International Journal of Applied and
Natural Sciences (IJANS)
ISSN (P): 2319–4014; ISSN (E): 2319–4022
Vol. 9, Issue 5, Jul–Dec 2020; 1–14

International Academy of Science, Engineering and Technology
Connecting Researchers; Nurturing Innovations

PRELIMINARY FIELD, PETROGRAPHICAL AND GEOCHEMICAL INVESTIGATIONS ON SYNPLUTONIC DIKES, SOUTHWEST JORDAN

Najel Yaseen

Research Scholar, Department of Geology, School of Science, The University of Jordan, Amman, Jordan

ABSTRACT

The basement granitoids exposed in Rahma area, South Jordan, consists mafic to intermediate in composition enclaves with variable shapes and sizes. They are interpreted as synplutonic dikes. Mode of occurrence, petrography, whole rock chemistry, and mineral chemistry indicate magma mingling and mixing with the host rock. Features of the magma mingling include dismembering of these dikes into rounded, sub rounded, and irregular shaped mafic enclaves. This mingling process took place at different levels where contact relationship with host rocks varies from sharp to gradational. Microscopic textures such as decreasing grain size of hornblend towards the contact with host rocks, resorbed relatively large plagioclase crystals and presence of acicular apatite are used as a further evidence of interaction between synplutonic dikes and host rocks.

Major, trace and rare earth elements geochemistry indicate that the magma of these dikes are calc-alkaline formed in a subduction zone environment. Furthermore both dikes and host rocks have different sources.

KEYWORDS: *Synplutonic Dikes, Magma Mixing and Mingling, Jordan*

Article History

Received: 31 Jul 2019 | Revised: 07 Aug 2020 | Accepted: 24 Aug 2020

INTRODUCTION

Synplutonic mafic dikes (SPMD) and mafic magmatic enclaves (MME) indicate mafic injections in partially molten felsic magma. Their occurrences are considered as common features associated with felsic intrusions, particularly incalc-alkaline granitoids (Pitcher, 1991, 1997; Cobbing, 2000; Barbarin, 2005).In the last three decades plenty of field, petrographic and geochemical studies have been carried out to shed light on the nature and petrogenesis of the SPMD and MME as well as their relation to the host rocks(Vernon, 1983; Frost and Mahood, 1987; Hyndman and Foster, 1988;Foster and Hyndman, 1990; Didier and Barbarin, 1991; Pitcher, 1991, 1997; Barbarin and Didier, 1992; Barbarin, 2005; Kumar, 2010; Jayananda et al. 2014). SPMD occur in various dimensions ranging in width from few centimeters upto hundreds of meters, are generally dismembered and rarely continuous (Pitcher, 1991; Jayananda et al 2009). They are characterized by necking along their length, back veining from the host rock, and dismembering into trains of angular or amoeboid enclaves (Pitcher 1991; Foster and Hyndman; 1990; Jayananda et al 2009). MME occur in various sizes ranging from centimeters up to few meters and usually with ovoid, elliptical, tabular and sometimes irregular shapes (Barbarin, 2005; Kumar, 2010). Several studies have confirmed that both SPMD and MME are interrelated with each other spatially and temporally, which led to the conclusion that there is a genetic link between them (Barbarin 2005). Based on the observations in many areas worldwide, that processes of magma mixing, mingling and hybridization between mafic enclaves and host felsic rocks are common, which suggest acoeval mafic – felsic magma interaction (Barbarin, 2005; Kumar, 2010; Ahmad, 2011; Jayananda et al. 2014).Consequently understanding the mode of occurrence and petrogenenitic mechanism of theses mafic bodies will provide vital information on the role of mafic magmas in the initiation and evolution of calc-alkaline granitoid magmas (Barbarin, 2005).

In this paper, SPMD and MME hosted in Ediacaran calc-alkaline granitoid from Jordan (Wadi Rahma), Central Wadi Araba, Jordanare being reported. The present study includes field, petrographic, mineral and whole-rock chemistry to characterize the mode of occurrence of these enclaves and discuss their formation.

Geological Setting

The basement rocks of Jordan are a part of the most northernmost extension of the Arabian Nubian shield (ANS). They are outcropping at the south western part of the country and cover an area of about 1400 km^2 (Fig. 1, inset). The ANS is considered as one of the largest juvenile crustson Earth that have been shaped during the East African Orogen in the time period from 900 to 530 Ma (Stern, 1994).The evolution of the ANS can be summarized in three major stages. The first stage started by accretion of island arc terranes during the closure of Mozambique Oceanin the time period from 900 to ~ 700 Ma (Bentor, 1985; Stern, 1994; Stoeser and Frost, 2006). A second stage represents continental collision resulting from convergence between East and West Gondwana at 650 - 625 Ma (Stern, 1994, 2002). The last stage (630-580 Ma) which is dominated by emplacement of voluminous post-collosional calc alkaline and alkaline intrusions (Beyth et al., 1994; Jarrar et al., 2003; Be'eri-Shlevin et al., 2009; Eyal et al., 2010). The final stage includes also the transition from compressional to an extensional setting which is terminated by uplift and erosion of the uppermost continental crust. The northern ANS became stable craton with a platform setting at ~530 Ma (Garfunkel, 1999).

The Neoproterozoic basement rocks of Jordan based on field, petrographical and geochemical studies are subdivided into two major complexes (McCourt and Ibrahim, 1990, Ibrahim and McCourt, 1995), the olderAqaba complex at 800–605 Ma and the younger Araba complex at 605–543 Ma. The two complexes are separated by a regional unconformity that has been given the name Araba Unconformity, which is overlain by the Saramuj Conglomerate and has been set the basis of field and geochronological data at ca. 605 Ma (Ghanem and Jarrar, 2013; Powell et al., 2015; Yaseen et al. 2013). Aqaba complex is comprised of several metamorphic and igneous suites. The latter are mainly post collisional calc-alkaline granitoids with subordinate occurrences of gabbroic, dioritic rocks. Araba complex contains all rocks that post date the Araba Unconformity and is characterized by alkaline to peralkaline bimodal igneous activity.

One of the spectacular features of the Neoproterozioc basement of southwest Jordan is the presence of intense dike swarms of variable composition from mafic to felsic (McCourt and Ibrahim, 1990, Jarrar et al. 2004). The majority of these dikes intersect all rock types of Aqaba complex and occur inform of simple, composite and hybrid dikes (Abdullah 1989, Jarrar, 2001, Jarrar et al. 2004; 2013). Field cross-cutting relationships (Abdullah, 1989) and age determination studies (Jarrar et al. 2004; 2012; 2013, Ghanem et al., 2020) demonstrate a multi generation evolution of these dikes and confirm them as a part of the Araba complex. The dolerite dikes are theyoungest generation among these, its age have recently been constrained at about 580 Ma (Ghanem et al., 2020).

