ORIGINAL PAPER

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# Petrogenetic Aspects of Wadi Akhdar-Wadi El-Sheikh Granitoid Rocks, Central Southern Sinai, Egypt: Evidence from the Chemistry of Ampiboles and Biotite

**Abstract:** Amphiboles and biotites from some calc-alkaline granitoid rocks ranging in composition from quartz-diorite (QD), through tonalite (TON), granodiorite (GD) to monzogranite (MGR) exposed at Wadi Akhdar-Wadi El-Sheikh area have been analysed for major, trace and REE. Both the amphiboles and biotites cover a wide compositional range which reflects the magmatic evolution of their host rocks.

The amphiboles belongs to the calcic-type, ranging from magnesio-hornblende in QD and TON, actinolitic hornblende in GD, and actinolite in MGR. Biotite varies from 45 to 64 mol-% phlogopite and classified as Fe-rich meroxene in QD, TON and GD and Fe-poor lepidopmelane in MGR.The proposed conditions of crystallization range from <1—3Kb and 650°-850°C for the amphibole and a lower pressure and 800°-600°C for the biotite equilibrium. Generally, the amphibole and biotite are characterized by an increase in Si, Fe, K and HFSE, a decrease in Ti, Ca, Mg and the third transitional element contents relative to Fe/(Fe+Mg) ratios. They also show a good parallelism with the successive enrichment of both the total REE contents and negative Eu anomalies, suggesting a progressive crystal fractionation from the more mafic melt to constitute the felsic QD-TON-GD-MGR crystallization trend.

The examined amphiboles and biotites from Wadi Akhdar-Wadi El-Sheikh granitoid complex are chemically similar to those from the orogenic calc-alkaline (I-type) suites.

**Keywords:** Granitoid rocks, Wadi Akhdar-Wadi El-Sheikh, Sinai, Egypt, Chemistry amphiboles and biotites

**الخصائص الصخرية لجرانيتات وادى أخضر-وادى الشيخ جنوب غرب سيناء بمصر: دلائل من كيميائية الامفيبول والبيوتايت**

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**المستخلص:** أثبتت الدراسة التفصيلية لمعدنى الأمفيبول والبيوتايت فى الصخور الجرانيتية في وادى أخضر ووادى الشيخ بجنوب سيناء، اتساع تركيبهما المعدنى الذى يعكس التطور الصهيرى لكل منهما . يتضمن أمفيبول هذه الصخور النوع الكلسى، الذى يتراوح فى تركيبه من الماغنسيو-هورنبلند فى صخور الكوارتز دايورايت والتونالايت الى الهورنبلند الاكتينوليتى فى الجرانودايورايت والاكتينولايت فى المونزوجرانيت .

أما تركيب البيوتايت فيتدرج من 36%-55% فلوجوبايت ، وينقسم من يروكسين غنى فى الحديد، يوجد فى صخور الكوارتز دايورايت والتونالايت والجرانودايورايت، الى ليبيدوميلان فقير فى الحديد، ويميز صخور المونزوجرانيت . كما دلت الدراسة على أن هذا الأمفيبول قد تكون فى حرارة تراوحت من 650°-850° وضغط من 3 كيلو بار إلى أقل من واحد كيلو بار ، بينما تكون البيوتايت عند حرارة تراوحت من600°-800° وضغط أقل .

يتميز كل من الأمفيبول والبيوتايت بزيادة فى عناصر السيليكون والحديد والبوتاسيوم وعناصر شحيحة أخرى، ونقص فى التيتانيوم والماغنسيوم والكالسيوم والعناصر الانتقالية الثلاثية، مع التدرج فى نسبة التمايز[Fe/(Fe+Mg)] ، كما يتناسب ذلك مع الانماء المتتالى فى العناصر الارضية النادرة، وفى مدى سالبية شذوذ الايروبيوم فيهما . ويدل ذلك على تقدم عملية التمايز من الصخور المافية الكلسية، مثل الكوارتز دايورايت والتونالايت، الى الصخور الاكثر حامضية مثل الجرانودايورايت والمونزوجرانيت .

كما دلت الدراسة على تشابه الأمفيبول والبيوتايت، تحت الدراسة، مع ذلك الموجود فى الجرانيتات الكلس-قلوية من النوع (I-type) الأوروجينية .

**كلمات مدخلية:** جرانيت، صخور، تباين عناصر التركيب ، الأمفيبول ، البيوتايت ، مصر، وادي أخضر، وادي الشيخ، سيناء.

## Introduction

Wadi Akhdar-Wadi El-Sheikh complex, Southern Sinai, is one of the late Proterozoic Older Granites (Gr.A) (El-Shatoury *et al.* 1984) or calc-alkaline tonalite to granodiorite (gα-granites) (El-Gaby *et al.* 1990). It composed mainly of syn-orogenic granitoids including quartz diorite, tonalite, granodiorite and monzogranite types.

The contacts between the different types are gradational and they are mingled with each other. The rocks are mostly hornblende and/or biotite rich, coarse-grained and macro-porphyritic rocks. Abundant xenoliths of different sizes, styles and shapes are enclosed within the present granitoid complex. The examined granitoids intrude into the Feiran gneisses and migmatites and in turn, they are intruded by Farsh Zobeir volcanics (Fig. 1).

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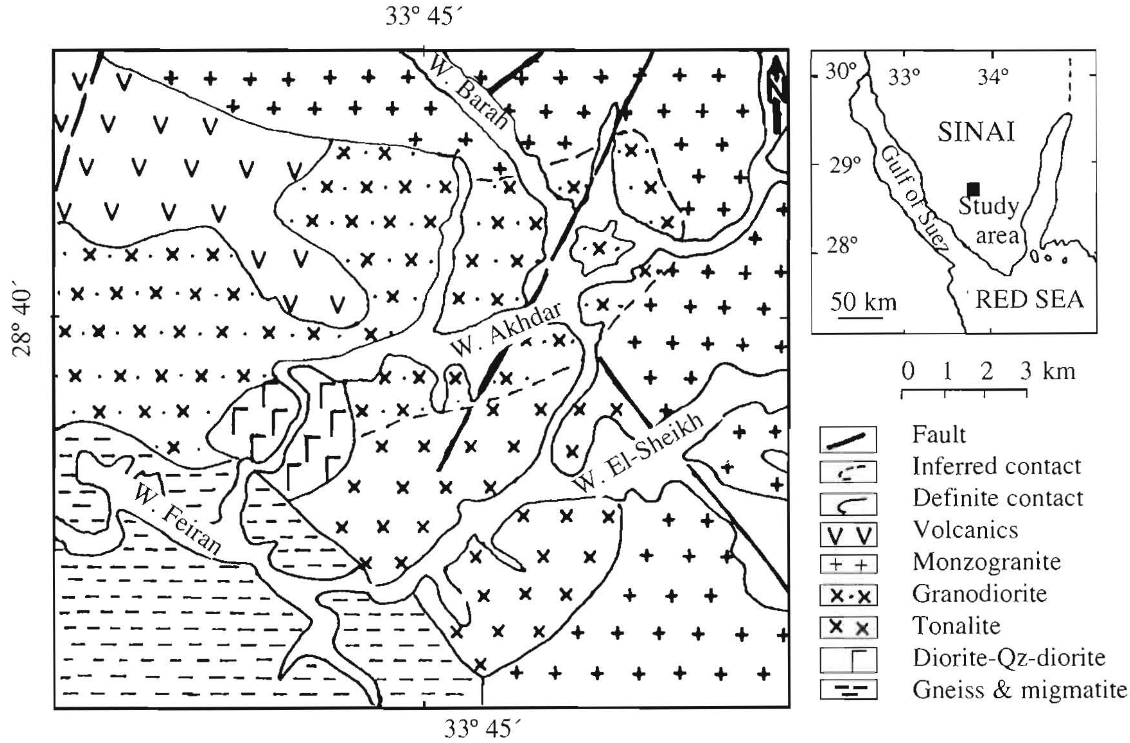



**Fig. 1:** Geologic map of Wadi Akhdar-Wadi El-Sheikh area, central Southern Sinai.

The granitoid rocks of Wadi Akhdar-Wadi El-Sheikh are considered as calc-alkaline granites, and show an affinity to the volcanic arc granites (Soliman *et al.* 1988, Soliman *et al.* 1998).

Amphibole and biotite are present in diverse varieties in many magmatic units of Wadi Akhdar-Wadi El-Sheikh area. In this work, a number of amphibole and biotite spots have been analyzed to enable examination of the mineralogical and chemical variations of mafic minerals within the granitoid varieties. The crystallization history and the role of amphibole and biotite in magma evolution are also elucidated.

## Analytical Technique

Electron microprobe analyses were carried out with a standardized AMRAY- 1830 I analyzer using polished thin sections, which were vacuum-coated with carbon. The standards used were natural silicates and oxides. Operating conditions were 20 kV accelerating potential and 1-2 nA sample current. The microprobe analyses were carried out at the Department of Petrology and Geochemistry, Eotvos University, Budapest. A total of 12 amphibole and 12 biotite analyses from eight samples (3 spots/sample) representative of the quartz diorite, tonalite, granodiorite and monzogranite are given in Tables 1 and 2. The microprobe analytical error is approximately ± 2 % for the major elements.

