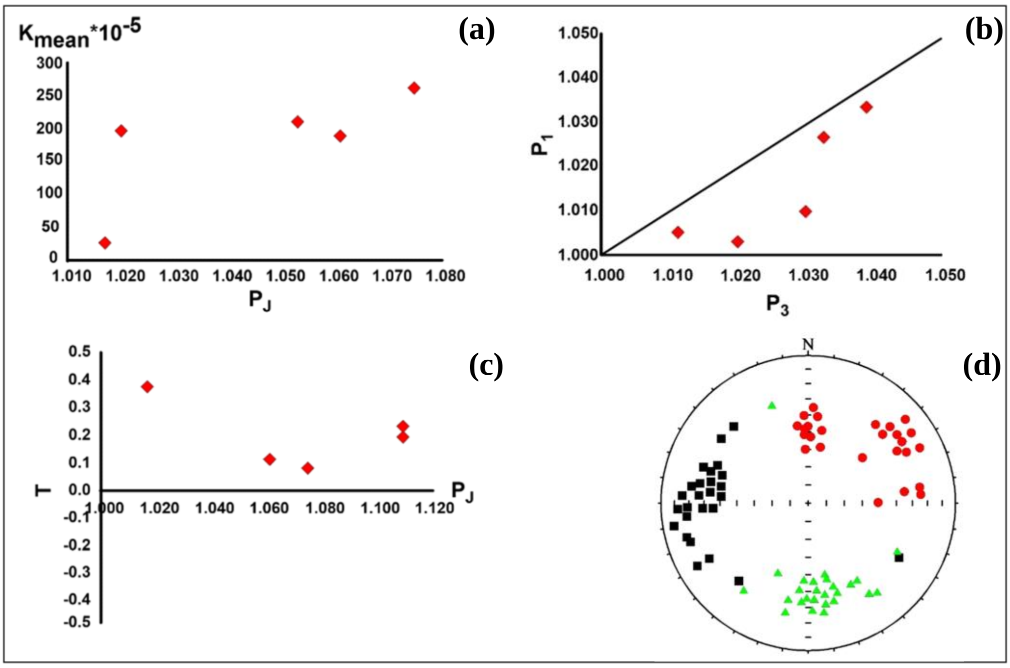

Fig. 9: (a) Anisotropy degree (P_J) and magnetic susceptibility (K), (b) Foliation (P_3) versus lineation (P_1) (c) anisotropy degree (P_J) and ellipsoid shape (T) and (d) Equal-area lower hemisphere stereographic projections of site-mean directions of the principal magnetic susceptibility axes for the monzogranite (MG), Abu-Shihat area, Northern Eastern Desert, Egypt.

■ Maximum axes (K_1). ▲ Intermediate axes (K_2). ● Minimum axes (K_3).

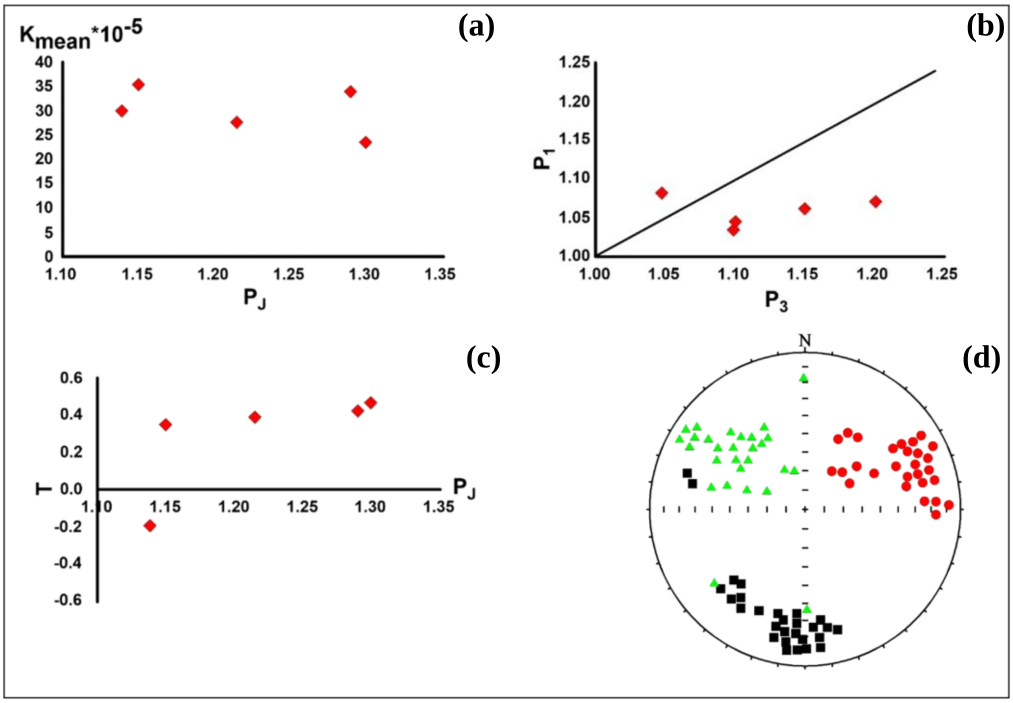

Fig. 10: (a) Anisotropy degree (P_J) and magnetic susceptibility (K), (b) Foliation (P_3) versus lineation (P_1) (c) anisotropy degree (P_J) and ellipsoid shape (T) and (d) Equal-area lower hemisphere stereographic projections of site-mean directions of the principal magnetic susceptibility axes for the pegmatites (PG), Abu-Shihat area, Northern Eastern Desert, Egypt.