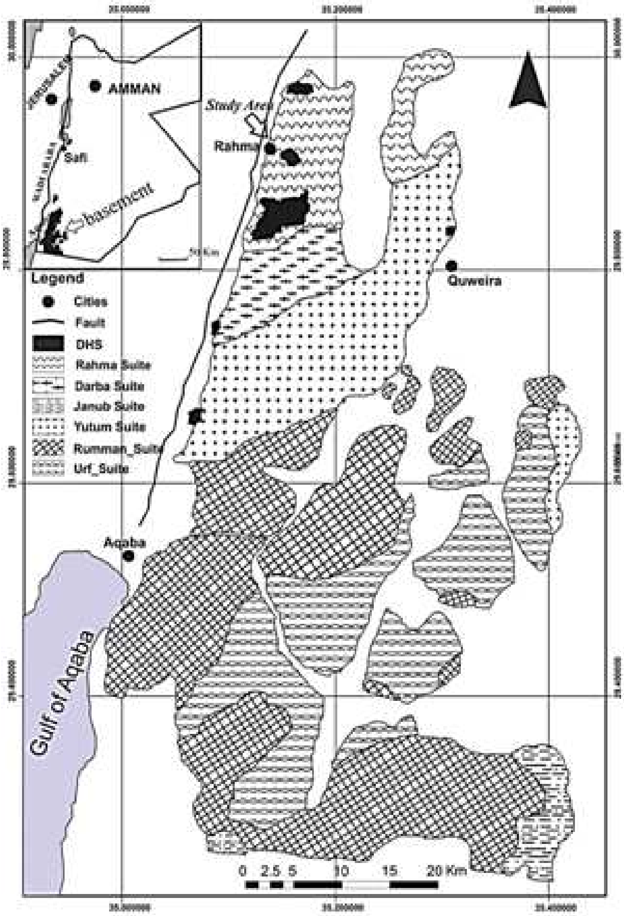

Figure 1: Geologic Map of Basement Rocks Southwest Jordan (Modified after Ibrahim and McCourt, 1995) Showing the Location of the Study Area.

Occurrences of mafic bodies with various sizes and shapes (the subject of this paper) are exposed mainly in Rahma area. They are identified as synplutonic dikes that have been injected before the complete solidification and cooling of the host rocks (Sha'ban 1995).

MATERIAL AND ANALYTICAL METHODS

This study includes field, petrography, whole rock and mineral chemistry. Field work was concerned with sampling and investigating the mode of occurrences of the synplutonic dikes and their interrelationships to the host rocks. Thin sections for petrographic analysis where prepared at the geology department, the university of Jordan. For mineral chemistry, polished thin sections of representative rock samples were made at the institute for mineralogy and crystal chemistry, Stuttgart University, Germany. The mineral chemistry was performed by using a CAMECA SX 100 WDS electron microprobe. The beam conditions were 15 kV accelerating voltage and 10 nA beam current. Calibration curve for the quantitative analysis was built by using natural minerals standards. Errors range between 0.01 and 15%. The amphibole classification is following recommendations by Leake et al. (2004). Major, trace and rare earth elements chemical analysis were obtained for 8 representative samples at Australian Laboratory Services Arabia Co.(ALS Arabia), Saudi Arabia. Whole-sample analyses for major elements were done by Inductively Coupled Plasma-Atomic Emission (ICP-AES), whiletrace and rare earth elements were carried out by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) after lithium borate fusion. Analytical uncertainties varied from 0.1% to 0.04% for major elements; 0.1% to 0.5% for trace elements; and 0.01 to 0.5 mg/kg for rare earth elements.

RESULTS

Field Relationships

Rahma area is dominated mainly by intrusive bodies as host rock ranging in lithology from mozogranite to granodiorite with calc-alkaline geochemical affinity (Abdullah, 1989; Ibrahim, 1991). Occurrences of metamorphic rocks (paragneiss and amphibolites) are also present as isolated rafts within the host rocks, commonly at the central part of Wadi Rahma area ranging in width from few meters up to 120 meters (Abdullah, 1989). These metamorphic rocks are considered as a part of the Abu Barqa and Businat metamorphic suites (Ibrahim, 1991, Jarrar et al., 2013). Host rocks and metamorphic rocks are all intersected by different types of dikes ranging in width from few centimeters up to several tens of meters. Dikes are mainly simple and composite with varying lithology of quartz-alkali-feldspar porphyry, trachyandesite, basaltic andesite and basalt (Abdullah, 1989). The investigated synplutonic mafic dikes are exposed mainly at Rahma area (Fig. 1) and are clearly visible along the main Wadi of Rahma area. They are pale to to dark green in color with variable sizes and shapes. Some of them occur as unusual sub horizontal discontinuous tabular sheets (Figs. 2 A, B, C, D) with variable thicknesses ranging from few decimeters up to 2 meters. These sheet-like structures can be followed for several hundreds of meters (Fig. 2 A, B) and are gently dipping to the east (Fig. 2 C) with variable degrees ranging from near horizontal to 30 degrees. Necking of dikes along their elongation and back veining from host rock are common (Fig. 2 B, E). In other cases the synplutonic dikes are disrupted and disaggregate into rounded, sub rounded and angular enclaves (Fig. 2 F, G, H). The contact relationship of these dikes with host rock is not regular. In most cases material of the host rock is injected within the dikes forming a sort of intrusion breccias. In other cases a sort of mixing zone between dikes and host is present ranging in width from few centimeters up to one meter. In some places sharp contacts are also present.

