GEOLOGY

Petrogenesis and tectonic implications of Seih Syn-tectonic gabbroic intrusion, South Sinai, Egypt: Insights from whole-rock geochemistry, mineral chemistry, and P-T estimate

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ABSTRACT
The present work deals with the gabbroic intrusion in Wadi Seih area as a part of the Neoproterozoic Pan-African basement in the southwestern part of Sinai, Egypt. It comprises as small plutons intruded into Seih metamorphic belt. The intrusions comprise hornblende gabbros, anorthositic gabbros, and sometimes occur as coarse-grained gabbros (appenites). These plutons belong to what is known throughout Egypt as Younger Gabbros. The present study includes petrography, whole-rock geochemistry, mineral chemistry, and geothermobarometry. Geochemically, the gabbroic intrusions are derived from tholeiitic magma with minor calc-alkaline affinity. They have the chemical signature of subduction-related arc magmatism formed at an active convergent plate margin by 15–30% of partial melting of garnet lherzolite and to a minor extent of spinel-garnet lherzolite sources, modified by fluids related to a subducting slab. Mineral chemistry indicates that the gabbroic rocks crystallized at a pressure between 2.9 and 4.4 kb and a temperature between 590 °C and 700 °C.

1. Introduction
The Seih Syn-tectonic gabbroic intrusion is one of the gabbroic intrusions in southwestern Sinai (Fig. 1). Gabbroic rocks in Egypt are considered as a key part of the Pan-African belt of Egypt and occur in two forms. The first is deformed, metamorphosed, and tectonically emplaced (ophiolitic gabbros) or magmatically intruded (metagabbro-diorite complex). The second, named younger gabbro, is undeformed, unmetamorphosed, layered in many areas, and was intruded before the post-tectonic granites but later than the molasse type sediment. The gabbroic rocks in Sinai are still controversial in terms of their origin, tectonic setting, and age. The intrusive gabbros have been studied in many localities in south Sinai and belong to intrusive layered younger gabbros (El-Mettwaly 1992; El-Tokhi and Katta 1993; Essawy et al. 1997; Basta 1998; Takla et al., 2001; Abu Anbar, 2009; Abdel-Karim, 2013). Other authors (e.g., Hassanen, 1989; Higazy and El-Gammal, 1989; Lebda et al.,
suggested that the gabbros in Sinai belong to metagabbro-diorite complexes.

The present work deals with the geology, petrology, mineral chemistry, and whole-rock chemistry of Seih gabbroic rocks in the south Sinai (Fig. 1.). The main objective of the present work is to explain the mineralogical and petrologic characteristics, magma type, tectonic setting, condition of crystallization, and petrogenesis of these gabbroic rocks.

2. Geological background

Regarding the metagabbro-diorite complex of south Sinai, most authors (El-Sheshtawy, 1984; El-Metwally, 1986; Belasy, 1991; and Abdel-Karim, 1995) argue it has a younger age than gneisses and migmatises. El-Tokhi (1990) disagreed with them and considered it as old. Based on geochemical criteria, El-Metwally (1986) concluded that the metagabbro-diorite complex, north of Wadi Feiran, South Sinai, was derived from tholeiitic magma. Belasy (1991) recognized that the rock complex evolved from calc-alkaline to tholeiitic magma and evolved within the volcanic arc environment. Abdel-Karim (1995) concluded that the metagabbro-diorite complex, southwest Sinai, was derived from subalkaline magma in an island arc setting. Mehanna and Soliman (2000) mentioned that the metagabbro-diorite complex of Wadi El-Gofa area is equivalent to the syntectonic metagabbro of the Eastern Desert. Basta (1998) studied the mineralogy and petrology of some gabbroic intrusions in the southern Sinai (e.g., Melhega, Sa’al, and Watier) and in the Eastern Desert. He concluded that these rocks were formed from calc-alkaline magma in an active continental margin setting. Hassanen and El-Gammal (1989) studied the petrography and geochemistry of the gabbros from the northwestern part of the basement rocks in Sinai and considered that the Nesryin gabbroic intrusion is related to the metagabbro–diorite complexes, whereas El-Tokhi and Katta (1993) studied the intrusive gabbro–diorite complex around Wadi El Akhdar and Wadi Nesryin, and concluded that the gabbros were intrusive in nature, tholeiitic, and probably represented differentiated mantle-derived magma intruded into an island arc setting.