The trace elements Sc, Cr, Co, Zn, Rb, Cs, Hf, Ta, Th, U, Nb, Y, Zr and 8 rare earth elements were determined by standard instrumental neutron activation analysis (INAA) except for Nb, Y and Zr which were measured by the optical atomic spectrophotometric method (PGS-2C Zeiss Jena). The precision for REE analysis is 2—5%. The analyses were carried out at the Technical University, Budapest, Hungary. Eight samples were selected to separate their amphibole and biotite contents. Each sample was crushed until completly pulverized, then sieved to separate the 63—125µm size. The samples were washed, dried and separated using bromoform, then washed with alcohol and subsequently dried. The heavy fractions were subjected to magnetic separation with adjustable standard pole pieces. The separated fractions of amphibole and biotite were, moreover, checked by binocular microscope. The results are given in Tables 3 and 4.

**Table 1:** Microprobe analyses and structural formulae of the amphiboles

| | Qz-diorite | | | Tonalite | | | Granodiorite | | | Monzogranite | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| $SiO_2$ | 45.98 | 46.05 | 45.85 | 48.20 | 48.05 | 47.54 | 49.85 | 49.50 | 49.75 | 51.65 | 51.30 | 50.94 |
| $TiO_2$ | 1.32 | 1.32 | 1.45 | 0.63 | 0.61 | 0.62 | 0.53 | 0.52 | 0.45 | 0.58 | 0.53 | 0.60 |
| $Al_2O_3$ | 7.63 | 7.80 | 7.67 | 5.50 | 5.42 | 5.57 | 4.32 | 4.52 | 4.42 | 4.05 | 4.12 | 4.15 |
| $FeO^t$ | 17.21 | 16.21 | 15.53 | 18.50 | 18.54 | 18.32 | 19.22 | 19.05 | 19.15 | 19.50 | 19.42 | 19.67 |
| MnO | - | - | 0.50 | 0.82 | 0.67 | 0.66 | 0.52 | 0.53 | 0.58 | 0.60 | 1.54 | 0.57 |
| CaO | 11.52 | 11.72 | 11.53 | 11.31 | 11.32 | 11.67 | 10.05 | 10.72 | 10.35 | 9.75 | 9.88 | 9.78 |
| MgO | 13.17 | 13.29 | 13.34 | 11.65 | 11.43 | 11.40 | 10.95 | 10.65 | 10.57 | 10.05 | 10.11 | 10.19 |
| $Na_2O$ | 1.74 | 1.78 | 1.73 | 1.53 | 1.55 | 1.45 | 1.52 | 1.35 | 1.43 | 1.30 | 1.52 | 1.44 |
| $K_2O$ | 0.45 | 0.46 | 0.53 | 0.54 | 0.55 | 0.54 | 0.87 | 0.89 | 0.79 | 0.93 | 0.94 | 1.00 |
| Sum | 98.94 | 98.73 | 98.14 | 98.67 | 98.44 | 97.77 | 97.83 | 97.73 | 97.49 | 98.41 | 98.36 | 98.63 |
| | Structural formulae calculated on an anhydrous basis of 23 oxygens | | | | | | | | | | | |
| Si | 6.65 | 6.68 | 6.68 | 7.07 | 7.10 | 7.07 | 7.35 | 7.36 | 7.39 | 7.57 | 7.55 | 7.49 |
| $Al^{iv}$. | 1.35 | 1.32 | 1.32 | 0.94 | 0.90 | 0.93 | 0.65 | 0.64 | 0.61 | 0.43 | 0.45 | 0.51 |
| T-site | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 |
| $Al^{vi}$. | - | 0.02 | - | 0.02 | 0.04 | 0.04 | 0.10 | 0.15 | 0.16 | 0.27 | 0.27 | 0.21 |
| Ti | 0.14 | 0.14 | 0.16 | 0.07 | 0.08 | 0.07 | 0.06 | 0.06 | 0.05 | 0.06 | 0.06 | 0.07 |
| $Fe_3$+. | 0.90 | 0.77 | 0.81 | 0.68 | 0.59 | 0.51 | 0.65 | 0.40 | 0.49 | 0.41 | 0.34 | 0.43 |
| Mg | 2.84 | 2.87 | 2.90 | 2.55 | 2.52 | 2.53 | 2.41 | 2.36 | 2.34 | 2.20 | 2.22 | 2.23 |
| $Fe_2$+. | 1.12 | 1.19 | 1.08 | 1.58 | 1.70 | 1.78 | 1.72 | 1.96 | 1.88 | 1.98 | 2.05 | 1.99 |
| Mn | - | - | 0.06 | 0.10 | 0.08 | 0.08 | 0.06 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 |
| M1, M2, M3 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| Ca | 1.78 | 1.82 | 1.80 | 1.78 | 1.79 | 1.86 | 1.59 | 1.71 | 1.65 | 1.63 | 1.56 | 1.59 |
| Na | 0.22 | 0.18 | 0.20 | 0.22 | 0.21 | 0.24 | 0.41 | 0.29 | 0.35 | 0.37 | 0.43 | 0.41 |
| M4-site | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| Na | 0.28 | 0.32 | 0.29 | 0.21 | 0.24 | 0.18 | 0.02 | 0.10 | 0.06 | - | - | - |
| K | 0.08 | 0.08 | 0.10 | 0.10 | 0.10 | 0.10 | 0.26 | 0.17 | 0.05 | 0.17 | 0.18 | 0.18 |
| Sum | 15.36 | 15.40 | 15.38 | 15.31 | 15.34 | 15.37 | 15.19 | 15.27 | 15.21 | 15.08 | 15.17 | 15.19 |
| mg | 0.71 | 0.71 | 0.73 | 0.62 | 0.60 | 0.59 | 0.58 | 0.55 | 0.55 | 0.53 | 0.52 | 0.53 |
| Fe# | 0.40 | 0.38 | 0.39 | 0.47 | 0.47 | 0.47 | 0.49 | 0.50 | O.50 | 0.52 | 0.51 | 0.52 |
| $Fe^3$+/Fe | 0.45 | 0.39 | 0.43 | 0.30 | 0.26 | 0.22 | 0.27 | 0.17 | 0.21 | 0.16 | 0.14 | 0.18 |
| $Fe^3$+/ $Fe^{3+}$+$Al^{vi}$ | 1.00 | 0.97 | 1.00 | 0.97 | 0.94 | 0.93 | 0.87 | 0.73 | 0.75 | 0.60 | 0.56 | 0.67 |

$FeO^t$=total iron as $FeO^t$, mg=Mg/(Mg+$Fe^2$+), F#=Fe/(Fe+Mg)

**Table 2:** Microprobe analyses and structural formulae of the biotites

| | | Qz-diorite | | | Tonalite | | | Granodiorite | | | Monzogranite | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| $SiO_2$ | 36.72 | 36.78 | 37.02 | 38.60 | 38.72 | 38.78 | 38.20 | 38.10 | 38.93 | 39.40 | 38.22 | 39.51 |
| $TiO_2$ | 3.54 | 3.44 | 3.52 | 2.02 | 2.82 | 2.97 | 2.91 | 2.80 | 2.88 | 2.13 | 2.05 | 2.15 |
| $Al_2O_3$ | 13.53 | 13.72 | 13.54 | 12.52 | 12.44 | 12.32 | 14.05 | 13.89 | 13.55 | 13.80 | 13.90 | 14.65 |
| $FeO^t$ | 17.75 | 17.05 | 17.12 | 18.50 | 18.13 | 18.60 | 19.80 | 19.52 | 19.85 | 21.18 | 21.28 | 20.52 |
| MnO | 0.31 | 0.32 | 0.35 | 0.21 | 0.28 | 0.37 | 0.38 | 0.30 | 0.32 | 0.52 | 0.45 | 0.46 |
| CaO | 1.50 | 1.41 | 1.40 | 0.70 | 0.61 | 0.51 | 0.25 | 0.28 | 0.19 | 0.18 | 0.15 | 0.10 |
| MgO | 13.82 | 13.40 | 13.94 | 12.42 | 12.52 | 12.40 | 10.91 | 10.85 | 10.70 | 9.33 | 9.53 | 8.95 |
| $Na_2O$ | - | - | - | 0.60 | 0.63 | 0.68 | 0.10 | 0.12 | 0.15 | 0.21 | 0.25 | 0.28 |
| $K_2O$ | 8.20 | 9.08 | 8.25 | 9.20 | 9.32 | 9.21 | 9.20 | 9.11 | 9.32 | 8.45 | 9.25 | 9.13 |
| Sum | 95.37 | 95.19 | 95.14 | 94.87 | 95.46 | 95.83 | 95.79 | 94.97 | 95.89 | 95.22 | 95.08 | 95.75 |
| Structural formulae calculated on an anhydrous basis of 22 oxygens | | | | | | | | | | | | |
| Si (Z) | 5.56 | 5.60 | 5.60 | 5.91 | 5.88 | 5.88 | 5.80 | 5.82 | 5.90 | 6.01 | 5.89 | 5.98 |
| $Al^{iv}$. (Z) | 2.44 | 2.415 | 2.40 | 2.10 | 2.12 | 2.13 | 2.20 | 2.18 | 2.10 | 1.99 | 2.115 | 2.02 |
| $Al^{vi}$. (Y) | - | 0.05 | 0.02 | 0.16 | 0.10 | 0.17 | 0.31 | 0.33 | 0.32 | 0.49 | 0.41 | 0.60 |
| Ti (Y) | 0.40 | 0.39 | 0.40 | 0.32 | 0.32 | 0.34 | 0.33 | 0.32 | 0.33 | 0.24 | 0.24 | 0.25 |
| Fet (Y) | 2.25 | 2.17 | 2.17 | 2.37 | 2.30 | 2.36 | 2.51 | 2.50 | 2.51 | 2.70 | 2.74 | 2.60 |
| Mn (Y) | 0.04 | 0.04 | 0.05 | 0.04 | 0.04 | 0.05 | 0.05 | 0.04 | 0.04 | 0.07 | 0.06 | 0.06 |
| Mg (Y) | 3.12 | 2.04 | 2.14 | 2.83 | 2.83 | 2.80 | 2.47 | 2.47 | 2.42 | 2.12 | 2.19 | 2.02 |
| Ca (X) | 0.24 | 0.23 | 0.23 | 0.12 | 0.10 | 0.08 | 0.04 | 0.05 | 0.03 | 0.03 | 0.03 | 0.02 |
| Na (X) | - | - | - | 0.18 | 0.19 | 0.20 | 0.03 | 0.04 | 0.04 | 0.06 | 0.08 | 0.08 |
| K (X) | 1.58 | 1.76 | 1.59 | 1.80 | 1.81 | 1.78 | 1.78 | 1.78 | 1.80 | 1.64 | 1.82 | 1.76 |
| Sum | 15.70 | 15.67 | 15.59 | 15.82 | 15.68 | 15.76 | 15.52 | 15.52 | 15.49 | 15.36 | 15.47 | 15.39 |
| Fe# | 0.42 | 0.42 | 0.41 | 0.45 | 0.45 | 0.46 | 0.50 | 0.50 | 0.51 | 0.56 | 0.56 | 0.56 |