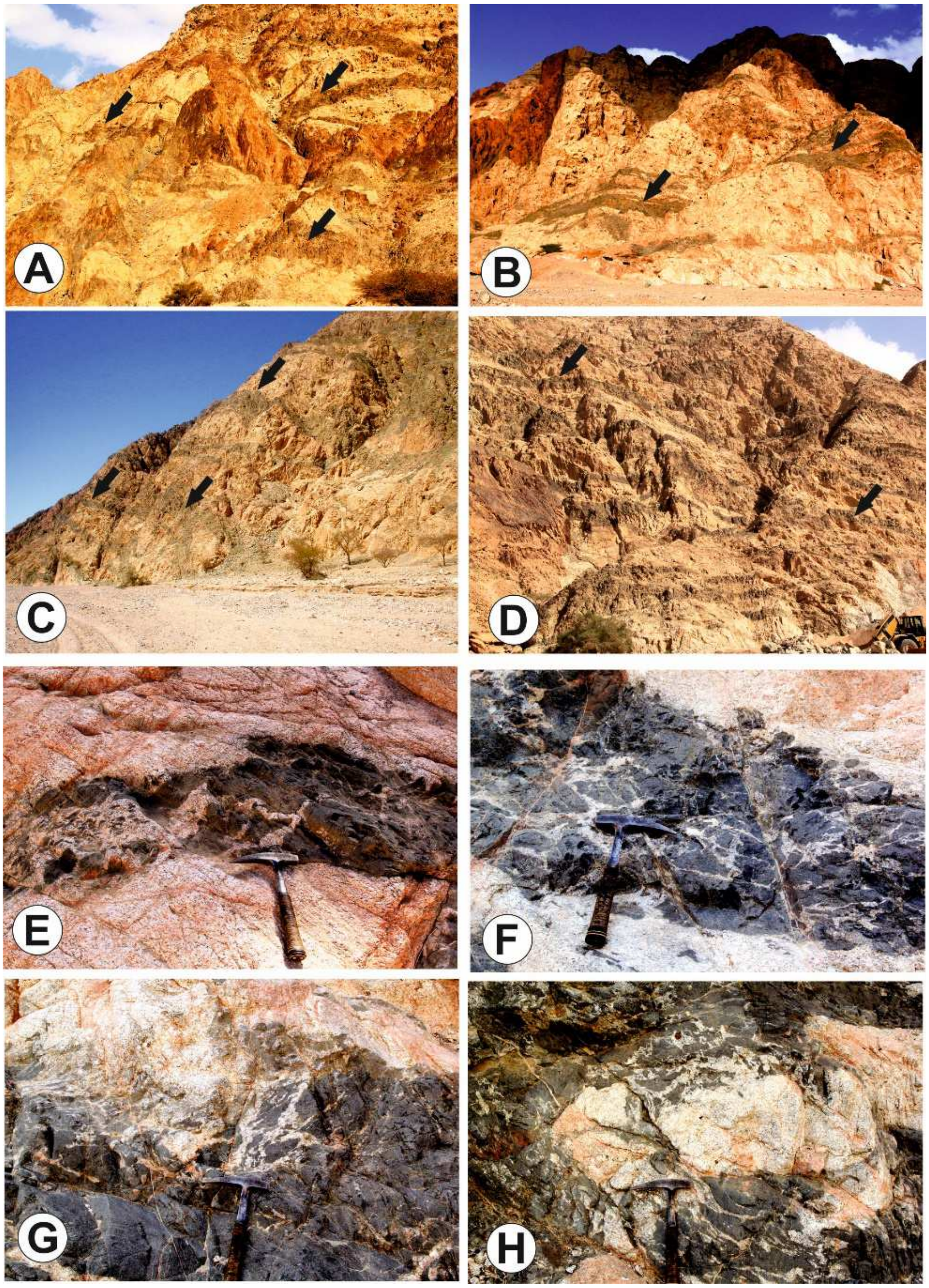

Figure 2: Mode of Occurrences of the Synplutonic Dikes. (A, B, C and D) Inform of Sheets Denoted by Arrows, (E, F, G, H) Dismembering into Enclaves with Sharp and Gradational Contact.

Petrography

The synplutonic dikes in the study area are mainly quartz monzodiorite to quartz diorite in composition (Abdullah, 1989; Shaban, 1995). Mineralogical content is mainly plagioclase with an average volume percentage of about 40%, hornblende (21%), biotite (17%), K-feldspar (11%), quartz (8 %), and accessory titanite, apatite, zircon and opaques. Texture is mainly fine-grained equigranular hypidiomorphic (Fig. 3A), in some cases porphyritic aphanitic as a result of presence of some relatively large plagioclase crystals (Fig. 3 B).