Furnes et al. (1985) reported that the Shahera gabbro–diorite complex (Kid area) is predominantly tholeiitic and showed both MORB and island arc affinity. Hassanen (1989) related the metagabbro–diorite complex in Wadi Kid to a transitional ocean floor environment of high K-tholeiitic gabbro and calc-alkaline quartz-diorite characteristic of the subduction zone. Hassanen (1989) indicated that the Melhega metagabbro–diorite complex in southeastern Sinai originated from magmas related to a subduction zone in a transitional ocean floor to arc environment. Ghoneim et al. (1991) stated that the Shahera metagabbros are similar to non-orogenic gabbros and were crystallized from alkaline magma. Madbouli (1991) studied the gabbroic rocks of southern Sinai, especially El Mahash, El Bida, Feiran, Sa’al, and Melhega, and showed that these gabbroic masses exhibit chilled margins at their contact with the country rocks. The chilled margins are represented by fine-grained fresh gabbro-norite and oxy hornblende gabbro, whereas the gabbroic masses are mainly oxy hornblende gabbro, olivine gabbro, pyroxene hornblende gabbro, leucogabbro, and gabbro-norite.

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K-Ar dating of some metagabbro-diorite masses in southwest Sinai yields 794 Ma (time of emplacement and crystallization). The age range between 690 and 667 Ma represents the thermal event (Abdel-Karim, 1995). The gabbroic rocks of Wadi Nesryin, southwest Sinai (southern part of the study area), are described as
coarse to medium-grained metagabbro, variably deformed, locally banded, hornblende, and olivine-bearing (EGSMA, 1994). Takla et al. (2001) concluded that most of the metagabbro–diorite complexes and the ophiolitic ultramafic rocks in Sinai belong to the group of younger gabbros and ultramafics.

Abu Anbar (2009) concluded that the Nesryin gabbroic intrusion has an island arc tholeiitic and volcanic arc signature. He concluded that the Nesryin gabbroic intrusion, emplaced at 617±19 Ma, is one of the mafic-ultramafic intrusions in the Pan-African belt in southern Sinai related to the Egyptian younger gabbros. The Nesryin gabbroic intrusion is therefore not part of the older metagabbro-diorite complexes or the ophiolitic suite.

Abdel-Karim (2013) studied five minor intrusions of younger gabbros at Wadis Tweiba, Nakhil, Wadi Rahaba, Imliq, and El-Khamila in south Sinai. The geochemical characteristics of these gabbroic rocks indicate their derivation from two magma types (tholeiitic and calc-alkaline). Both types are closely related in time and space, but with different geochemical trends. The tholeiitic younger gabbros at W. Tweiba, W. Rahaba, and Khamila areas are generally characterized by high FeO, TiO₂, MnO, and LILE (e.g., Zr, Y, Nb, Th, and LREE) contents as compared with the calc-alkaline younger gabbros. The calc-alkaline younger gabbros at Imliq and W. Nakhil areas are characterized by high contents of SiO₂, Al₂O₃, CaO, Sr, and U. The investigated gabbros of all localities have LREE enrichment; HREE depletion and a small positive Eu anomaly suggest their moderate differentiation. The existence of the present two magma types reveals a heterogeneous mantle (or upper mantle-lower crust) source. They were mostly generated and emplaced in the continental crust and tend to be formed by a transitional compression–extension regime dominated by the final arc stage to the active continental margin.
Lebda et al., 2019 studied some older granite (OG) and metagabbro-diorite complex (MG) outcrops pertaining to the island arc regime in south Sinai. Three selected areas via Nesryin, El-Fringa-Minader, and Shahera outcrops are selected as a case example. The OG compositions are tonalite and granodiorite, whereas MG constitutes hornblende-metagabbros, hornblende-leucogabbro, and diorite. Geochemically, the OG rocks are peraluminous, calc-alkaline, and I-type and belong to syn-collision volcanic arc. The MG varieties exhibit transitional calc-alkaline/tholeiite magma types and are comparable to rocks of island arc setting.

3. Geological setting and field relations

The gabbroic rock intrusion of Wadi Seih occurs in the northern part of the Arabian shield in southern Sinai. It forms as rounded masses at Wadi Naba in the southwestern part of Seih area and also occurs as small masses at the intersection between Wadi Seih and Wadi Umm Agraf, Wadi Tayeba, Wadi Seih, and at Wadi Baraq (Fig. 1). These rocks are coarse-grained and range in size from 1 mm to 1 cm. Gabbro in Wadi Naba, in the western part of Wadi Seih, is intruded by post-tectonic granites of Gabal Ataitir El Dehami. The gabbroic intrusion exhibits sharp intrusive contacts with the surrounding gneisses and sends offshoots and apophyses into the gneisses (Fig. 2a). The present gabbros contain a lot of enclaves from the gneisses in different forms near the contact, sometimes in irregular forms (Fig. 2b) and as sheets from gneisses (Fig. 2c). It also contains small quartz veins (2-3 cm) (Fig. 2d). The gabbroic outcrop in Wadi Tayeba shows magmatic layering from leuco and melagabbro (Fig. 2e). Also, it shows anorthositic veins in random distribution within the gabbroic mass (Fig. 2f).

