

**PETROGENESIS OF NORTHERN MIDYAN TERRANE GRANITOIDS,
ARABIAN SHIELD: CONSTRAINTS FROM GEOCHEMISTRY, Sr-Nd
ISOTOPES, AND U-Pb ZIRCON DATING**

BY

WAFI AL-HAKIMI

A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

GEOLOGY

JUNE 2024

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by Wafa Abdulaaser AL-Hakimi under the direction of her thesis advisor and approved by her thesis committee, has been presented and accepted by the Dean of Graduate Studies in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN GEOLOGY**.



Dr. Scott Whattam
(Advisor)



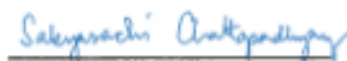
Dr. John Humphrey
Department Chairman



Dr. Israa S. Abu-Mahfouz
(Member)



Prof. Suliman Saleh Al-Homidan
Dean of Graduate Studies



Dr. Sabyasachi Chattopadhyay
(Member)

June 2024



© Wafa Abdulnaser AL-Hakimi

2024

Dedication

To my family |

ACKNOWLEDGMENTS

I sincerely thank the Almighty, the Most Gracious and the Most Merciful, for granting me the fortitude and direction to complete my master's studies. I wish to extend my profound appreciation to King Fahd University of Petroleum and Minerals (KFUPM) and CPG for their invaluable financial backing and support, which played an indispensable role in surmounting the challenges encountered during my academic and research endeavors.

My heartfelt appreciation goes to my esteemed advisor, Dr. Scott, whose unwavering commitment to excellence in supervision, guidance, and academic mentorship has been instrumental to my journey. I am deeply grateful for his consistent support and understanding, particularly when life's complexities challenged my academic timelines. Additionally, I am indebted to my committee members for their significant contributions to my research journey. Dr. Sabyasachi's expertise and meticulous guidance, particularly in thin section preparation techniques and geochemical analysis, have been pivotal. Dr. Israa's steadfast support and dedication have been paramount to the success and integrity of my work. I also thank Mr. Faris and Mr. Mutasim for their generous mentorship and guidance.

I am immensely thankful to my cherished family for their endless support and encouragement throughout my academic pursuit. Special appreciation is extended to my sisters, Tamara and Rana, whose constant inspiration and support have played an instrumental role in shaping me into the best version of myself. I express profound gratitude to my Yemeni Family for their unwavering support and encouragement within and beyond the Kingdom.

Finally, I deeply thank the friends who have become like family at KFUPM and CPG. To all my colleagues, your presence and encouragement have been a constant source of strength and inspiration, rendering this chapter of my life truly extraordinary.

LIST OF CONTENTS

ACKNOWLEDGMENTS.....	IV
LIST OF CONTENTS	V
LIST OF TABLES.....	IX
LIST OF FIGURES.....	X
ABSTRACT	XV
ملخص الرسالة.....	XVI
1 CHAPTER 1	1
2 INTRODUCTION	1
1.1 Granitoid Rocks Overview	1
1.2 A-type Development and Characteristics.....	5
1.3 I-Type Granitoids	6
1.4 Slab Failure Granitoids.....	7
1.5 Problem Statement	9
1.6 Research Questions	10
1.7 Research Aim	11
1.8 Research Objectives	11

CHAPTER 2 LITERATURE REVIEW	12
2.1 Regional Geological and Tectonic Settings	12
2.2 Background of Study Area	19
2.5 Previous Work	21
CHAPTER 3 METHODOLOGY	25
3.1 Field Characteristics	25
3.2 Petrography with the Aid of SEM and XRD-QEMSCAN	25
3.3 Analytical Methods.....	26
3.3.1 Whole Rock Geochemistry ICP-MS and ICP-AES	26
3.3.2 Whole Rock Isotopes.....	27
3.3.3 Sr and Nd Isotopes	27
3.3.4 Pb Isotope	27
3.3.5 SHRIMP U-Pb Dating.....	27
3.3.5 Data and Interpretation	28
CHAPTER 4 RESULTS	29
4.1 Petrography	29
4.2 Mineralogy and Texture with the Aid of XRD and QEMSCAN	31
4.2.1 Mineral Chemistry.....	32
4.2.2 Texture.....	40
4.3 NW Midyan Rocks Unit.....	42
4.3.1 A-type Granitoid Group	43
4.3.2 I- type Granitoid Group.....	43
4.3.3 Gabbro	44
4.4 Whole Rock Chemistry	44

4.2.1 Major Oxides	44
4.2.2 Trace Elements	51
4.2.2 Chondrite-Normalized REE and Primitive-Mantle Normalized Diagrams	53
4.3 Whole Rock Isotopes	56
4.4 U-Pb SHRIMP Zircon Dating	59
4.4.1 Concordia Plots of A-type Group	61
4.4.2 Concordia Plots I- type Group	62
4.2 Temperature estimation.....	65
CHAPTER 5	67
DISCUSSION.....	67
5.1 Tectonic Affinities.....	67
5.1.1 Whole Rocks Chemistry	67
5.2 Magmatic Source from Isotope Constraints	74
5.3 Slab Failure Granitoid	77
5.3.1 Mechanisms and Geochemical Evidence	77
5.3.2 Slab Failure Magma Sources.....	78
5.3.3 Slab Failure Model of NW Midyan Region	79
CHAPTER 6 CONCLUSIONS AND FUTURE RECOMMENDATIONS	84
6.1 Research Conclusions.....	84
6.2 Research Recommendations.....	84
REFERENCES	85
LIST OF TABLES.....	101

LIST OF ABBREVIATIONS.....	114
VITAE	115

LIST OF TABLES

Table. 1	Plutonic rocks from the Midyan region, Northwestern Saudi Arabia (after Clark 1985).	101
Table. 2	The mineral chemistry of the NW Midyan shows the different rock groups and the different ratios of major and minor minerals.	103
Table. 3	Major oxides of the NW Midya region	105
Table. 4	Trace element contents ($\mu\text{g/g}$) of NW Midyan samples	110
Table. 5	Rare earth element contents (μmg) of NW Midyan samples	111
Table. 6	Nd isotopes analyses.....	113

LIST OF FIGURES

Figure. 1	Classification of Granitoid Rocks Based on Tectonic Setting (from Ramsay, 1983).....	2
Figure. 2	A simplified geological map illustrates the locations of the granitoid rocks along the Arabian Shield (after Robinson et al. (2014) and Genna et al. 2002)	4
Figure. 3	Simplified geological map of the Arabian–Nubian shield (modified from Fritz et al. 2013).....	13
Figure. 4	(a)Tectonic map of the Arabian Shield showing the granitoid occurrences in NW Saudi Arabia (from Robinson et al., 2014). (b)The study area of NW Midyan is defined by a rectangle. The simplified geological map of our study area showing the samples location and ages obtained in this study (after Aboud et al., 2023).....	17
Figure. 5	Simplified geological map of the NW Midyan terrane study area, showing the different granitoid complexes and the location site of sample dating.....	18
Figure. 6	Field and petrographic aspects of the NW Midyan granite. (a) Pink, coarse-grained, weathered granite. (b) White granite intersected by joints. (c, d, and e) Granite intruded by mafic dykes. (f) Felsic fresh medium-grained granite...	30
Figure. 7	Outcrop photographs (a-f) of the granitoid complexes in the NW Midyan Peninsula.	31
Figure. 8	(a, b, c, d) Photomicrographs (cross-polarized light) of A-type Biotite Monzogranite granitoid, showing felsic mineral assemblages. (d) shows coarse grain k-feldspar (perthitic texture). abbreviations Abbreviation for Alb: albite, Qz: quartz, Btt: biotite, Zr: zircon, Pth: perthite, Opq: Opaque minerals.....	34
Figure. 9	(a, d) perthite texture and sericitization alteration on the surface of the Kfs grains, (b) accessories minerals (zircon and titanite), (c) the hornblende grain altered by magnetite oxides and hosts the cassiterite assemblages’ grains, surrounded by felsic quartz and k-feldspar, (d) cross-hatch twining on the microcline. Abbreviation for Kfs: k-feldspar Mc: microcline, Qz: quartz, Ttn: titanite, Hb: hornblende, Cas: cassiterite, Zr: zircon, Opq: Opaque minerals.....	50

- Figure. 10** (a, d) porphyritic texture, showing Mega Qtz with a fine groundmass of micro Qtz, k-feldspar, and hornblende. (b) coarse-grained quartz and k-feldspar intersected by k-feldspar veins, (c) plagioclase heavily altered by the sericite and parallel twinning. Abbreviation for Kfs: K-feldspar, Plg: plagioclase, Qz: quartz, Cpx: clinopyroxene,35
- Figure. 11** (a, b, c) intergranular texture(subophitic) of hornblende and plagioclase, (c) cassiterite mineral within altered hornblende with iron oxides minerals. Abbreviation for Hb: hornblende, Kfs: k-feldspar, Cs: cassiterite, Plg: plagioclase.....52
- Figure. 12** (a) I- type -granodiorite showing biotite, plagioclase, and quartz. (b, c, d) biotite, pyroxene, iron oxide, with altered alkali feldspar, plagioclase with parallel twinning and quartz, (e) heavily altered plagioclase, k-feldspar by sericite and hematite are appearing the rims of quartz and plagioclase, (f) secondary biotite show alteration in the rims by chlorite. Abbreviation for Kfs: K-feldspar Plg: plagioclase, Cpx: clinopyroxene microcline, Qz: quartz, Btt: biotite, Hb: hornblende, Pyx: pyroxene, Hmt: hematite.....54
- Figure. 13** QEMSCAN microphotographs showing the different mineral compositions, in particular mafic and accessories minerals in the I-type granodiorite rocks (a, b, c) reveal the small sphene crystals in the light purple color, pyrite yellow color, (d) medium-grained amphibole. For the mineral color index, see Fig. 15.....39
- Figure. 15** (a, b, and c), the A-type biotite monzogranite consists of coarse to fine-grained plagioclase and quartz associated with amphibole.....42
- Figure. 16** (a) total alkalis-silica (TAS) plot of Middlemost (1994) showing the fields of all major igneous rock types (plutonic) and the subdivision of rock types into ultramafic, mafic, intermediate, and felsic. Subdivision of the sub-alkaline series from the alkali of sub alkaline series from the alkaline series is shown by a dashed line, (b) K₂O vs SiO₂ plot, showing the high, medium, and low calc-alkali series (Peccerillo and Taylor, 1976).....46

Figure. 17 (a) Distribution of granitoids types on the $10^4\text{Ga}/\text{Al}$ vs Zr plot (Whalen, 1986), and (b) Na_2O vs K_2O diagram. The line is the border of I- and S-type granites (after Chappell and White, 1974).....	47
Figure. 18 (a) diagram of alkalis versus silica illustrates the sub-alkaline nature of the NW Midyan (from Irvine and Baragar, 1971), (b)Modified alkali lime index ($\text{Na}_2\text{O}+\text{K}_2\text{O}-\text{CaO}$) vs. SiO_2 (%) of the A-type and I- type granitoid group, (from Frost et al. 2011).	47
Figure. 19 Selected Harker diagrams for the NW Midyan terrane. (a to f), showing a clear negative correlation with SiO_2	49
Figure. 20 Selected Harker diagrams for the NW Midyan (a) show a negative trend with increasing silica content, and (b) linear correlation Na_2O vs. silica.	50
Figure. 21 (a) A/CNK (molar $\text{Al}_2\text{O}_3/(\text{CaO} + (\text{Na}_2\text{O} + \text{K}_2\text{O}))$ vs. A/NK ($\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O})$) diagram (Shand, 1943), showing major-element compositional variation, and metaluminous nature for the A and I-type samples, (b) Aluminum saturation index (ASI) versus SiO_2 plot portraying the A and I-type composition for NW Midyan region.	51
Figure. 22 Harker plots of selected trace element concentrations of the NW Midyan region.	53
Figure. 23 (a, b) Chondrite-normalized REE patterns of the A-type granite, and (c, d) I-type granite (chondritic abundances from Sun and McDonough, 1989), the shaded area compared with (Robison et al.,2017).	55
Figure. 24 primitive mantle (PM)-normalized plots of NW Midyan intrusive (after McDonough and Sun, 1995).	56
Figure. 25 Sr, Pb isotope correlations of A- and I-type granitoid rocks from the NW Midyan region.	58
Figure. 26 Cathodoluminescence (CL) images of selected zircon crystals from the various rock types. Circles indicate the location of the analysed spots.	60
Figure. 27 Cathodoluminescence (CL) images of selected zircon crystals from the various rock types. Circles indicate the location of the analyzed spots.....	61
Figure. 28 Concordia plots of dated A-type samples TB-(55b, 11b, and 20) and I-type samples TB (29, 51a, and 39b).....	64

Figure. 29	Concordia plots of dated I-type TB-4b and TB-5b samples.	65
Figure. 30	Zircon saturation temperature of Midyan terrane A- and I-type granitoids of this NW Midyan region (from Watson & Harrison, 1983).	66
Figure. 31	a) $\text{FeO}t/(\text{FeO}+\text{MgO})$ versus SiO_2 diagram after Frost et al. (2001) showing the distribution of the A – and I-type granitic rocks with respect to the ferroan and magnesian fields (e, f) Nb/Ta versus Y/Nb, Y/Nb versus Ce/Nb diagrams and Y/Nb versus Y/Nb, Y/Nb versus Ce/Nb diagrams and Y/Nb versus Rb/Nb for the NW Midyan region A-type granites (Eby, 1992). OIB = oceanic island basalt; IAB = island arc basalt.	70
Figure. 32	Rb versus (Y + Nb), Y vs Nb, Yb vs Ta, and Yb+Ta versus Rb plots of Pearce et al. (1984) and Pearce (1996). Abbreviations: WPG – within-plate granitoid, ORG – ocean-ridge granitoid, VAG – volcanic arc granitoid, COLG – collisional granitoid.....	72
Figure. 33	(a) Rb/Zr vs SiO_2 discrimination diagram (Harris et al. 1986), (b) Geochemical discrimination diagrams of R1/R2(after Batchelor and Bowden 1985) for the NW Midyan granites. $\text{R2} = 6\text{Ca}+2\text{Mg}+\text{Al}$; $\text{R1} = 4\text{Si}-11(\text{Na}+\text{K})-2(\text{Fe}+\text{Ti})$.73	73
Figure. 34	(a) Nd model age Samples of the NW Midyan occupy the post-orogenic interval between ~598 to 645 Ma reflecting the juvenile nature (b) Plot of epsilon Nd versus crystallization age Plot for all data of the Proterozoic rocks of the ANS from this and previous studies. The reference line for the chondritic uniform reservoir (CHUR) and the depleted mantle evolution curves of DM DePaolo (1981) and DM Goldstein et al. (1984), CED = central eastern desert, WED=West eastern desert(from) Ali et al. (2009) (c) our samples of the post-collisional magmas compared with the older terranes of the Arabian Shield (from Robinson et al. 2014)	76
Figure. 35	granitoid rock discrimination plots modified to better discriminate between I-type arc, slab failure, and A1- and A2-type granitoid compositions. Tectonomagmatic discrimination diagrams (Hildebrand and Whalen, 2017; Whalen and Hildebrand, 2019) for our study area	81

Figure. 36 Cartoon diagram illustrating slab failure mechanism in the NW Midyan, Arabian Shield (after Whattam et al.,2024; Johnson and Kattan, 2012; Bastos et al., 2024)83

]

ABSTRACT

Full Name :Wafa Abdulnaser AL-Hakimi

Thesis Title :Petrogenesis of northern Midyan terrane granitoids, Arabian Shield:
Constraints from geochemistry, Sr-Nd isotopes, and U-Pb zircon dating

Major Field :Geology

Date of Degree :June, 2024

The Arabian-Nubian Shield (ANS), formed between 900 and 550 Ma through the accretion of Neoproterozoic juvenile crust. This began with the breakup of the supercontinent Rodinia and ended with the amalgamation of eastern and western Gondwana in the Cambrian age. The Arabian Shield (AS) representing one of the largest alkaline granitoids on Earth experienced final accretion and consolidation followed by the emplacement of within-plate alkaline plutons around 640-550 Ma. This study focuses on the granitoid complexes in the northwestern part of the Midyan terrane, providing insights into their petrogenesis. Whole rock data reveals clear distinctions between A-type and I-type granitoids, with A-types being metaluminous and enriched in Light rare earth elements (LREE), and I-types being metaluminous-peraluminous. U-Pb zircon dating indicates two distinct pulses of granitoid magmatism at around ~640 - 624 Ma for A-types and ~ 618-598 Ma for I-types. The isotopic compositions suggest a juvenile crustal source for the ANS, with some I-types potentially derived from partial melting of the pre-existing crust. Furthermore, the enriched Sr-Nd isotope compositions suggest derivation from slab failure. These were generated when the oceanic slab detached then the asthenosphere upwelling in the slab break off gap during the Ediacaran. This origin is supported by the relatively high Sm/Yb, Nb/Y, La/Yb, and Gd/Yb ratios, a signature of slab failure magmatism. Thus, we argue that the postcollisional granitoid complexes in the NW Midyan might be generated by slab failure in the subduction zone which addresses a new magmatic event in the AS besides the A and I-type arc magmas in the Arabian Shield.

