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RESEARCH ARTICLE

NEW GEOLOGICAL AND GEOCHEMICAL ASPECTS OF ABU KHALAG AREA, BAYUDA DESERT, NILE STATE, NORTHERN SUDAN

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ABSTRACT

Detailed geological and geochemical investigations, which have done in the studied Abu Khalag area showed that the area constitutes a part of Arabian-Nubian Shield (ANS). Lithogeochemical data derived from rock samples collected from the study area, were plotted on AFM diagram, and have shown calc-alkaline affinity, that confirms the subduction-related geological environment for these rock assemblages. Rock assemblages in Abu Khalag area, for the first time, were mapped in detail on scale of 1:350000. Rocks of the area are composed of gneisses, schists, quartzites, calc-silicates rocks, marbles, and amphibolites, all of the above-mentioned units were affected later with retrogressive regional metamorphism to greenschist facies.

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INTRODUCTION

Abu Khalag area, which represents a part of Bayuda Desert, is Located west of the River Nile, northern Sudan (Fig. 1). In the northeast Sudan, the Pan-African involved the tectono-magmatic episodes of Late-Proterozoic age. The Precambrian basement of Sudan and adjacent areas in north-eastern Africa can be divided into two major geodynamic systems, namely gneisses with interfolded supracrustal metasediments, and a dominantly low-grade, juvenile ophiolitic island-arc assemblage (Abdel Rahman, 1993) (Fig. 2). The two types of basement complexes comprise distinct tectonic domains: an older (Archaean/Early-Middle Proterozoic) sialic continental plate, and late-Proterozoic Pan-African Arabian-Nubian Shield (ANS) (Abdel Rahman, 1993). The high-grade older units make up most of the basement exposures west of the River Nile, while rocks belonging to the (ANS) dominate the region east of the River Nile (Fig. 3), the comprises mainly Late-Proterozoic to Early Paleozoic, variably deformed, greenschist facies rocks. Most of the (ANS) basement is exposed in western Arabia and NE Sudan (Abdel Rahman, 1993).

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In this study, the (ANS) rock assemblages were found extending in the west of the River Nile (previously thought the border between the two tectonic domains), in Abu Khalag area. Isotopic and structural studies in the (ANS) have revealed an abundance of volcanoclastic sequences and related sediments. Several discontinuous ophiolite slices in linear zones have been identified. Collective evidences indicate that the evolution of the (ANS) was mainly one of continental island arc development and related syn-, late-, and post-tectonic magmatism (Gass, 1981). The evolution of the (ANS) was completed over a period extending from about 1100 Ma to 500 Ma, through the progressive cratonization of numerous intra-oceanic island arc, and back arc basins complexes (Vail, 1983), and continental micro-plates (Kröner *et al.*, 1987). Geochronological and isotopic data indicated that the (ANS) crust contains heterogeneous mixture of Archaean, Paleo-, Meso-, and Neoproterozoic rocks, which have old continental, as well as juvenile, isotopic signatures (Abdel Salam *et al.*, 2002). This region is largely comprised of continental crust dominated by medium-to high grade gneisses and migmatites as well as a significant amount of Neoproterozoic juvenile material including arc assemblage and dismembered ophiolite belts and A-type granitoids (Abdel Salam *et al.*, 2002).

Küster and Liégeois, (2001) proposed large oceanic domain accreted with the East Saharan Ghost Craton (ESGC) which identified in the Uweinat area, during an intense NW-directed frontal collision (in fact probably a series of collisions) at approximately 700 Ma. This accretion induced the regional amphibolite-granulite facies metamorphism into the juvenile terrains, and the re-melting of older terrains to the NW.

MATERIALS AND METHODS

The present work has been applied to all geological studies. Analytical techniques such as Atomic Absorption Spectrometry (AAS), which has been done in the laboratory of Alneelain University and X-Ray Florescence (XRF), which has been done in laboratory of Technical University of Berlin were used to measure major and trace elements of the collected samples. The geochemical data have been plotted in variation diagrams using Minpet 2.02 geochemical software for rock assemblages, and statistical methods have been used to determine the geochemical parameters. All the maps based on Landsat images were done with the help of Corel draw 12, GIS arc view and ENVI 4 remote sensing software's.

RESULTS AND DISCUSSION

Rocks assemblages of the Abu Khalag area

The Abu Khalag area has been investigated in detail (Fig 4). It is bounded by Long 33° 15´E, and 33° 30´E and Lat. 18° 10´E, and 18° 25´E. It is composed of high-grade amphibolite facies metamorphic rocks e.g. Hornblende gneisses (Plate 1), and medium to low greenschist facies, e.g. garnet-biotite schists, kyanite, staurolite schists, wollastonite schist, amphibolite schist (Plate 2), and low-grade metamorphic rocks of green schist facies, e.g. mica quartz schists, quartz muscovite calc-silicates and marbles (Plate 3). A careful study of mineralogical and textural features of above-mentioned rocks, guides to, these rocks are Volcano-sedimentary origin (turbidites), and the varying in the metamorphism grades due to the levels of depth in which they are deposited in. These rocks were cut by slightly deformed syn-orogenic granite-granodiorite intrusions in shape of stocks, and ring complexes, such as J. Kurbi and J. Abu Handal. These ring complexes formed number of alkali ring crosscut unconformably the above-mentioned old units. The dykes are composed of spherulitic rhyolites (Plate 4), and trachytes and micro granites. No significant sedimentary rocks observed in the study area. Cenozoic alkali olivine basalt (Plate 5) flows were injected in the area following the weak planes of the country rocks (foliation, bedding, and fractures). From field relationships, the sequence of rock units in the Abu Khalag area are shown in Table 1, following stratigraphic units based on deformation and metamorphism.