4. Petrography

Petrographic compositions of studied syn-tectonic gabbro are mainly hornblende gabbro and anorthosite gabbro. The hornblende gabbro is medium- to coarse-grained with a light greyish color, composed mainly of plagioclase (An$_{35-70}$) and hornblende. Accessory minerals include iron oxides, magnetite, apatite, and sphene. The rock shows hypidiomorphic, ophitic, and sub-ophitic textures (Figs. 3.a, b, and d). Plagioclase (An$_{35-70}$) occurs as twinned subhedral crystals enclosed by hornblende, forming ophitic and sub-ophitic textures. It is commonly twinned. Crystals are partially altered to sericite. Hornblende occurs either as euhedral or subhedral prismatic crystals and is partly twinned (Fig. 3e). It is strongly pleochroic with X= yellowish-brown, Y= pale brown, and Z= dark brown. Quartz occupies the interstices between plagioclase and hornblende and commonly corrodes their boundaries. Apatite occurs in association with plagioclase with moderate relief and first-order grey interference color. Sphene occurs as anhedral grains. Iron oxides are represented by anhedral grains of magnetite, which sometimes form clusters or scattered ones.

Anorthosite gabbro is a coarse-grained igneous rock. It is composed mainly of anorthite (> 90%) with a minimal amount of pyroxene, and there is hornblende (Fig. 3f). Iron oxides occur as accessory minerals.

5. Whole-rock geochemistry

Geochemical analyses were carried out at the Earth Sciences Department, Ferrara University, Italy. Major elements and Pb, Zn, Ni, Co, Cr, V, Rb, Sr, Ba, Nb, Zr, and Y were determined by X-ray fluorescence spectrometry (XRF) on pressed powder pellets using an ARL Advant-XP spectrometer, following the full matrix
correction method proposed by Lachance and Traill (1966). Accuracy is generally less than 2% for major oxides and less than 5% for trace element determinations. Detection limits for trace elements are in the few ppm range. Replicate analyses for some trace elements gave a precision better than 5%. Loss on ignition (LOI) was determined gravimetrically after heating the sample powder to 1,000 °C for 1 h.

The geochemistry of the Syn tectonic gabbros is based on five representative samples from Wadi Seih (E78, E88, SA7, SA25, and SA3A). Data of El-Fringa Minader gabbro after Lebda et al. (2019) are used for comparison. Table 1 represents major and trace element composition as well as geochemical parameters of the present gabbros.

Fig. 2. Field photograph of syn-tectonic gabbro. (a) Sharp contact between gneisses and syn-tectonic gabbro, (b) Enclaves of gneisses inside syn-tectonic gabbro, (c) Gneisses occur as sheets inside the syn-tectonic gabbro, (d) Small quartz veins inside syn-tectonic gabbro, (e) Magmatic layering from leuco and melagabbro, (f) Anorthositic veins in the gabbroic mass.
5.1 Major oxides and trace element compositions

Major oxides such as SiO$_2$ ranges from (44.13 wt.% to 48.76 wt.%) and TiO$_2$ ranges from (0.24 to 1.48 wt.%). Al$_2$O$_3$ ranges from (11.27 to 17.19 wt.%), whereas Fe$_2$O$_3$ shows a range from (5.68 to 14.59 wt.%). MnO ranges from (0.12 to 0.17 wt.%), MgO ranges from (6.67 to 14.58 wt.%), CaO ranges from (1.04 to 2.33 wt.%), and K$_2$O ranges from (0.37 to 1.52 wt.%).

Trace elements are widely varied in their concentrations among the samples. The most variable transition metals include, Cr ranges from (36.6 ppm to 369.8 ppm), Ni (13.2 ppm to 166.1 ppm), V (110.5 ppm to...
286.1 ppm), Sc (29.7 ppm to 47.5 ppm), Co (37.6 ppm to 58.9 ppm) and Ga (2.1 ppm to 13.19 ppm). The sample E88 has the highest ppm value for Cr, Ni, Co, and Sc, while SA7 has the lowest comparative values.