ملخص الرسالة

الاسم الكامل: وفاء عبد الناصر حمود عبده الحكيمي

عنوان الرسالة: دراسة أصل تكوين الصخور الجرانيتية في الجزء الشمالي الغربي من إقليم مدين، الدرع العربي: من منظور جيوكيميائي، نظائر الاسترشيوم-نيدميوم وعمر الزركون

التخصص: جيولوجيا

تاريخ الدرجة العلمية: ذو القعدة 1445

يعود عمر تشكل الدرع العربي النوبي الى حقبة الطلائع الحديثة وذلك بين 900 الى 550 مليون سنة. وبدأ ذلك بعد تفكك قارة رودينيا وبعدها التصادم الحاصل بين قارة جندوانا الشرقية بالغربية في عصر الكامبري. ومن هذا المنطلق فان الدرع العربي يمثل أحد أكبر التشكيلات الجرانيتية الصخرية القلوية. هذه الدراسة استهدفت الصخور الجرانيتية في الجزء الشمالي الغربي من إقليم مدين وذلك لفهم أصل وتكون هذه الصخور. أوضحت الدراسة وجود تنوع صخاري جرانيتي واضح يتراوح ما بين صخور جرانيتيه من النوع A والنوع I. حيث تظهر هذه الصخور تركيز نسبة عالية من العناصر الأرضية النادرة الخفيفة وكذلك تميزها خاصية الميتالومينوس. أيضا أظهرت تحاليل اليورانيوم – رصاص عمر الزركون ان المنطقة تكونت فيها صخور الجرانيت في مرحلتين مختلفتين ما بين العمر 645 – 620 للمرحلة الأولى بينما ال عمر 618- 598 مليون سنة يعود الى المرحلة اللاحقة. وبالمقابل عكست نتائج تحاليل النظائر حدثا القشرة في الدرع العربي. بحسب ما أظهرته نتائج العناصر النادرة وطرق تمييز البيئات التكتونية ان هناك نوع جرانيت اخر. وبالتالي، فإننا نرى أن المجمعات الجرانيتية بعد الاصطدام في شمال غرب مدين قد تكون ناتجة عن فشل البلاطة في منطقة الاندساس التي تناولت حدثاً منصهراً جديداً إلى جانب الصحارة القوسية من النوع A و I في الدرع العربي.

CHAPTER 1

INTRODUCTION

1.1 Granitoid Rocks Overview

In orogens, granite rocks are the predominantly widespread rocks relative to other igneous rocks, comprising a total volume of approximately $3.49 \times 10^9 \text{ km}^3$ worldwide (Bonin, 2007) (Fig. 1). Orogens play an essential role in understanding the growth and reworking of continental crust, mantle differentiation, and the tectonic setting of emplacement (Brown, 2013; Gao et al., 2019). Geophysical data indicates that these rocks constitute the major components of the continental crust and occur in the upper middle and middle continental crust (Bonin, 2007; Whalen et al., 1987). The thickness of the granitic upper crust is estimated to range between 10–20 km. The upper crust is more prosperous in SiO_2 , K_2O , and light rare earth elements (LREE) and exhibits a crucial negative Eu anomaly compared to the lower part of the crust (Louis Vigneresse, 1995). Generally, granitoid magmas undergo various processes to form, involving crustal and mantle sources or integrating both, a hybrid of granitoids, as described by Jacob et al. (2021) and Moyen et al. (2017). For instance, granite formation occurs through the differentiation, crystallization, or melting, of mantle-derived basaltic material or by the partial melting of felsic, meta-igneous, or meta-sedimentary rocks, which may contain hydrous minerals, rendering them susceptible to melting, (Winter, 2014). In addition, it can occur by assimilation and magma mixing in upper-crustal plutons, lower crustal melting, assimilation, storage, and homogenization (MASH) zones, as well as contamination and metasomatism of the mantle by crust-obtained material (Brown, 2013).

Granitoids mainly occur at collisional plate boundaries (Miller et al., 2003). Whether oceanic or continental, the fate of these boundaries can be influenced by subduction and recycling within the mantle or accreted onto the overriding plate (Nandedkar et al., 2014; Vanderhaeghe, 2012). However, some authors, e.g., Moyen et al.

(2017), Miller et al. (2003), Whalen et al. (1987) and Pearce et al. (1984) subdivided granites into four subgroups based on their intrusive setting by using trace element discrimination- ocean ridge granites (ORG), volcanic arc granites (VAG), within plate granites (WPG), and collisional granites (COLG). Besides that, granitoids have several classifications based on their mineralogy, texture, and chemical composition as well as based on iron-titanium mineralogy, such as magnetite and ilmenite-series (Barbarin, 1990; Frost et al., 2001). Another approach involves an integration of minerals and aluminum saturation. These granites can be classified as peraluminous, metaluminous, or peralkaline (Harris et al., 1986).

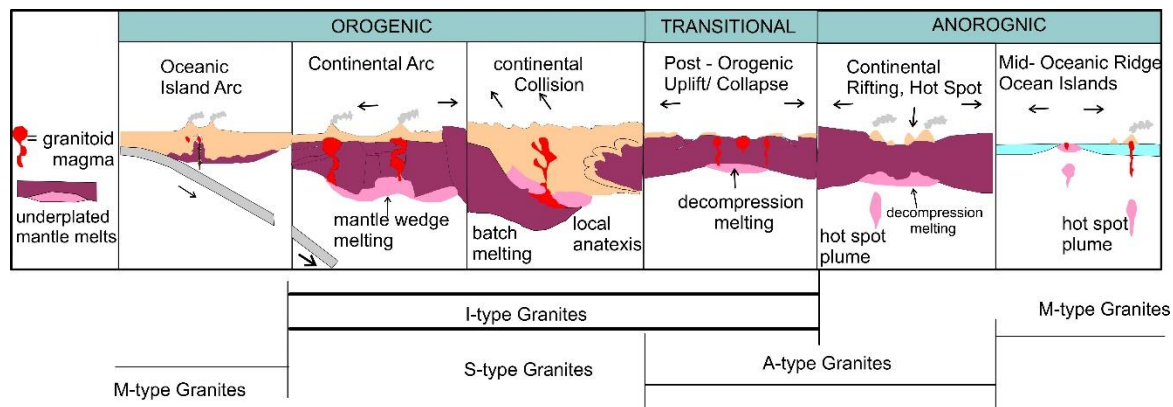


Figure. 1 Classification of Granitoid Rocks Based on Tectonic Setting (from Ramsay, 1983)

This dissertation focuses on the most common alphabet classification, particularly A- and I-types, and the recent classification of Whalen and Hildebrand (2019) into arc, and slab break-off granitic rocks. The alphabet-type classification was defined in various studies (Fig. 1), including Frost & Ronald Frost. (2011); Stoeser & Frost (2006); Frost et al. (2001); Eby (1992); Whalen et al. (1987); Collins et al. (1982). For example, based on the magmatic sources, such as I (igneous or intracrustal source) and S (melting or partial melting of metasedimentary or supracrustal protoliths)- M (mantle-like granites)-type, and A (alkaline anhydrous granite, and/or anorogenic such as cratons or rift zones), which has subdivisions of A1 and A2. In the Arabian Shield, Neoproterozoic granitoids show a diversity in their geochemical, tectonic, and origin characteristics. These rocks comprise about 63% of the plutonic occurrences, including three groups: 1) granite-

granodiorite group (760-660 Ma), 2) monzogranite and syenogranite (660-610 Ma), and 3) alkali feldspar granite (610-565 Ma) (Aleinikoff & Stoesser, 1988; Stoesser, 1986). Furthermore, the A-types are considered the largest alkali granite field in the world and comprise around 7% of all intrusive rocks of the Shield. Jackson (1986) and Ramsay (1983) subdivided the Arabian alkali granites into three classes based on their mineralogy: biotite-hornblende alkali feldspar granitoid (metaluminous), aluminous, and alkali granite. These represent an excellent economic environment for various metallic mineral deposits, including gold, copper, iron, rare earth elements (REE), Nb, Th, U, and Zr (Dostal, 2023; Hinchey et al., 2024) (Fig. 2). The slab failure classification of Whalen and Hildebrand (2019) is an extension of their earlier works and entails identifying granitoid, rocks which form above an excised slab.

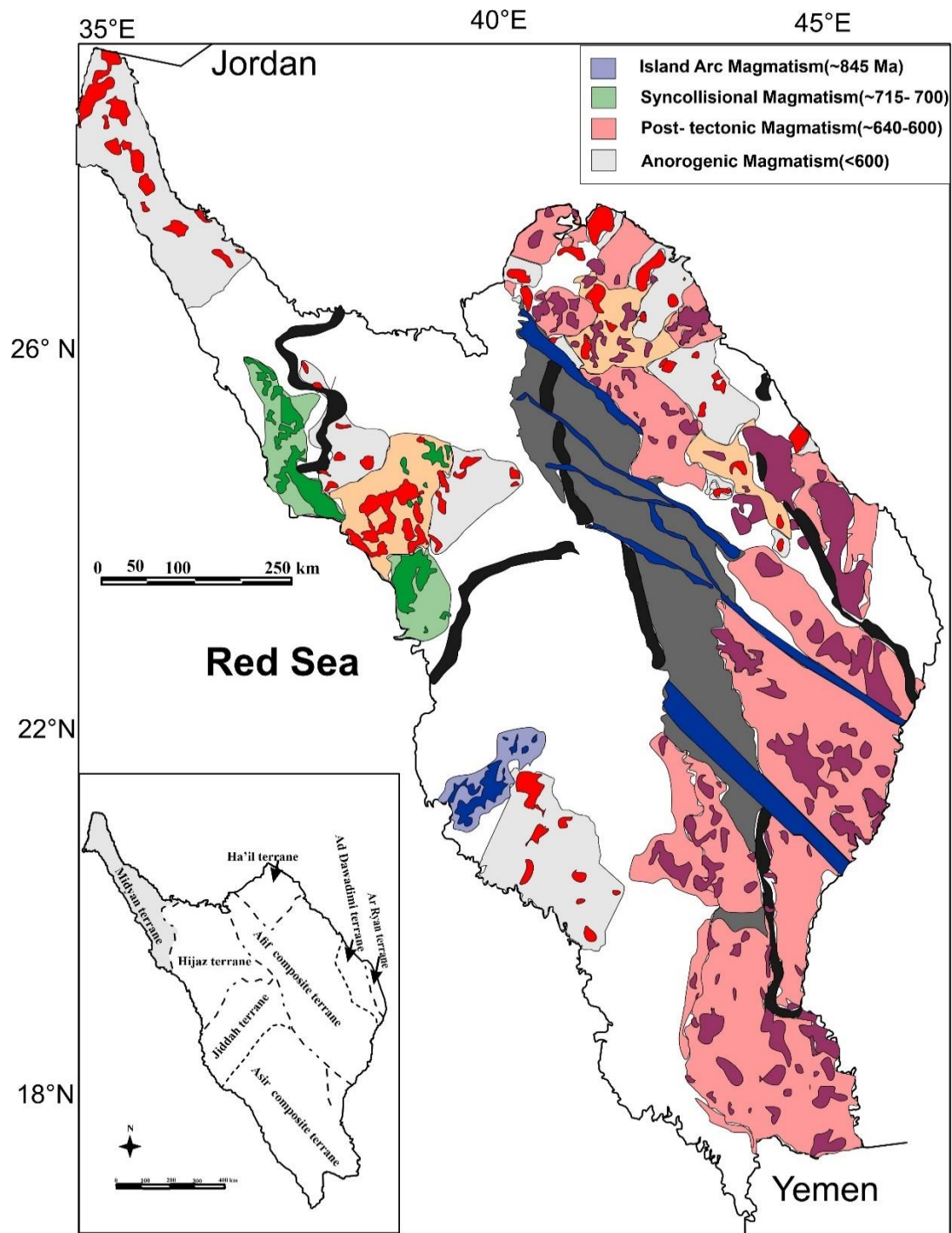


Figure. 2 A simplified geological map illustrates the locations of the granitoid rocks along the Arabian Shield (after Robinson et al. (2014) and Genna et al. 2002)

1.2 A-type Development and Characteristics

A-type magmatic rocks are commonly discovered in multi-tectonic environments ranging from plate boundaries to within the plate (Brown, 2013; Grebennikov, 2014), (Fig. 1). They commonly occur in the lower depth of the lower crust and form ring complexes, especially at the subvolcanic level (Bonin, 2007; Robinson, 2014). This rock type has garnered significant interest from researchers due to its role as an indicator of magmatic processes, formation conditions, and tectonic environment. Moreover, their association with crucial deposits and rare earth elements further emphasizes their importance. The term A-type was first introduced within the last fifty years and stands for many concepts. The concept was first formulated by Loiselle and Wones (1979) to differentiate significant amounts of alkali metals ($\text{Na}_2\text{O}+\text{K}_2\text{O}$), $\text{FeO}^*/\text{FeO}^*+\text{MgO}$) and incompatible REE and other important trace elements (particularly, Zr, Ta, Nb, Eu, Co, Cr, Ni, Sr, Ba, Sc and Hf), and high Hf/ H₂O but low CaO, H₂O, O₂ and Al₂O₃. This concept was appended over time by Chappell & White, (1992) and Chappell & White (2001), who developed a scheme and suggested that all granitoids formed by partial melting of the crust. Collins et al. (1982) and Collins et al. (2020) proposed that A-type granitoids could be identified based on their high Ga/Al ratios. Pearce et al. (1984) developed a scheme for the tectonic discriminant diagram of A-type granitoids, revealing that this type is equivalent to within-plate granites and post-collisional setting granites. The categorizing scheme of Pearce et al. (1984) was followed by Jackson (1986), and Whalen et al. (1987), who referred to (A) as anorogenic or cratonic relative to the orogenic event while within continental and oceanic plates or near the plate boundaries. Sylvester & Sylvester (1998) distinguished a class of granites called post-collisional A-types.

Maniar & Piccoli (1979), subdivide anorogenic granites into several classes and separate them from the post-orogenic granites. Then, Eby (1992) and Eby (1990) distinguished two subgroups of A-type based on the tectonic environment. The A1 group is classified as anorogenic, indicating that it originates from magmas similar to those found in oceanic-island basalts. However, it is emplaced during intraplate rifting or as a result of plume or hotspot activity. On the other hand, the A2 group is categorized as post-orogenic, indicating that it originates from magmas derived from the partial melting of continental crust or underplated crust. This crust has typically undergone a cycle of continent-continent

collision or island-arc magmatism. Bonin et al. (1998) used this term as a chemical term, according to Jacobson et al. (1958), who related them to the alkali content and divided them into two subtypes: alkaline and alkali. However, Grebennikov (2014); Eby (1992); and Clemens et al. (1986) implied that this term refers to the anhydrous source that yields small amounts of hydrated minerals, such as mica and amphibole. Then, the aluminous terms are revealed as not alkaline in composition but contain significant meta/peraluminous types rich in REE. Frost & Frost. (2011), Frost et al. (2001), Bonin (2007), Bonin et al. (2019), and Vander Auwera et al. (2003) defined the A-type as an assemblage of rocks encompassing metaluminous to slightly peraluminous, ferroan, alkaline to alkali-calcic, and peralkaline types.

Consecutively, the alkaline peralkaline granitoids are enriched in REE, and other incompatible elements (such as Ta, Hf, Nb, Th, Zr, and U)(Stoeser & Elliott, 1983). In general, they form in rift zones within continents, where magmas from the mantle may experience minimal contamination from the crust. In the late magmatism phases of crystallization, fluid phase exsolution from the highly differentiated residual melt occurs (Khalil et al., 2018; Massari & Ruberti, 2013).

1.3 I-Type Granitoids

I-type granitoids contribute to understanding the geological evolution, composition, and earth origin. The 'I', infra-crustal term refers to the metagneous protolith source (Chappell & White, 2001; Whalen et al., 1987). Several studies indicate that I-types form by melting high-grade metamorphic rocks characterized by granitic or mafic composition. The presence of mafic to intermediate igneous enclaves (Clemens et al., 2011), suggests this type is produced by processes such as fractional crystallization and partial melting with magma mixing and mingling, which plays a crucial role in their genesis. Mineralogically, I-types contain amphibole and pyroxene, in contrast to the muscovite and biotite commonly found in S-type granites. To distinguish between I-type and other granitoid types, Chappell & White (2001) showed the behavior of the major elements like P_2O_5 versus SiO_2 as I-type P_2O_5 decreases with increasing SiO_2 (Fig. 19). This negative correlation was interpreted as a result of the different portions of separation between restite-containing apatite crystals and metagneous rocks-derived melt. Sami et al. (2023), Bonin

et al. (2019), and Chappell & White (2001) proposed that the high molar ratio, $1 < ASI < 1.15$, defines the compositional boundary of different magma types. Nevertheless, Clemens et al. (2011) and Roberts & Clemens (1993) observed that I-type granitoid change gradationally from metaluminous ($A/CNK < 1.0$) to peraluminous ($A/CNK > 1.0$) with rising SiO_2 . Collins et al. (1982), used zircon as an indicator to identify two subtypes of I-type: the high-temperature I-type lacking inherited zircon and the low-temperature I-type enriched in inherited zircon, which reflected a metasedimentary source. Further clarified by Sisson et al. (2005) and Roberts & Clemens (1993), the magma has high calc-alkaline to high K, calc-alkaline, aluminous, and meta/peraluminous composition and is derived from partial melting of hydrous sources only.