Ultrabasic (Ophiolites) Rocks

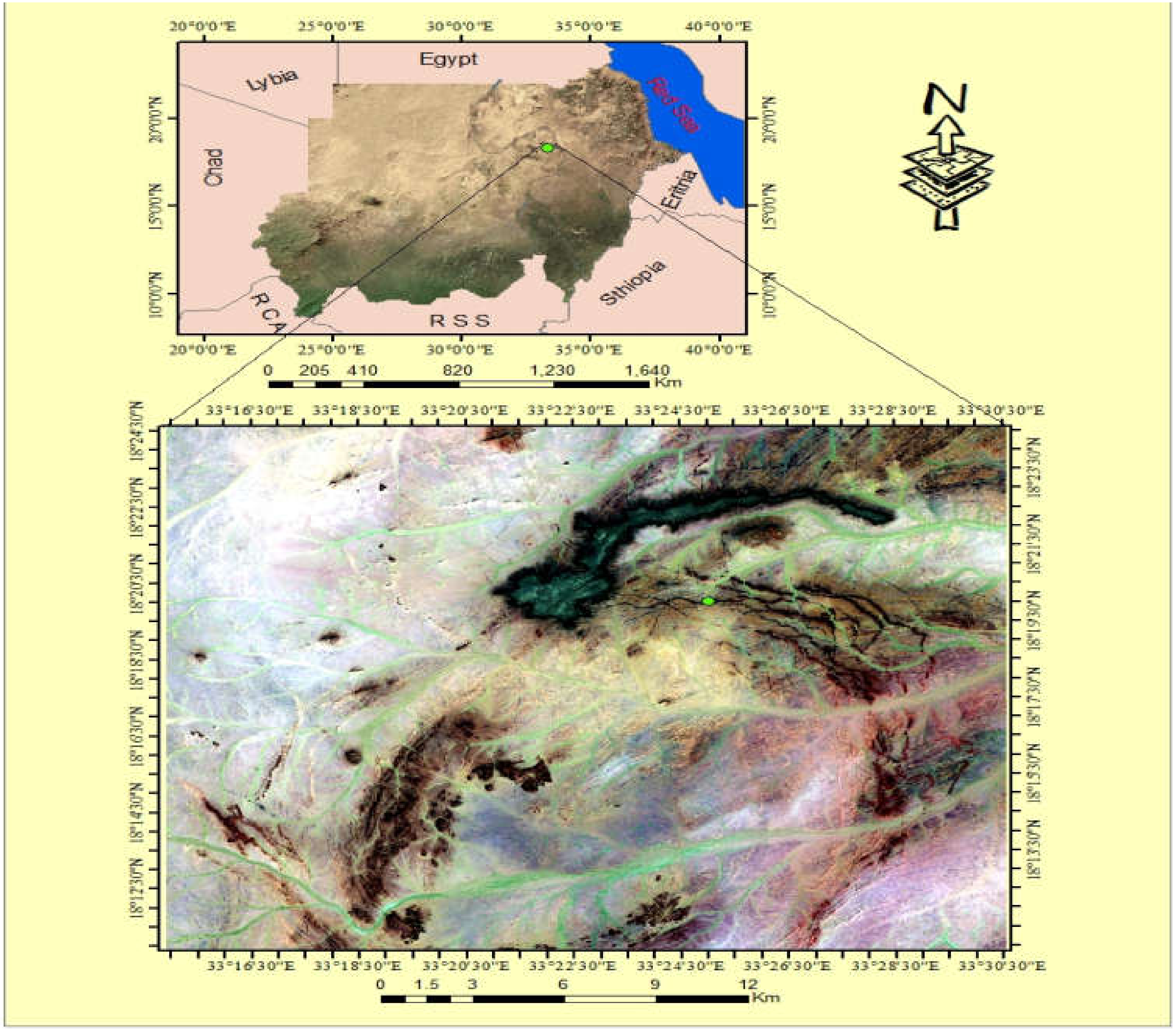
Ultramafic rocks found as unmappable, low-lying outcrops, dismembered ophiolites, are occurring northeast of the study area. Four samples have been analyzed for major and trace elements by the pressed powder pellet XRF technique (Table 2).

The chemical composition, and Loss On Ignition (LOI) values of the mafic and ultramafic units in Abu Khalag area, are nearly same, and similar to values that have been reported from similar lithologies in the (ANS), such as the Keraf petrotectonic assemblages, J. Rahib fold belt, Red Sea Hills, and Ingassana Hills (Bailo, 2000; Abdel Rahman, 1993; Bakheit, 1991), this correlation indicates the Abu Khalag area is a part of (ANS).
According to the chemical data plotted on the AFM diagram (Irvine and Baragar, 1971) the analysed ultramafic samples showed a tholeiitic trend (Fig. 5, and6). On the Mg-FeOt-Al_2O_3 discrimination diagram (Pearce *et al*., 1977) the rocks are distributed around the boundary between zone 1 (spreading center) and zone 5 (continental), this distribution of plotted samples supports the sea floor spreading center origin of ultrabasic rocks. The distribution of the other two samples of ultrabasic rocks plotted in zone 3 (oceanic ridge) and zone 4 (oceanic island) may be attributed to the low-grade retrogressive metamorphism (Fig. 7).

The subdivision of sub-alkaline rocks using the K_2O vs. silica diagram (Gill, 1981) show low-K tholeiite trend of the ultramafic rocks in the study area (Fig. 8) thus, indicating the ophiolitic origin of these ultramafic rocks (Raymond, 2002). The mid-oceanic ridges cannot account for all ophiolites, most likely the more common environment for formation of ophiolites is a back-arc basin or intra-arc basin (Raymond, 2002) and beneath the island arcs (Miyashiro, 1973). The highest values of CaO reported in this group (Table 2) indicate these ultramafic rocks had a peridotite average composition, because the excess Ca is accommodated in the formation of the secondary calcite, which is easily identified in thin sections (Plate 1). The enrichment of CaO also can be attributed to the carbonization during the low-grade metamorphism. The enrichment of Mg, Ni, V and deficiency in SiO_2, MnO, P_2O_5, Na_2O and K_2O and the values of Fe_2O_3 are in the range of 7.76 to 21.22 weight %, which are conformable with the values reported by (Carmichael, 1964) for the alpine-type orogenic peridotites. By using Zr-Ti_2O variation diagram (Pearce and Cann, 1973; Rock *et al*., 1990) most of the ultramafic rocks were distributed in komatiite, basalts + dolerite sills (Fig. 9 and10). Komatiite has been classified as ultramafic volcanic rock, low in Ti and Mg (Raymond, 2002). By using Zr-TiO_2 variation diagram (Halberg, 1985 modified after Winchester and Floyd, 1977) most of the mafic/ultramafic rocks plotted in Mg-rich ultramafic zone (MUM) (Fig. 11). By using variation diagram of chemical classification and terminology of volcanic rocks most of mafic/ultramafic rocks plotted in sub-alkaline basalt. All above-mentioned evidences supported the concept of ophiolitic origin of the ultramafic rocks in the Abu Khalag area.

Meta-Volcano-sedimentary Sequence (Turbidites)

Four samples of volcano-sedimentary (volcanoclastic) rocks have been collected from Abu Khalag area. It can be correlated geochemically with rock assemblages in the Haya terrane of the Red Sea Hills (Abdel Rahman, 1993). The volcano-sedimentary sequence is presented here as turbidites, the rocks which form from turbidity currents that develop where sediments accumulations become unstable, and move down slope in turbid flows.


Egypt
Lybia
Chad
Red Sea
Eritria
Ethiopia
R C A
R S S
20°0'0"E
25°0'0"E
30°0'0"E
35°0'0"E
40°0'0"E
20°0'0"N
15°0'0"N
10°0'0"N
0 205 410 820 1,230 1,640
Km
33°16'30"E
33°18'30"E
33°20'30"E
33°22'30"E
33°24'30"E
33°26'30"E
33°28'30"E
33°30'30"E
0 1.5 3 6 9 12
Km
N