Chalcophile elements, including Cu and Zn, are also varied. Copper ranges from (12.3 ppm to 121.6 ppm) and Zn ranges from (35.5 ppm to 132.1 ppm).

Table 1. Chemical analyses of gabbroic rocks.

| Oxides/Trace| Wadi Seih syn-tectonic gabbro E78 | E88 | SA7 | SA25 | SA3A | Average | N22 | N30 | N31 | N33 | N34 | Average |
|-------------|-----------------------------|-----|-----|------|------|----------|-----|-----|-----|-----|-----|----------|
| SiO2        | 47.11                       | 48.09 | 48.75 | 44.13 | 43.73 | 47.0849 | 51.8 | 56.01 | 54.13 | 57  | 58.08   | 55.404  |
| TiO2        | 1.356                       | 0.272 | 0.243 | 1.481 | 0.303 | 0.73119 | 1.8  | 1.5   | 1.3  | 0.9  | 0.49   | 1.198  |
| AL2O3       | 11.27                       | 15.75 | 15.91 | 17   | 17.19 | 15.4241 | 15.5 | 16.28 | 16.79 | 17.8 | 16.81   | 16.636 |
| Fe2O3 tot   | 11.22                       | 7.075 | 5.68  | 14.59 | 7.914 | 9.29571 | 12.1 | 8.48  | 7.25  | 10.2 | 7.67    | 9.14   |
| MnO         | 0.163                       | 0.142 | 0.124 | 0.169 | 0.126 | 0.14485 | 0   | 0.14  | 0.13  | 0.11 | 0.076  | 0.11   |
| MgO         | 14.58                       | 13.46 | 13.44 | 6.666 | 11.27 | 11.8841 | 2.1  | 5.4   | 8    | 2.8  | 6      | 4.86   |
| CaO         | 10.34                       | 11.34 | 12.57 | 10.23 | 12.91 | 11.48   | 10   | 8.44  | 8.4   | 6.7  | 7      | 8.108  |
| Na2O        | 1.694                       | 1.098 | 1.039 | 2.329 | 1.407 | 1.51349 | 4.3  | 0.94  | 1.08  | 1.2  | 1.89    | 1.882  |
| K2O         | 0.804                       | 0.537 | 0.487 | 1.522 | 0.371 | 0.7442  | 1.3  | 0.51  | 0.66  | 1.6  | 1.17    | 1.048  |
| P2O5        | 0.188                       | 0.016 | 0.013 | 0.732 | 0.029 | 0.19554 | 0.5  | 0.52  | 0.63  | 0.5  | 0.16    | 0.462  |
| LOI         | 1.27                        | 2.21  | 1.73  | 1.15  | 1.15  | 1.502   | 100  | 100   | 100   | 100  | 99.9    | 98.814 |
| Total       | 100                         | 100   | 100   | 100   | 100   | 100     | 99.4 | 98.22 | 98.37 | 98.7 | 99.38   | 98.814 |

| CIPW Norm   | Q  | Or (KAS6) | Ab (NAS6) | An (CAS2) | C(A) | Di wOl(CS) | Di en(MS) | Di fs(FS) | Hy en(MS) | Hy fs(FS) | Ol fs(M2S) | Mt(FF) | He(F) | Ap(CP) | Totals |
|-------------|----|-----------|------------|-----------|------|------------|-----------|-----------|-----------|-----------|------------|--------|-------|--------|--------|
|             | 4.79 | 3.27      | 2.95       | 9.1       | 2.21 | 14.47      | 9.51      | 19.92     | 12.06     | 21.04     | 25.72     | 16.21  | 11    | 0.42   | 98.62  |

Data of El-Fringa-Minader gabbro after Lebda et al., 2019.
Considering the large ion lithophile elements (LILEs), Ba ranges from (57.7 ppm to 374.2 ppm), Sr from (454.7 to 973.9 ppm), and Rb from (1.9 ppm to 48.1 ppm). As for the high field strength elements (HFSEs), Zr ranges between (3.2 ppm to 72.2 ppm) (one sample not detected), Nb content is (0.4 ppm to 5.4 ppm) (3 samples are not detected), Th is (0.3 ppm to 1.1 ppm) (3 samples not detected), and Y composition ranges between (6.3 ppm to 25.2 ppm). With respect to the rare earth elements (REEs), Ce is not detected, La is (4.8 ppm to 16.8 ppm) (one sample not detected), and Nd one sample only (SA25) reported 1 ppm.