Fe#= Fe/(Fe+Mg)

**Table 3:** Trace elements analyses of the amphiboles

| | Qz-diorite | | Tonalite | | Granodiorite | | Monzogranite | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 4 | 6 | 7 | 9 | 10 | 12 |
| Sc | 282.0 | 235.0 | 200.0 | 99.0 | 52.0 | 49.7 | 27.0 | 29.0 |
| Cr | 620.0 | 640.0 | 505.0 | 450.0 | 245.0 | 239.0 | 118.0 | 105.0 |
| Co | 143.0 | 150.0 | 68.0 | 61.0 | 52.0 | 48.5 | 43.0 | 29.0 |
| Zn | 302.0 | 310.0 | 210.0 | 200.0 | 50.0 | 38.0 | 30.0 | 22.0 |
| Rb | 10.0 | 6.0 | 15.0 | 18.0 | 22.0 | 27.0 | 24.0 | 29.0 |
| Hf | 2.1 | 2.3 | 7.3 | 6.7 | 10.5 | 11.8 | 12.9 | 13.7 |
| Ta | 1.9 | 1.8 | 2.2 | 2.4 | 2.5 | 2.9 | 3.3 | 3.5 |
| Th | - | - | 1.1 | 1.2 | 2.6 | 2.5 | 7.7 | 7.5 |
| U | 0.5 | 0.5 | 0.9 | 0.7 | 2.3 | 2.4 | 4.2 | 5.2 |
| Nb | 10.0 | 8.0 | 18.0 | 20.0 | 21.0 | 23.0 | 22.0 | 30.0 |
| Y | 33.0 | 30.0 | 32.0 | 38.0 | 30.0 | 35.0 | 37.0 | 40.0 |
| Zr | 112.0 | 102.0 | 140.0 | 147.0 | 148.0 | 154.0 | 170.0 | 165.0 |
| La | 23.1 | 24.0 | 62.0 | 53.0 | 128.0 | 144.0 | 230.0 | 243.0 |
| Ce | 42.0 | 44.0 | 110.0 | 135.0 | 320.0 | 370.0 | 600.0 | 677.0 |
| Nd | 26.0 | 30.0 | 55.0 | 51.0 | 223.0 | 335.0 | 400.0 | 430.0 |
| Sm | 6.3 | 6.9 | 16.8 | 17.3 | 64.0 | 69.0 | 83.0 | 87.0 |
| Eu | 1.2 | 1.3 | 2.2 | 2.3 | 5.7 | 6.4 | 0.6 | 0.6 |
| Tb | 0.8 | 0.9 | 2.3 | 2.4 | 7.1 | 8.5 | 14.5 | 15.1 |
| Yb | 3.1 | 3.2 | 6.1 | 6.5 | 12.2 | 14.8 | 33.3 | 36.7 |
| Lu | 0.5 | 0.5 | 1.5 | 1.6 | 2.9 | 3.3 | 7.3 | 8.2 |
| ΣREE | 103.8 | 110.8 | 255.9 | 269.1 | 924.9 | 951.0 | 1375.5 | 1508.6 |

**Table 4:** Trace elements analyses of the biotites

| | Qz-diorite | | Tonalite | | Granodiorite | | Monzogranite | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 4 | 6 | 7 | 9 | 10 | 12 |
| Sc | 117.0 | 110.0 | 93.0 | 85.0 | 37.2 | 40.0 | 28.0 | 30.0 |
| Cr | 201.0 | 205.0 | 150.0 | 143.0 | 45.0 | 43.0 | 40.0 | 38.0 |
| Co | 56.1 | 57.4 | 49.8 | 46.0 | 17.5 | 16.7 | 16.1 | 14.8 |
| Zn | 750.0 | 702.0 | 680.0 | 613.0 | 550.0 | 532.0 | 370.0 | 290.0 |
| Rb | 122.0 | 130.0 | 340.0 | 335.0 | 337.0 | 370.0 | 550.0 | 363.0 |
| Cs | 8.9 | 9.5 | 16.0 | 19.0 | 14.0 | 19.0 | 32.0 | 30.0 |
| Hf | 9.3 | 10.5 | 15.8 | 17.3 | 17.1 | 22.7 | 38.2 | 30.9 |
| Ta | 1.2 | 1.3 | 3.1 | 2.9 | 11.5 | 15.0 | 43.0 | 45.0 |
| Th | 1.5 | 1.7 | 6.5 | 7.3 | 94.0 | 103.0 | 205.0 | 218.0 |
| U | 1.5 | 1.5 | 3.5 | 2.4 | 20.0 | 33.0 | 64.0 | 73.0 |
| Nb | 9.0 | 9.4 | 11.0 | 11.5 | 12.0 | 13.0 | 14.0 | 13.0 |
| Y | 20.0 | 18.0 | 22.0 | 24.0 | 25.0 | 29.0 | 30.0 | 27.0 |
| Zr | 76.0 | 73.0 | 102.0 | 112.0 | 148.0 | 140.0 | 170.0 | 173.0 |
| La | 12.7 | 10.1 | 20.0 | 22.3 | 50.0 | 63.0 | 80.0 | 87.0 |
| Ce | 37.0 | 30.0 | 50.0 | 66.0 | 110.0 | 132.0 | 148.0 | 159.0 |
| Nd | 23.0 | 20.0 | 40.0 | 44.0 | 63.0 | 67.0 | 38.0 | 97.0 |
| Sm | 5.8 | 5.6 | 9.1 | 10.2 | 18.1 | 20.3 | 29.0 | 34.0 |
| Eu | 1.7 | 1.6 | 2.0 | 2.2 | 2.6 | 2.8 | 3.6 | 3.9 |
| Tb | 1.4 | 1.6 | 2.1 | 2.3 | 2.5 | 2.8 | 2.9 | 3.3 |
| Yb | 2.9 | 2.8 | 3.4 | 3.3 | 7.0 | 9.0 | 12.0 | 16.0 |
| Lu | 0.5 | 0.4 | 0.6 | 0.7 | 1.0 | 1.1 | 1.7 | 2.3 |
| ΣREE | 85.0 | 72.1 | 127.2 | 151.4 | 254.2 | 298.0 | 365.2 | 402.5 |

## Textural Features

The studied amphiboles and biotites were concentrated mainly in all the investigated granitoids.

### Amphibole

In the QD and TON rock types, sieved textured, large patchy amphibole grains (3-6.5 mm across) are the most common; generally they make up 6.5 to 13.5% of the rock mode and 42 to 55% of the mafic minerals. They are strongly pleochroic with X=yellow, Y=brown and Z=dark brown. Hydrothermal fluids partly affected the amphibole. The alteration of amphibole into chlorite and epidote caused the liberation of iron oxide scattered in the amphibole (Fig. 2a).

In the GD, amphiboles occur as greenish brown, subhedral pleochroic crystals (about 3.3% of the rock mode and 33% of the mafic minerals). They are occasionally twinned and enclose biotite, zircon and quartz granules. Frequently, the amphibole is associated with biotite and iron oxides. Quartz is poikilitically enclosed in amphibole crystals.