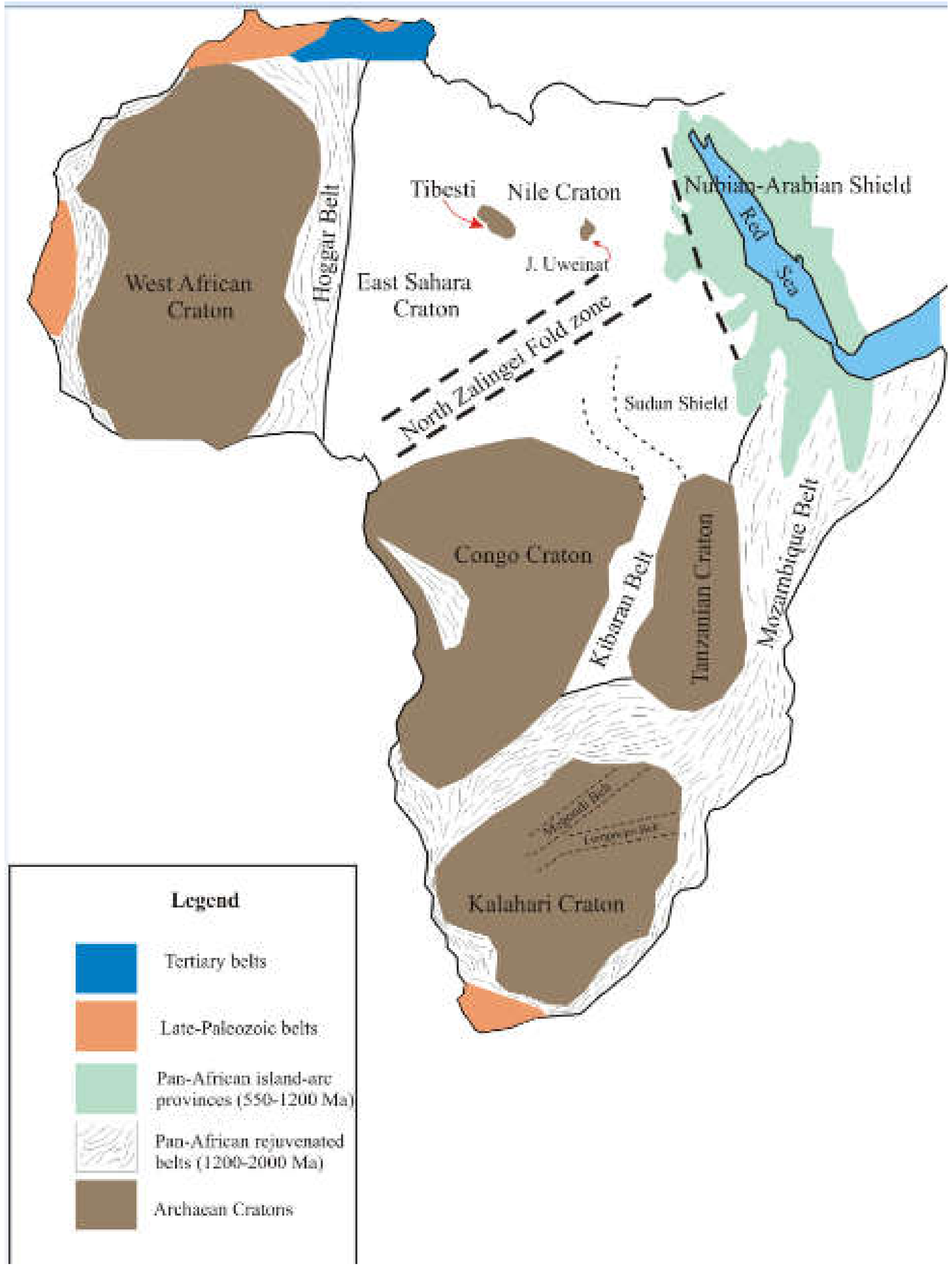


Fig. 2. The Pan-African Mobile Belts and the Main Structural elements of African Cratons, (modified Abu Fatima, 1992)

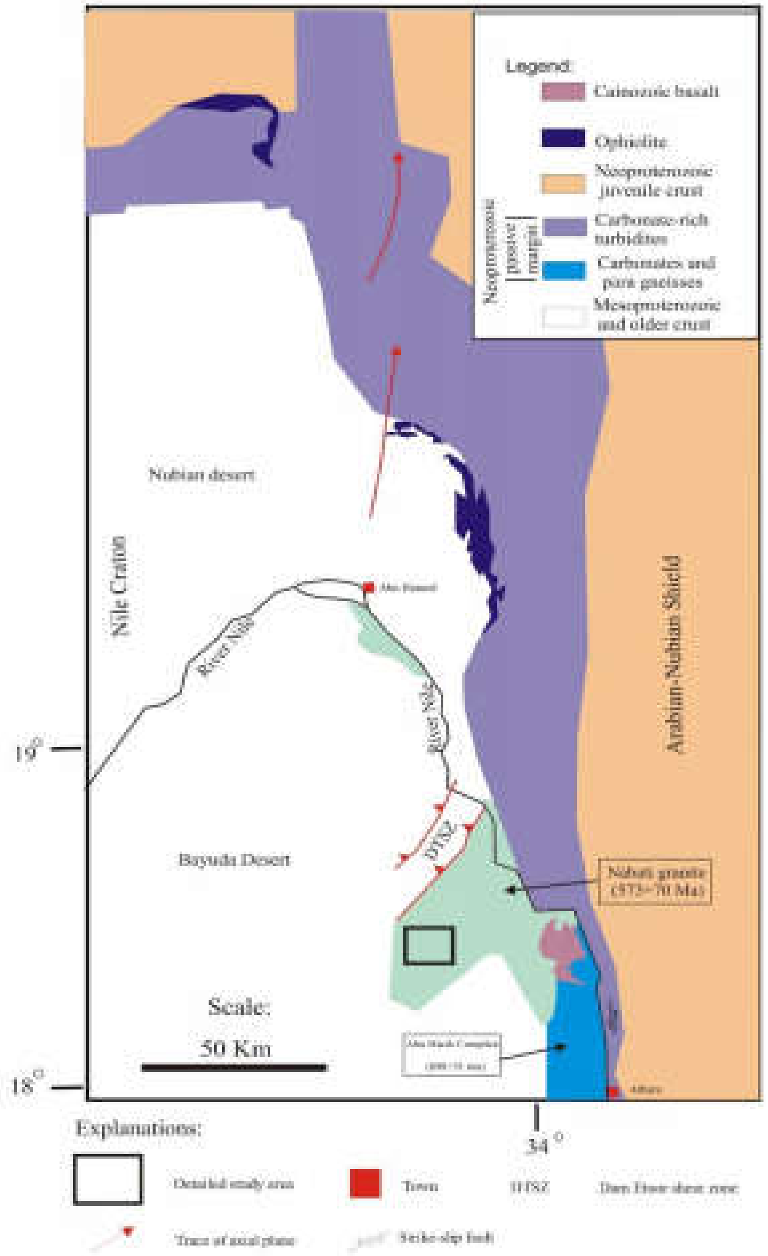


Fig. 3. Geological sketch show the proposed boundaries between Arabian-Nubian Shield and Nile Craton, after (Bailo, 2000)