5.2. Spider diagram

The behavior of trace elements is commonly illustrated by normalized diagrams. The present data are normalized to MORB (Sun and McDonough, 1989) and compared with gabbro of El-Fringa-Minader South Sinai, Egypt (Lebda et al., 2019), as shown in (Fig. 4a). It is clear from the figure that both Wadi Seih syn-tectonic gabbro and El-Fringa-Minader gabbro show similarities in their depletion of (Zn, Cr, and Ni) and enrichment of (Ba, Rb, Th, Pb, and Sr). In contrast, El-Fringa-Minader gabbro is relatively enriched in Nb, Zr, and Y compared to Wadi Seih syn-tectonic gabbro, which is depleted.

5.3. Chemical classification, Magma type and Tectonic setting

SiO₂ versus (Na₂O+K₂O) diagram (Cox et al., 1979) and (Wilson, 1989 and 1985) (Fig. 4b) is used for the nomenclature of the present syn-tectonic gabbro. The studied samples are plotted in gabbro field. The recognition of the magma type, its chemical nature, and its behavior on differentiation help to elucidate the tectonic setting of the present syn-tectonic gabbro. On the SiO₂ versus (Na₂O+ K₂O) diagram (Fig. 4b) of (Cox et al.,1979) and (Kuno, 1968) diagram (Fig. 4.c) Wadi Seih syn-tectonic gabbro and El-Fringa-Minader gabbro fall within the subalkaline field except one sample lies in the alkaline field. Many diagrams are used to distinguish between the tholeiitic and calc-alkaline series.AFM (Fig. 4d) diagram was suggested by (Irvine and Baragar, 1971). The plotted data on this diagram clarifies the transitional nature (merging between calc-alkaline and tholeiite nature) for both of Wadi Seih syn-tectonic gabbro and El-Fringa-Minader gabbro. The Zr vs. Y discrimination diagram (Ross and Bédard, 2009) suggests that the syn-tectonic gabbro of Wadi Seih area belongs to the tholeiitic to transitional series, whereas El-Fringa-Minader gabbro belongs to the calc-alkaline magma series (Fig.4c).

The tectonic setting of the studied syn-tectonic gabbro is depicted in published diagrams. The FeO₄t-MgO-Al₂O₃ ternary diagram proposed by (Pearce et al., 1977) is commonly used to discriminate between different tectonic settings of similar rocks. On this diagram, 4 samples of the Wadi Seih syn-tectonic gabbro fall into the mid-ocean ridge basalt field (MORB), and one sample falls into the continental field (Fig. 4f). The comparative rocks of El-Fringa-Minader gabbro, four samples lie in the island and active continental margin and one sample lies in the spreading center island (E-MORB) field as in (Fig. 4f).

6. Mineral Chemistry

About 25 single-point analyses were performed using an electron microprobe at the Institute of Geological Sciences, Wroclaw University, Poland, for some selected minerals (amphibole, feldspars, chlorite, biotite, and some Fe-Ti oxides). The chemistry of analyzed minerals was used to give important information about the chemical features of the magma source, tectonic setting, and P-T condition of crystallization.
6.1. Amphibole

The main objective of the present study is to estimate the variation in the chemical composition of the amphiboles to determine their nomenclature and throw some light on the condition of their formation. Electron microprobe analyses for about 9 single points of the amphibole minerals and their chemical formulae based on 23 oxygen atoms are listed in (Table 2).
Generally, amphiboles are classified according to the recommendations of the International Mineralogical Association (I.M.A.). These were compiled by Leake (1978), Rock and Leake (1984), and Leake et al. (1997) as iron-magnesium-manganese group, calcic group, sodic-calcic group, and Alkali group. Accordingly, in the BNa versus BCa + BNa diagram, the amphiboles of syn-tectonic gabbro are grouped as calcic amphibole group (Fig. 5a). The amphiboles of syn-tectonic gabbro are classified chiefly as magnesio-hornblende except for one sample located at the boundary between magnesio-hornblende and tschermakite hornblende (Fig. 5b).

The composition of amphibole minerals can be used to determine the geochemical affinity and tectonic setting of the parent magma. The studied syn-tectonic gabbro falls within the sub alkaline field (Fig. 5c) on the diagram of Molina et al. (2009).

### 6.2. Biotite
A total of 6 single points microprobe analyses were performed from syn-tectonic gabbro (sample E78). EMPA analyses of biotite minerals and their chemical formulae are calculated on the basis of 24 oxygen atoms are listed in (Table 3).