Green amphibole crystals in the MGR forms are very scarce (2.5% of the rock mode and 23% of the mafic minerals) anhedral, large grains (2.5-5 mm across). Their pleochroic formula is of X=pale green, Y= green and Z=dark green. Amphibole is oftenly interleaved by biotite and partially altered to chlorite. The alteration of amphiboles is increased from QD to MGR. Amphibole occurs in two distinct textural forms:

i) as large poikilitic crystals (Fig. 2b) enclosing some other mineral phases including iron oxides, apatite and quartz, which are present in all varieties

ii) as subparallel crystals arranged with long axes (Fig 2c), which is recorded in the TON

iii) as glomeroporphyritic texture formed by hornblende crystal aggregates (Fig. 2f), which is observed in QD and TON

### Biotite

Biotite is the main mafic mineral (44—77%) in the granitoid varieties of the area. The average modal biotite contents are 10.5, 8.7, 6.6 and 5.4% in the studied samples of QD, TON, GD and MGR, respectively. It occurs as large irregular-shaped flakes or shreds up to 1.4 mm long. The biotites are pleochroic except those in some monzogranites, where the mineral is partially chloritized (Fig. 2d). The pleochroism is yellow to brown in the basic varieties and pale green to dark green in the felsic varieties of the granitoid complex. Biotite occurs in four distinct textural relationships:

i) as large poikilitic crystals (Fig. 2e) enclosing some other mineral phases including apatite and zircon, which are observed in all varieties;

ii) as glomeroporphyritic textures formed by hornblende and biotite crystal aggregates (Fig. 2f), which is observed in QD and TON

iii) as interstitial crystals with other mineral phases such as amphibole, titanite and iron oxides, which are present in the QD

iv) as small crystals enclosed within the K-feldspar and quartz, in the MGR

## Geochemistry

### i) Major elements

### Amphibole

The chemical data of the major elements of amphibole from QD, TON, GD and MGR of Wadi Akhdar-Wadi El-Sheikh complex with the structural formulae calculated on the basis of 23 oxygens are given in Table 1. The major element analyses of the studied amphiboles exhibit high contents of silica in the range of 45.98-51.65% and low $TiO_2$ and $Al_2O_3$ contents, (0.45 to 1.45%) and (4.05 to 7.80%) respectively.

The studied amphiboles are classified according to the content of $(Na+K)_A$, Ti, $Fe^{3+}$ , $Al^{vi}$ of Leake (1978) as calcic amphibole. They are magnesio-hornblende in QD and TON, actinolitic hornblende in GD and actinolite in MGR rock types (Fig. 3).

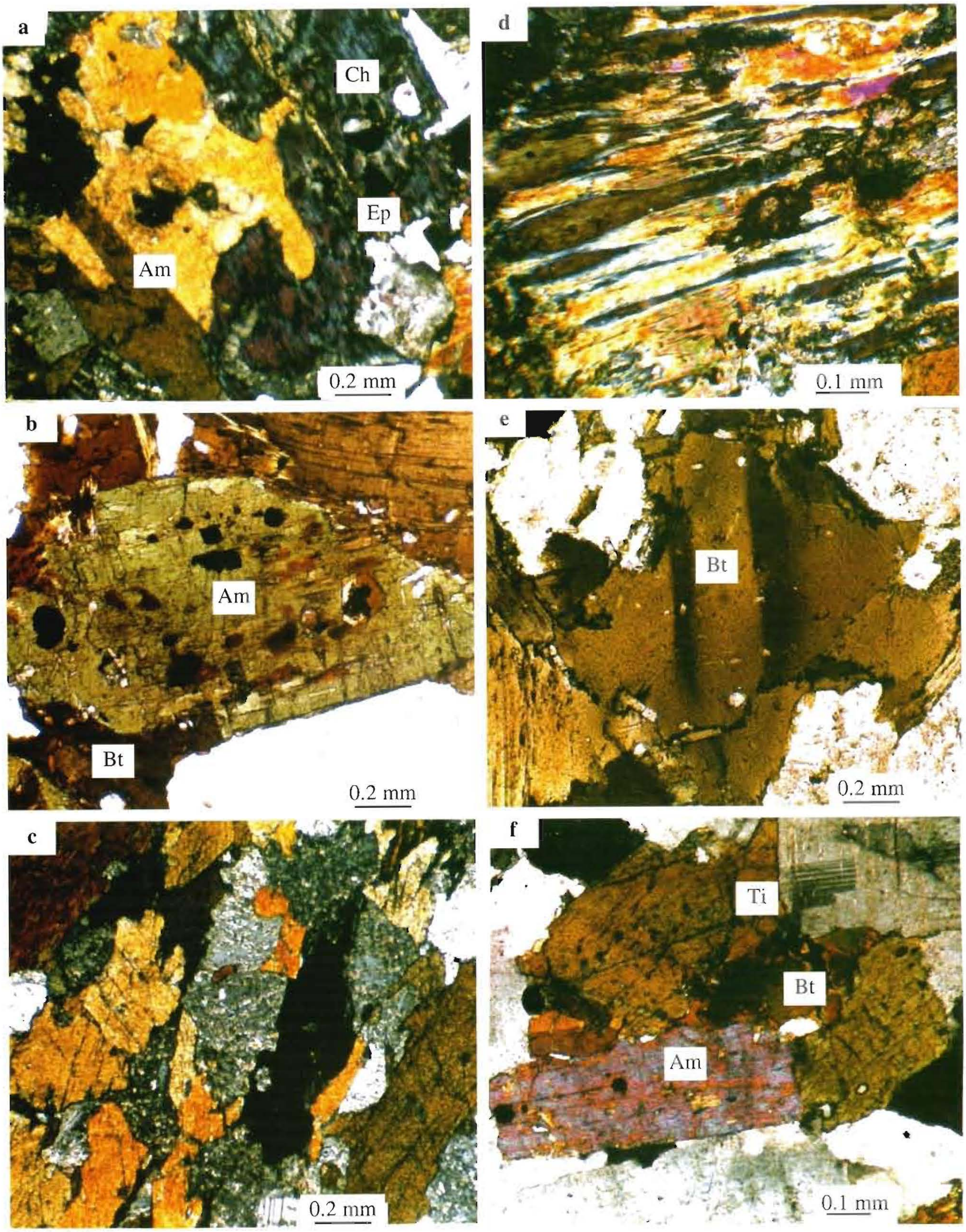



**Fig 2:** Photomicrographs showing the textural features. (a) Large twinned crystal of amphibole (Am) partially altered to chlorite (Ch), epidote (Ep) and iron oxides, (b) Poikilitic ampbibole (Am) enclosing minute apatite, quartz and iron oxides and partially replaced by biotite (Bt), (c) Subparallel of amphibole crystals arranged with long axes, (d) Interleaved chlorite (Ch) replacing biotite (Bt), (e) Kink-banded biotite plate enclosing minute crystals of apatite and zircon, (f) Glomeroporphyritic aggregate of amphibole (Am) and biotite (Bt) enclosing titanite (Ti), apatite and quartz.

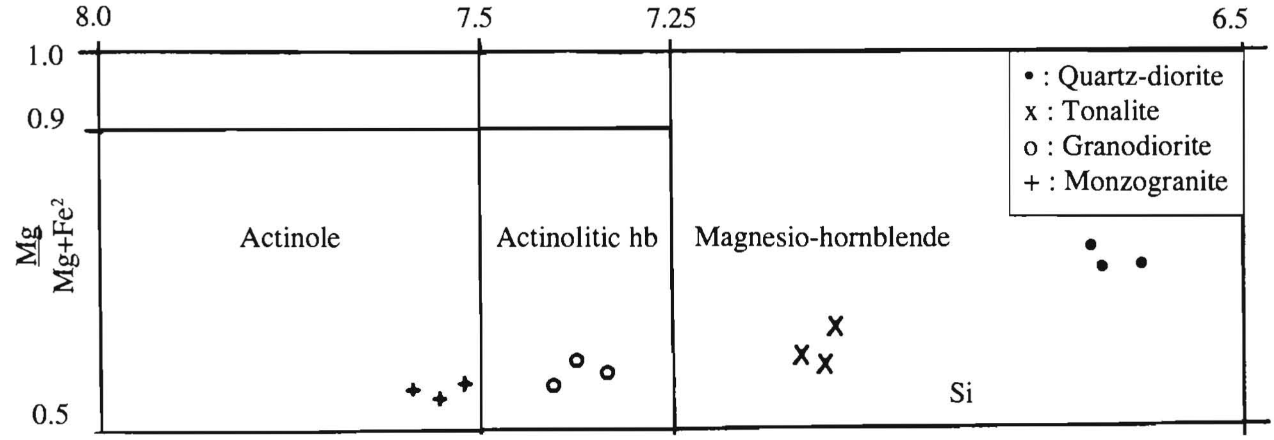



**Fig. 3:** Classification of the amphiboles from Wadi El-Akdar granitoids (after Leake, 1978): $(Na=k)_A > 0.5$, $Ti < 0.5$, $Fe^{3+} < Al^{vi}$

Papike *et al.* (1969) suggested that Na substitution for Ca in the $(M_4)$ site is coupled with Na substitution for vacancy in the (A) structural site. A plot of Na $(M_4)$ versus Ca $(M_4)$ reveals this idea of Na substitution for Ca in the analyzed ampbiboles, which decreases from QD to MGR (Fig. 4a). The relation between $Fe^{2+}$ and $Fe^{3+}$ (Fig. 4b) indicates that amphiboles gradually decrease in ferric iron contents from QD to MGR. This feature is supported by the gradual decrease of the $Fe^{3+}/(Fe^{3+}+Fe^{2+})$ and $Fe^{3+}/(Fe^{3+}+Al^{vi})$ ratios from QD through TON and GD to MGR (see, Table 1), respectively.