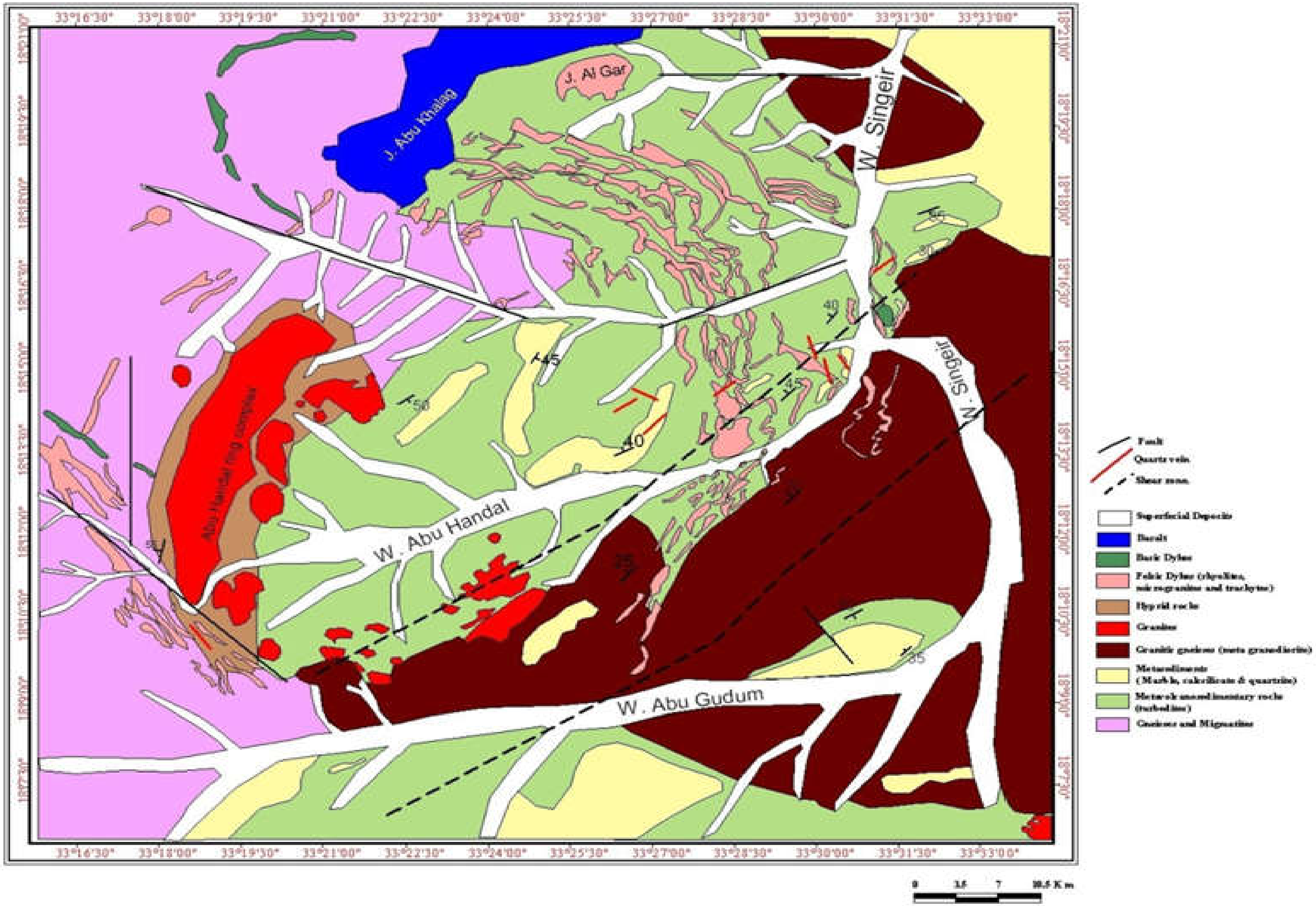


Fig. 4. Geological Map of Abu Khalag area

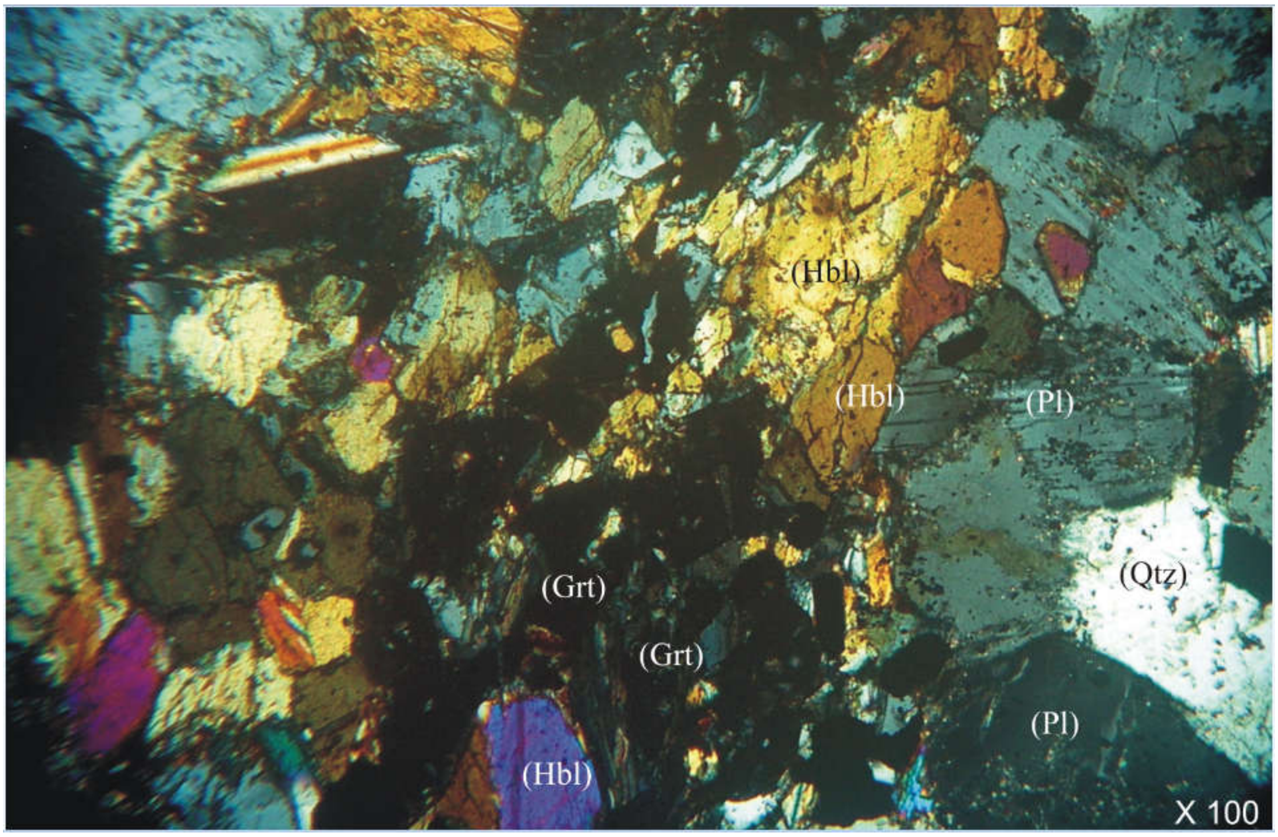


Plate 1. Photomicrograph of garnetifreous hornblende gneiss from north east of the study area, (Hbl): hornblende, (Grt): garnet, (Pl): plagioclase, (Qtz): quartz