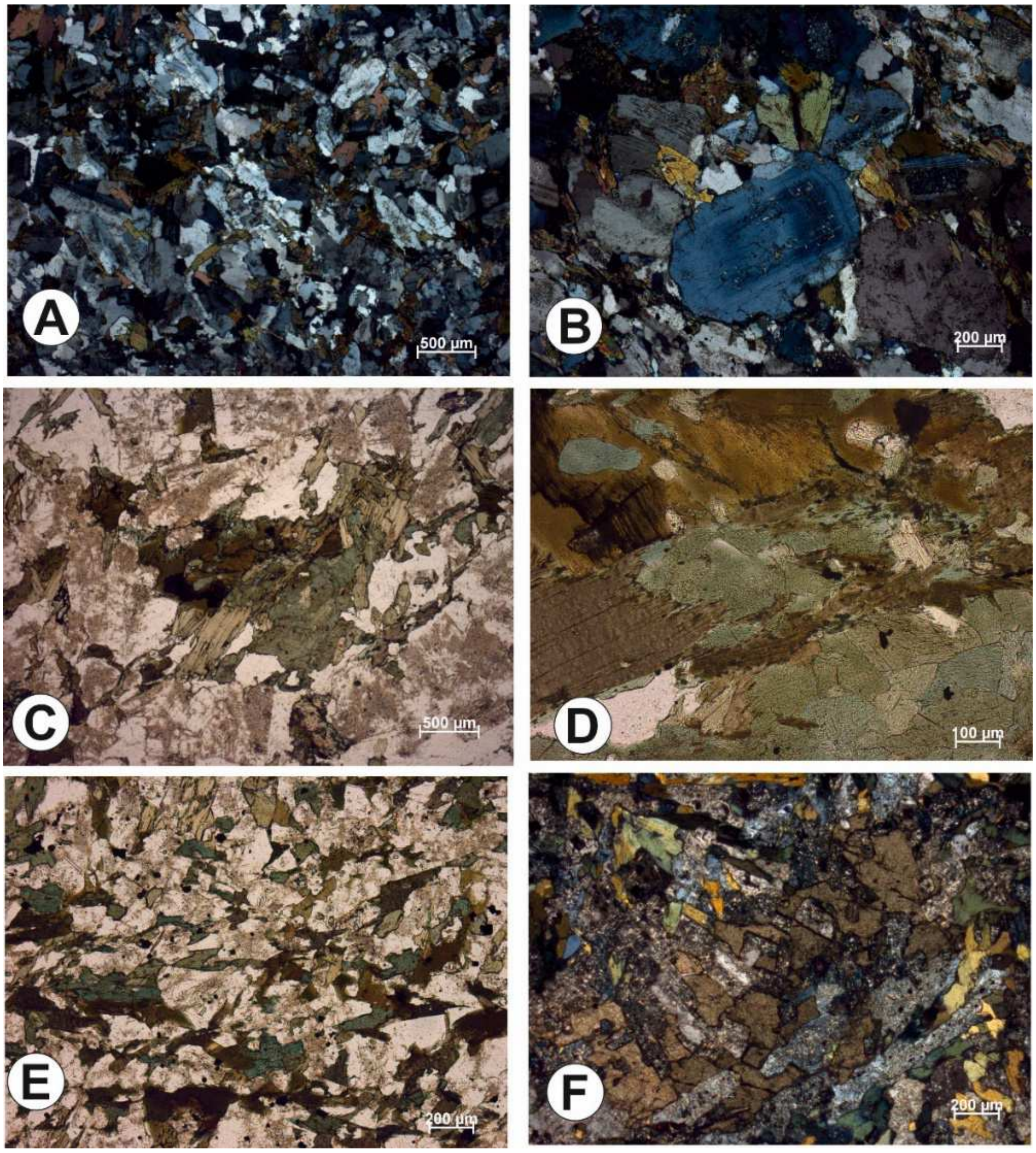

Figure 3: Petrographic Features of the Synplutonic Dikes: (A) Fine Grained Equigranular; (B) Large Plagioclase Crystals with Resorbed Boundaries; (C) Subhedral Hornblend (Green Colored); (D) Hornblend (green) Associated with Platy Biotite (Brown Coloured); (E) weakly Sub-Parallel Arrangement of Biotite and Hornblend; (F) Titanite Crystal.

Plagioclase shows two distinct grain sizes, most common are fine grain (<0.5mm) making up the bulk composition of the rock and the less common relatively larger grains (>0.5 mm and rarely up to 3mm) (Fig. 3 B). Plagioclaseoccurs as subhedral to euhedral grains with albite and pericline twining and enclose zircon and apatite, but rarely amphiboles thus displaying poikilitic texture. Oscillatory zoning and slightly resorbed boundaries are common especially in large grains (Fig. 3 B). Sericite is the common as alteration product. Amphibole mainly hornblende is green pleochroic and occurs as euhedral to subhedral prismatic grains (Fig. 3 C).Few hornblende grains show simple twinning. Hornblende in many cases is accompanied with biotite (Fig. 3 D). Both hornblende and biotite show subparallel arrangement indicating magmatic flow during crystallization and cooling (Fig. 3 E).Both modal content and size of hornblende decrease at the contact to the host rocks. Biotite occurs as euhedral to subhedral crystals and has a tabular and platy form. Biotite crystals show occasionally slight alteration to chlorite especially along cleavage traces and crystals boundaries. Alkali feldspar occurs as subhedral to anhedral crystals ranging in size from 0.5 to 1.5 mm. It lacks twinning and shows graphic intergrowth with quartz. Quartz is the least abundant mineral and occurs as anhedral small grains with interstitial growth. Titanite and apatite are the most common accessory minerals. Titanite occurs as euhedral to subhedral crystalswith relatively considerable grain size (Fig. 3 F). Apatite is poikiliticaly included in plagioclase and hornblende and characterized by acicular crystals.

Mineral Chemistry

Microprobe analyses of plagioclase minerals from three representative samples of synplutonic dikes are listed in Table 1 and displayed in the ternary plot of the An-Ab-Or system (Fig. 4 A).Plagioclase shows a compositional range from $An_{0.19}$to $An_{0.34}$.The majority of an orthite content is in the range of $An_{0.27}$ to $An_{0.32}$ with low variation from core to rim, where rims are slightly richer in calcium. Microprobe analysis of amphiboles are listed in Table 2. According to the IMA modified nomenclature (Leak et.al. 2004), amphiboles are classified as magnesiohornblende of the calcic amphiboles (Fig. 4 B)). Chemical composition of hornblende doesn't show remarkable variation and can be considered as homogeneous. They have narrow Al_2O_3 and SiO_2 ranges from 6.11 to 7.01 wt% and from 45.55 to 48.65 wt%, respectively.

Table 1: Some Representative Microprobe Plagioclase Analyses

	Sample R1					Sample R3					Sample R4			
SiO2	60.73	63.72	62.09	62.01		62.62	61.53	61.90	63.36		60.20	60.46	61.53	59.73
Al2O3	23.67	22.18	23.40	22.97		22.95	23.20	22.59	22.17		24.17	24.01	23.20	23.86
CaO	5.83	3.89	4.89	4.76		5.00	5.62	4.94	4.28		6.90	6.36	5.62	6.24
Na2O	7.98	9.06	8.22	8.22		8.40	8.01	8.44	9.03		7.18	7.70	8.01	7.47
K2O	0.36	0.33	0.38	0.64		0.27	0.22	0.28	0.17		0.22	0.21	0.22	0.40
Total	98.69	99.31	99.11	98.75		99.37	98.67	98.39	99.19		98.75	99.06	98.67	97.91
Si	2.74	2.83	2.77	2.78		2.79	2.76	2.79	2.82		2.71	2.72	2.76	2.71
Al	1.26	1.16	1.23	1.22		1.20	1.23	1.20	1.16		1.28	1.27	1.23	1.28
Ca	0.28	0.19	0.23	0.23		0.24	0.27	0.24	0.20		0.33	0.31	0.27	0.30
Na	0.70	0.78	0.71	0.72		0.73	0.70	0.74	0.78		0.63	0.67	0.70	0.66
K	0.02	0.02	0.02	0.04		0.02	0.01	0.02	0.01		0.01	0.01	0.01	0.02
An	0.28	0.19	0.24	0.23		0.24	0.28	0.24	0.21		0.34	0.31	0.28	0.31
Ab	0.70	0.79	0.74	0.73		0.74	0.71	0.74	0.78		0.64	0.68	0.71	0.67
Or	0.02	0.02	0.02	0.04		0.02	0.01	0.02	0.01		0.01	0.01	0.01	0.02