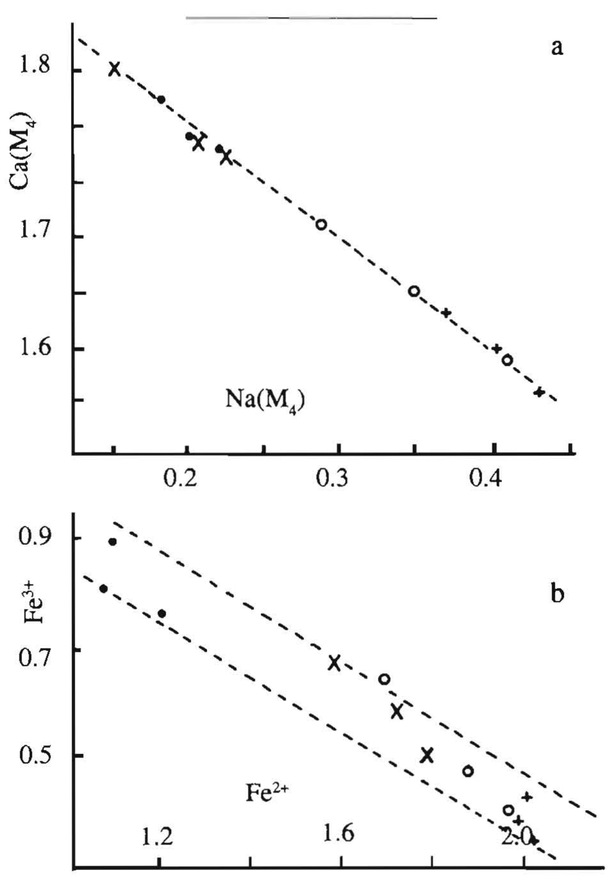



**Fig. 4:** The Ca $(M_4)$ vs. Na $(M_4)$ (a) and $Fe^{3+}$ vs. $Fe^{2+}$ (b) diagrams for the studied amphiboles. symbols as in Fig. 2.

**Biotite**

The chemical composition of biotite and the corresponding structural formulae calculated on the basis of 22 oxygens is given in Table 2. The chemical data of biotites in the granitoid varieties exhibit a wide compositional range. The biotites of the GD and MGR rocks are enriched in $SiO_2$, $FeO^t$ and $K_2O$ and depleted in CaO, MgO and $TiO_2$ contents compared with those of the QD and TON, suggesting a higher degree of fractionation.

The relationships of Si against $Al^{vi}$ and $Al^{iv}$ is plotted in Fig. 5. In general $Al^{vi}$ of biotite exhibits a positive correlation with Si, while, $Al^{iv}$ shows a negative one. The dominant mechanism for Al-enrichment in biotites is through the Al-Tschermak substitution: $(R^{2+})^{vi} + Si^{iv} = Al^{vi} + Al^{iv}$ , (Labotka, 1983).

The chemical data are plotted in the Mg - $Al^{vi}$ + $Fe^{3+}$ + $Ti^{4+}$ - $Fe^{2+}$+ Mn Foster triangle diagram of Schulz-Kuhnt *et al.* (1990) (Fig. 6). On this diagram, the studied biotites range between 45 and 64 mol-% phlogopite. The biotites of the investigated QD, TON and GD correspond to the Fe-rich meroxene, while those from MGR belong to Fe-poor lepidomelanes.

In the $Fe^{2+}$-$Fe^{3+}$-Mg diagram of Wones and Eugster (1965), biotite composition of the studied granitoid rocks lies on the phlogopite-annite join and between the nickel-nickel oxide (NNO) and Hematite-Magnetite (HM) buffer curves (Fig. 7) in granitic rocks. Biotites in the studied rocks appear to have oxygen fugacities slightly higher than those of the NNO buffer.

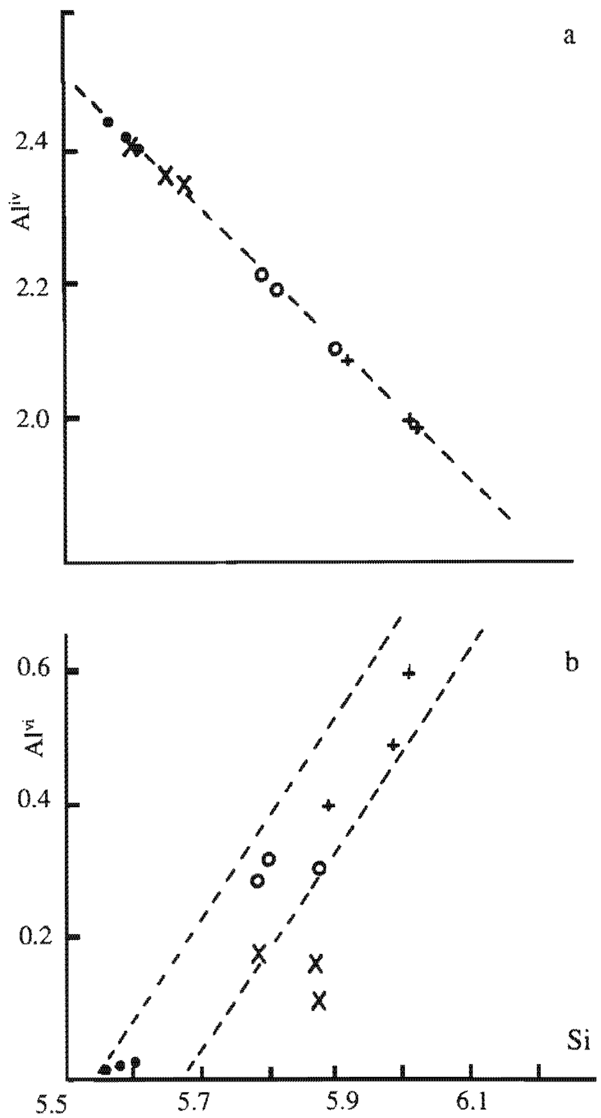



**Fig. 5.**: $Al^{iv}$ (a) and $Al^{vi}$ (b) vs. Si for the studies amphiboles

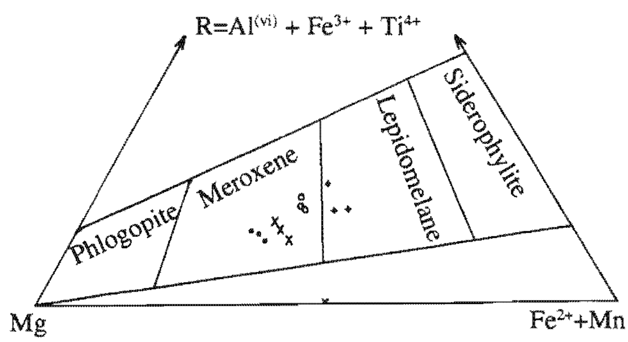
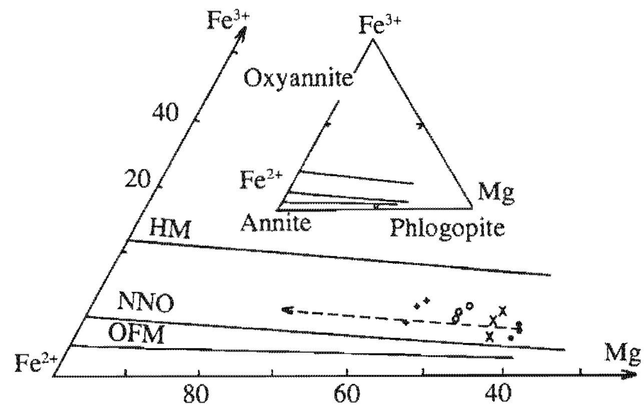



**Fig. 6.**: Composition of biotites from Wadi El-Akhdar granitoid suites plotted into Foster triangle (after Schulz-Kuhnt *et al*, 1990)




• : Quartz-diorite x : Tonalite
o : Granodiorite + : Monzogranite

**Fig. 7.**: Plot of biotite compositions in $Fe^{2+}$ -$Fe^{3+}$ - Mg triangle (after Wones and Eugster, 1965). Dashed line represents the evolution trend of biotites from calc-alkaline granites (Dodge *et al.*, 1969)

**ii) Trace elements**

The trace element contents in the studied amphiboles and biotites are given in Tables 3 and 4. The third transitional elements (such as, Sc, Cr, Co and Zn) are rather concentrated in both amphibole and biotite from QD compared to those from MGR. On the other hand, some of LILE (i.e., Rb) and HFSE (i.e., Hf, Ta, U, Nb, Y and Zr) are much concentrated in amphibole and biotite of the MGR relative to those from the QD, which suggests a higher degree of fractionation from early (magnesio-hornblende) to late (actinolite) amphiboles and from Fe-rich meroxene to Fe-poor lepidomelane biotites of the investigated granitoid complex.

The values of the ratio Fe# [Fe/(Fe+Mg)], (see, Tables 1 and 2), are plotted against some trace elements of the studied amphiboles and biotite in the various granitoid varieties (Fig. 8 and 9). Concentration of the third transitional elements in the amphiboles and biotites decrease regularly towards the felsic end members (GD and MGR) while LILE and HSFE and total REE increase in the same direction. These are in accordance with the assumed differentiation trend from the QD to MGR suite of Wadi Akhdar-Wadi El-Sheikh complex.