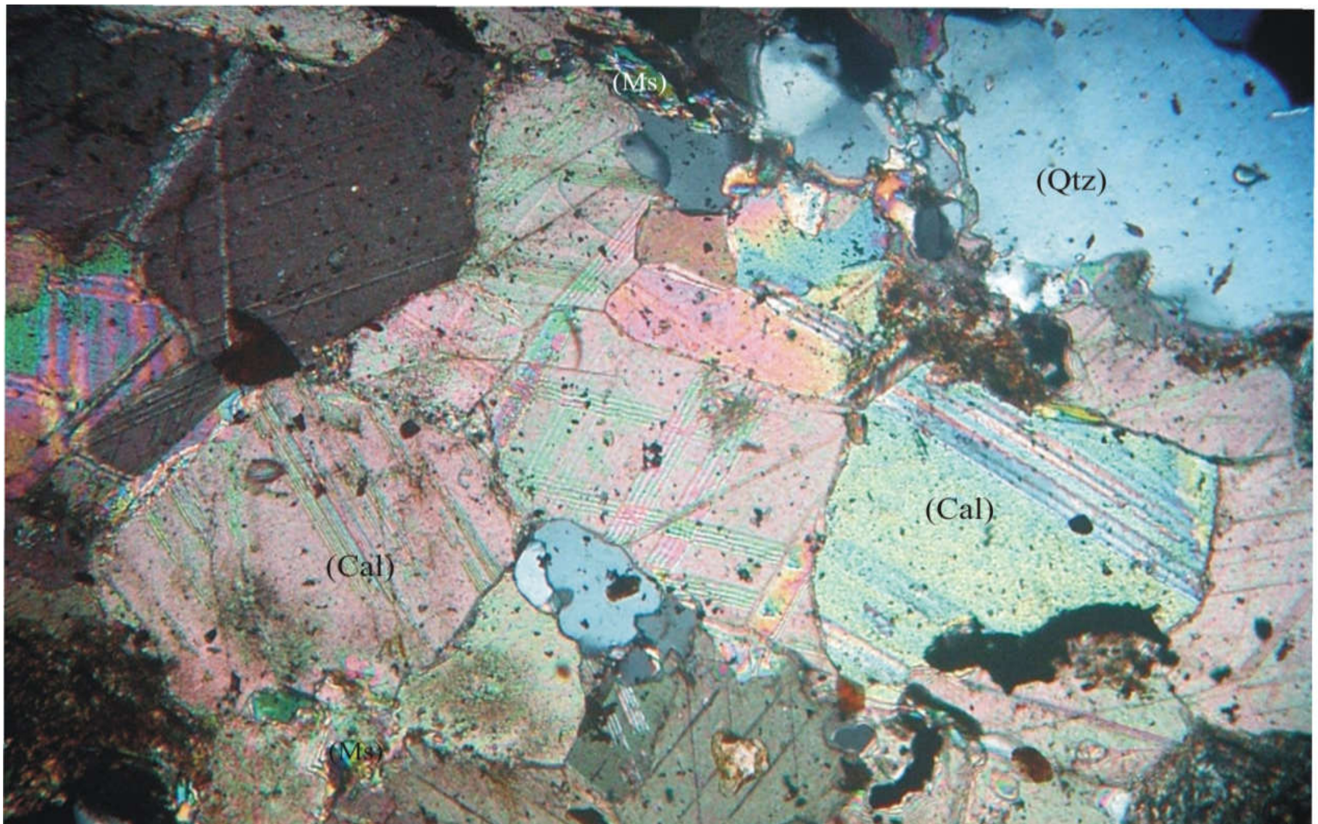


Plate 2. Photomicrograph Shows Calc-silicate and marble, (Cal): calcite, (Qtz) quartz, (Ms) muscovite

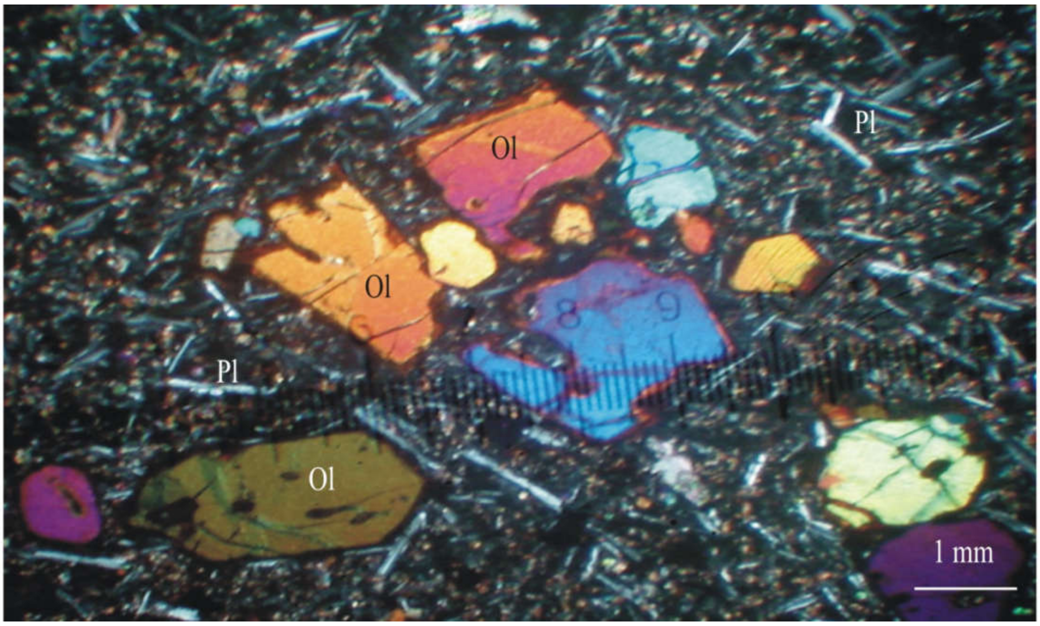


Plate 3. Photomicrograph shows alkali-olivine basalt, (Ol) olivine, (Pl) plagioclase

Table 1. Geological Sequence of the study area

Superficial deposits
Cainozoic basic volcanics
Post-tectonic intrusions (dykes).
Pegmatitoids and quartz veins.
Late to post-tectonic intrusions (ring complexes).
Low-grade metasediments.
Low-grade metavolcano-sedimentary rocks.
High-grade metavolcanic and metasedimentary rocks.

Table 2. The Geochemical Analysis of the Rock Samples from the Study Area (XRF powder pellet technique)

Sample No.	N1	N4	N9	N10	N11	N14	N15	N19	N20	N23
SiO_2	66.86	50.29	56.29	47.2	47.3	55.49	54.97	47.29	46.38	58.24
Al_2O_3	14.05	14.66	14.34	8.32	12.33	15.22	14.63	8.01	9.1	12.79
Fe_2O_3	5.16	12.1	6.2	11.17	14.79	11.76	13.05	15.38	13.87	3.44
MgO	1.74	5.85	3.36	22.85	3.55	3.91	3.76	14.28	14.18	5.57
CaO	5.26	8.83	5.5	6.79	5.5	5.63	5.68	10.45	4.08	2.89
Na_2O	1.74	2.94	3.25	0.51	3.57	4.39	4.32	1.01	0.82	2.6
K_2O	1.12	0.63	2.35	0.06	0.1	0.27	0.18	0.11	0.11	1.28
TiO_2	0.49	1.52	0.89	0.33	3.01	1.44	1.45	0.77	0.57	0.45
P_2O_5	0.13	0.32	0.39	0.08	1.18	0.2	0.19	0.07	0.13	0.13
MnO	0.1	0.19	0.14	0.15	0.25	0.13	0.13	0.25	0.22	0.13
LOI%	0.915	2.065	4.63	1.8	0.955	1	1.095	1.63	1.605	0.995
Total	97.565	99.395	97.34	99.26	92.535	99.44	99.455	99.25	91.065	87.52
Ag	<20	<20	<20	<20	<20	b.d.l	<20	b.d.l	b.d.l	<20
As	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l
Ba	171	360	453	29	253	211	88	36	52	585
Cd	b.d.l.	b.d.l	<15	<15	<15	b.d.l	b.d.l	b.d.l	b.d.l	<15
Co	13	29	<10	73	20	23	32	58	71	21
Cu	<15	<15	<15	35	<15	b.d.l	19	180	b.d.l	55
Cr	25	75	31	1477	b.d.l	b.d.l	b.d.l	528	585	51
Cs	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Ga	15	14	14	12	<10	16	16	15	<10	<10
Mn	599	1178	643	1020	1555	673	820	1353	1435	575
Ni	<15	41	19	478	<15	<15	<15	93	111	20
Pb	b.d.l	<20	<20	b.d.l	<20	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
Rb	<10	<10	26	<10	<10	<10	<10	b.d.l	<10	29
Sb	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
Se	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	<3	b.d.l	b.d.l	b.d.l	b.d.l
Sn	b.d.l	<10	<10	<10	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l	b.d.l
Sr	103	256	261	16	505	198	131	2	27	287
Th	b.d.l	b.d.l	<12	b.d.l	<12	b.d.l	b.d.l	<12	<12	<12
U	<6	b.d.l	<6	<6	<6	b.d.l	b.d.l	b.d.l	b.d.l	6
V	101	232	95	107	259	302	291	197	184	156
Zn	43	88	*46*	60	98	61	61	70	79	44
Zr	94	128	163	34	150	70	73	39	39	242