Clemens et al. (2011) and Sylvester & Sylvester (1998) demonstrated that peraluminous I-type granite forms resulting in the partial melting of the continental crust. The I-type isotope composition is characterized by a high concentration of incompatible elements and heavy REE (HREE). According to Chappell & White (2001) these types have been derived from the lower part of the crust by partial melting and combined with a dominant mantle source. Moreover, Gan et al. (2022), Nandedkar et al. (2014), and Sisson et al. (2005) support the idea that generated partial melting of intermediate and mafic rocks in the lower deep crust can also result from fractionation of basic melt derived from the mantle and magma mixing of crust and mantle. Chapters two and four present more discussion and explanation about the age and geochemical composition of the granitoids types in the NW Midyan terrane.

1.4 Slab Failure Granitoids

The slab failure concept involves processes associated with the subduction zone, due to the collision of tectonic plates (Hildebrand & Bowring, 1999) and Von Blanckenburg & Davies, 1995). Slab failure specifically means the breaking or tearing of the subducting slab. Several studies have explained the magmatic manifestation of slab failure (Atherton & Ghani, 2002; Billen, 2008; Hildebrand & Bowring, 1999). This may result in changes in mineral composition or mechanical stresses, buoyancy of the continental crust, hydrous fluids, and melting (Billen, 2008). These lead to different geodynamic processes such as earthquakes, evaluation of continental and oceanic crust, rapid uplift, and volcanic

activities. However, several models were designed to investigate the conditions under which slab failure forms. Bird (1978) introduced the idea of slab breakoff and suggested rupture of the subducting slab from the descending lithosphere under different mechanical forces. This was followed by the classic work of Von Blanckenburg & Davies (1995), who evaluated a model for slab failure to explain syn-collisional magmatism and tectonic evolution of the Alps. Van der Voo (1999) identified the subducted slabs in Pakistan and Nepal driven by convergent tectonic activity between the Asian and plate the Indian plate. DeCelles et al. (2002) referred to the slab failure of the Tibetan Plateau by modifying a model of the crustal underthrusting model for Himalayan-Tibetan orogenesis, incorporating surface geological data, mantle tomographic, and broadband seismic studies. Atherton & Ghani (2002) provide a comprehensive model for the genesis of calc-alkaline granite in the metamorphic Caledonian orogenic belt by slab failure.

Freeburn et al. (2017) designed a model for the dynamic melting of slab failure to interpret the occurrence of slab failure. However, they found that slab break-off magmatism may predominantly occur in conditions where there is a very shallow break-off. When the subduction angle is steep, especially in the case of subducting old, dense oceanic plate or during deep break-off events, the asthenosphere doesn't rise but instead tends to move laterally or downward. This movement of the asthenosphere likely prevents adiabatic melting, thereby obscuring the genesis of syn to post-collisional magmatism. Garzanti et al. (2018) criticized the widespread application of the slab breakoff model. The model is created mostly based on untested assumptions and may be reinforced through circular reasoning. They emphasize the need for more rigorous testing and consideration of alternative explanations for the observed geological phenomena. Wang et al. (2018) slab failure in the context of the Neoproterozoic Igneous Suite of Malani (ISM) and the associated bimodal volcanism in the Punagarh and Sindreth basins, NW India seems to be related associated with the decompression melting of upwelling sub-slab asthenosphere through a slab window. This geological scenario provides a mechanism to explain the distinct geochemical characteristics observed in the basaltic rocks of these basins, which indicate heterogeneous mantle sources.

Whalen & Hildebrand (2019) and Hildebrand et al. (2018) developed tectonic discrimination diagrams to illustrate the difference between the formation of magmatic rocks in various tectonic settings from a slab failure setting. The creation of these rocks in the pre-collisional arc, based on geochemical signatures, is distinct from those formed in post-collisional settings influenced by slab failure. As well as Hildebrand & Whalen (2021), Whalen & Hildebrand (2019) developed a slab failure or breakoff magma model which involved the rupture of the subduction slab followed by partial melting of the metabasalts and gabbro from the oceanic crust. Slab breakoff magmatism is the least well-understood magmatic mechanism and its occurrence has not yet been constrained in the Arabian Shield. Hence, this study coupled tectonic discrimination models to understand the slab breakoff conditions so that its effect can be more clearly understood and distinguished from other processes. This is achieved by interpreting the models we create (see Chapter 5). This model is aligned with previous studies and reproduced many of the features that have been previously observed during collision and slab breakoff (Lawrence et al. (2023); Hildebrand & Whalen, 2021; Hildebrand et al., 2018, ; Duretz & Gerya, 2013; Hildebrand & Bowring, 1999), then use these models to investigate the magmatic processes in the NW Midyan terrane, Arabian Shield (Fig. 25).

1.5 Problem Statement

The largest fate of Earth's Neoproterozoic juvenile, mantle-derived continental crust is that of the ANS (Jackson, 1986). Basement assemblage rocks of the Precambrian Arabian Shield are mostly igneous intrusions, and some are associated with high metal concentrations and hold potential economic importance. Despite recognition of metalliferous igneous intrusions in Saudi Arabia, exploration of these Late Cryogenian-Ediacaran granitoid types, such as those at the northwestern Midyan Terrane, is limited. In recent times, especially following the unveiling of Vision 2030 by the Kingdom of Saudi Arabia, there has been a notable emphasis on expediting the shift towards a metals exploration and mining paradigm, particularly in the development initiatives within the northwest region, notably Line City and Neom (Vision 2030). Consequently, mineral exploration within the kingdom emerges as an imperative facet in realizing the envisioned transition toward the mining industry.

Despite the recognized significance of mining exploration in the Kingdom, a notable gap exists in the literature regarding detailed investigations into petrogenesis, mineral paragenesis, potential ore-forming processes, and the assessment of magma origins within the region. This deficiency leaves several critical questions and challenges unanswered. Of particular relevance, numerous types of granite possess the potential to serve as viable hosts for concentrations of critical metals, with the Arabian Shield standing out as a region abundant in such granitic formations. However, a comprehensive review of existing literature reveals a significant dearth of detailed studies on many of these granites within the study area. This lack of geological data has obscured insights into their geological characteristics and tectonic evolution. Consequently, there arises a pressing need for a thorough geological investigation aimed at characterizing these intrusive formations, explaining their nature and ages, and assessing their potential economic viability.

Hence, the selection of study locations aims to enhance our understanding of the geological evolution of the ANS and the Midyan terrane in particular, delve into the magma processes underlying the formation of Arabian Shield granite, and establish the chronological timeline of granitoid complexes. Notably, this research significantly augments existing knowledge by introducing novel isotope data and applying the U-Pb sensitive high-resolution ion micro-probe (SHRIMP) method to identify ages. Furthermore, it sheds light on the previously unrecognized significance of slab failure magmatism within the study area.

1.6 Research Questions

By combining our newly acquired data with previously published results, our investigation aims to tackle the following significant questions:

1. What is the exact age of the Midyan terrane (Ifal, Midyan, Muwaylih, Laws) complexes?
2. How do these Ediacaran granites match the broader tectonic history of the Arabian Shield, and what are the indications for regional geology and tectonics?
3. What is the source of NW Midyan terrane granitoid magma, and what tectonic signature is responsible for producing the NW Midyan granitoids?

1.7 Research Aim

This research aims to describe the tectonic evolution of the northern Midyan terrane and determine the granitoid age.

1.8 Research Objectives

To accomplish the stated research, aim in section 1.6, we have adopted the following research objectives as follow:

1. To investigate the petrographic, chemical, and isotopic nature of granitoids that occur in the most northeastern Midyan Terrane.
2. To define the ages of granite emplacement, and evaluate the magmatic sources.
3. To comprehend the geological and tectonic setting of the Midyan Region complexes.

CHAPTER 2

LITERATURE REVIEW

2.1 Regional Geological and Tectonic Settings

The crystalline basement of the Arabian Nubian Shield (ANS) is recognized as one of the sizable juvenile tracts of continental crust on Earth and comprises oceanic, oceanic island arcs, supra subduction zone ophiolites, volcano-sedimentary basins, and microcontinental suites (Stern & Johnson, 2010). It is also one of the largest mineralized blocks that formed through the amalgamation of the west and east Gondwana in the Neoproterozoic era (Fig. 3). This formation was apportioned of the complex East Africa Antarctic Orogen (EAAO) process (Abd El-Wahed & Attia, 2023; Ali et al., 2016; Johnson & Kattan, 2012; Fritz et al., 2013; Johnson et al., 2011; Stern, 2004). The EAAO can be split into four phases (Jacobs & Thomas, 2007); (1) fragmentation of the earlier supercontinent Rodinia and the formation of oceanic crust, (2) initiation of subduction and the formation of arc terranes, (3) collision of arcs and their accretion, and (4) development of strike-slip shear zones through escape tectonics. The Arabian-Nubian Shield (ANS) is exposed on both sides of the Red Sea (Fig. 3). It spans over 3500 km from north to south, and 1500 km to the west and east (Johnson & Kattan, 2012; Stern et al., 2010; Ali et al., 2010; Stern, 2004; Meert & Torsvik, 2003) and is surrounded by Phanerozoic sedimentary and volcanic rocks. The ANS encompasses several countries, including Jordan, Saudi Arabia, Egypt, Sudan, Eritrea, Ethiopia, Yemen, and Somalia. These areas share similar geological, magmatic, and tectonic events ranging in age from ~900- 550 Ma El-Desoky et al. (2024), Azer & Asimow (2021), Johnson (2006), and Johnson (2014) , and encompasses three phases: pre-collisional, characterized by altered ophiolite and intra-oceanic island arc assemblages (800-750 Ma), syn-collisional, which records subduction and continental margin magmatism (720-630 Ma), and post-collisional stages, marked by intra-crustal melting (620-580 Ma).

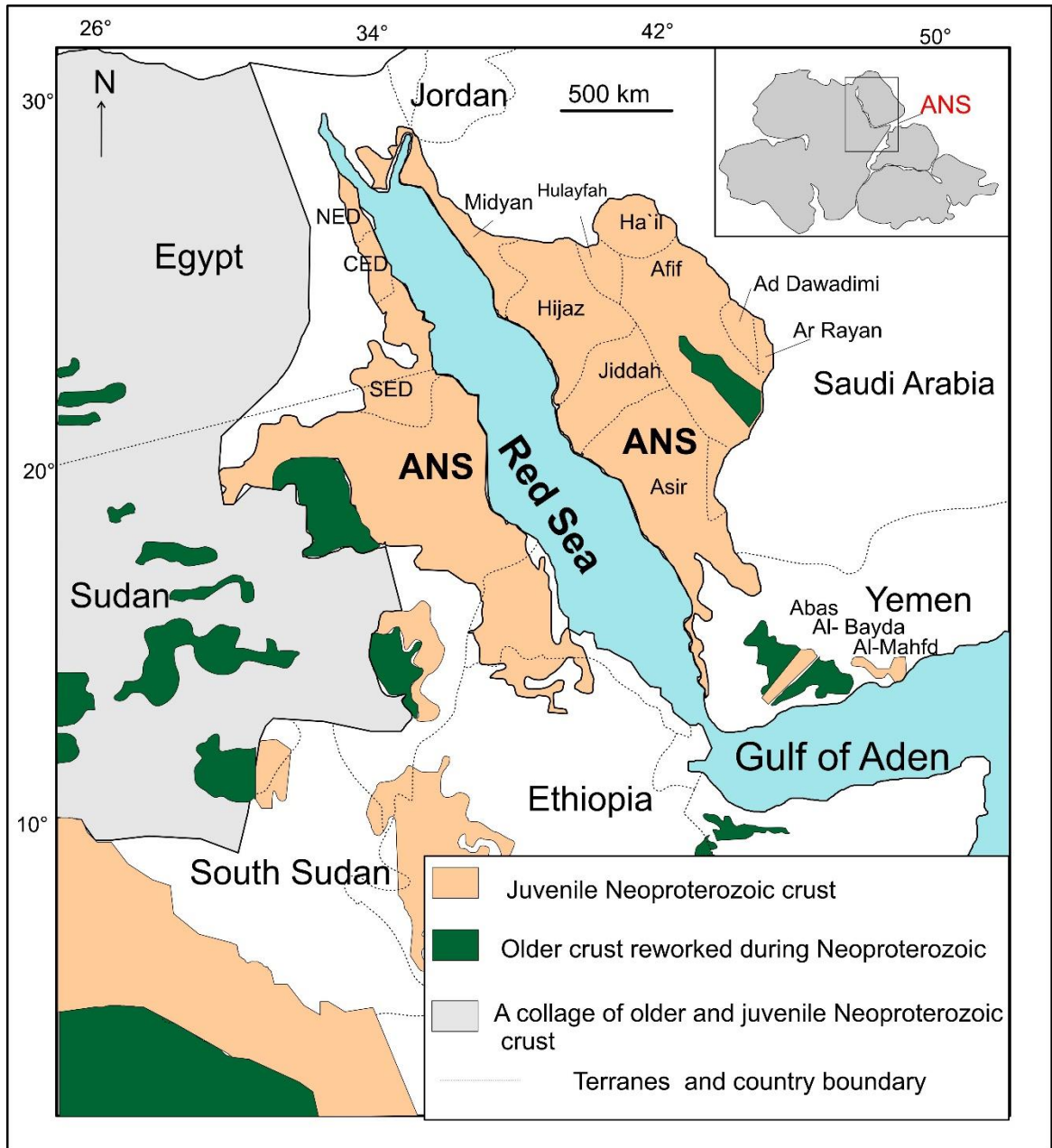


Figure. 3 Simplified geological map of the Arabian–Nubian shield (modified from Fritz et al. 2013)

Sharland et al. (2001) divided the Arabian Shield lithosphere into eight tectonostratigraphic terranes (Fig. 3) including Hail, Afif, Ad Dwydim, and Ar Ryan in the east and Hijaz, Asir, Jiddah, and Midyan on the western side Johnson (2021), Stoeser and Frost (2006), Nehlig et al. (2002), Genna et al. (2002), and Stoeser and Camp (1984) divided by ophiolite-bearing suture zones (El-Fakharani et al., 2020). The total area of this outcrop

~ is 770,000 km² (Stern & Johnson, 2010), comprising about one-third of the Arabian Peninsula. Nevertheless, the U-Pb zircon ages for the Shield demonstrate its formation between 900 to 550 Ma and is distinguished by two overlapping stages (1) an island arc stage between the late Tonian–Cryogenian (ca. 870–635 Ma) accretion, and (2) a post accretion stage in the Ediacaran (ca. 635–580 Ma) entailing collision, and orogenic collapse, which was dominated by granite production (~ 70% of all rock types) (Abuamarah et al., 2023; Ali et al., 2010; Stern et al., 2010).

The Arabian Shield contains one of the biggest peralkaline granite regions in the world. At least 49 separate alkaline to peralkaline granite intrusions are known (Fig. 2), with a total outcrop area greater than 5000 km² constituting approximately 2.35% of the Arabian Shield (Fig. 2 and 3). These granitoid suites are subdivided into two main groups Dawood & Abd El-Naby (2022), Robinson (2014), and Brown (1989) in terms of age: The older portion of the granitic suite, dating from approximately 775 to 740 Ma, is linked to the Ablah orogeny and early cratonization in the western and earlier-formed half of the shield. The younger portion of the granitic suite, dating from about 660 to 580 Ma, is associated with the culmination of orogeny and late cratonization that affected the entire shield. These rocks have been extensively studied due to their enrichment in several economically important elements, including radioactive elements such as uranium, thorium, and potassium. (Hassan et al., 2016; Johnson & Kattan, 2012). The occurrences of these heavy metals and hydrothermal deposits are linked with the Najd fault system (Edward, 1986). The Midyan terrane in the western Arabian Shield represents one of these alkaline peralkaline granitoid associations, which are enriched in U, Th, Nb, W, Mo, Zr, Y, Ta, Sn, and REE, as discussed below.