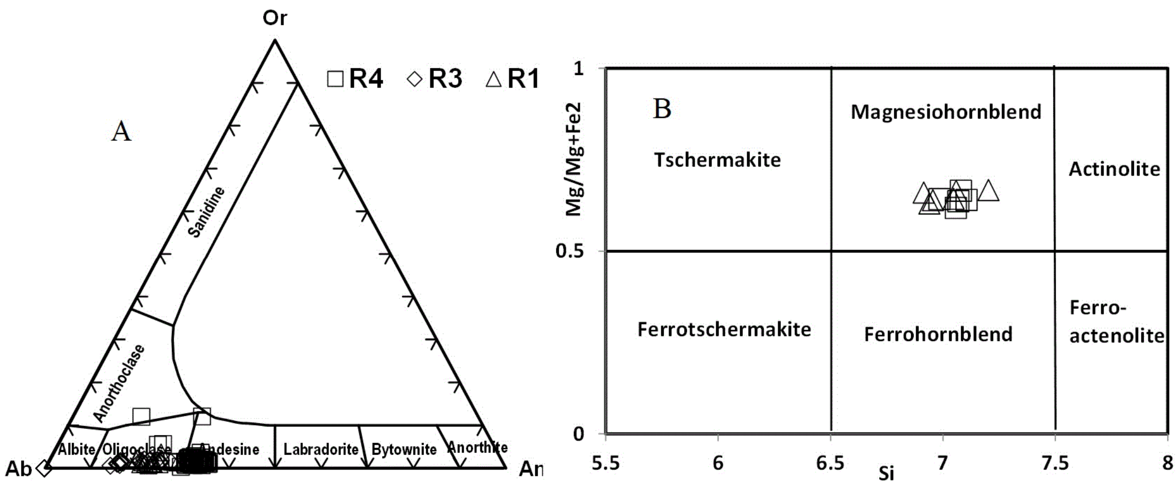

Figure 4: (A) Nomenclature of Plagioclase; (B) Classification of Amphiboles (Leake at. El. 2004).

Table 2: Some Representative Microprobe Amphibole Analyses

	Sample R1						Sample R4				
SiO2	46.391	45.570	47.711	45.155	47.388		47.301	48.165	48.090	47.645	47.765
TiO2	0.699	0.662	0.641	0.662	0.629		0.360	0.269	0.250	0.314	0.224
Al2O3	7.051	6.575	6.156	6.696	6.371		6.759	6.111	6.609	6.513	6.203
FeO	11.049	11.805	11.411	12.155	12.203		11.946	11.341	12.257	12.949	12.151
Fe2O3	5.700	4.730	4.617	4.158	4.067		5.619	5.536	5.062	4.621	4.715
MnO	0.630	0.513	0.500	0.528	0.493		0.403	0.426	0.390	0.471	0.405
MgO	12.024	11.729	12.732	11.605	12.308		12.031	12.651	12.059	11.731	12.144
CaO	11.543	11.482	11.888	11.539	11.932		12.148	12.152	12.051	12.144	12.131
Na2O	1.070	1.058	0.915	1.116	0.868		0.764	0.740	0.778	0.783	0.621
K2O	0.720	0.696	0.628	0.711	0.683		0.453	0.379	0.443	0.402	0.401
BaO	0.017	0.049	0.023	0.010	0.060		0.007	0.000	0.000	0.038	0.031
Total	98.907	96.833	99.248	96.287	99.019		99.821	99.810	100.030	99.634	98.807
Si	6.915	6.956	7.059	6.940	7.048		6.985	7.080	7.069	7.059	7.105
Al_T	1.085	1.044	0.941	1.060	0.952		1.015	0.920	0.931	0.941	0.895
sum4	8.000	8.000	8.000	8.000	8.000		8.000	8.000	8.000	8.000	8.000
Ti	0.078	0.076	0.071	0.077	0.070		0.040	0.030	0.028	0.035	0.025
Al_O	0.154	0.139	0.132	0.153	0.165		0.161	0.138	0.214	0.196	0.192
Fe3	0.639	0.543	0.514	0.481	0.455		0.624	0.612	0.560	0.515	0.528
Fe2	1.377	1.507	1.412	1.562	1.518		1.475	1.394	1.507	1.604	1.511
Mn	0.080	0.066	0.063	0.069	0.062		0.050	0.053	0.049	0.059	0.051
Mg	2.672	2.669	2.808	2.659	2.729		2.649	2.772	2.643	2.591	2.693
Ca	1.844	1.878	1.884	1.900	1.902		1.922	1.914	1.898	1.928	1.933
Na	0.309	0.313	0.263	0.333	0.250		0.219	0.211	0.222	0.225	0.179
K	0.137	0.136	0.118	0.139	0.130		0.085	0.071	0.083	0.076	0.076
Ba	0.001	0.003	0.001	0.001	0.004		0.000	0.000	0.000	0.002	0.002
sum8	7.291	7.329	7.267	7.373	7.285		7.227	7.196	7.203	7.231	7.190
Mg/Mg+Fe2	0.660	0.639	0.665	0.630	0.643		0.642	0.665	0.637	0.618	0.640
P(Kbar)	2.886	2.620	2.099	2.763	2.306		2.589	2.029	2.440	2.403	2.166

Geothermobarometry

Field and experimental observations have proved that total Aluminum content of hornblende is a function of pressure and to a less degree as a function of temperature (Hammarstorm and Zen, 1986; Hollister et al. 1987; Blundy and Holland, 1990; Schmidt, 1992). In this study estimation of crystallization pressures, temperatures and the equivalent depth of emplacement were made using amphibole and plagioclase analysis (Tables 2 & 3). Using Schmidt 1992 geobarometer Al content of amphiboles indicate a crystallization pressure from 2.02 to 2.88 kbar (Table2) with an average of 2.43 kbar, which is equivalent to crystallization depth from 7 to 10 km with an average of 8.5 km. Temperature of crystallization is calculated based on the hornblende-plagioclase geothermometer of Blundy & Holland (1990). This geothermometer indicate a crystallization temperature for the magmatic enclaves in the range from 631 to 704 °C with average temperature of 673.4 °C.

Whole Rock Major and Trace Geochemistry

The whole rock major and trace elements composition of eight representative samples from the synplutonic dikes and mafic enclaves are given in Table 4.The investigated rocks show variation in silica content ranging from 50.2 to 61.3 wt % which indicates that synplutonic dikes are mafic to intermediate in composition. In the classification diagram of Cox et al. 1979 (Fig. 5 A), samples fall mainly in the field of diorite with some affinity to the field of gabbro. The total alkalivs. silica plot and the AFM diagram (Fig. 5 A, B)indicates the subalkaline and calc-alkaline nature, respectively, of the synplutonic dikes.