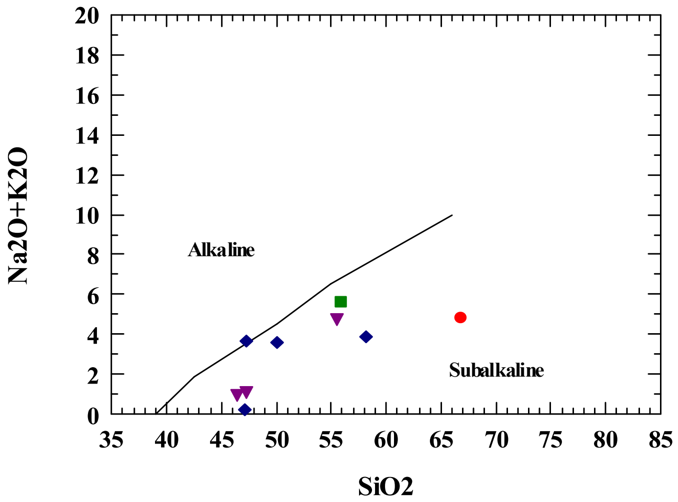


Fig. 5. The subdivision of volcanic rocks into alkaline and sub-alkaline (tholeiitic). In total alkali vs silica diagram (Irvine and Bargar 1971)

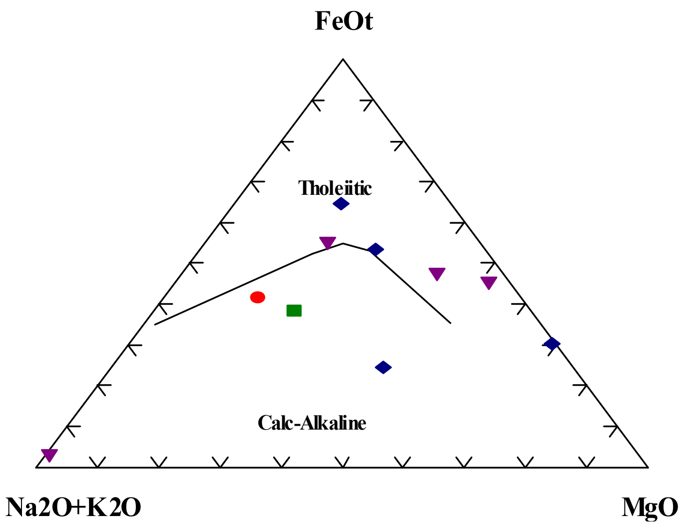


Fig. 6. AFM diagram showing the boundary between the calc-alkaline field and the tholeiitic field (after Irvine and Bargar, 1971)

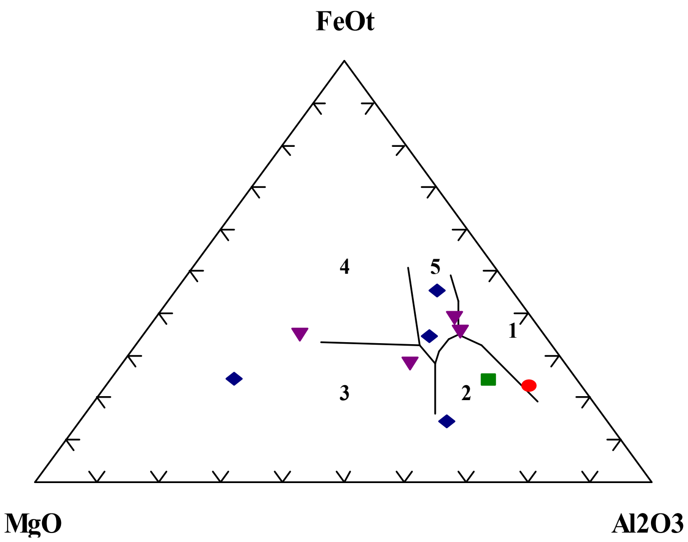


Fig. 7. The MgO-FeO$_t$-Al$_2$O$_3$ diagram showing the discriminant boundaries of tectonic settings based upon the compositional range of recent volcanic rocks, zone 1 is MORB, zone 2 is island arc (spreading center island), zone 3 island, zone 4 is ocean active continental margin, zone 5 is continental (after Pearce *et al*., 1977)

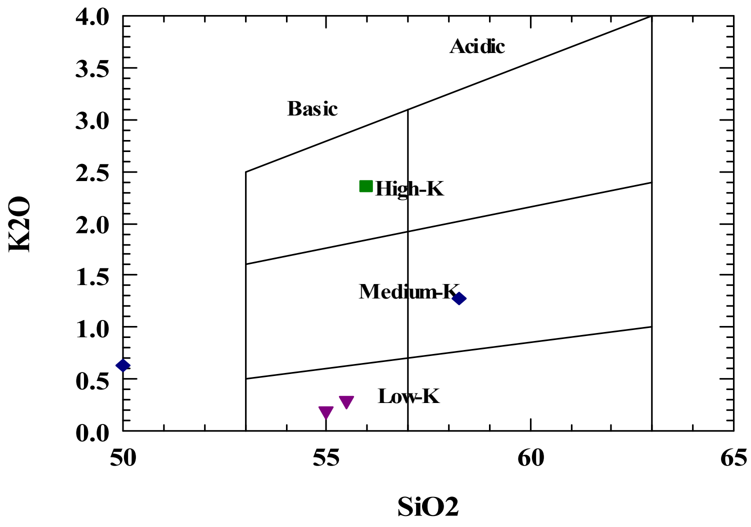


Fig. 8. The subdivision sub-alkaline rocks using the K2O vs. silica diagram (after Gill, 1981)

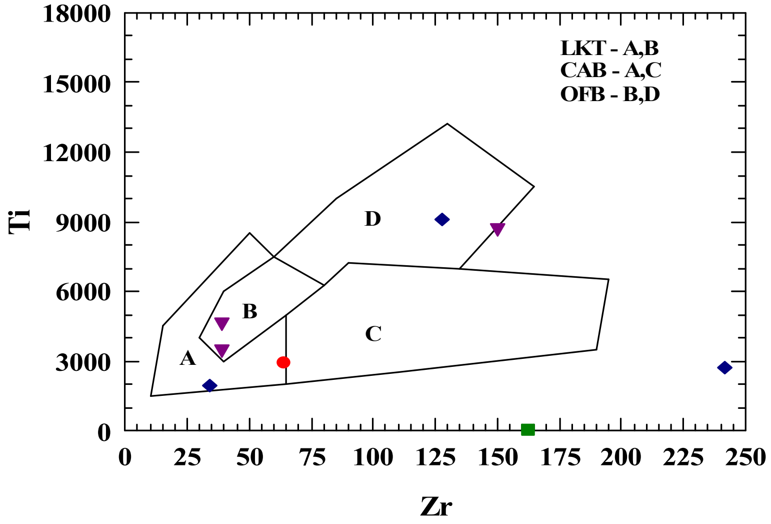


Fig. 9. Discrimination diagram for basalt based upon Ti-Zr variations the fields are: A, island arc tholleiite; B, MORB, calc-alkaline basalt and island arc tholleiite; C, calc-alkaline basalt; D, MORB (after Pearce and Cann, 1973)