2.1.1 Midyan Terrane

The Midyan terrane provides an exceptional opportunity in which to examine the Neoproterozoic outcrops. The Midyan terrane is situated in the northwest of the Kingdom of Saudi Arabia, south Jordan (Aqaba complex and Araba complex), and northeast Egypt. The terrane is part of the African tectonic plate and recognized as the Eastern Desert terrane (ED), known as the Gerf terrane (Aboud et al., 2023; Johnson, 2006; Stern & Johnson, 2010; Stoeser, 1986) (Fig.3). To the south, this terrane is detached from the Hijaz terrane

by the Yanbu suture. The granite of the northern part suggests a difference from the southern part (Stoeser, 1986). According to Johnson & Kattan (2012), the northern terrane contains a large volume of plutonic rocks of high silica granite and makes up a tonalite-trondhjemite-granodiorite (TTG) assemblage assigned to the Jar supersuite, as well as deformed layered rock units intruded by diorite, tonalite, granodiorite (related to volcanic arcs, 680 Ma), and more recent I-type granites. (Kozdrój et al., 2018; Stern et al., 2010). These granites are divided into tectonic, syn-arc low-K-calc-alkaline plutons of gabbro, tonalite, trondhjemite diorite, and quartz diorite (Muwaylih suite, ~745-695 Ma) and late syn-arc to syn-amalgamation low-K, calc-alkaline complexes of diorite, granite, and granodiorite (Hamadat suite, ~685-650 Ma) (Johnson & Kattan, 2012a; Kozdrój et al., 2018).

Therefore, granitoid rocks of the Midyan terrane consist of two main supersuite granite groups. The first group is called the Al Bad supersuite (Fig. 5), which represents a large group of post-tectonic granites that range in age from Ediacaran (575–570 Ma). Aboud et al. (2023), Bakhsh (2013), Hughes (1999), Stoeser (1986), and Clark (1985) described the mineralogical compositions of the Al Bad suite, which are mainly composed of syenogranite and alkali feldspar granite, with high radioactive anomalies in some plutons. It is a rich source of uranium, rare earth elements, and beryllium, fluorine, tin, and tungsten. Meanwhile, Lashin et al. (2023), Aboud et al. (2023), Johnson (2006), and Stoeser (1986) illustrated the composition of the second group of the Muwaylih suite, which exhibits varying degrees of metamorphism and deformation, with contacts ranging from discordant to concordant. The primary rock types include tonalite, trondhjemite, diorite, quartz diorite, gabbro, and norite, with ages spanning from 710 Ma to 725 Ma. Both suites intrude into layered volcano-sedimentary country rocks. (Johnson, 2006; Johnson & Kattan, 2012a). Geographically, the northwesternmost part of the Arabian Plate, situated at the junction of the Red Sea and the Gulf of Aqaba, consists of the Midyan Peninsula (Tubbs et al., 2014). Geologically, the peninsula has a complex structural evolution due to extensional tectonics in the Red Sea during the Oligocene-Miocene. Additionally, there is an ongoing post-Pliocene anticlockwise rotation of the Arabian Plate relative to Africa along the Dead Sea transform fault. (Hughes, 1999; Tubbs et al., 2014). Besides that, the area lies to the north of the Muwaylih fault zone, which is a significant structure, and over the past three decades, was affected by the two most powerful earthquakes in Haql town, northwestern Saudi

Arabia (Ali et al, 2022). Following the earthquakes, the Saudi Geological Survey initiated a geological investigation to identify the most recent fault systems responsible for these seismic events in northwest Saudi Arabia and adjacent regions. In general, the Midyan Peninsula has a mass of granitic/radioactive granitoid rocks, which comprise approximately 60% of the Precambrian outcrop (Aboud, Lashin, et al., 2023; Hughes, 1999; Stoesser, 1986). Geochemical studies have established the economic significance of the alkali granites in the Midyan terrain. It has the most promising hosts for enrichment in REEs and rare metals. Meanwhile, it consists of about 80 large Late Neoproterozoic felsic intrusives that were deposited in the Midyan region of the northwestern Arabian Shield between 725 and 570 Ma (Ramsay, 1983). These are considered a good source for polymetallic mineralization, including Mo, Nb, W, Zr, REE, Sn, Ta, and U (Bakhsh, 2013; Harris and Marriner, 1980; Lashin et al., 2023; Robinson, 2014).

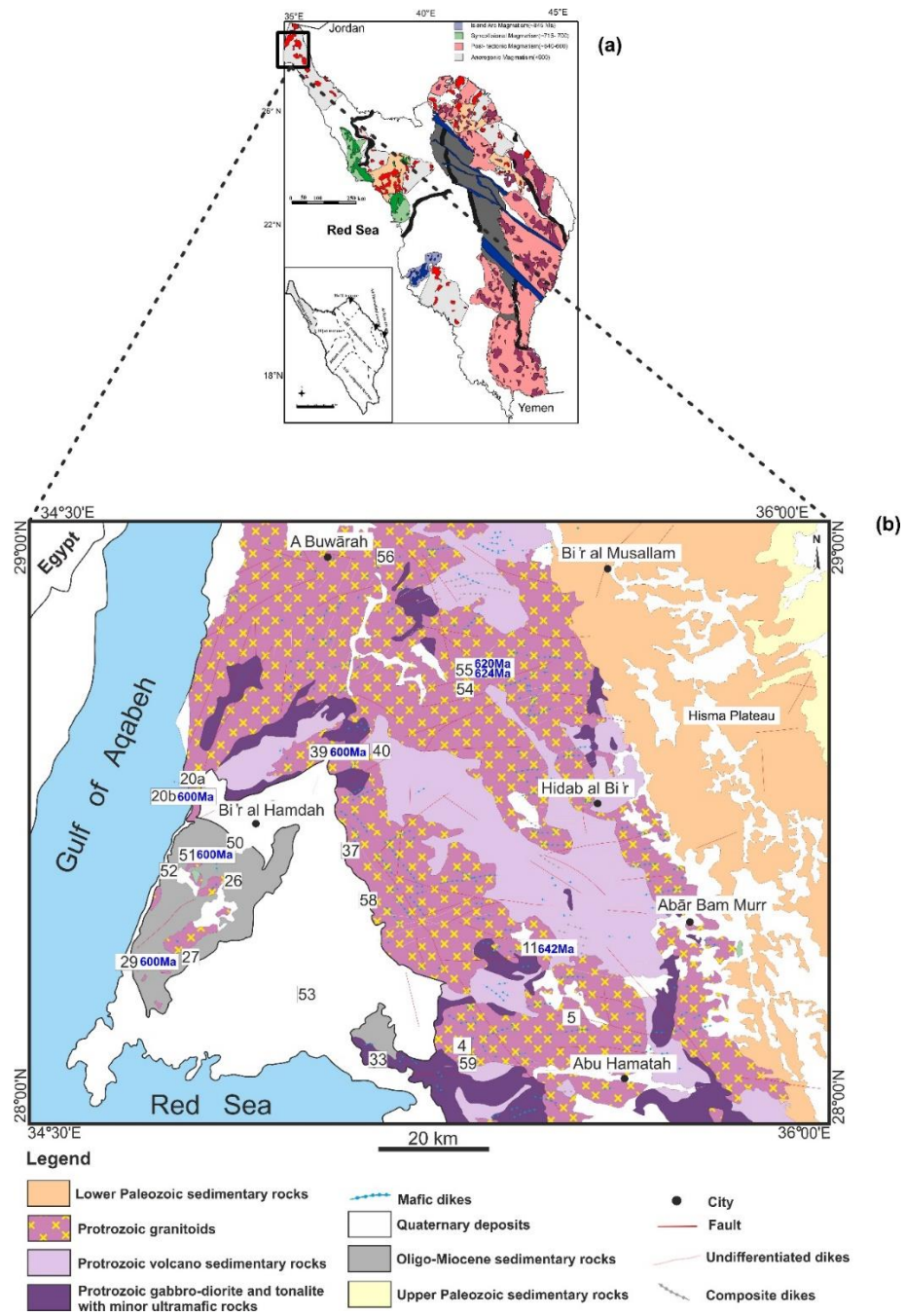


Figure. 4 (a)Tectonic map of the Arabian Shield showing the granitoid occurrences in NW Saudi Arabia (from Robinson et al., 2014). (b)The study area of NW Midyan is defined by a rectangle. The simplified geological map of our study area showing the samples location and ages obtained in this study (after Aboud et al., 2023)

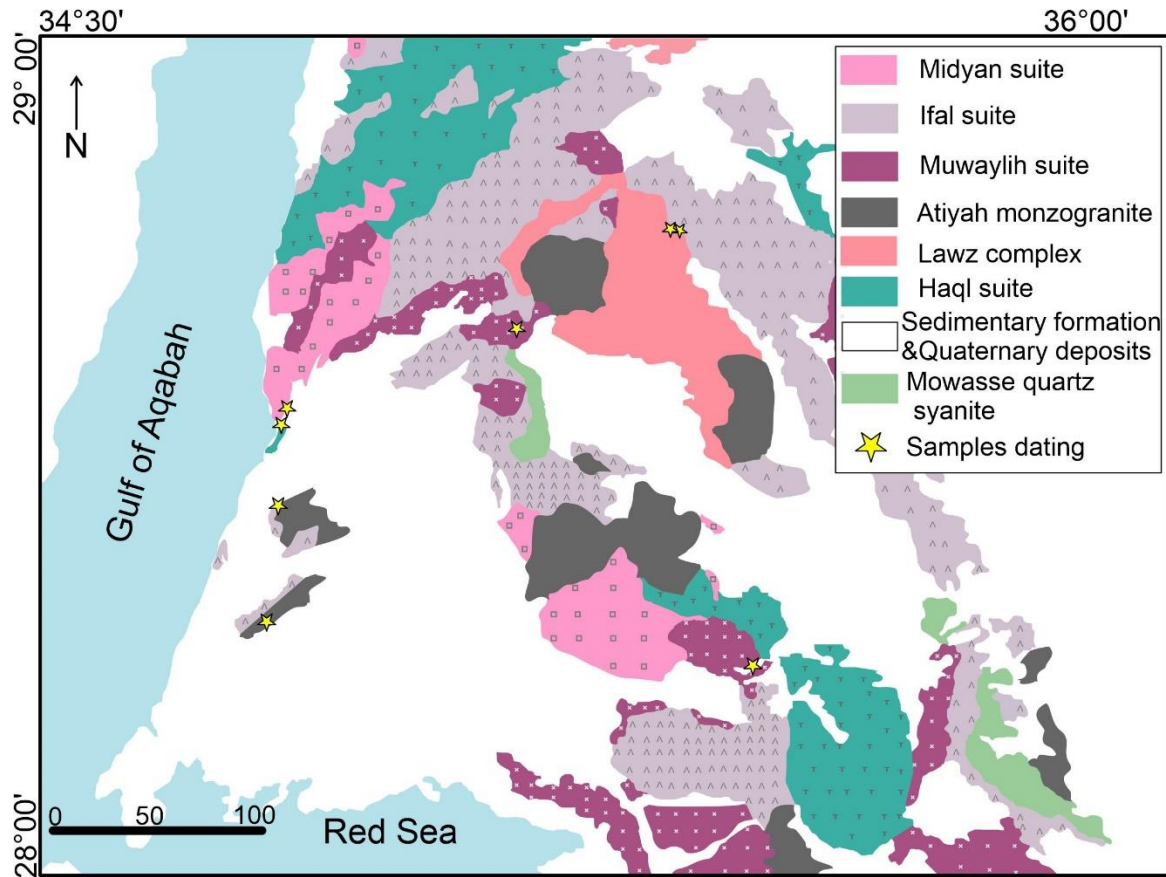


Figure. 5 Simplified geological map of the NW Midyan terrane study area, showing the different granitoid complexes and the location site of sample dating.

Geologically, the western portion of the Midyan region comprises Proterozoic basement rocks and stratiform of the Arabian Shield. These rocks are overlain unconformably by Mesozoic and Cenozoic sedimentary rocks in some area (Fig. 4 and 5) (Johnson & Robert, 1968). The study area occupies the Midyan region, part of the Al Bad quadrangle (Aboud et al., 2023; Lashin et al., 2023). These regions host a batholith that is widely acknowledged as an A-type granite suite, the region also contains several distinct I-type igneous complexes known for their varied sodic or potassic compositions. Among these complexes, the youngest is the I-type, which features a diverse range of lithologies from peraluminous to peralkaline granite, along with minor associated rock types. Previous investigations of the region demonstrated that petrogenesis of the region could be subdivided into five complexes of granite of regional extent that have been recorded in the Midyan region (Aboud et al., 2023; Ramsay, 1983; Stern, 1986). These complexes are the

Muwaylih, Ifal, Atiya, Haql, and Midyan (Fnais et al., 2016; Lashin et al., 2023; Ramsay, 1983) (Fig. 5).

Muwaylih suite represents the oldest unit, and the most voluminous is the Ifal suite, which is intruded by the Atiyah complex, which is one of the main lithological units of the Neom project. Large plutons of the Haql suite are intruded by Midyan granite Jamal (1991), the Lawz complex, the Mowasse quartz, the Sawda (nepheline syenite) complex, Jabal Tawlah and Ghurayyah and Al Bad super suite (Brown, 1989; Stoesser, 1986). In addition, the mafic plutons and younger I-type granite and granodiorite intrude the Za'am and Bayda groups (Aboud et al., 2023; Bakhsh, 2013; Robinson, 2014). The Paleozoic sandstone suite of the eastern side of the Midyan region forms the extensive Hadabet Hisma or Hisma Plateau (Fnais et al., 2016) (Fig. 4b and 5). Structurally, the area is largely controlled and deformed by three major tectonic systems: (1) the Najd system, oriented NW-SE; (2) the Red Sea system, oriented NNW-SSE; and (3) the Gulf of Aqaba system, oriented NNE-SSW. These normal and sinistral faults primarily originated in the Late Proterozoic and experienced reactivation during the Tertiary (Ali et al, 2022).

2.2 Background of Study Area

The study areas are situated in different parts of the Midyan region, which is administratively part of the Tabuk Province (Fig. 4b and 5) in particular, in the most northwestern part (longitude 26° 40`E to 28° 21` E; latitude from 35° 10` N to 36° 51` N), Neom City, Midyan Peninsula. It is bounded by the Hisma plateau to the east, the Red Sea to the west and the Gulf of Aqaba to the northwest (Brown, 1989). The Midyan region encompasses different plutons (e.g., Muwaylih, Ifal, laws, Atiyah, Sawda, Haql, and Maydian, Fig.5), The granites within these plutons have been classified using rigorous mineralogical and geochemical classification schemes. The mineralogy and geochemistry have also contributed to understanding the formation processes of these plutons.

According to Johnson & Kattan (2012) post-tectonic granitoid rocks dominate in the northern and southern Midyan terrane and range from gabbro to granite, such as those found at Ghurayyah, Jabal Tawlah, and Jabal Hamra, which serve as hosts for various elements encompassing Mo, Nb, Ta, U, W, REE, Sn, and Zr. According to Clark (1985), all units we had mentioned above constitute a post-tectonic granite ranging in age from

middle to late Ediacaran, including alkali-feldspar granite, monzogranite, granodiorite, alkali granite, and trondhjemite. These plutons are described in terms of lithology and ages as follows (Table 1):

Muwaylih Suite

This group located in the central part of the Midyan terrane and consists of mafic plutons intruded by the Za'am and Bayda groups (Johnson & Robert, 1968). The primary rock types in this suite are diorite, quartz and gabbro diorite, tonalite and trondhjemite. The plutons have undergone variable degrees of metamorphism and deformation, and their boundaries also vary from discordant in some locations to concordant in others. Ages are ca. 710-725 Ma.

Ifal Suite

Ifal is the most voluminous suite in the Midyan terrane and consists of a heterogeneous assemblage of granodiorite, monzogranite, quartz monzodiorite, and biotite-hornblende monzogranite (Clark, 1985; Kahal, 2020). In the Midyan region of Neom city, this suite is characterized by an oval to irregular shape, which is intruded by the Hegaf Formation, Atiyah monzogranite complex, and Sawawin complex and cut by multiple numerous mafic and felsic dikes.

Midyan Suite

The Midyan Suite is composed of alkali granite to alkali-feldspar granite, ranging from metaluminous to peralkaline compositions. It also includes alkali quartz syenite, alkali microgranite, alkali granite, and monzogranite (Clark, 1985). Among these, the polymetallic Nb, and Zr deposits found at Jabal Tawlah and Ghurayyah are the most significant mineral resources associated with the alkali granite of the Midyan suite.

Sawda Complex

This complex represents the nepheline syenite suite identified within the Arabian Shield and is situated approximately 30 km south of Haql in the most northwestern segment of Saudi Arabia. It is distinguished as posttectonic, encircled partially in the core by mela-

nepheline syenite and an almost complete outer ring of alkali-feldspar syenite. Intrusions of various rock types are also present, such as porphyritic nepheline syenite, nepheline monzosyenite, and ijolite within the leuco-nepheline syenite component. The suite contains high concentrations of Ba, La, Zr, Nb, Sr, Al₂O₃, and Na₂O. U-Pb isotope dating has determined a formation age of approximately 553 ± 4 Ma (Liddicoat et al., 1983).

Haql Suite

This large, irregular pluton contains perthitic leucogranite, which is marginally peraluminous or peralkaline to metaluminous, alkali-feldspar granite and syenogranite, granophyre and alkali-feldspar microgranite. Some complexes, such as the Ratamah granite, have low Sn W Ta Nb mineralize concentration (Clark, 1985).