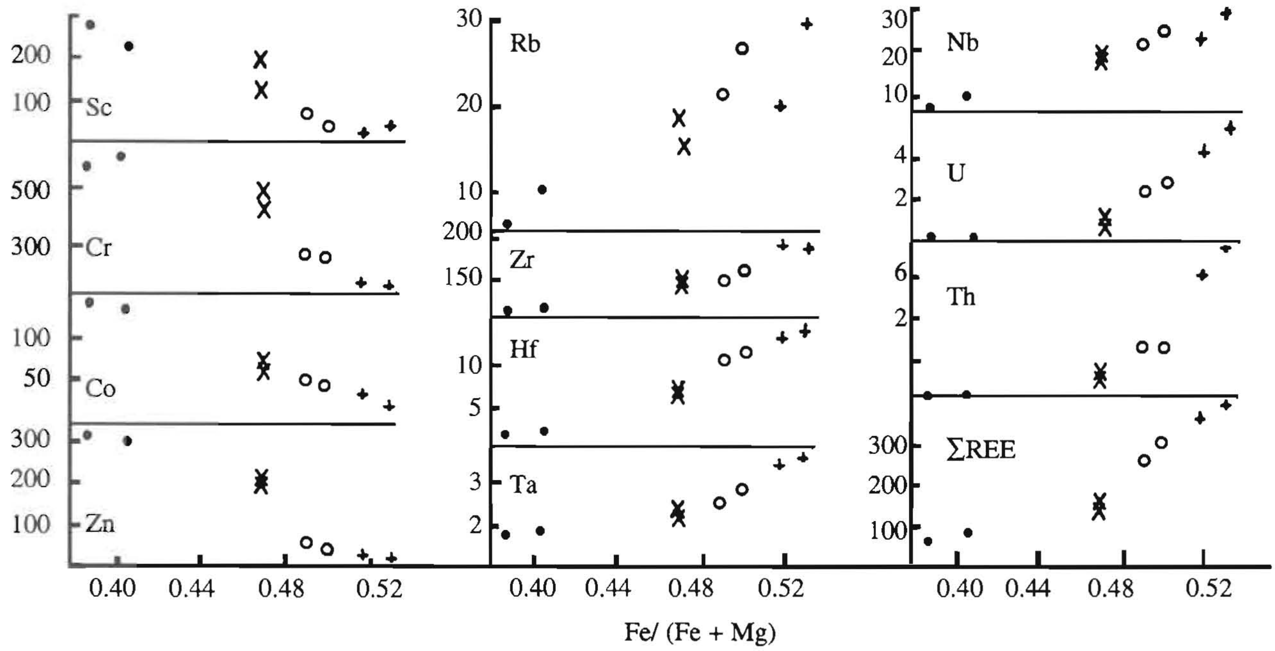



**Fig. 8.**: Plot of the contents of the trace elements vs. Fe/(Fe (Fe=Mg) ratios in the studied amphiboles.

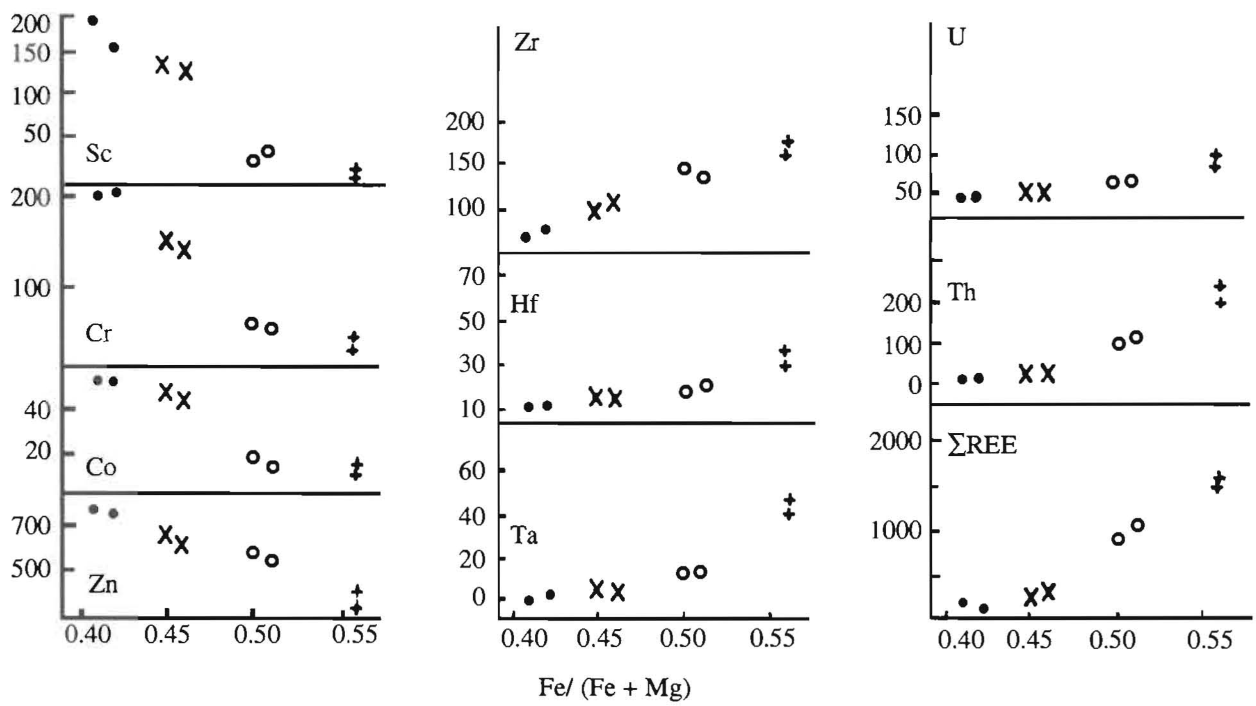



**Fig. 9.**: Plot of the contents of the trace elements vs. Fe/(Fe(Fe=Mg) ratios in the studied amphiboles.

Some interelemental relations in the studied amphibole and biotite are reported in Tables 3 and 4. There is positive correlation between Nb-Ta, Zr-Hf and Nb-Y in the analyzed amphibole and biotite. There is higher Cr and Co in amphiboles than in biotites, whereas Rb, Hf, Ta, Th, U and Zr occur in biotites rather than in amphiboles which indicate higher fractionation of the biotites. In QD, Cr and Co are more enriched, while Rb, Hf and U are more depleted in amphiboles than in biotites. The biotite of the felsic end member is more enriched in Rb, Hf, Ta, Th, U and Zr and more depleted in Sc and Co compared with the amphibole of the same rock. It indicates fractionation from a Mg-rich to Mg-poor biotite.

**iii) Rare earth elements**

REE data for some representative amphiboles and biotites are listed in Tables 3 and 4, and the chondrite-normalized patterns (after Fourcade and Allegre, 1981) are illustrated in Fig. 10. As a whole, the REE patterns of the analyzed minerals from QD, TON, GD and MGR display rather uniform shapes and are broadly similar [$(La_n/Yb_n)$ = 4.34-3.93 for amphibole and 2.30-3.51 for biotite]. However, from QD to MGR there is a significant increase of the total REE contents (from 103.8 to 1508.6 ppm in amphibole and from 85 to 402.5 ppm in biotite) and negative Eu anomaly (Eu/Eu* varies from 0.70 down to 0.33 in amphibole and from 0.34 up to 0.51 in biotite, on average). These features are probably due to the fractional crystallization of either the analyzed minerals, the REE-rich accessory mineral inclusions (such as apatite and allanite in amphibole or apatite, titanite and zircon in biotite) which could not be removed, or both.

The REE patterns (Fig. 10) of the present minerals are charcterized by the relative higher abundance in light REE ($La_n/Sm_n$: 1.61-2.05 for amphibole, 1.15-1.53 for biotite, on average) with a slight heavy REE depletion ($Tb_n/Lu_n$ : 1.16-1.29 for amphibole, 2.30-1.06 for biotite, on average) probably suggesting their crystal fractionation. These differences within the amphiboles and biotites of the granitoid rocks can be readily explained as representing one melt with successive different stages of crystallization.