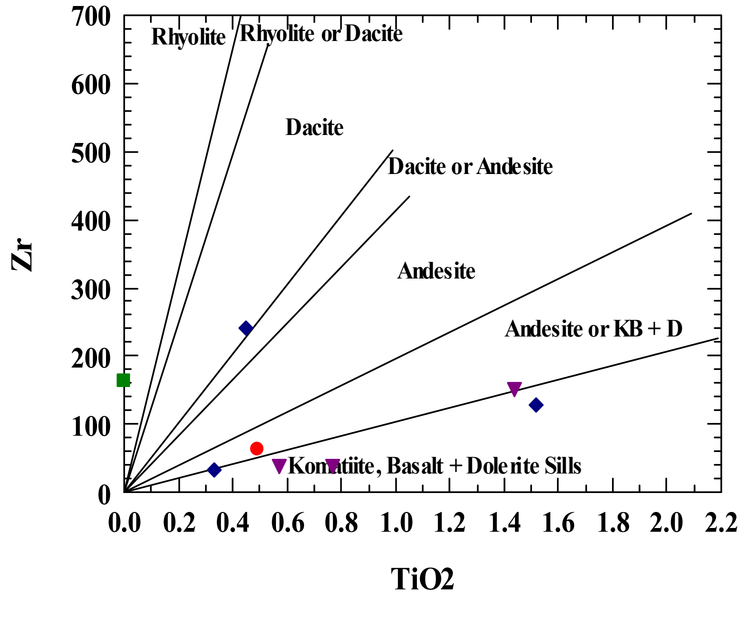


Fig. 10. Discrimination diagram of rocks classification based upon TiO2 and variations for ancient mafic-ultramafic rocks in green stone belts and probably other geological setting (after Rock *et al.*, 1990)

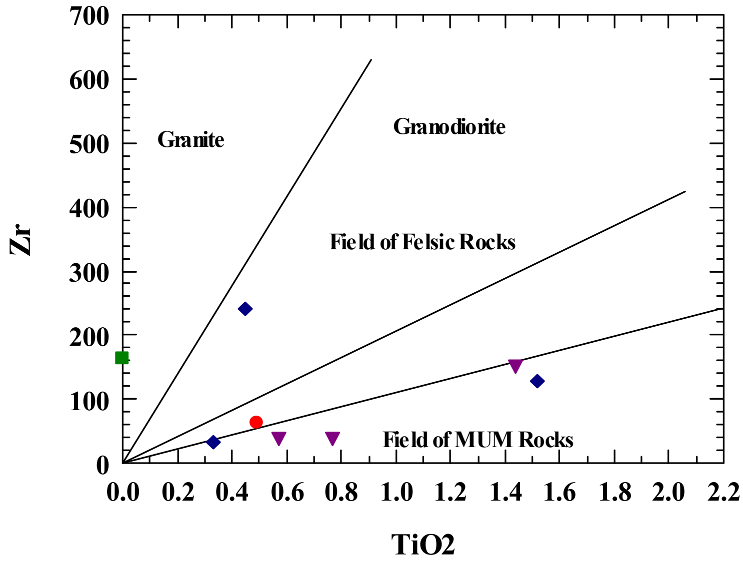


Fig. 11. The TiO2-Zr geochemical classification diagram of cumulate rocks of the ophiolite sequence (Halberg, 1985). MUM is Mg rich ultrabasic

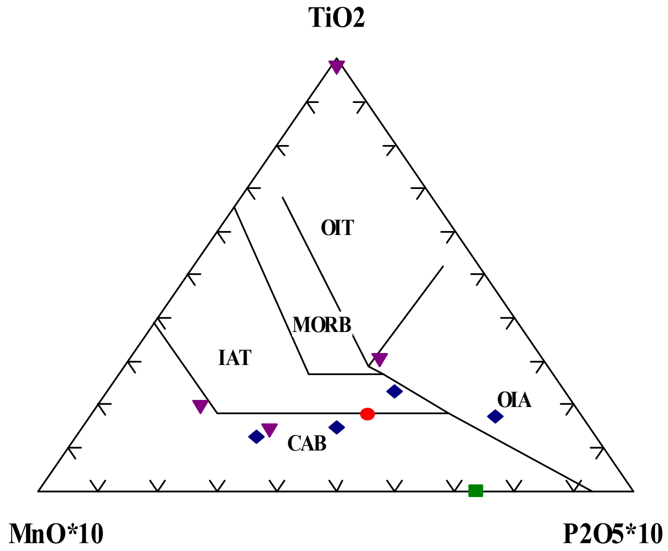


Fig. 12. The MnO-TiO-P2O5 discrimination diagram for basalts and basaltic-andesites. The fields are MORB; .OIT-ocean-island tholeiite or seamount tholeiite; OIA-ocean-island alkali basalt or seamount alkali basalt; CAB-island-arc calc-alkaline basalt;IAT island-arc tholeiite (after Mullen, 1983)

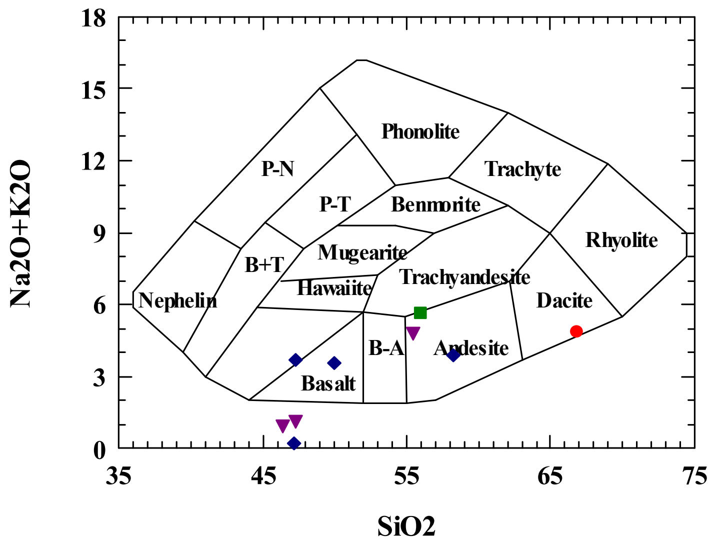


Fig.13. the chemical classification and nomenclature of volcanic rocks using the total alkalis vs. silica (TAS) diagram of Le Maitre *et al.* (1989)