2.5 Previous Work

Many studies have been conducted on the study area in terms of mineralization and rare earth elements (REE) distribution, geothermal, and structural occurrences. Although several significant studies on some Midyan crystalline rocks have been conducted, more investigation and documentation are necessary for these features, and their relative inaccessibility remains a critical research challenge. The NW part of the Midyan Peninsula has already been subjected to some initial publications that mainly focused on the lithological characteristics and economic promise of the Arabian Shield. These investigations suggest that alkali granites hold significant promise as hosts for concentrations of REEs. The initial geological survey of the Midyan region, Midyan terrane, driven by the pursuit of gold exploration, attracted interest and was conducted in the 19th century (Burton, 1878). This was followed by Bogue (1953) and Philby (1956) who conducted early investigations into the mineral resources of the area. Subsequently, there was a resurgence of interest in the region's mineral deposits, leading to studies by the Japanese Geological Survey and British Steel Corporation. In addition, Clark (1985), produced a comprehensive map of the Midyan Peninsula, documenting numerous studies conducted on the Proterozoic basement. Clark (1985) outlines the various ages of the main complexes in the Midyan region at Sawda at 553 Ma, Lawas and Haql at 575 Ma, Ifal and Atiyah at 600-625 Ma, and Muwaylih at 710 Ma. Nonetheless, these complexes have a poorly constrained age obtained by Rb-Sr and U-Pb in zircon using a conventional method.

Ramsay (1983), conducted a study on the I-type classification of the Midyan region granitoids, which encompass five intrusive suites. Stern et al. (2010) and Ali et al. (2010) compared the Ghawjah metavolcanic rocks in Midyan to the Central Eastern Desert (CED) of Egypt "Younger Volcanic" concluding their similarity in terms of chemical compositions, stratigraphic relations, Nd-isotopic contents, and U–Pb zircon ages (~750 Ma). The study indicates that both were formed by the partial melting of subduction-depleted mantle. Johnson & Kattan (2012), note that the ages of plutonic rocks in the Midyan region range from ~638-575 Ma. Furthermore, Midyan terrane records a magmatic transition from syntectonic I-type low-K calc-alkaline plutons which were emplaced into the Za'am and Bayda groups before 650 Ma. Subsequently, during the late-tectonic phase, a suite of calc-alkaline monzogranite to granodiorite plutons, along with monzogranite to syenogranite plutons, were intruded between 635 and 580 Ma. This was ensured by the emplacement of A-type granites after 575 Ma. These A-types are abundant as alkali granite, alkali-feldspar granite, monzogranite, granodiorite, and trondhjemite. In addition, the Midyan terrane in Jordan exhibits a comparable trend (Jarrar et al., 2004), featuring a sequence ranging from high potassic calc-alkaline gabbro to high-silica granitoid within the Aqaba complex (640-600 Ma). These formations are indicative of a subduction, arc-related process in the terrane's crustal evolution. Subsequently, the region saw the emergence of bimodal alkali-calcic to alkali rocks forming the Araba complex (600-560 Ma), which signifies the concurrent emplacement of mafic and felsic magmas during the final steps of shield development.

The study conducted by Bakhsh (2013) aimed to comprehensively characterize and understand the Neoproterozoic felsic intrusive that included the Jabal Az Zuhd, Thawlah, Al Massah, Raydan, and Al Wajh suites situated in the northwestern portion of the Arabian Shield. The research employed ICP-MS in the Midyan region, which is proximate to our study area. The outcomes of the study offer valuable information that can be utilized for further investigations and assessments in the field of geology and mineral resource exploration, and the potential economic significance of rare elements in the region. Robinson (2014), studied the Al Bad super granite suite in the NW Midyan terrane, near the Jordan border. Their study revealed that the geochemistry and geochronology of this suite is anorogenic alkali granite dated as 597.4 ± 4.8 to 603 ± 30 Ma based on U-Pb zircon

analysis. Al-Husseini (2015) carried out a study on the Midyan Peninsula, with a primary focus on seismic imaging to enhance comprehension of the tectonic evolution and stratigraphic history of the region. The investigation particularly emphasized the interplay of rifting, salt tectonics, and strike-slip faulting. The integration of 3-D seismic data, drilling, and on-site observations played a pivotal role in constructing a comprehensive geological model for the area. The ongoing exploration, initiated in 2006, is expected to yield substantial insights into the hydrocarbon potential, geological evolution, and tectonic processes of both the Midyan Peninsula and the broader northern Red Sea.

Alharbi (2016) assessed the hazard of the iron ore deposits in Duba, Wadi Sawawin, by XRD, gamma-ray spectrometry, and atomic absorption analysis which showed that the area is radiologically safe to use as construction materials. Fnais et al. (2016) employed seismological data and the high-resolution aeromagnetic, guided by on-site structural studies, to map and define the structural features influencing the Midyan region in the northwest region of Saudi Arabia. The region has been categorized into four primary domains based on the identification of faults with NNE, NNW, NW, and ENE trends. These fault trends were discerned by analyzing the patterns and intensity of magnetic anomalies. Aseri (2020), focused on the rare metals Nb, Ta, Zr, Y, and REE of the alkaline granites in the Al-Ghurayyah with concentrations of heavy REE (HREE). Lashin et al. (2023) aimed to advance the understanding of the source of anorogenic magmatism and post-collisional in the Midyan terrane and its geodynamic implications. Their findings displayed distinctive characteristics, including enrichment in large-ion lithophile elements (particularly Rb and Th), light REE (LREEs), and some high-field strength elements (HFSE, such as Nb, Ta, Zr, and U). Additionally, there is a slight depletion of heavy rare earth elements (HREEs). Consequently, the granites in the Midyan and Hael regions, as studied in this paper, are identified as significant sources of uranium-thorium, geothermal heat, and rare earth element (REE) mineralization.

Recently, Aboud et al. (2023) and Zaidi et al. (2022) estimated the thermal structure of the NEOM city area which is crucial for identifying potential geohazards like faults and predicting the presence of geothermal resources. The study suggests a geological connection between the southern Sinai Peninsula and the northern Arabian Shield,

separated by the Gulf of Aqaba. Besides that, Aboud et al. (2023) conducted a comprehensive gravity study of the high heat generating granites in the northwest Midyan terrane. The study incorporated various geophysical surveys, including gravity and audio magnetotelluric methods, to explore the structural characteristics in the subsurface of the region. The research recognized both shallow fault and regional deep systems, revealing the subsurface geometry and of the granitic rocks, along with determining the thickness of sedimentary basins near the coastal area. Both areas warrant further exploration to assess the energy potential of geothermal.

This work provides a new comprehensive study of NW Midyan terrane granitoids, which covers their petrogenesis, whole rock chemistry, isotopic nature, and SHRIMP U-Pb zircon age (see chapters four and five).

CHAPTER 3

METHODOLOGY

This research achieved its goals by conducting both field investigations and laboratory analysis. Each objective is addressed using specific methods and analysis as described below.

3.1 Field Characteristics

During a field camp conducted in July 2019, Dr. Whattam and his team spent two weeks in the Tabuk area to provide a comprehensive study of the granitoid complexes and associated dikes in the northwestern-most part of the Midyan Peninsula, focusing on five major complexes Muwaylih, Lawas, Ifal, Atiyah and Midyan. These complexes represent apparent A- and I-type granitoids. The major objective was to understand each unit using different approaches. To establish the sampling methods for fieldwork and locations of different sites, the team utilized a geological map from previous works for example, Bakhsh (2013), Ghrefat et al. (2013), and Hughes (1999) along with a map from the Ministry of Industry and Mineral Resources (2013) (Fig. 4 and 5). Collection methods included in-situ examination and collection of samples of fresh rock, with a particular focus on the east and west parts of this region. The outcrop locations were accurately recorded using GPS, supplemented by detailed field notes and photos. Each sample was collected and labeled for further analysis.

3.2 Petrography with the Aid of SEM and XRD-QEMSCAN

A total of forty-nine samples of granitoids rock were collected on the field trip. A Felker bay cutting machine in the Sample Preparation Laboratory of the Center for Integrative Petroleum Research (CIPR) was used to remove the weathered surfaces and cut samples into smaller pieces. A Braun chipmunk stainless steel jaw crusher in Building 78, KFUPM was used to break the samples into smaller pieces. Subsequently, these representative pieces were used for whole rock and isotope analysis with quantities between 35 – 50 gr and 20 – 30 gr respectively. A subset of thirty representative samples were

selected for petrographic preparation and polished thin section construction at Vancouver Petrographics (VanPetro), Vancouver, Canada. Zeiss Axioscope 5 was used to identify specific mineralogy, texture, alteration, and zircon characteristics. As well, 37 samples were chosen for geochemical analysis (analyses provided in Appendix 1.) Twenty -six and fourteen samples were chosen for QEMSCAN and SEM analysis respectively. We used SEM, XRD, and QEMSCAN (see Fig. 9 and 10) to aid in petrographic description and determination of mineralogy. QEMSCAN and SEM images of representative samples are provided in Fig. 9 and 10. Samples are subdivided based on SiO₂ content (see Chapter 4 Section 4.1) into basic, intermediate, and acidic types (representative thin section micrographs of each type from each group are provided in (Fig. 7 and 8). Further discrimination was made into A- & I-type (see Chapter 4).

3.3 Analytical Methods

3.3.1 Whole Rock Geochemistry ICP-MS and ICP-AES

Major and trace element contents of the Midyan terrane samples were determined by ICP-AES (major elements) and ICP-MS (trace elements) at Bureau Veritas Minerals (BVM) Laboratories, Vancouver, Canada (Lithogeochemical Whole Rock Fusion, BVM Code LV 200, <http://acmelab.com/pdfs/FeeSchedule-2016.pdf>). Samples for whole-rock analysis were trimmed to remove weathered surfaces and pulverized to 85%, passing 75 µm. Crushed rock powders were then analyzed for whole rock major and trace element determinations (Table 2). Powders were mixed with a LiBO₂/Li₂B₄O₇ flux and crucibles were fused in a furnace. The fused melts were dissolved in ACS-grade nitric acid and analyzed by ICP-AES. Major element detection limits were 0.01% for all oxides except for Cr₂O₃ (0.002%) and Fe₂O₃ and K₂O (0.04%). Loss on ignition (LOI) was determined by combusting a sample split at 1050 °C and determining the weight loss after cooling. Trace and rare earth elements were analyzed by ICP-MS on the same digestions as for major elements; detection limits of most trace elements are <0.01 µg/g. Further details of BVM geochemical methods can be found at <http://acmelab.com/pdfs/FeeSchedule-2016.pdf>.

3.3.2 Whole Rock Isotopes

3.3.3 Sr and Nd Isotopes

Thermal ionization mass spectrometry was used to obtain whole-rock Rb-Sr and Sm-Nd isotopic compositions (Table 3) at Beijing Geo Analysis Co. Ltd (China). 100 mg of whole-rock powdered samples were dissolved in a 3:1 mixture of HF and HClO₄ acid and spiked with mixed isotope tracers. This mixture sat in Teflon capsules for one week before isotopic measurement. To correct for mass fractionation, the measured $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were corrected using $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, respectively. For the purpose of reproducibility, the standards BCR-2 with $^{87}\text{Sr}/^{86}\text{Sr} = 0.705074 \pm 0.000009$ (2σ) and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512626 \pm 0.000006$ (2σ), were measured alongside the samples. These values are consistent with the reference values of $^{87}\text{Sr}/^{86}\text{Sr} = 0.705015$ Balcaen et al. (2005) and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512637$ (Jweda et al., 2016).

3.3.4 Pb Isotope

Pb isotope analysis (Table 4) was performed on a Neptune Plus MC-ICP-MS (Thermo Fisher Scientific, Dreieich, Germany) at Beijing Geo Analysis Technology Co., Ltd., China. 50 mg of whole-rock powdered samples were dissolved in 1.0 mL of 1.0 M HBr. After centrifugation, the supernatant solution was loaded into an ion-exchange column packed with AG resin. After complete draining of the sample solution, columns were rinsed with 1.0 M HBr to remove undesirable matrix elements. Finally, the Pb fraction was eluted using 6.0 M HCl and gently evaporated to dryness prior to mass-spectrometric measurement. During Pb isotopic analysis, the $^{205}\text{Tl}/^{203}\text{Tl}$ ratio of 2.3889 and an exponential law were used to correct the instrumental mass discrimination.

3.3.5 SHRIMP U-Pb Dating

After sample pulverizing, zircons ranging from 63 μm to 245 μm were separated using magnetic separation and heavy liquids. Separated zircons together with standard grains were mounted in epoxy resin and polished to expose the middle of the grain. The measured $^{206}\text{Pb}/^{238}\text{U}$ ratio was calibrated using the FC1 zircons (1099.0 Ma) standards, which were collected from the gabbroic anorthosite of the Duluth Complex in Minnesota (Paces and Miller, 1993). Sri Lankan gem zircon SL13 (U = 238 ppm) was also used for

calibrating U and Th concentrations. Cathodoluminescence (CL) and backscattered electron (BSE) images were obtained using the scanning electron microscopes of JEOL 6610LV at the Korea Basic Science Institute (KBSI). The phase identification of zircon and its inclusions was performed by INCA x-act energy dispersive spectrometer (EDS). Zircon U–Pb dating was carried out using the SHRIMP-IIe/MC at KBSI. The analytical procedures for SHRIMP dating were mostly based on (Williams, 1997). A 20–25 μm spot size was used for all analyses under a negative ion oxygen beam (O_2^-) in 3–4 nA of beam current. The data were collected in sets of five scans throughout the mass measurements for each isotope. For common Pb, the $^{206}\text{Pb}^*/^{238}\text{U}$ ages were corrected based on the measured $^{207}\text{Pb}/^{206}\text{Pb}$ ratio (Williams, 1997). FC-1 standard grains were repeatedly analyzed after every three unknown analyses. Data reduction and processing were carried out using the Squid 2.50 and Isoplot 3.71 programs of Ludwig (2008, 2009). When the drift in Pb/U ratios of repeated FC-1 standard is obvious, the drift correction of secular variation was chosen on SQUID 2.5 software. The mean age of each specimen was calculated using ^{207}Pb -corrected $^{206}\text{Pb}^*/^{238}\text{U}$ ages after excluding outliers under the statistical t-test. Concordia diagrams were plotted using ^{208}Pb -corrected ratios of $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{207}\text{Pb}$. All uncertainties are in (Table. 3).

3.3.5 Data and Interpretation

Petrography and geochemistry results are presented in tables 1, 2, bivariate and ternary plots, primitive mantle-normalized multi-element diagrams, and chondrite-normalized rare earth element (REE) diagrams. Figures were constructed with the aid of IgPet software (Carr & Gazel, 2017). The software allows users to input geochemical data to produce geochemical variation diagrams. Further edits were applied by Affinity Designer software. Reference data were extracted when presented in the source. Additional data was also acquired by accessing the open-source geochemical database websites GEOROC and PetDB.

CHAPTER 4

RESULTS

4.1 Petrography

Clark (1985) provides a geological map for the research area and classifies the plutonic rocks of the Midyan terrane into the Sawda, Lawaz, Muklar complexes and the Midyan, Muwaylih, Ifal, and Haql Suites. These complexes exhibit diverse granitoid rocks in the NW Midyan terrane and show wide differences in their mineralogical composition, grain size, and textures. All samples were described in the field and under the microscope. The field observations reveal that the plutons are composed of pink and white, coarse to very coarse-grained, white to gray, and medium to fine-grained granitoids (Fig. 6 and 7), with gabbro-to-gabbro diorite and diorite being cut by basaltic and rhyolitic dikes with width ranging from 30 cm 4 m (Fig. 6 c, d, e). The following sections elaborate on the petrographic properties of the different granitoid rocks.



Figure. 6 Field and petrographic aspects of the NW Midyan granite. (a) Pink, coarse-grained, weathered granite. (b) White granite intersected by joints. (c, d, and e) Granite intruded by mafic dykes. (f) Felsic fresh medium-grained granite.