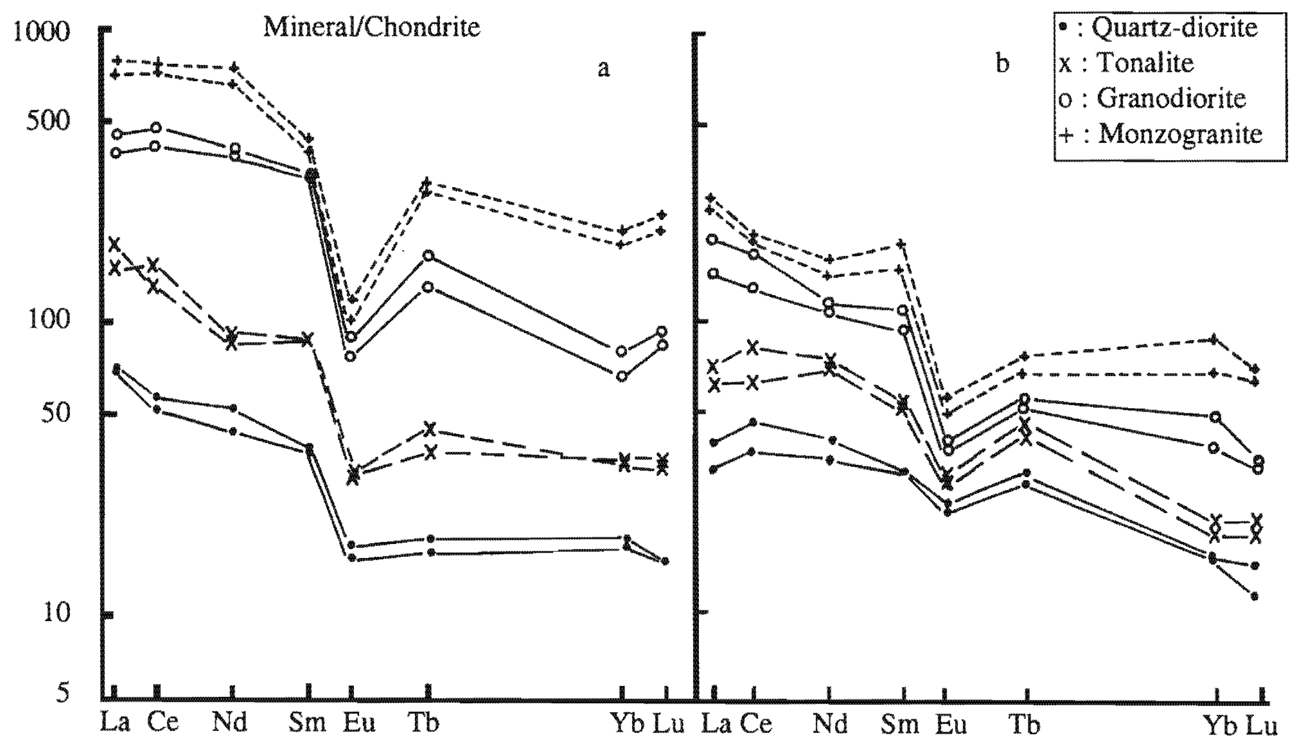



**Fig. 10:** ∑REE-normalized patterns for the studied amphiboles (a) and biotites (b) from Wadi El-Akhadar granitoid suites. (normalizing values after Courcade and Allegre, 1981)

## Discussion

The data presented here allow some interpretations to be made concerning: a) the evolutionary trend of the amphiboles and biotites, b) condition of crystallization, c) implications for magma type and d) significance of mineral trace elements.

### a) Evolutionary Trend

The (Ca+Al) versus (Si+Na+K) diagram (Fig. 11) demonstrates that amphiboles of the QD and TON exhibit higher values of Ca and Al. The evolution of these amphiboles was mainly controlled by the Fe<=>Mg and Ca+Al<=>Na+Si substitution schemes.

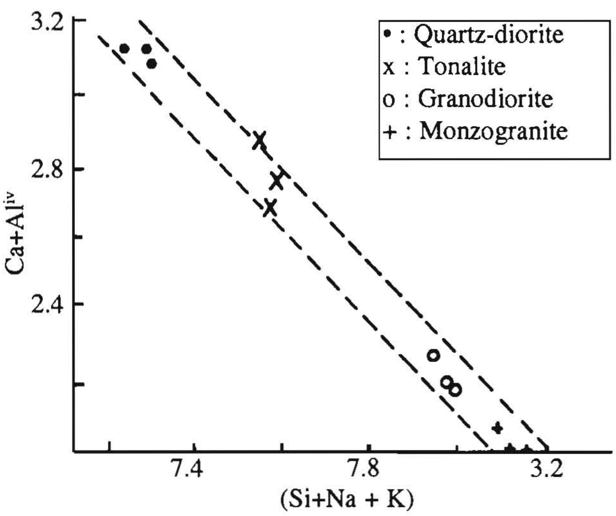



**Fig. 11:** The ($Ca+Al^{iv}$) vs (Si+Na+k) diagram for the studied amphiboles.

Based on thermodynamic calculations, Ague (1989) indicates that at magmatic conditions, the Fe-Mg exchange between amphibole and biotite is probably an insignificant function of crystallization temperature. However, theoretical predictions and natural mafic phase compositions show that the Fe-Mg distribution is dependent upon amphibole composition. Particularly, a decrease in amphibole total Al and A-site occupancy leads to an increase in the mg (Mg/Mg+Fe) of the amphibole (0.60, on average) relative to the mg of coexisting biotite (0.46, on average, Table 1 and 2). The Fe# of both minerals imply a positive correlation (Fig. 12), suggesting again a progressive fractionation form mafic to felsic end members of the present granitoid rocks.

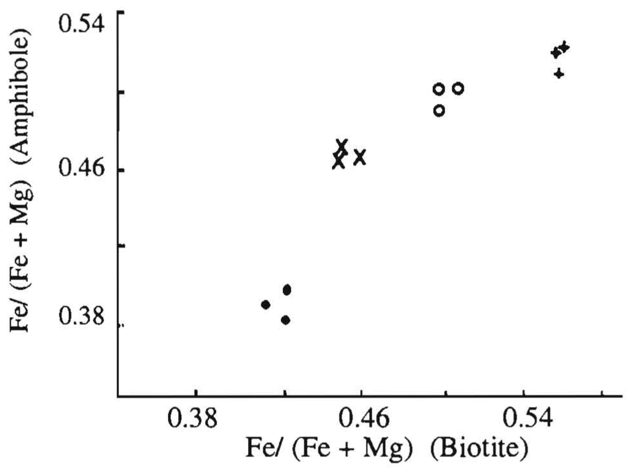



**Fig. 12:** Plot of thr Fe/(Fe+Mg) ratios in the studied amphiboles and biotites.

### b) Crystallization conditions

#### i) Amphibole

By imposing Leake's (1971) proposed limit of Si <7.5 and Ca >1.6 for "igneous" hornblende, the analyzed amphiboles are of magmatic origin (Table 1). As the amphiboles of MGR are Al-poor, their growth probably occurred at late crystallization stages of the calc alkaline magma (Czamanske *et al.* 1981).

Decreasing Al and Ti contents in amphiboles correspond to successively higher intrusive levels, and decrease of crystallization temperature and pressure (Percival and Card, 1983). The amphiboles of the QD exhibit higher Al (1.34) and Ti contents (0.15) compared to those of the MGR (0.71) & (0.06), suggesting greater depth and higher temperature and pressure for the more mafic end member relative to the felsic one.

The $Al^t$ content of hornblende in the calc alkaline plutonic rocks has been suggested as an indicator of pressure (Hammarstrom and Zen, 1986, Blundy and Holand, 1990). $Al^{iv}$ versus $Al^t$ (Fig.13) reveals that the analyzed amphiboles fall in the field of Finnmarka (Oslo) and Pliny (New Hampshire) granitoid complexes. These complexes have an amphibole + biotite + plagioclase + K-feldspar + Quartz assemblage, $SiO_2$: 50-72%, amphibole with $Al^t$: 0.65-1.93 and $Al^{iv}$: 0.02-0.42. Their estimated pressure and temperature range from <1—3Kb and 540-740°C (Czamanske *et al.* 1977 and Czamanaske and Wones, 1973). Abdel Aal (1994) suggested a 585-655°C for the crystallization temperature of magnesio- and actinolitic hornblende from biotite-hornblende granodiorite, Abu Bedun area, north Eastern Desert, Egypt.

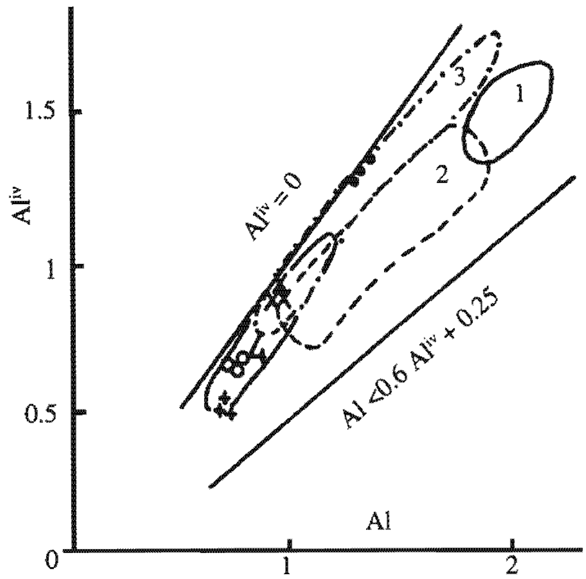



**Fig. 13:** Plot of Aliv vs. Al for the studied amphiboles (after Hammarstrom and Zen, 1986). Fields show the estimated pressure of amphiboles from 1 = Hardwick pluton (~ 6kb), 2 = Inner zone pluton, Japan (1-5kb), 3 = Pliny pluton (2-3kb), 4 = Finnmarka pluton (<1kb).

Hammarstrom and Zen (1986) sharply criticized the hornblende barometer, suggesting that the empirical correlations between Al in igneous hornblende and pressure may instead reflect variations in calc alkaline granitoid solidus pressure and temperature. Applying this model, the calculated pressure gives about 3, 1 and <1Kb for amphiboles from the QD, TON, GD and MGR, which are consistent with the data of Finnmarka and Pliny plutons (Hammarstrom and Zen, op. cit).

Experimental studies applied to the phase equilibria of some calcic amphiboles are available. For example, Naney (1983) has studied the stability of hornblende and other ferromagnesian minerals from synthetic granodiorite composition as a function of temperature and water content at 2 and 8 kbar. On the phase diagram, hornblende ranged in temperature from 750-860°C, restricted to compositions containing at least 4 wt.% $H_2O$, at a confining pressure of 2 kbar.

From the foregoing, it can be concluded that the amphibole crystallization of the studied granitoids occurred at <1 to 3Kb pressure. and from 650 to 850°C temperature.