On Fe/(Fe+Mg) vs. AlIV diagram (Fig. 5d) for biotite nomenclature of syn-tectonic

### Table 2. Microprobe analyses and structural formulae of amphiboles.

| Sample | E78-iaa | E78-iac | E78-ead | SA3A-ja | SA3A-jab | SA3A-jac | SA3A-jad | SA3A-jae |
|--------|---------|---------|---------|---------|----------|----------|----------|---------|
| core/rim | c | r | c | c | r | c | c | c | c | c |
| SiO2 | 44.55 | 46.39 | 47.46 | 48.44 | 49.33 | 49.02 | 47.75 | 50.49 | 49.52 |
| TiO2 | 1.15 | 1.17 | 1.00 | 0.84 | 0.49 | 0.48 | 0.38 | 0.55 | 0.35 |
| AI2O3 | 12.09 | 10.16 | 8.44 | 8.25 | 7.92 | 9.26 | 8.22 | 7.07 | 7.91 |
| Fe2O3 | 4.06 | 0.89 | 2.28 | 2.29 | 4.64 | 3.42 | 3.91 | 3.96 | 3.92 |
| FeO | 8.12 | 10.59 | 8.81 | 8.94 | 6.87 | 7.59 | 7.35 | 8.11 | 6.81 |
| MnO | 0.19 | 0.21 | 0.25 | 0.21 | 0.22 | 0.21 | 0.19 | 0.27 | 0.17 |
| MgO | 12.97 | 13.75 | 14.52 | 14.89 | 15.26 | 14.95 | 14.24 | 15.18 | 15.57 |
| CaO | 11.74 | 12.40 | 12.09 | 12.29 | 11.70 | 11.98 | 11.14 | 11.87 | 11.96 |
| Na2O | 1.43 | 1.58 | 1.22 | 1.32 | 1.35 | 1.39 | 1.38 | 1.20 | 1.22 |
| K2O | 0.68 | 0.62 | 0.56 | 0.43 | 0.32 | 0.34 | 0.35 | 0.34 | 0.26 |
| H2O | 2.05 | 2.06 | 2.05 | 2.08 | 2.10 | 2.11 | 2.03 | 2.12 | 2.10 |
| Total | 99.03 | 99.82 | 98.68 | 99.98 | 100.21 | 100.76 | 96.95 | 101.16 | 99.79 |
| Si | 6.51 | 6.74 | 6.92 | 6.97 | 7.03 | 6.95 | 7.04 | 7.15 | 7.07 |
| Al | 1.49 | 1.26 | 1.08 | 1.03 | 0.97 | 1.05 | 0.96 | 0.85 | 0.93 |
| Fe | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 |
| Mg | 0.59 | 0.48 | 0.38 | 0.37 | 0.36 | 0.50 | 0.47 | 0.33 | 0.40 |
| Ca | 0.45 | 0.10 | 0.25 | 0.25 | 0.50 | 0.37 | 0.43 | 0.42 | 0.42 |
| Ti | 0.13 | 0.13 | 0.11 | 0.09 | 0.05 | 0.05 | 0.04 | 0.06 | 0.04 |
| Mn | 2.82 | 2.98 | 3.16 | 3.19 | 3.24 | 3.16 | 3.13 | 3.20 | 3.31 |
| Fe | 0.99 | 1.29 | 1.07 | 1.08 | 0.82 | 0.90 | 0.91 | 0.96 | 0.81 |
| Ca | 0.05 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 | 0.03 | 0.02 |
| Ca | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| Ca | 1.84 | 1.93 | 1.89 | 1.89 | 1.79 | 1.82 | 1.76 | 1.80 | 1.83 |
| Na | 0.16 | 0.07 | 0.11 | 0.11 | 0.21 | 0.18 | 0.24 | 0.20 | 0.17 |
| Na | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| Na | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| K | 0.24 | 0.38 | 0.24 | 0.26 | 0.16 | 0.20 | 0.15 | 0.13 | 0.17 |
| Site | 0.13 | 0.11 | 0.10 | 0.08 | 0.06 | 0.06 | 0.07 | 0.06 | 0.05 |
| Na | 0.37 | 0.49 | 0.34 | 0.34 | 0.22 | 0.26 | 0.22 | 0.19 | 0.21 |
| Na | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| Charge | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
gabbro Kubovicz et al. (1989), it is evident that samples of syn-tectonic gabbro (E78) lie in the phlogopite field and have a composition between phlogopite and estonite. De Albuquerque (1973) classified the biotites of different mineral associations into the following four fields:– 1) fields of biotites co-existing with amphibole, 2) fields of biotites unaccompanied by ferromagnesian minerals, 3) fields of biotites co-existing with muscovite, and 4) fields of biotites co-existing with aluminosilicates. Plots of biotite of syn-tectonic gabbro fall within field III, except one sample lies in field IV (Fig. 5e). Abdel Rahman (1994) discriminates between alkaline, calc-alkaline, and peraluminous nature. Plotting the analyzed biotite of the syn-tectonic gabbro shows that the parent magma has a calc-alkaline nature (Fig. 5f).
6.3. Plagioclase