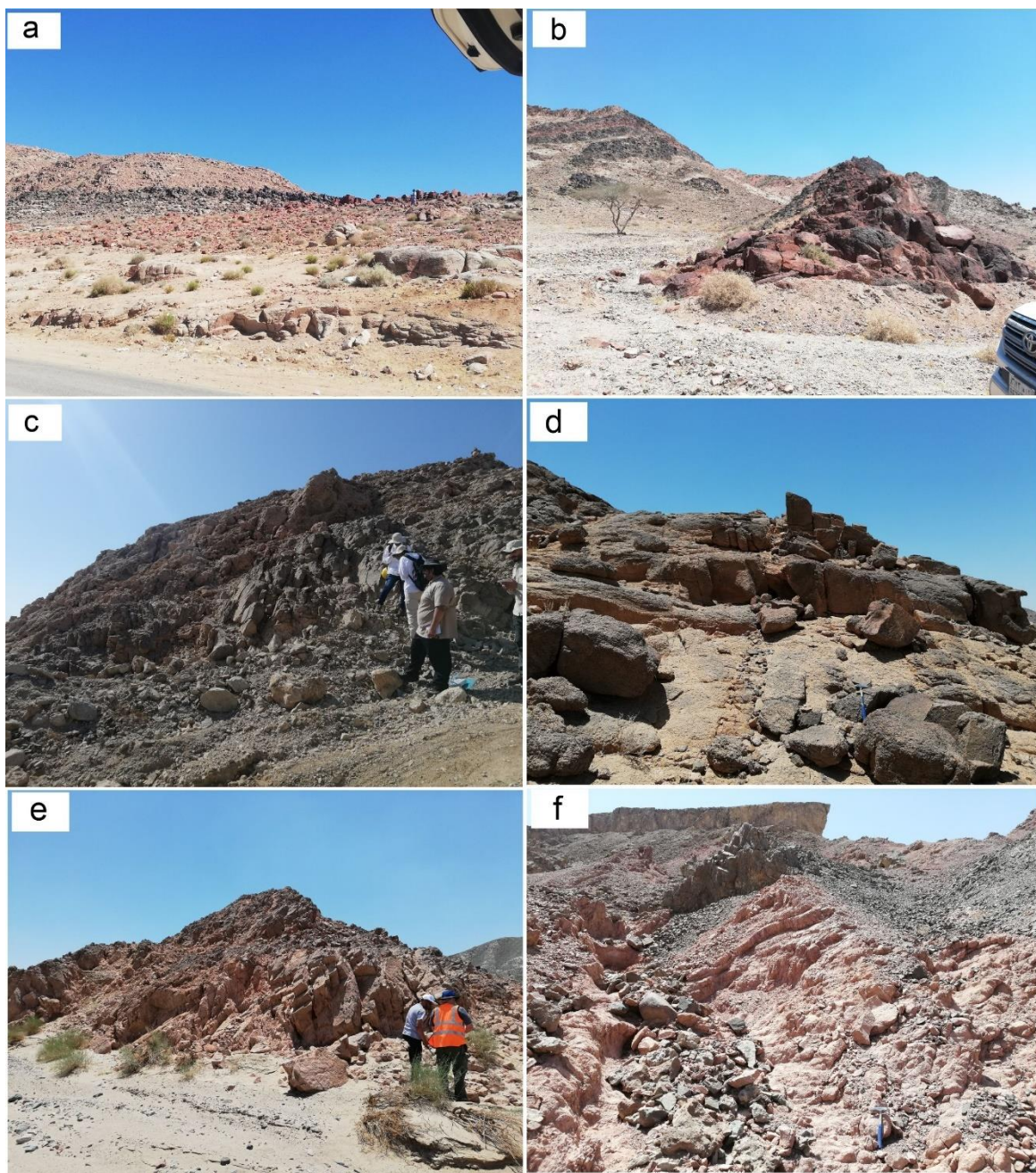


Figure. 7 Outcrop photographs (a-f) of the granitoid complexes in the NW Midyan Peninsula.

4.2 Mineralogy and Texture with the Aid of XRD and QEMSCAN

To identify the mineral textures of our samples, the thin sections of these minerals have been studied under a microscope and supported by X-ray diffraction (XRD) and quantitative evaluation of minerals scanning electron microscopy (QEMSCAN).

4.2.1 Mineral Chemistry

Twenty-six granite samples revealed varieties in their mineralogical composition, from felsic, representing the majority of contents, to mafic and minor accessory minerals. Based on the XRD mineral analyses, the granitoid samples mainly consist of quartz (15–42%), K-Feldspar (22– 58%), plagioclase (39–63%), amphibole (6–28%), biotite (3–14%), muscovite (0–4%) and pyroxene (0.1 – 2%) (Table.2). Additionally, minor and accessory minerals such as zircon, titanite, cassiterite, apatite, chlorite, and iron oxide occur in small amounts (0–3%) (Fig.8 to 16). For example, TB- 37c(f), TB- 39b, TB- 55a, TB- 54b, TB- 52a, TB- 33c(f) shows high contents of quartz >43%. The K- Feldspar shows high occurrences in the samples of TB- 56 (58.6%), TB- 58 (55%), TB- 54a (53.7%), TB- 39c (44.5%), TB- 39b, TB- 51a, TB- 52a, TB- 54c, TB- 54b, TB- 55b, TB- 56a (20 – 43%). Plagioclase is observed to occur at a high percentage of 62% in sample TB- 37a (Table. 2). Below is a description of all major and minor minerals.

Quartz

The quartz crystals in the thin section exhibit various shapes, sizes, and textures, including euhedral, subhedral, and anhedral. It appears inequigranular and intergrowths with other minerals like K-feldspar, forming perthitic and myrmekitic textures. The crystals are coarse, and medium to fine-grained. Some grains are cut by small feldspar veins (Fig. 10b), and the quartz veins intersect k-feldspar grains. Quartz in some samples is semi-rounded, like mega quartz, within a k- feldspar mass, and shows a porphyritic texture (Fig. 10a).

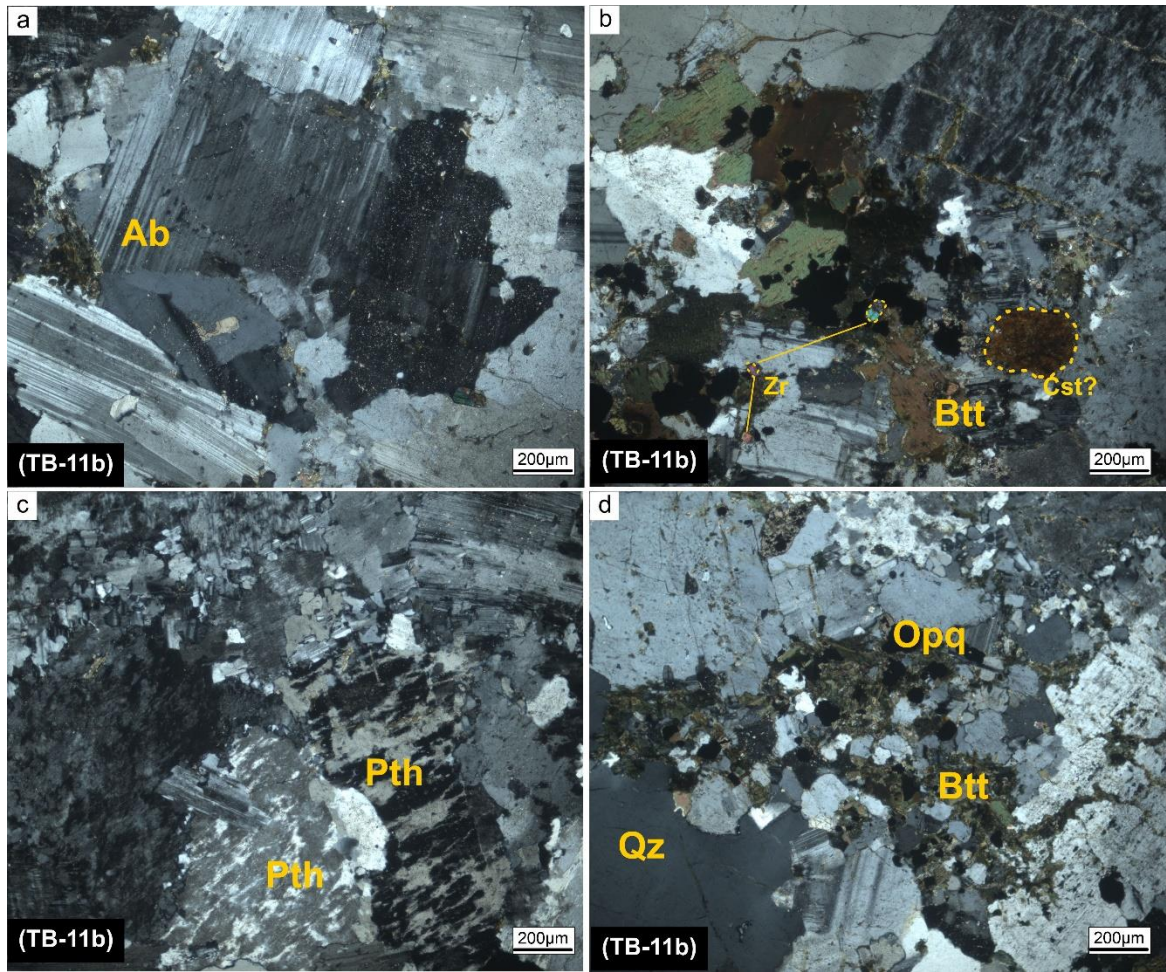


Figure. 8 (a, b, c, d) Photomicrographs (cross-polarized light) of A-type Biotite Monzogranite granitoid, showing felsic mineral assemblages. (d) shows coarse grain k-feldspar (perthitic texture). abbreviations Abbreviation for Alb: albite, Qz: quartz, Btt: biotite, Zr: zircon, Pth: perthite, Opq: Opaque minerals.

Plagioclase Feldspar and Potassium Feldspar

The feldspars commonly occur as megacrains with perthitic and antiperthitic exsolution which are transformed into a coarse patch and vein perthite (Mondal et al., 2017). Crystal shapes range from euhedral to anhedral and vary from coarse to medium-grained. Carlsbad and flame shape or lamellar twinning, deformation, cross-hatched twins, perthite, and zoning are observed (Fig. 8a, Fig.12c&e, and Fig. 14b). The feldspar mega grains are edged by albite, which is rimmed by myrmekitic-like intergrowth of quartz, K-feldspar, and albite (Fig. 8). Also, iron oxides patches fill and replace some feldspar grains. With the

cross-hatched twinning of the microcline, K-feldspar shows incomplete order. Inclusions of feldspar, zircon, and silica develop in quartz, biotite, amphibole, and perthite crystals (Fig. 9b). Some of the plagioclase feldspar and potassium feldspar crystals show heavy sericite alteration. Hematite alteration was found on some crystal surfaces (Fig. 10c, 12e).

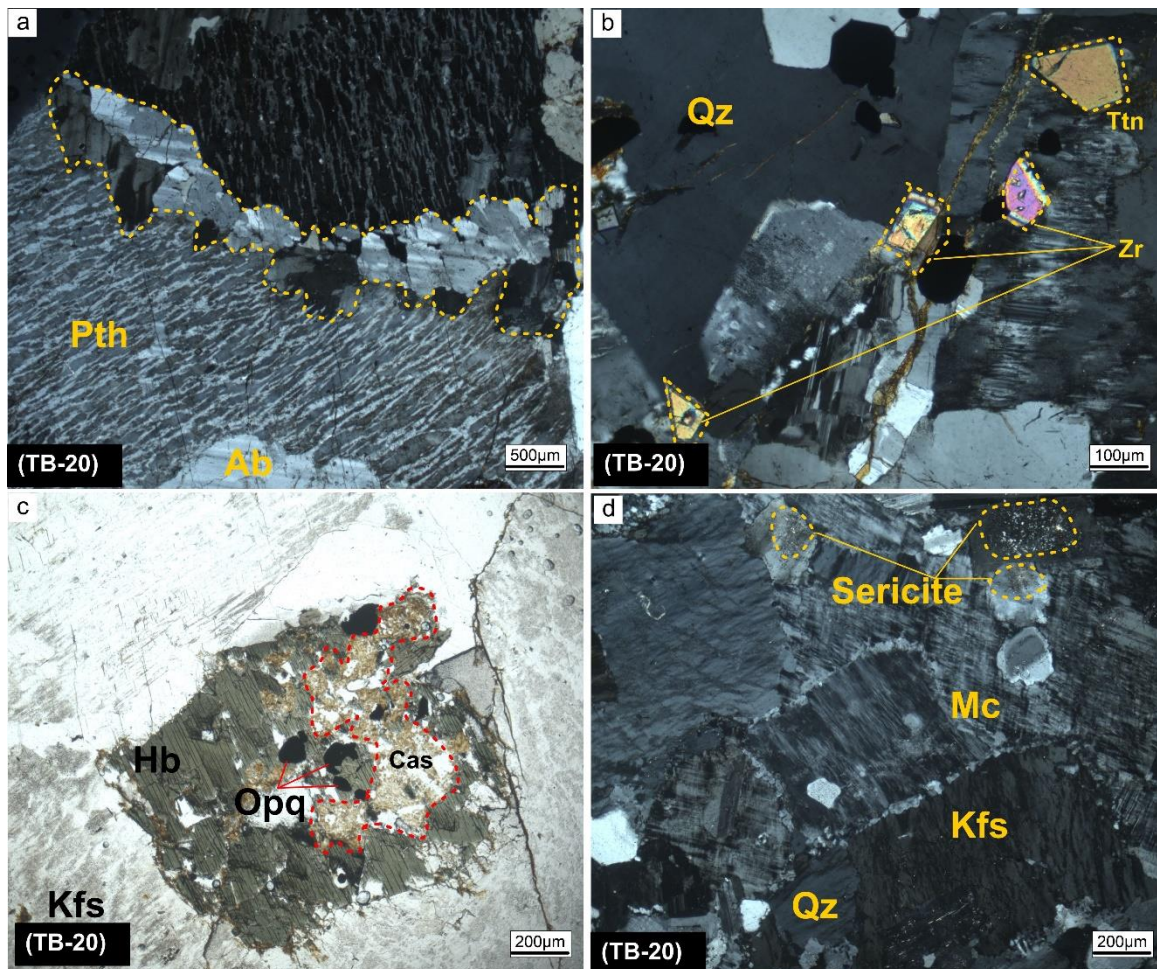


Figure. 9 (a, d) perthite texture and sericitization alteration on the surface of the Kfs grains, (b) accessories minerals (zircon and titanite), (c) the hornblende grain altered by magnetite oxides and hosts the cassiterite assemblages' grains, surrounded by felsic quartz and k-feldspar, (d) cross-hatch twinning on the microcline. Abbreviation for Kfs: k-feldspar Mc: microcline, Qz: quartz, Ttn: titanite, Hb: hornblende, Cas: cassiterite, Zr: zircon, Opq: Opaque minerals

Micas

Biotite represents the most abundant mafic minerals in our samples, and it shows a brownish color. Its crystals are subhedral to anhedral (Fig 12c and f). The crystals also exhibit semi-tabular shapes surrounded by quartz and feldspar grains. Some small grains appear to be included on the surface of the crystals of quartz. Also, some grains are altered to chlorite. The muscovite is also recorded in sample TB-5b (Fig.14e), characterized by high relief with clear edges compared with neighboring minerals. It appears that muscovitization has altered some feldspar crystals.

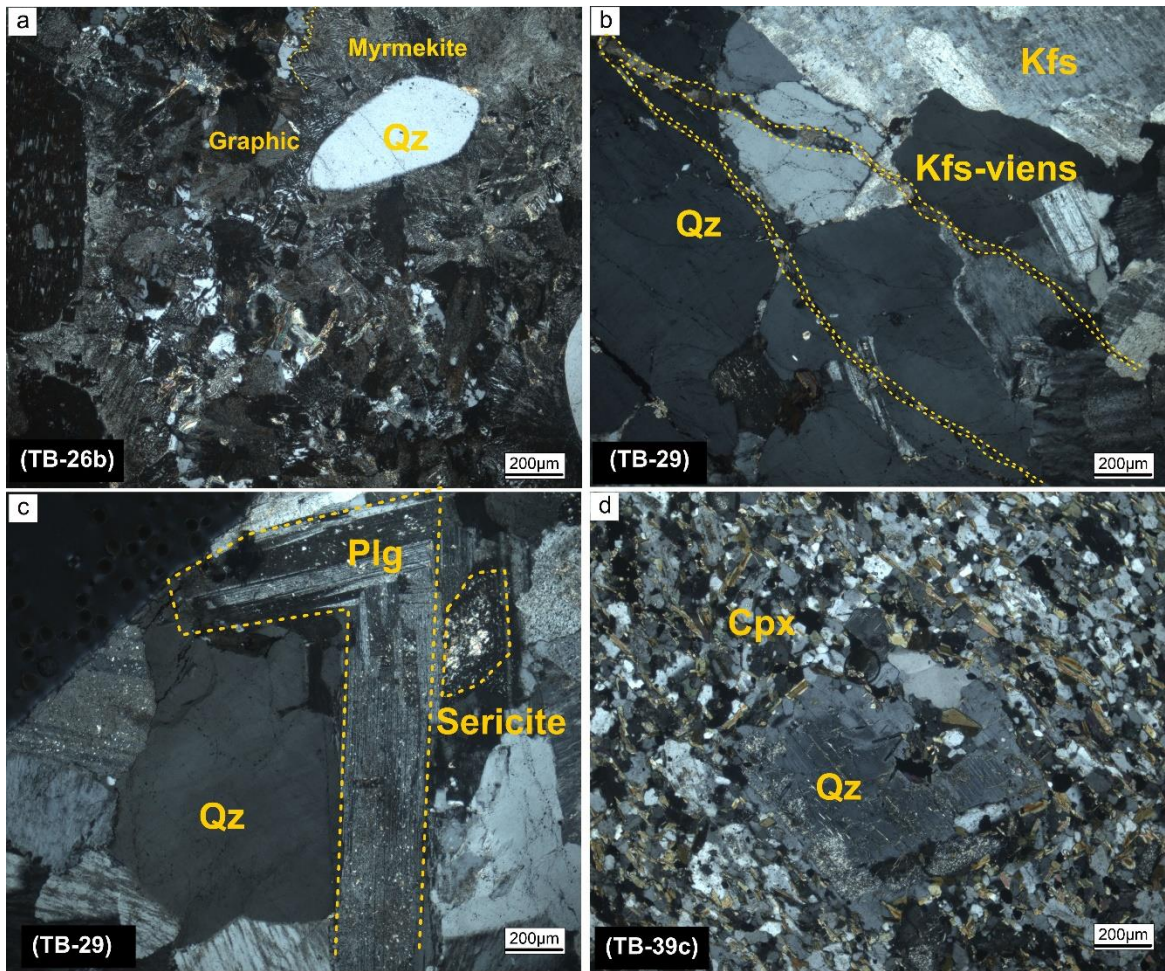


Figure. 10 (a, d) porphyritic texture, showing Mega Qtz with a fine groundmass of micro Qtz, k-feldspar, and hornblende. (b) coarse-grained quartz and k-feldspar intersected by k-feldspar veins, (c) plagioclase heavily altered by the sericite and parallel twinning. Abbreviation for Kfs: K-feldspar, Plg: plagioclase, Qz: quartz, Cpx: clinopyroxene,

Pyroxene and Amphibole

Amphibole crystals show clear cleavage and occur as hornblende, which exhibits a prismatic and diamond shape as in samples TB-55b and TB-54b (Fig.11a, b, and d). The grains have different sizes, from fine to medium. These prismatic shapes form intergranular or ophitic and subophitic textures altered by oxide minerals as black dots on crystal surfaces. Clinopyroxene is also present in sample TB33c. Some of these grains are grown on the surface of hornblende crystals (Fig. 10d), also (see Fig. 13 and 15).