**ii) Biotite**

A better evaluation of the crystallization temperature can be made from the Fe# ratio of biotite using the calibrated curves of Wones and Eugster (1965) (Fig. 14). It is evident that the 100 Fe# ratio of the studied biotite ranges between 41 and 56, which corresponds to crysallization temperature approximately between 600—800°C. Therefore, the crystallization temperature of biotites from QD (Fe-rich meroxene) is higher than the MGR (Fe-poor lepidomelane).

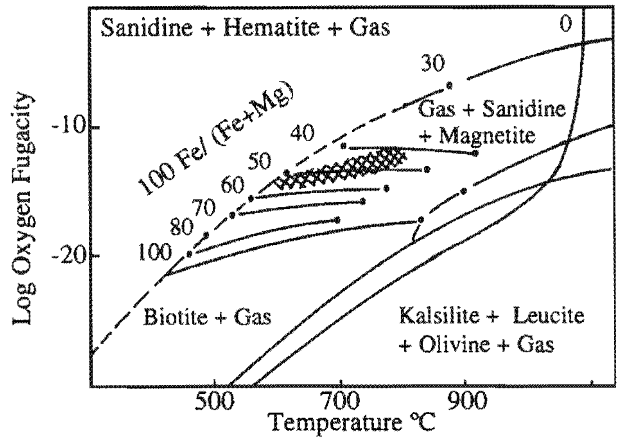



**Fig. 14:** Biotite stability diagram of specific Fe/(Fe+Mg) values as a function of oxygen fugacity (after Wones and Eugester, 1965). Heavily shaded area represents the studied biotites.

**c) Implications for Magma Type**

On the Al$^{iv}$-Al diagram (see, Fig. 13), the amphiboles of the investigated granitoid copmlex are similar to those from the calc-alkaline granitoid rocks of Pliny and Finnmarka complexes (Hammarstrom and Zen, 1986).

On the $Fe^{2+}$-$Fe^{3+}$-Mg diagram (see Fig 7), biotite composition of the studied rocks follows the trend of biotitesof the calc-alkaline granitoids of central Sierra Nevada batholith. (Dodge *et al.* 1969).

The $FeO^t$ -$Al_2O_3$ and MgO-$Al_2O_3$ diagrams (Fig. 15) discriminate among biotites from various magmatic rock groups (Abdel-Rahman, 1994, 1996). On both diagrams, the analyzed biotites fall in the field of biotites of orogenic calc-alkaline (mostly I-type) suites. The calc-alkaline magma is commonly associated with subduction zones, of intermediate to felsic compositions, and typically are I-type melts, with or without a mantle component. These results are consistent with those given by Soliman *et al.* (1988) for the whole rock chemistry of the present granitoid complex.

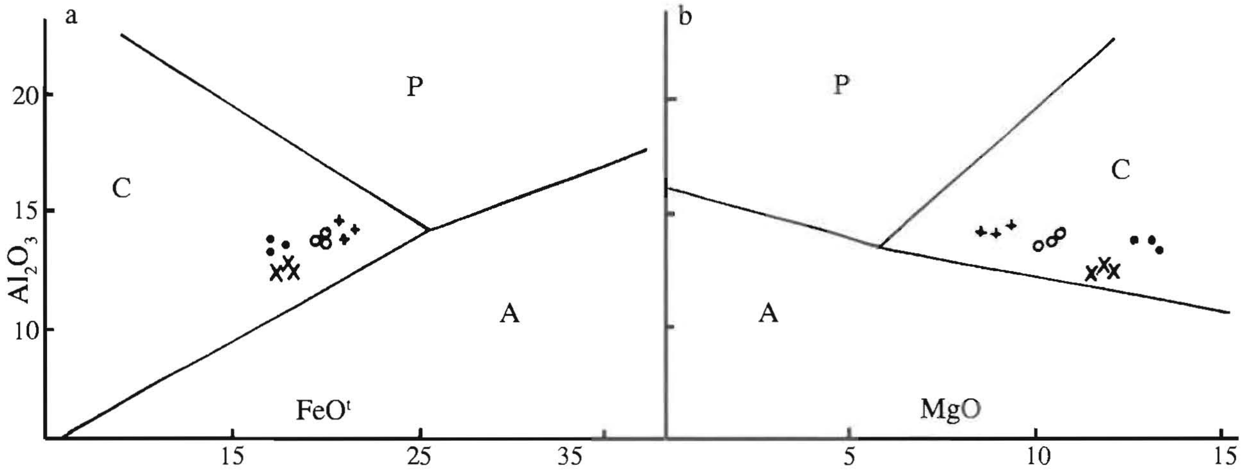



**Fig. 15:** The $Al_2O_3$ vs. $FeO^t$ (a) and MgO (b) diagrams for the studied biotites (after Abdel-Rahman, 1994, 1996). Fields show biotites from A = anorogenic alkaline suites, P = peraluminous suites and C = calc-alkaline suites.

**d) Significance of Mineral Trace Elements**

A good parallelism and a progressive enrichment of the amphibole and biotite REE from QD to MGR are probably a result of successive magmatic differentiation and emplacement at different levels in the crust. This is consistent with the data given by Fourcade and Allegre (1981) on Querigut calc-alkaline granitoids, France. The REE patterns (see Fig. 9), particularly the Eu/Eu* anomalies, reflect variations in the degree of plagioclase fractionation associating the present amphibole and biotite, while the light REE are controlled by the occurrence of minute light REE-rich inclusions, presumably apatite, titanite and/or allanite in the amphibole and biotite. Towell *et al.* (1965) found that the most important sites for the REE in granitic rocks appeared to be amphibole and biotite, respectively. Eu depletion in amphibole and biotite of the investigated granitoid rocks, is correlated with increase of the Fe/(Fe+Mg) ratio (Tables 1—4), probably reflecting crystallization in a closed system (Shimizu *et al.* 1978).

The increase in REE abundance (see Fig. 10), together with a decrease of Sc, Cr, Co and Zn (Fig. 8 and 9) in the analyzed amphibole and biotite suggest that crystal fractionation has taken place within the host granitoids. The regular increasing Zr, Hf, Ta, U and Th concentrations in the mafic rocks from QD to MGR reinforces this hypothesis.

The particularly lower REE concentration in the analyzed biotites relative to amphiboles is probably attributed to: a) the precipitation of biotite from a melt with REE contents much lower than those of amphibole, b) the early precipitation of apatite and/or allanite prior to the crystallizing of the bulk biotite, or c) the slower rate and lower crystallization temperature of biotite relative to amphibole, which affect the exclusion of REE (Gromet and Silver, 1983).

The earlier stage of crystallization produced QD and TON which are marked by the accumulation of plagioclase and amphibole and rare biotite, causing a depletion in the REE abundance and a slight negative Eu anomaly in amphibole and biotite. The later stage, moreover, produced the GD and MGR which have abundant REE and a more pronounced negative Eu anomaly in the amphibole and biotite, reflecting an early separation of plagioclase, amphibole and accessory minerals causing the relative light REE enrichment. Thus, the crystallization of plagioclase could counterbalance in some degree the effect of amphibole and biotite fractionation as the plagioclase is a dominant phase in granitic rocks (Fourcade and Allegre, 1981).

## Conclusions

The textural and chemical features of the amphiboles and biotites from Wadi Akhdar-Wadi El-Sheikh granitoid varieties reveal a progressive crystal fractionation from relaively more mafic rocks, such as QD and TON to the more evolved felsic ones, such as GD and MGR. This is due to:

i) The increase of Si, Fe and K and the decrease of Ti, Ca and Mg contents relative to Fe# ratios in the amphiboles and biotites (Tables 1 and 2).

ii) The change in amphibole composition from magnesio-hornblende in QD and TON to actinolitic hornblende in GD and actionlite in MGR.

iii) The increase of Na-substitution for Ca in $M_4$ site in amphiboles.

iv) The change in the biotite composition from Fe-rich meroxene in QD, TON and GD to Fe-poor lepidomelane in MGR.

v) The decrease of the 3rd transitional elements (Sc, Cr, Co and Zn) and the increase of LILE (Rb) and HFSE (Hf, Ta, U, Nb, Y and Zr) relative to the Fe# ratios in amphiboles and biotites.

vi) The good parallelism of the REE patterns with successive enrichment (increase) of the total REE contents and the intensity of the negative Eu anomalies in amphiboles and biotites.

The lower concentrations of the major and trace elements in biotites relative to those of amphiboles are due to: a) the precipitation of biotite from a melt depleted in these elements, b) the early precipitation of apatite and allanite prior the crystallizing of the bulk biotite and/or c) the slower rate and lower temperature and pressure of biotite crystallization relative to the amphibole.

Regarding the Al and Ti contents of the calc-alkaline granitic rocks, the amphibole of the more mafic rocks could be formed at greater depth and at high temperature and pressure than those from the more evolved felsic ones. Based on the estimated calibration data given by Wones and Eugster (1965), Czamanske *et al.* (1977), Czamanaske and Wones (1973), Naney (1983), Hammarstrom and Zen (1986), the proposed conditions of crystallization range from <1—3Kb and 650-850°C for the amphiboles and lower pressure and 600-800°C for the biotites.

The present study shows that the amphiboles and biotites from the granitoid complex of Wadi Akhdar-Wadi El-Sheikh are similar to those from the calc-alkaline granitoids of other areas of the world, such as Pliny, Finnmarka and Sierra Nevada batholiths (Hammarstrom and Zen, 1986; Dodge *et al.*, 1969) and they are analogous to the those from orogenic calc-alkaline (I-type) suites (Abdel-Rahman, 1994, 1996).

### Acknowledgements

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