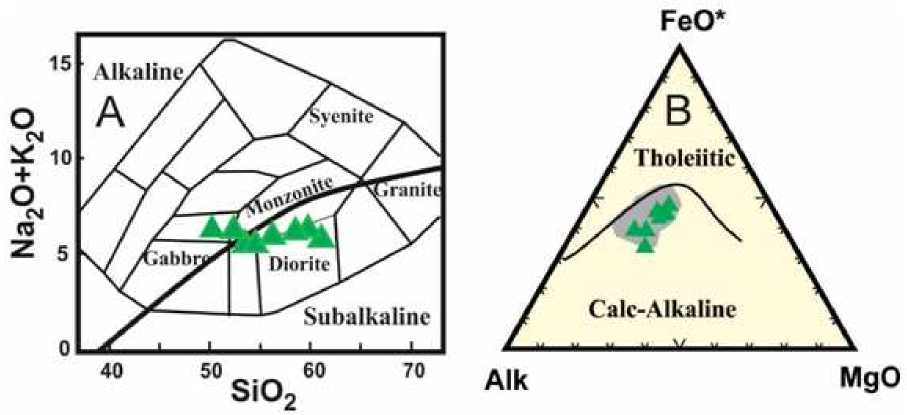

Figure 5: (A) Total Alkali vs. Silica (TAS) Classification Diagram (Cox et al. 1997), with Thick Solid Line from Irvine and Barager 1979. (B) AFM Diagram (Irvine and Barager 1979). Grey Field Represent Sample Analysis of Same Rocks by Sha'aban 1996.

Normalized trace elements to primitive mantel spider diagram (Fig 6 A) shows enrichment in large ion lithophile (LIL) elements (e.g., Cs, K, Ba, Sr) and pronounced negative anomalies in high filed strength (HFS) elements such as Nb, Ta and to a lesser degree in Ti. In addition to that a notable depletion in P is obvious. Chondrite-normalized pattern (Fig. 6 B) indicates a slightly enrichment in LREE with moderately smooth decrease in HREE.

Table 4: Whole Rock Analysis of Synplutonic Dikes Samples

Sample	R-1	R-4	R-5	R-6	R-7	R-8	R-9	R-10
SiO2	60.80	61.30	50.20	54.40	52.44	59.23	56.44	53.65
TiO2	0.77	0.78	1.25	1.13	0.22	0.90	0.94	1.22
Al2O3	16.05	17.35	17.95	16.90	17.32	16.50	16.95	17.80
Fe2O3t	5.57	5.95	9.42	8.68	9.76	6.75	8.37	9.90
MnO	0.10	0.08	0.15	0.14	0.14	0.08	0.18	0.18
MgO	3.44	2.36	4.32	4.16	4.01	3.22	3.95	4.33
CaO	4.20	5.13	7.02	7.12	6.55	3.95	6.51	5.74
Na2O	4.30	4.30	3.82	3.72	3.77	4.10	3.95	3.55
K2O	2.10	1.57	2.48	1.78	2.73	2.10	2.09	1.92
P2O5	0.27	0.26	0.34	0.30	0.40	0.33	0.22	0.33
LOI	1.44	1.37	2.64	0.99	2.47	2.30	0.91	1.10
Total	99.04	100.45	99.59	99.32	99.81	99.46	100.51	99.72
Trace and REE (ppm)								
Cs	3.03	2.41	2.63	0.95				
Rb	87.00	38.70	69.70	37.80	50.00	60.00	41.00	29.00
Ba	606.00	721.00	863.00	613.00	780.00	800.00	669.00	830.00
Sr	710.00	882.00	822.00	740.00	790.00	790.00	733.00	761.00
U	3.96	1.17	1.15	1.21				
Th	5.91	5.13	2.87	3.47				
Zr	188.00	213.00	145.00	144.00	122.00	130.00	98.00	103.00
Hf	5.30	5.40	4.20	4.00				
Nb	8.20	5.30	6.70	7.50				
Y	14.10	14.60	23.20	24.70	20.00	23.00	19.00	17.00
Sn	3.00	2.00	2.00	2.00				
Ta	0.80	0.40	0.40	0.50				
Ga	24.50	21.10	22.20	22.10				
Cr	110.00	20.00	20.00	30.00	184.00	102.00	55.00	73.00
V	96.00	124.00	218.00	203.00				
La	25.90	33.40	27.60	25.90				
Ce	54.80	64.40	60.10	62.10				
Pr	6.47	7.07	7.31	8.04				

Table 4: Contd.,

Nd	24.90	26.30	30.60	33.20				
Sm	4.70	4.32	5.90	6.59				
Eu	1.29	1.12	1.82	1.93				
Gd	3.93	3.96	5.52	6.15				
Tb	0.51	0.51	0.82	0.86				
Dy	2.79	2.92	4.73	4.55				
Ho	0.52	0.55	0.93	0.91				
Er	1.57	1.75	2.39	2.60				
Tm	0.20	0.21	0.36	0.38				
Yb	1.63	1.55	2.29	2.41	2.33	3.50	3.30	2.44
Lu	0.23	0.27	0.33	0.36				
∑ REE	129.44	148.33	150.70	155.98				

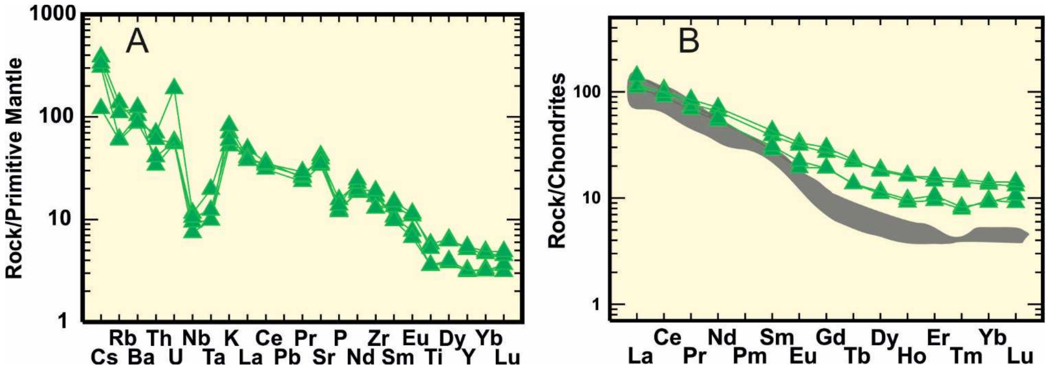

Figure 6: Normalized Plots of Trace and Rare Earth Elements of Synplutonic Dikes. (A) Primitive Mantel-Normalized; (B) Chondrite-Normalized (Sun and McDonough (1989). Grey Pattern Represent Results of Host Rock (Jarrar et al. 2003).

DISCUSSION

Mineralogy and chemistry of the synplutonic dikes and their dismembering parts (MME) show that they crystalized from mafic to intermediate magma that injected into a felsic magma. The mode of occurrence of synplutonic dikes in some cases as enclaves with different shapes (rounded, subrounded and irregular) and subhorizontal sheets with different sizes indicates mingling between mafic and felsic magmas. Mafic sheets and various shapes of MME are interpreted as strong evidence of mafic-felsic interaction and mingling (Barbarine and Didier, 1992). Contact relationship to the host rock suggests that the interaction took place at different levels as it is apparent from the presence of sharp and gradational contacts with host rocks.