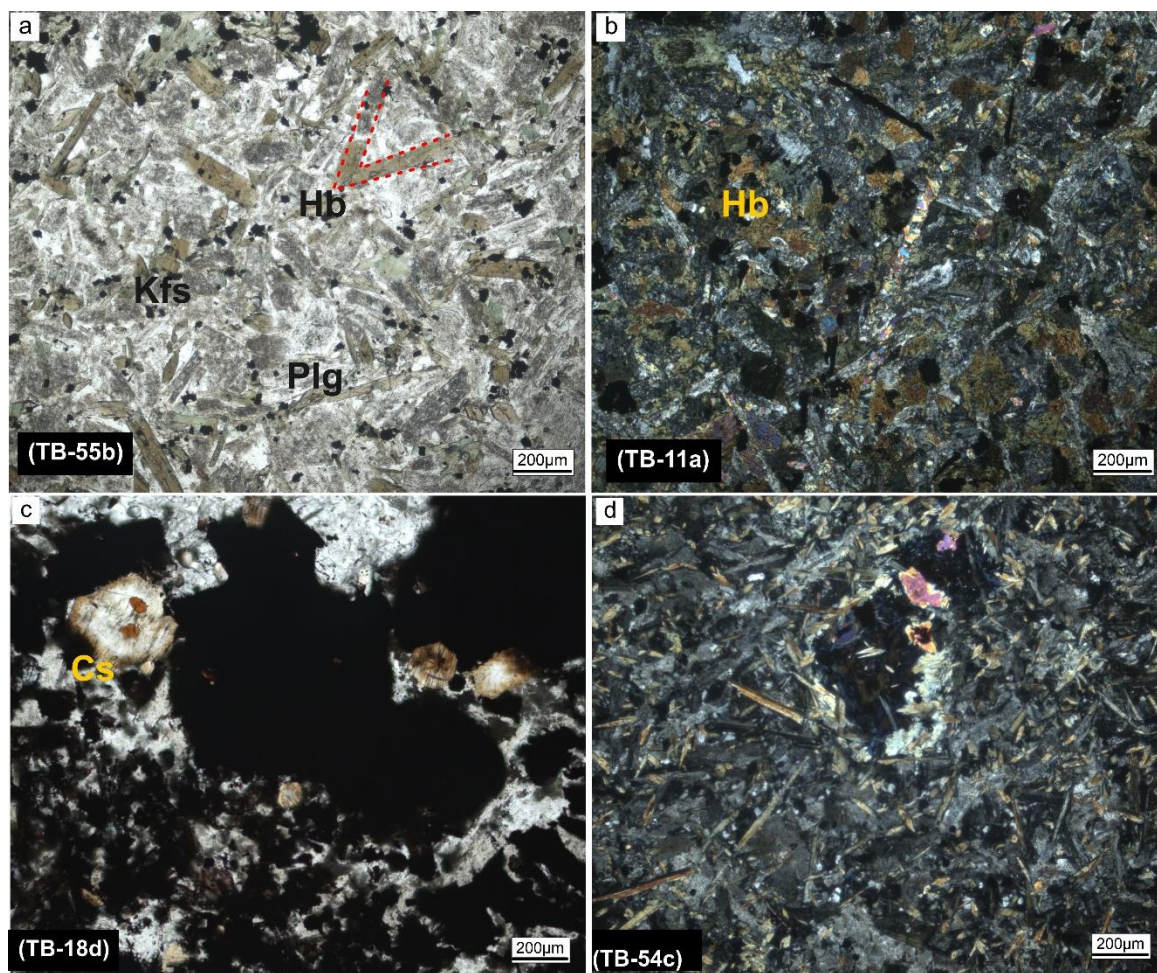


Figure. 11 (a, b, c) intergranular texture(subophitic) of hornblende and plagioclase, (c) cassiterite mineral within altered hornblende with iron oxides minerals. Abbreviation for Hb: hornblende, Kfs: k-feldspar, Cs: cassiterite, Plg: plagioclase.

Accessory Minerals

Most of the accessory minerals found such as titanite (sphene), zircon, cassiterite, and iron oxides appear in samples TB-55-a and TB-56a and b, TB-58, TB-11b, TB-20 (Fig. 9b and c, Fig. 13c). Cassiterite is observed in TB-11b on the surface of plagioclase crystals (Fig. 11 c). Zircon is dominant and found on the rims of other major minerals like albite, biotite, and hornblende (Fig. 9b). In sample TB-20, titanite is recognized with high relief and prismatic shape. The most abundant iron oxides in our samples are magnetite on the surface of hornblende, biotite, and pyroxene crystals. Hematite is also observed in the feldspar minerals and surrounding biotite grains.

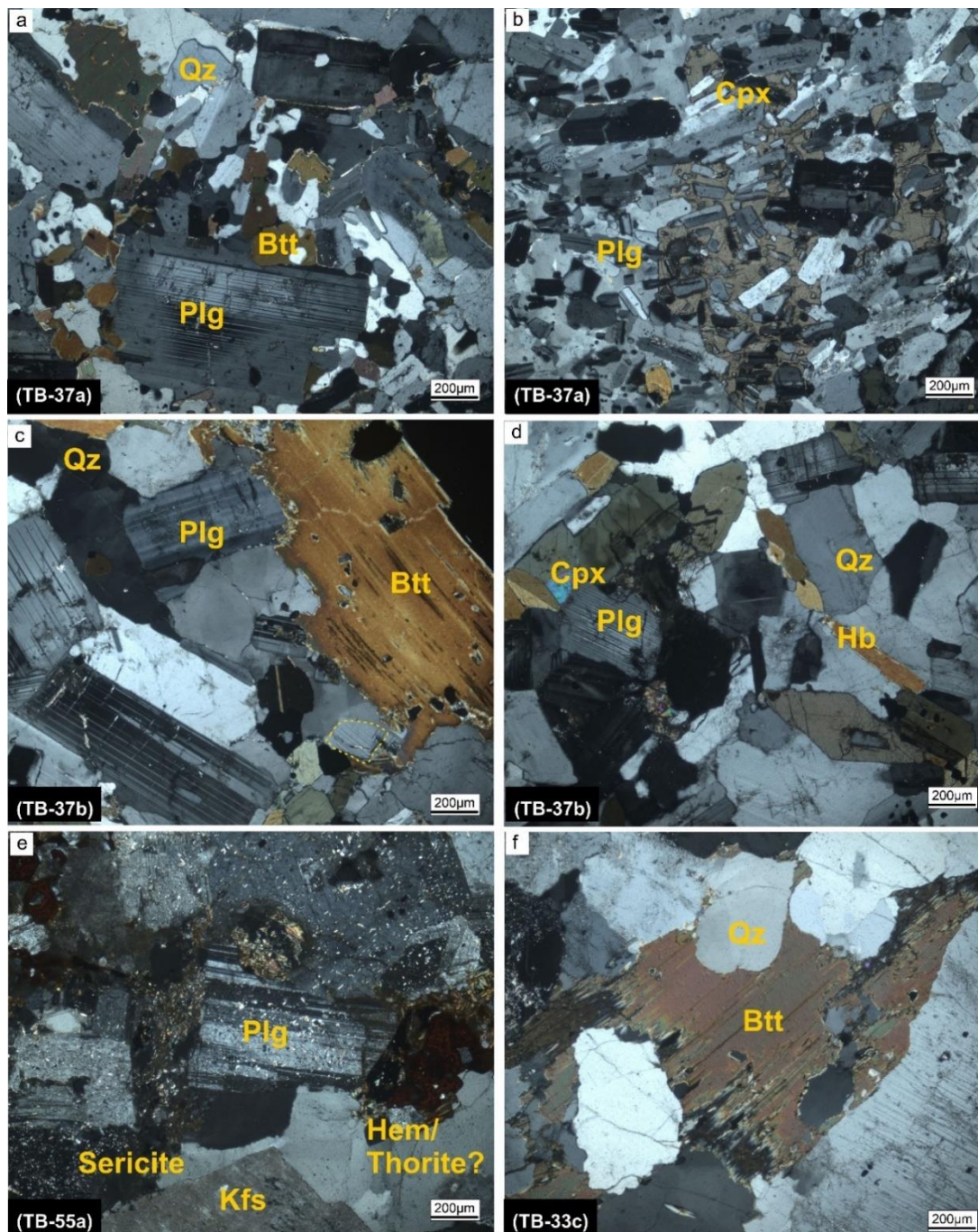


Figure. 12 (a) I- type -granodiorite showing biotite, plagioclase, and quartz. (b, c, d) biotite, pyroxene, iron oxide, with altered alkali feldspar, plagioclase with parallel twinning and quartz, (e) heavily altered plagioclase, k-feldspar by sericite and hematite are appearing the rims of quartz and plagioclase, (f) secondary biotite show alteration in the rims by chlorite. Abbreviation for Kfs: K-feldspar Plg: plagioclase, Cpx: clinopyroxene microcline, Qz: quartz, Btt: biotite, Hb: hornblende, Pyx: pyroxene, Hmt: hematite

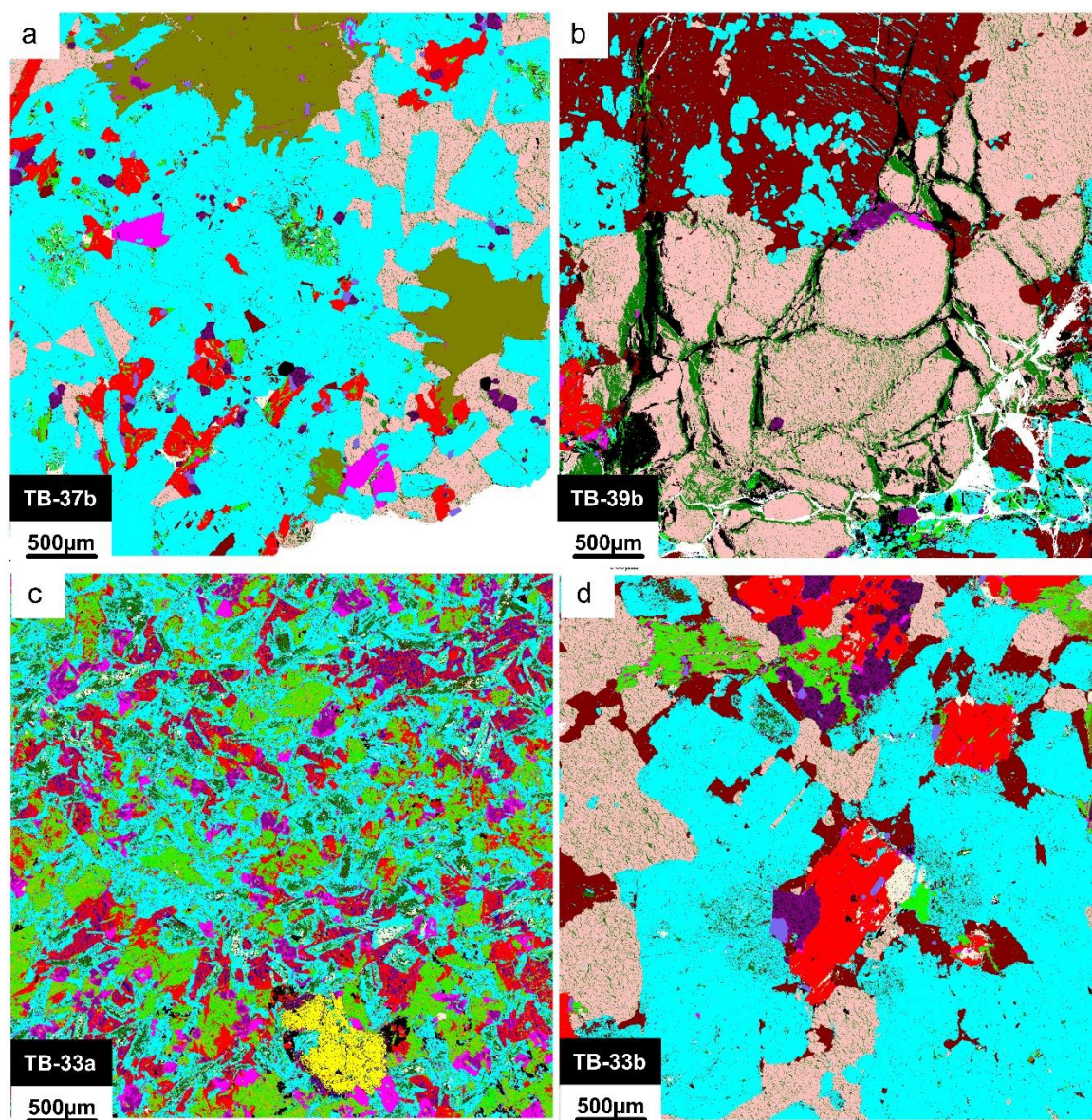


Figure. 13 QEMSCAN microphotographs showing the different mineral compositions, in particular mafic and accessories minerals in the I-type granodiorite rocks (a, b, c) reveal the small sphene crystals in the light purple color, pyrite yellow color, (d) medium-grained amphibole. For the mineral color index, see Fig. 15

4.2.2 Texture

In terms of texture, also observed different types of textures. (Fig. 8, 9, 10, 11, 12, and 14). The crystals display intergranular, intergrowth (graphic to micrographic), inclusion (poikilitic), and granophyric textures (myrmekitic, perthitic, and microperthitic). The manifest of these textures in the NW Midyan implies that the rock contains several accessory minerals, including zircon, which is observed in most of the samples, titanite, and cassiterite. Nevertheless, by examining the similarities or differences in the crystallographic orientation of minerals that replace others within individual grains in granites. This study concludes that this results from replacement through various alteration phases (albitization, sericitization, muscovitization, silicification, and hematitization), which can indicate a high/low-temperature hydrothermally altered and oxidized environment (Medzno and Allen, 1998; Rong & Wang, 2016).