Ten single-point analyses of feldspars from two representative samples of syntectonic gabbro (E78, SA3A) have been analyzed and listed in (Table 4). The chemical formula was computed from the obtained analyses on the basis of 32 oxygen atoms. The present data for feldspar are plotted on the Or-Ab-An ternary diagram (Fig. 6a) of Deer et al. (1978). The analyzed samples show that plagioclase from syntectonic gabbro (E78) is plotted in the andesine field. In contrast, plagioclase (SA3A) is plotted in the bytownite field, where it has a high content of CaO and a medium content of SiO₂.

7. Crystallization conditions (P-T estimate)

7.1. Geothermometry

The formation temperature of the studied syn-tectonic gabbro is obtained by using a ternary composition diagram of feldspar with the solvus isotherms of Elkins and Grove (1990) (Fig. 6b). The investigated plagioclase compositions reveal that the plagioclase from Wadi El Tayeba (E78) was formed around (600°C) while the other plagioclase from El Seih area (i.e., sample SA3A) was formed around (650 °C).

The AlIV of the amphibole is considered as geothermometer and a function of temperature. The temperature of
amphibole formation can be estimated by plotting $\text{Al}^{IV}$ on the temperature- $\text{Al}^{IV}$ standard diagram of Blundy and Holland (1990). The diagram reveals that the amphiboles of syn-tectonic gabbro from Seih area (i.e., sample SA3A) indicate a formation temperature in the range of (610 °C-710 °C) (Fig. 6c). Ti in hornblende (after Otten, 1984) indicates a formation temperature range of (654°C - 699 °C) for E78 and of (590 °C - 615 °C) for SA3A.

The chemistry of the co-existing amphibole and plagioclase pairs is plotted on the diagram of Perchuk (1970) and yields an approximate temperature ranging of (654°C - 699 °C) for E78 and of (590 °C - 615 °C) for SA3A.

The pressure of syn-tectonic gabbro was calculated by applying the geobarometer equations proposed by (Hammarstrom and Zen, 1986), (Hollister et al., 1987), (Johnson and Rutherford, 1989), and (Schmidt, 1992) using Al in amphiboles as barometers. From the four Al-barometers, the pressure was calculated using the average of the four equations, which is about (4.4 kb) and the depth of emplacement is about 14.5 km for syn-tectonic gabbros in Wadi Tayeba (sample E78) and about (2.9 kb) for syn-tectonic gabbros from Wadi Seih (SA3A) with a depth of about 9.57 km. Ti versus $\text{Al}^{tot}$ of the studied amphibole (after Hynes, 1982) (Fig. 6e) indicates that the (SA3A) was formed under medium pressure conditions, while sample (E78) shows low-pressure conditions. $\text{Al}^{tot}$ vs. Na diagram of Brown (1977) suggests a pressure range of (4-6 kb) for sample (E78) and (5-6 kb) for sample SA3A (Fig. 6f).