Such currents have been recognized or inferred to have occurred in environments ranging from continental lakes to deep marine basins. Nevertheless, most of turbidites in the geologic record probably represent submarine deposits formed in trenches, in slope basins, or on continental rise / basin plain sites, recognized as sub-marine fan litho-facies channel basin plain areas (Raymond, 2002). Most of the recorded turbidites composed of wakes, ancient reported turbidites is in sand size, but most of the modern reported turbidites size is clay or still ash (Raymond, 2002).The turbidites of Abu Khalag area are characterized by intercalation of basic meta-volcanoclastic, and metasediments which were formed in an island arc/ marginal basin setting (Abdel Rahman, 1993). The old sediments were derived from an oceanic arc, and sometimes mixed with a pre-Neoproterozoic continental source (Küster and Liégeois 2001). The volcano-sedimentary rocks were formed in sub-aqueous environment, indicated by the thin lenses of carbonates included within them, and the remnants of hydro-currents sedimentary primary structures, such as trough cross bedding, and graded bedding. This suggests the recirculation of volcanic episodes and sedimentation in arc-related basins which Abu Khalag turbidites were deposited. The meta-volcano-sedimentary sequences are composed of basic and intermediate to acidic tuffs, and flows, all in a sedimentary matrix (Ries *et al*., 1985). Also, they include rhyolites, andesites, and basalts intercalated with volcanoclastic sedimentary units (Abdel Rahman, 1993). Using MgO-FeO_t-Al_2O_3 discrimination diagram (Pearce *et al*., 1977) two of sample plotted in field 5 (continental), one of the samples plotted in zone 2 (orogenic), the other in field 3 (oceanic ridge) (Fig. 7).

Most of the meta-volcano-sedimentary samples have alkaline geochemical affinity; this due to: (1) increasing of Na_2O which has been enriched by the reaction between basic extrusive rocks and sea water and/or (2) Crustal assimilation, fractional crystallization, and magma mixing (crustal contamination) may yield chemically altered magmas that form more alkali rocks as andesites, dacites, and rhyodacites (Raymond, 2002). Except one meta-volcano-sedimentary sample plotted in calc-alkaline zone, which may belong to an island arc assemblage. Fig. 9 shows that two out of four of the meta-volcano-sedimentary samples are tholeiitic derived from slightly mature island arc, supporting the concept of rift basins such as mid-oceanic and back arc basins (Raymond, 2002). The other two meta-volcano-sedimentary samples show calc-alkaline geochemical affinity suggesting island-arc assemblage; this is supported by plotting in (Fig. 12) (Mullen, 1983).

Metasediments

It is too difficult to approve the original provenance of the metasediments without using (HFS) elements, and REE (Levinson, 1980), because all of the major oxides are expected to be highly mobilized due to the sediments transport, deposition in marine environments, and subjection with low to medium-grade metamorphism. Unfortunately the REE content of the sediments were not determined, thus the data is not sufficient to construct a conclusive tectonic environment for the deposition of the sediments. The metasediments in Abu Khalag area is composed of marbles, calc-silicates, quartzites, muscovite schist, biotite schist, and garnet-kyanite schist.

The enrichment of Al_2O_3 in the only one sample collected is high, due to the existence of al-rich silicate minerals and alteration of feldspar during the sedimentation process. The high value of SiO_2 (56.3 weight %) explained the appearance of quartz in thin section, the high value Fe_2O_3 may indicate oxidizing depositional environments (shallow basins and continental shelf). TiO_2 value is above the average level of the upper crust this could favor igneous rocks as a source of these sediments (Table 2). Küster and Liégeois (2001) suggest volcanic island arc environment for the metasediments of the eastern Bayuda Desert, and continental arc environment for the metasediments of central Bayuda Desert. They believed low degrees of weathering of the source of the sediments (igneous rocks). Their collected samples deviate from the normally observed weathering trends. Their collected samples chemical composition is more potasic than usual and might be the result of metasomatic or digenetic changes or correspond to weathering of a high-K-granite protolith. The REE patterns suggest that the central Bayuda Desert metasediments were derived from a mature continental crust as terrigeneous sediments (Küster and Liégeois, 2001). Abdel Rahman (1993) suggested that, the low-grade metasediments belt with a thin dismembered ophiolite at its center may represent remnants of a back-arc basin between the reworked Bayuda Terrain in the west and the Gabgaba volcano-sedimentary Terrain in the east. The metasediments represent material coming exclusively from the oceanic island arc (eastern Bayuda) as well as material from older continental mass in western Bayuda (Küster and Liégeois 2001). The metasediments represent the host rocks of gold mineralization in the study area, especially the carbonate-rich metasediments (calc-silicates).

Syn-Tectonic Intrusions (Metagranodiorite)

One sample was analysed from the so called Abu Harik gneisses (Barth and Meinhold, 1979); they were considered Abu Harik gneisses as Archaean geosynclinal rocks. Küster and Liégeois (2001) suggested a syn-collision setting of muscovite–biotite gneisses of Abu Harik Series, and they interpreted the epidote-bearing gneisses from khor Dam Et Tor and Abu Harik Series to represent acid volcanism in an oceanic arc-environment. The field observations showed a basic, and volcanic xenoliths included in the epidote-biotite-muscovite gneisses of Abu Harik Series, thus indicating the magmatic origin of these gneisses, this also indicates that the pre-existence of country rocks older than the biotite gneisses of Abu Harik series occur. So, the gneisses are syn-collision intrusions related to a source generated by subduction. Stein (2003) suggested a geological model supported by the appearance of mafic xenoliths and veins within the granites, assuming that the calc-alkaline granites are indeed anatexis products of the pre-existing meta-mafic crust. He interpreted the significant rate exceeding of juvenile mantle materials along subduction zone, due to the growth rate of some major orogenies such as (ANS). Large (ANS) crust was comprised of thick sequences of the calc-alkaline metavolcanics, which were produced over 200 Ma of subduction processes, after the appropriate conditions for melting to produce the calc-alkaline granitic magmas, which was associated with subduction activity in the (ANS), these large volumes of calc-alkaline granitic batholiths were formed mainly in the northern parts of the (ANS) Around 600 Ma, and lasted for more than 200 Ma (Stein, 2003).The gneisses of Abu Harik series show spikes of (Rb) and (Th) elements which are typically of crustal contaminated continental margin arc magmas (Küster and Liégeois, 2001). Using the Total Alkali-Silica variation diagram (TAS) (Le Maitre, *et al*., 1989), the sample of biotite–muscovite–epidote gneiss of Abu Harik Series plotted on dacite zone, it has calc-alkaline low-to medium–K- dacites and rhyodacite affinity (Fig. 13), which represents the volcanic equivalent of granodiorite. Using Ti-Zr discrimination diagram (Pearce and Cann, 1973) a calc-alkaline affinity of the sample, and a syn-collisional-related setting are clear (Fig. 9). Figure (12) showing the volcanic equivalent of these rocks as rhyodacites and dacites, indicating the acidic to intermediate igneous origin of these intrusions.

Conclusion

Detailed geological and geochemical investigations had led to that, Abu Khalag area, which occupied central Bayuda Desert, is a part of Arabian-Nubian Shield; this is clear from the geochemical data of study area. The calc-alkaline affinity of turbidites shows the island arc origin of these rocks. unmappable dismembered ophiolites occurred northeast of the study area. The supracrustal metasediments of Abu Khalag area comprised of shelf continental metasediments indicated by high values of aluminum due to garnet, kyanite and muscovite assemblage. These metasediments are dominated by quartzites, schists, calc-silicates and marbles. The supracrustal metasediments are metamorphosed under greenchist and medium amphibolite facies. Field observations, microscopic investigation, and geochemical analyses of previously called Abu Harik Series gneisses, confirmed the igneous origin of this geological unit as syn-tectonic calc-alkaline intrusions.

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