Petrographical observations support mixing and mingling processes. Decreasing grain size of hornblend in mafic enclaves towards the contact with felsic host rocks indicates rapid cooling as a result of temperature contrast between the two interacting magmas (Vernon, 1983). The presence of two distinct grain size of plagioclase where the larger ones are characterized by resorbed boundaries. This could indicate a mechanically transfer of plagioclase from the felsic host to the mafic magma (hybridization process). The presence of acicular apatite in mafic enclaves indicate rapid cooling of mafic magma during interaction with cooler felsic magma (Baxter and Feely, 2002).

The geochemical calc- alkaline character (Fig. 5B) and the strong negative anomalies of Nb and Ta (Fig. 6A) place the intrusion of these dikes in a subduction related tectonic setting (Rollinson, 1993). Minor anomalies at P and Ti are attributed to apatite and ilmenite fractionation.

Chondrite-normalized REE plot (Fig. 6 B) shows a gentle slope of the LREE, more or less flat HREE, and barely seen Eu anomaly. The Overall slope of the pattern is gentle (La/Lu)N ~ 10. The absence of the anomaly indicates that plagioclase fractionation did not play a major role in the evolution of these rocks. Furthermore, the gentle overall slope can be taken as an evidence that the source area of the magma which gave rise to these synplutonic dikes has no garnet or other HREE-loving mineral as residual phases (Rollinson, 1993). However, enrichment in in LIL elements including the LREE suggest contamination of the source from slab-derived fluid. This is in contrast to the host granitoids (gray pattern, Fig. 6B) which show a steep slope of about 20-25, thus suggesting the presence of garnet in the source area of these granitoids.

CONCLUSIONS

The following conclusions can be drawn from this study:

- The synplutonic dikes and related enclaves are mafic to intermediate in composition.
- The mode of occurrence, structures and mineralogical relationships of these dikes indicate a process of magma mingling and to lesser degree mixing during injection in not fully crystalized felsic magma.
- Synplutonic dikes and host rocks have different magma sources.
- The interaction between these two different magmas took place in a subduction related environment at relatively shallow depth of about 8.5 km.

ACKNOWLEDGMENT

The author is highly appreciating the deanship of the scientific research at the University of Jordan for logistic support and partially funding of this research project.

REFERENCES

1. *Abdullah, N. 1989. Geology, geochemistry and petrology of the Precambrian rocks of Wadi Rahma, Wadi Araba, SW Jordan, M. Sc Thesis, The University of Jordan.*
2. *Ahmad, M. 2011. Enclaves in Granitoids of North of Jonnagiri Schist Belt, Kurnool District, Andhra Pradesh: Evidence of Magma Mixing and Mingling. Journal Geological Society of India, 77, 557-573.*
3. *Barbarin, B., Didier, J. 1992. Genesis and evolution of mafic microgranular enclaves through various types of interaction between coexisting felsic and mafic magmas. Trans R Soc Edin: Earth Sci: 83, 145-153*
4. *Barbarin, B., 2005. Mafic magmatic enclaves and mafic associated with some granitoids of the central Sierra Nevada batholiths, California: nature, origin, and relations with the hosts. Lithos, 80, 155-177.*
5. *Baxter, S., Feely, M. 2002. Magma mixing and mingling textures in granitoids: examples from the Galway Granite, Connemara, Irland. Mineralogy and Petrology, 76, 63-74.*
6. *Be'eri-Shlevin, Y., Katzir, Y., Whitehouse, M.J., 2009b. Post-collisional tectono-magmatic evolution in the northern Arabian-Nubian Shield: time constraints from ion-probe U–Pb dating of zircon. Journal of the Geological Society, London 166, 71-85.*
7. *Bentor, Y.K., 1985. The crustal evolution of the Arabian-Nubian Massif with specialreference to the Sinai Peninsula. Precambrian research 28, 1-74.*

8. *Beyth, M., Stern, R., Altherr, R., Kröner, A., 1994. The late Precambrian Timan igneouscomplex, Southern Israel: evidence for comagmatic – type sanukitoid monzodioriteand alkali granite magma. Lithos 31, 103-124.*
9. *Blundy, J.D., Holland, T.J.B., 1990. Calcic amphibole equilibria and a new amphibole-plagioclase geothermometer. Contributions to Mineralogy and Petrology 104 (2), 208-224.*
10. *Cobbing, J., 2000. The Geology and Mapping of Granite Batholiths. Springer, Berlin, 141 p*
11. *Cox, K.G., Beli, J.D., Pankhurst, R.J. 1979.The interpretation of igneous Rocks. London (George Allen & Unwin), 450 pp*
12. *Didier, J., Barbarin, B. (1991). The different types of enclaves in granites-nomenclature. In: Didier, J. and Barbarine, B. (Eds.), Enclaves and Granite Petrology, Developments in Petrology. vol. 13, Elsevier, Amesterdam, 19-24.*
13. *Eyal, M., Litvinovsky, B., Jahn, B.M., Zanvilevich, A., Katzir, Y., 2010. Origin and evolution of the post-collisional magmatism: Coeval Neoproterozoic calc-alkaline and alkaline suites of the Sinai Peninsula. Chemical Geology 269, 153-179.*
14. *Foster, D.A., Hyndman, D.W. 1990. Magma mixing and mingling between synplutonic mafic dikes and granite in the Idaho-Bitterroot batholiths. In: Anderson, J.L. (ed.), The Nature and origin of Cordilleran magmatism: Boulder, Colorado, Geological Society of America, Memoir 174, 347-358.*
15. *Frost, T.P., Mahood, G.A. 1987. Field, chemical, and physical constrains on mafic-felsic magma interaction in the Lamark Granodiorite, Sierra Nevada, California. Geological Society of America Bulletin. 99, 272-291.*
16. *Garfunkel, Z., 1999. History and paleogegraphy during the Pan-African-Orogen to stable platform transition: reappraisal of the evidence from the Elat area and the northern Arabian-Nubian Shield. Israel Journal of Earth Sciences 48,135-157.*
17. *Ghanem, H., McAleer, R., Jarrar, GH. Al Hseinat, M., Whitehouse, M., 2020. 40Ar/39Ar and U-Pb SIMS zircon Ages of Ediacaran Dikes from the Arabian-Nubian Shield of South Jordan. Precambrian Research, 343, https://doi.org/10.1016/j.precamres.2020.105714*
18. *Hammarstrom, J.M., Zen, E., 1986. Aluminium in hornblende: an empirical igneous geobarometer. American Mineralogist 71 (1112), 1297-313*
19. *Hollister, L.S., Grisson, G.C., Peters, E.K., Stowell, H.H., Sisson, V.B., 1987. Confirmation of the empirical correlation of Al in hornblende with pressure of solidification of calc-alkaline plutons. American Mineralogist 72 (34), 231-239.*
20. *Hyndman, D.W., Foster, D.A. 1988. The role of tonalities and mafic dikes in the generation of the Idaho batholiths. Journal of Geology, 96, 31-46.*
21. *Ibrahim, K. 1991. The Geology of Wadi Rahma. Bull. 15, NRA*
22. *Ibrahim, K.M., McCourt, W.J. 1995. Neoproterozoic granitic magmatism and tectonic evolution of the northern Arabian Shield: evidence from Southwest Jordan. Journal of African Earth Sciences 20, 103-118.*