### Table 4. Microprobe analyses and structural formulae of plagioclase.

| Sample | E78- ipa | E78- ipb | E78- ipc | E78- ipc' | SA3A- jpb | SA3A- jpc | SA3A- jpa | SA3A- jpe | SA3A- jpf |
|--------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Core/rim | c       | r       | c       | c       | r       | c       | c       | c       | r       |
| SiO2   | 61.53   | 61.96   | 61.95   | 60.02   | 47.19   | 47.24   | 46.73   | 49.41   | 47.48   |
| Al2O3  | 25.40   | 24.78   | 24.25   | 25.01   | 32.14   | 31.94   | 34.71   | 31.84   | 31.85   |
| Fe2O3  | 0.08    | 0.10    | 0.09    | 0.04    | 0.23    | 0.12    | 0.13    | 0.12    | 0.13    |
| MgO    | 0.02    | 0.03    | 0.02    | 0.03    | 0.05    | 0.03    | 0.03    | 0.03    | 0.02    |
| MnO    | 0.02    | 0.02    | 0.03    | 0.02    | 0.00    | 0.03    | 0.02    | 0.00    | 0.00    |
| CaO    | 7.10    | 6.64    | 6.43    | 7.23    | 16.82   | 16.41   | 17.56   | 16.28   | 16.22   |
| Na2O   | 7.15    | 7.83    | 7.84    | 8.12    | 2.18    | 2.20    | 1.38    | 2.56    | 2.36    |
| K2O    | 0.11    | 0.10    | 0.09    | 0.14    | 0.01    | 0.01    | 0.01    | 0.01    | 0.00    |
| Total  | 101.41  | 101.46  | 100.70  | 100.61  | 98.62   | 97.98   | 100.57  | 100.25  | 98.06   |
| #Si+4  | 2.69    | 2.71    | 2.73    | 2.67    | 2.20    | 2.21    | 2.13    | 2.26    | 2.22    |
| #Al+3  | 1.31    | 1.28    | 1.26    | 1.31    | 1.77    | 1.76    | 1.87    | 1.71    | 1.75    |
| #Fe+3  | 0.00    | 0.00    | 0.00    | 0.00    | 0.01    | 0.00    | 0.00    | 0.00    | 0.00    |
| #Mg+2  | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    |
| #Mn+2  | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    |
| #Ca+2  | 0.33    | 0.31    | 0.30    | 0.34    | 0.84    | 0.82    | 0.86    | 0.80    | 0.81    |
| #Na+1  | 0.61    | 0.66    | 0.67    | 0.70    | 0.20    | 0.20    | 0.12    | 0.23    | 0.21    |
| #K+1   | 0.01    | 0.01    | 0.01    | 0.01    | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    |
| #Total | 4.96    | 4.98    | 4.98    | 5.03    | 5.01    | 5.01    | 4.99    | 5.00    | 5.01    |
| #O-2   | 8.00    | 8.00    | 8.00    | 8.00    | 8.00    | 8.00    | 8.00    | 8.00    | 8.00    |
| Na+K+Ca | 0.95  | 0.98    | 0.98    | 1.05    | 1.04    | 1.02    | 0.98    | 1.02    | 1.03    |
| Ab     | 0.64    | 0.68    | 0.68    | 0.67    | 0.19    | 0.20    | 0.12    | 0.22    | 0.21    |
| Or     | 0.01    | 0.01    | 0.01    | 0.01    | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    |
| An     | 0.35    | 0.32    | 0.31    | 0.33    | 0.81    | 0.80    | 0.87    | 0.78    | 0.79    |
8. Summary and tectonic evolution

The present study revealed the following characteristics:

1. There is no evidence for folding, deformation, and metamorphism, which indicates that the present gabbros are related to late to syn-tectonic stage of the Pan-African orogeny and are not related to the ophiolite suite.

2. The present gabbroic intrusion displays characteristics of a tholeitic affinity magma type with minor calc-alkaline in transitional from arc stage at the plate margin to continental magmatism and intruded into the continental crust derived from a mantle source strongly modified by fluids related to subduction of an oceanic slab, as suggested by Essawy et al. (1997).
3. Microprobe data of amphiboles indicate that the amphiboles are classified as magnesio-hornblende, whereas biotite lies in the phlogopite field and has a composition between phlogopite and estonite. Plagioclase varies in composition from andesine to bytownite in the present gabbros. The presence of hornblende as a separate crystal reflects that the present gabbros derived from hydrous magma, most probably as a result of the introduction of water into the gabbro during a metamorphic event that occurred early and formed gneisses in the present area.

4. The Seih gabbro was formed at a temperature range of 590 °C to 700 °C and a pressure of between 2.9 and 4.4 kb, as indicated by many geothermometers and geobarometers.

5. The tectonic evolution proposed for the syn-tectonic gabbros in Seih area is as follows: After the arc – arc collision stage at ~ 617 Ma (i.e., the Ediacaran age) (Abu Anbar, 2009), the northern part of the Arabian-Nubian Shield was subjected to an extension regime that formed a series of back-arc basins (Hassan et al., 2020; Abu-Alam et al., in print). At this stage, syn-tectonic gabbro formed with a chemical signature of tholeiitic to calc-alkaline nature, indicating MORB affinity. This magma intruded shallower crustal level rocks and crystallized at a temperature range of (550 - 710°C) and pressure (3-4.4 kb) at a depth of emplacement of (10-14.5 km) (Fig. 7).

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