■ Maximum axes (K_1). ▲ Intermediate axes (K_2). ● Minimum axes (K_3).

The overall site-mean directions of the principal magnetic susceptibility axes for all sites are shown on Figure (9d). The magnetic lineation (K_1 axes) takes an average WNW trend at a moderate inclination, while K_2 axes show little scatter in a general, with an ESE direction (Fig. 9d). The K_3 axes (magnetic foliation poles) are moderate and trend in the N-S and NE-SW directions (Fig. 9d).

3.2.4. Pegmatites

Magnetic susceptibility measurements displayed low values, with an average of 30.1 x 10^{-5} S.I. units. The anisotropy degree (P_J) showed high values (Table 1), with an average of 1.218. No relation between the anisotropy degree and magnetic susceptibility could be observed (Fig. 10a).

Both magnetic lineation P_1 and magnetic foliation P_3 are moderate, with averages reaching 1.059 and 1.119 for P_1 and P_3, respectively. P_3 is higher than P_1 in the four sites, indicating the predominance of oblateness, while the remaining site displays prolatenes, which is confirmed by its negative value of the shape parameter T (Table. 1). On the other hand, P_J shows no relation with increasing oblateness (Fig. 10b and c).

The overall site-mean directions of the principal magnetic susceptibility axes for all sites are shown on Figure (10d). K_1 axes are scattered along a single NW-SE direction, with shallow inclinations. The K_3 axes are scattered at shallow to moderate inclinations and trend in a general ENE-WSW direction.

3.3. Discussion

Diorites and pegmatites show low mean values of magnetic susceptibilities, of the order of 10^{-4} S.I. units. Meanwhile, for monzogranites and amphibolites show relatively high mean magnetic susceptibility values, of the order of 10^{-3} S.I. units. According on the classification of Ellwood and Wenner, 1981, the magnetic susceptibilities of diorites and pegmatites are due to paramagnetic minerals. Regarding amphibolites and monzogranites, they are considered as magnetic rocks, reflecting the presence of magnetite and/or magnetite with ilmenite (Ellwood and Wenner, 1981). This is confirmed from the petrographic investigation, which indicates the presence of hornblende associated with some biotite flakes in diorites, large mica plates with biotite in pegmatites, and the presence of magnetite in amphibolites and monzogranites. The difference between the magnetic susceptibility values of amphibolites and monzogranites is due to their magnetite contents, which is abundant in the amphibolites and to a lesser extent in the monzogranites.

Generally, the shapes of magnetite grains dominate the AMS in magnetite-rich rocks (Hargraves et al., 1991; Hillhouse and Wells, 1991 and others). Therefore, AMS of the amphibolites and monzogranites were originated through shape alignment of magnetite grains, which is in agreement with the direct relation between the anisotropy degree and magnetic susceptibility. Regarding the diorites and pegmatites, the lack of the relations between magnetic susceptibility and anisotropy degree for these rocks suggest that their AMS were originated through the crystalline alignment of hornblende, biotite and mica.

In the plutonic rocks, where emplacement occurred through magma flow, the magnetic anisotropy is generally characterized by low values, less than 10 percent (Hargraves et al., 1991). Thus, it is important to know if the observed fabrics were acquired during magmatic flow at the time of emplacement in the subsolidus stage (primary fabrics), or during late tectonic stages after emplacement and cooling (secondary or deformational fabric). The anisotropy degrees of the diorites and monzogranites of the study area are relatively low (averages of 1.028 and 1.045); these values indicate very low deformations (2.8 % and 4.5 %), i.e., less than 10 % which suggest a primary magnetic fabric. Meanwhile, the deformation degrees of amphibolites and pegmatites are fairly high (averages of 1.15 (15 %) and 1.218 (21.8 %)), suggesting that the magnetic fabric of these rocks could not be acquired during the original emplacement process through magma flow and were acquired during late tectonic stages after emplacement and cooling (secondary fabric).

The determined AMS directions for the four rock types revealed relatively well-defined poles of magnetic foliation (K_3), which were used to infer the flow directions. On the other hand, the foliation planes for these rocks were shallow to moderate, with directions parallel to their elongation trends in the study area.

CONCLUSIONS

The results of the present study can be summarized as follows:

1- Petrographically, four main rock types constitute the Abu-Shihat area. They are from the oldest to the youngest: amphibolites, diorites, monzogranites and pegmatites. These rocks belong to the Precambrian age.

2- The susceptibilities of diorites and pegmatites are mainly due to paramagnetic minerals, e.g., hornblende, biotite and mica. Meanwhile, the susceptibilities of amphibolites and monzogranites mainly belong to magnetite with ilmenite and magnetite.

3- Depending on the anisotropy degree (P_J) values, the AMS of diorites and monzogranites could be interpreted as being primary, related to the original emplacement process through magma flow, with subsequent cooling and crystallization under relatively static conditions. On the other hand, the magnetic fabric of amphibolites and pegmatites were acquired during late tectonic stages after emplacement and cooling (secondary fabric).

4- The relation between the magnetic susceptibilities and the anisotropy degrees for the four rock types revealed that, the AMS were originated through shape alignment of magnetite grains in amphibolites and monzogranites and through crystalline alignment of paramagnetic minerals in diorites and pegmatites.

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