23. *Irvine, T.N., Baragar, W.R.A 1971. A Guide to the chemical classification of the common volcanic rocks. Cand. J. Earth Sci., 8, 523-548.*
24. *Ghanem, H. and Jarrar, GH. 2013. Geochemistry and petrogenesis of the 595 Ma Qunai monzogabbro, Jordan. Journal of African Earth Sciences. 88, 1-14.*
25. *Jarrar, G., 2001. The youngest Neoproterozoic mafic dyke suite in the Arabian Shield: mildly alkaline dolerites from South Jordan – their geochemistry and petrogenesis. Geological Magazine 138, 309-323.*
26. *Jarrar, G., Wachendorf, H., Zachman, D. 1993. A Pan African pluton intruding the Saramuj Conglomerate, South-west Jordan. Geol. Rundschau 82, 121-135.*
27. *Jarrar, G., Stern, R.J., Saffarini, H., Al-Zubi, H., 2003. Late- and post-orogenic Neo-proterozoic intrusions of Jordan: implications for crustal growth in the northernmost segment of the East African Orogen. Precambrian research 123, 295-319.*
28. *Jarrar, G., Saffarini, G., Baumann, A., Wachendorf, H., 2004. Origin, age and petrogenesis of Neoproterozoic composite dikes from the Arabian–Nubian Shield, SW Jordan. Geological Journal 39, 157-178.*
29. *Jarrar, G., Dill, H.G., Yaseen, N., Whitehouse, M.J., 2012. The Aheimir volcanic suite,an Ediacaran post-collisional sequence from the northernmost Arabian-NubianShield, Wadi Araba, SW Jordan: age, geochemistry and petrogenesis. GeologicalSociety of America, Abstract with Programs 44 (5), 58.*
30. *Jarrar, G., Yaseen, N., Theye, T., 2013. A hybrid composite dike suite from the northern Arabian Nubian Shield, southwest Jordan: Implications for magma mixing and partial melting of granite by mafic magma. Journal of Volcanology and Geothermal Research 254, 80-93.*
31. *Jayananda, N., Gireesh, R.V., Sekhamo, K., Miyazaki, T. 2014. Coeval Felsic and Mafic Magmas in Neoarchean Calc-alkaline Magmatic Arcs, Dharwar Craton, Southern India: Field and Perographic Evidence from Mafic o Hybride Magmatic Enclaves and Synplutonic Mafic Dykes. Journal Geological Society of India, 84, 5-28.*
32. *Jayananda, N., Miyazakei, T., Gireesh, R.V., Mahesha, N., Kano, T. 2009. Synplutonic Mafic Dykes from late Archaean Granitoids in the Eastern Dharwar Craton India. Journal Geological Society of India, 73, 117-130.*
33. *Kumar, S. 2010. Mafic to Hybrid Microgranular Enclaves in the Ladakh Batholith, Northwest Himalaya: Implication on Calc-alkaline Magma Chamber Processes. Journal Geological Society of India, 76, 5-25.*
34. *Leake, B. E. et al. 2004. Nomenclature of amphiboles: Additions and revisions to the International Mineralogical Association's amphibole nomenclature. European Journal of Mineralogy, 16, 191-196.*
35. *McCourt, W.J., Ibrahim, K.M. 1990. The geology, geochemistry and tectonic setting of the ranitic and associated rocks in the Aqaba and Araba complexes of southwest Jordan. Bulletin Geological mapping Division 10. Natural Resource Authority, Amman, Jordan, 90 pp.*
36. *Pitcher, W.S., 1991. Synplutonic dykes and mafic enclaves. In: Didier, J. and Barbarine, B. (Eds.), Enclaves and Granite Petrology, Developments in Petrology.vol. 13, Elsevier, Amesterdam, 383-391.*
37. *Pitcher, W.S., 1997. The nature and origin of Granite. Second edition. Chapman and Hall, 387p.*

38. *Powell J.,H., Abed, A., Jarrar G. H., 2015. Ediacaran Araba Complex of Jordan. GeoArabia 20(1):99-156*
39. *Rollinson, H., 1993. Using geochemical data: evaluation, presentation, interpretation. Longman scientific & Technical*
40. *Schmidt, M.W., 1992. Amphibole composition in tonalite as a function of pressure: an experimental calibration of the Al-in-hornblende barometer. Contribution to Mineralogy and Petrology 110 (23), 304-310.*
41. *Sha'ban, K.H., 1996. Rahma Synplutonic diorite dikes: Geology, petrography and geochemistry. MSc Thesis, The University of Jordan, Jordan.*
42. *Stern, R,J., 1994. Arc assembly and continental collision in the Neoproterozoic East African Orogen: Implications for the consolidation of Gondwanaland. Ann. Rev. Earth Planet. Sci. 22, 319-351.*
43. *Stern, R.J., 2002. Crustal evolution in the East African Orogen: a neodymium sotopic perspective. Journal of African Earth Sciences 34, 109–117.*
44. *Stoeser, D., Frost, C.D., 2006. Nd, Pb, Sr and O isotopic characterization of Saudi Arabian Shield terranes. Chemical Geology 226, 163–188.*
45. *Vernon, R.H., 1983. Restite, xenoliths and microgranitoid enclaves in granites. Journal and Proceedings of the Royal Society of New South Wales. 116, 77-103*
46. *Yaseen, N., Pease, V., Jarrar, G. H., Whitehouse, M., 2013. U–Pb detrital zircon provenance of the Saramuj Conglomerate, Jordan, and implications for the Neoproterozoic evolution of the Red Sea region. Precambrian Research 239, 6-23.*
47. *Yavuz, F.,2007. WinAmphcal: A Windows program for the IMA-04 amphibole classification. Geochemistry Geophysics Geosystems, 8, 1-12*