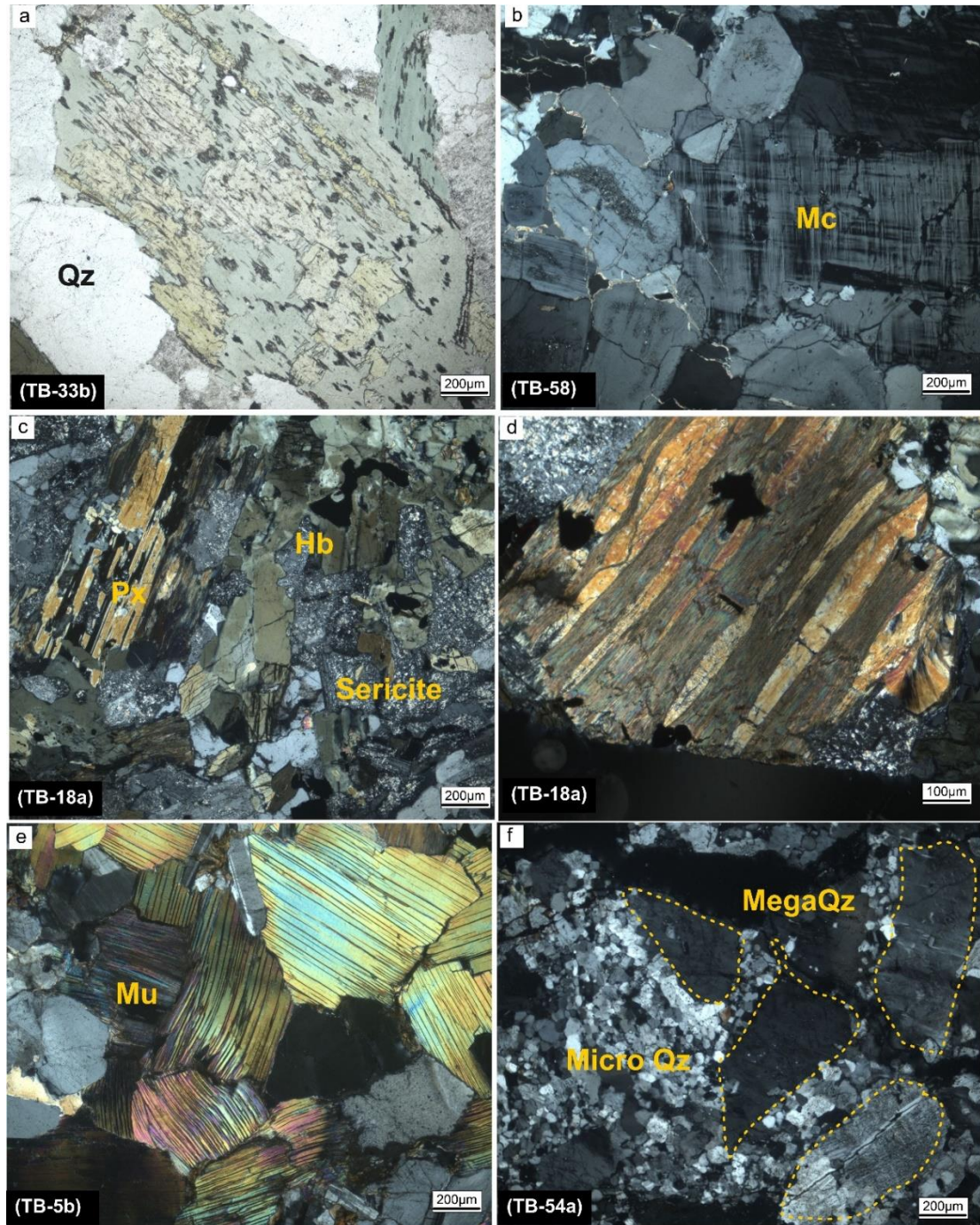


Figure. 14 (a, c) I-type granodiorite showing hornblende altered by pyroxene, sericite and surrounded by quartz, (b) coarse-grained microcline appears the cross-hatch twinning. (d) ??, (e) subhedral muscovite, (f) porphyritic texture shows mega quartz surrounded by fine-grained mass ground quartz. Abbreviation for Mc: microcline, Qz: quartz, Btt: biotite, Hb: hornblende, Pyx: pyroxene, Hmt: hematite, Mu: muscovite.

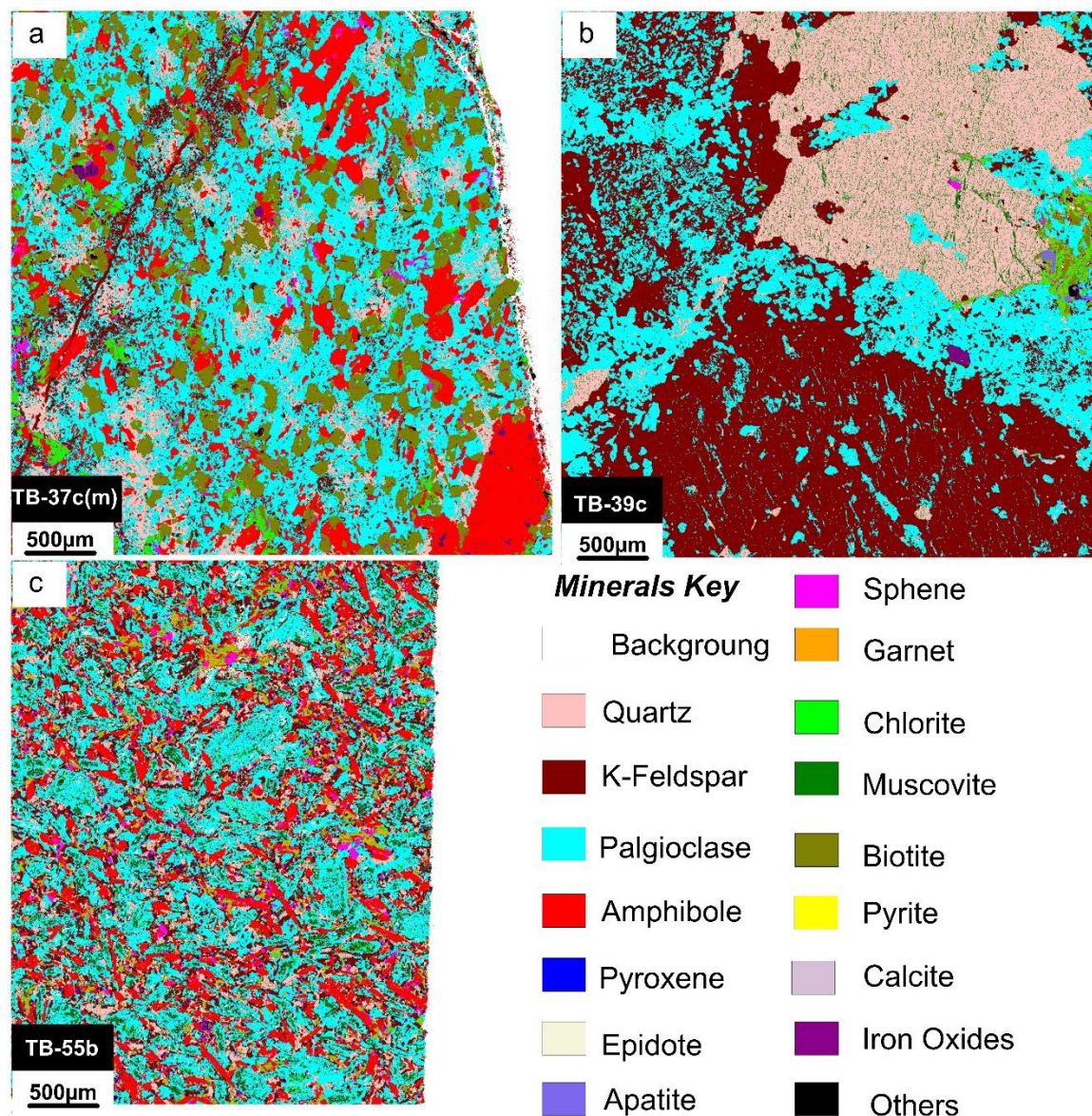


Figure. 15 (a, b, and c), the A-type biotite monzogranite consists of coarse to fine-grained plagioclase and quartz associated with amphibole.

4.3 NW Midyan Rocks Unit

Based on mineral chemistry in the previous section, we also rely on whole rock chemistry and TAS classification to divide thirty samples of the rocks in our study area into three groups: A-type, I-type granitoid rocks, and gabbro, described in the following section.

4.3.1 A-type Granitoid Group

This group occupies the northwest part of the Midyan region. It is most abundant in the Muwaylih and Lawas suite (Fig. 4). It is composed mainly of alkali feldspar, plagioclase, biotite, quartz, and muscovite as major minerals (see Figs. 8, 9, and 10). Zircon, cassiterite, and iron oxides are accessory minerals. Quartz is present in clusters and isolated with regular and irregular boundaries; intergrowth texture and graphic texture are present. Strained and undulatory extinction, in addition to wavy extinction, is also recorded. Potash feldspar is the most dominant feldspar in the rock and is depicted mainly by orthoclase perthite, microcline perthite, and microcline; it revealed as large anhedral to subhedral crystals partially altered to sericite (Fig. 9, 10, 11, 12, and 16). Plagioclases (mainly albite and oligoclase) are present with lamellar, multiple twinning, and minute inclusions of quartz. It commonly shows tabular shapes, perthitic textures, and zoning (Fig. 14). Biotite is the most abundant mineral, with pleochroic haloes resulting from the presence of radioactive zircon, altered to chlorite (Fig. 11, and 12). It exhibits a tabular elongated crystal behavior. Muscovite is rarely an essential mineral but is observed as such in some samples (Fig. 14). Pyroxene and hornblende show cleavages and simple twinning.

4.3.2 I- type Granitoid Group

This group represents the most abundant distribution and covers most complexes and suites, including the Ifal, Haql, Midyan, and Atiyah suites. This group is divided into two subgroups.

4.3.2.1 I- type Granodiorite

This group comprises coarse-grained, subhedral K-feldspar, quartz, and plagioclase. The alkali feldspar exhibits altered perthite exsolution textures (Brown, 1989). Medium-grained quartz displayed as anhedral to subhedral crystals; secondary biotite, amphibole, pyroxene, and some feldspar crystals are heavily altered to sericite, whereas other orthoclase is oxidized to hematite. Zircon grains are euhedral and subhedral and are present as inclusions on the pyroxene, biotite, and hornblende rims. Poikilitic textures are also observed (Fig.11, and 12). The biotite is variably shaped (tabular, prismatic) surrounded by fine-grained sericite, and altered by opaque minerals. Plagioclase represents variable sizes (> 5 mm) and zoned, twinned types (Fig. 12). It hosts some inclusions of

muscovite, opaque minerals, and biotite. The quartz is the second most abundant mineral with anhedral shape. K-feldspar (perthitic) is much less abundant than plagioclase and quartz. It is usually invaded by ferromagnesian minerals, especially biotite, but in some cases, there are sharp boundaries between these two minerals. The opaque minerals are often associated with other mafic minerals.

4.3.2.2 I-type (Diorite)

Diorite has a poikilitic texture and is mainly composed of plagioclase, hornblende, K-feldspar, clinopyroxene, sericite, zircon, and some fine-grained quartz as veins. Much orthoclase is mostly altered, and the hornblende shows a tabular shape, which makes an intergranular texture (Fig. 11). Large crystals of K-feldspar and quartz occur mainly as medium-grained crystals, subhedral, but anhedral fine-grained crystals occur as inclusions in alkali feldspar and plagioclase.

4.3.3 Gabbro

This group reveals a predominantly dark-colored matrix composed of minerals such as pyroxene, amphibole, and plagioclase feldspar. It has a very high content of amphibole minerals, up to 63% in sample TB-40a (Table 2) and shows a high content of chlorite and epidote. Felsic minerals are rare (see Fig. 11)

4.4 Whole Rock Chemistry

Thirty-seven samples were chosen for whole rock chemistry. Major and trace elements of the NW Midyan region granitoids show different compositions which are provided in (Tables 3 to 6). The primary basis for this classification is the geochemical analysis with the aid of the granitoid discrimination diagrams and petrographic description (see Chapter Four, section 4.1). All samples are categorized into two groups; I-type and A-type as provided below.

4.2.1 Major Oxides

The major elements data are provided in (Tables 3 to 5). The total alkalis-silica (TAS) (silica vs. $\text{Na}_2\text{O}+\text{K}_2\text{O}$) scheme of Wilson (1989), and the subalkalic subdivision diagrams of Le Maitre et al. (1989; 2002), were used to define and discriminate between felsic, intermediate, mafic, and ultramafic rocks. The NW Midyan samples are mainly felsic

to intermediate. The samples are mainly sub-alkaline (~90%) to alkaline (~10%) with high silica content between 55-77 wt.% comprising granite, granodiorite, diorite, and gabbro (Fig. 16a, and Fig. 18). In general, the granitic rocks cover a wide range of major oxides compositions. Hence, all samples in this study are divided based on the chemical contents and characteristics into A-type and I-type groups. To discriminate between A-type granites and other granites (M, I, and S-types) Stoeser & Frost (2006) and Whalen et al. (1987) used the 10,000 Ga/Al vs. Zr diagram. In our case, seven samples plot in the A-type field, and twenty-six plot in the I- and S-type field (Fig. 17a). The studied A-type granites of the NW Midyan terrane have 10,000Ga/Al ratios >2.5, which are higher than the average values of S- and I-type granites (<2.5). For additional validation that our samples are a part of the I-type group, we use the discriminating I-type and S-type granitic rock K₂O vs. Na₂O diagram (Chappell and White, 1974) (Fig. 17b).

Here, the I-type group shows a diverse range of SiO₂ (54.08-77.48 wt.%), and comparatively high total alkalis (Na₂O + K₂O) ranging from 2.40 to 11.2 wt.%, TiO₂ (0.09–1.8 wt.%), Al₂O₃ (12.48–18.61 wt.%), K₂O (0.52–5.34 wt.%), and low contents of MgO (0.10–5.46 wt.%), and high to low content of F₂O₃ (10.3–6.9 wt.%) (Table. 3). In the K₂O vs SiO₂ graph Peccerillo and Taylor, (1976), this granitoid group indicates a medium to high-K affinity and only one sample (TB-33c(m)) reveals very low K with increasing silica content (Fig. 16b). However, A-type granitoids are characterized by SiO₂ (75.46-86.69 wt.%), somewhat high total alkalis (Na₂O + K₂O) ranging from 9.5 to 7.3 wt.%, TiO₂ (0.12–0.120 wt.%), Al₂O₃ (12.71–19.11 wt.%), K₂O (2.29–5.93 wt.%), and low MgO (0.14–5.25 wt.%), and high to low content of F₂O₃ (9.4–1.4 wt.%) (Table. 3 to 5). In the K₂O vs SiO₂ diagram of Peccerillo and Taylor, (1976), the A- type granitoid group shows a high to the very high positive correlation of K₂O with increasing silica (Fig. 16b). Moreover, the other major oxides Al₂O₃, Fe₂O₃, MgO, CaO, Na₂O, TiO₂, MnO, and P₂O₃ show decreasing with increasing silica content.

The modified alkali lime index (MALI, Na₂O + K₂O-CaO) vs SiO₂ reveals the contact between calc-alkalic, alkali-calcic, calcic, and alkali granitoid (Frost et al., 2001). This diagram emphasizes the sub-alkaline to alkaline signature of our samples. Nevertheless, it demonstrates that most of the A-type samples fall in the alkali to calc-alkali

fields whereas the majority of I- types fall in the calc-alkaline domain. Samples containing 50 to 65 wt% SiO_2 are calcic to calc-alkalic (Fig. 18), whereas those with > 65 wt% SiO_2 are typically classified as calc-alkalic to alkali-calcic.

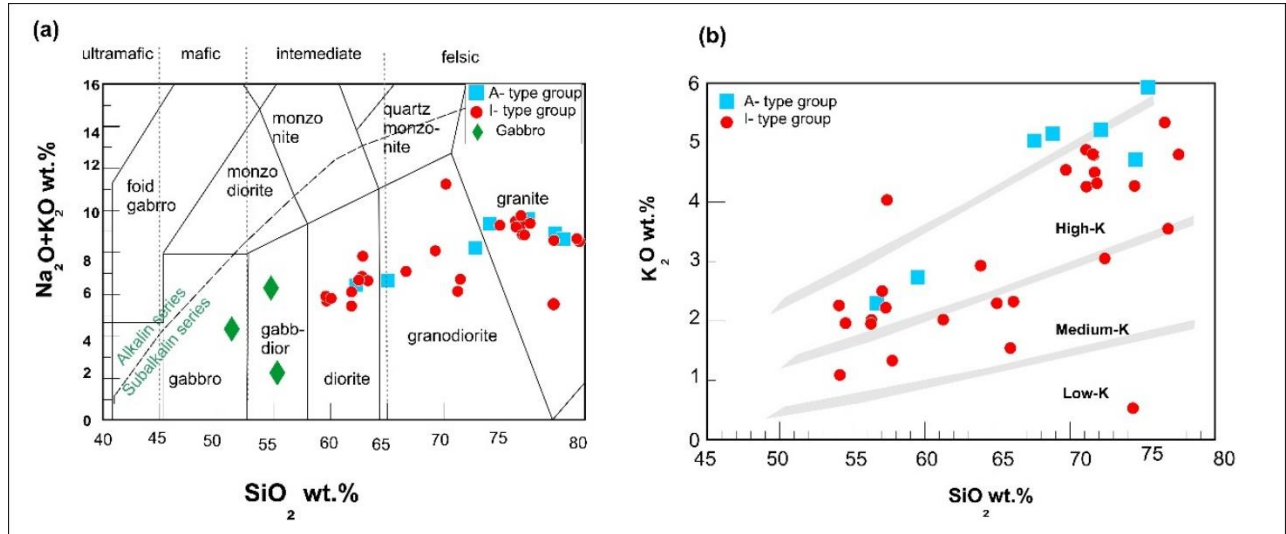


Figure. 16 (a) total alkalis-silica (TAS) plot of Middlemost (1994) showing the fields of all major igneous rock types (plutonic) and the subdivision of rock types into ultramafic, mafic, intermediate, and felsic. Subdivision of the sub-alkaline series from the alkali of sub alkaline series from the alkaline series is shown by a dashed line, (b) K_2O vs SiO_2 plot, showing the high, medium, and low calc-alkali series (Peccerillo and Taylor, 1976).

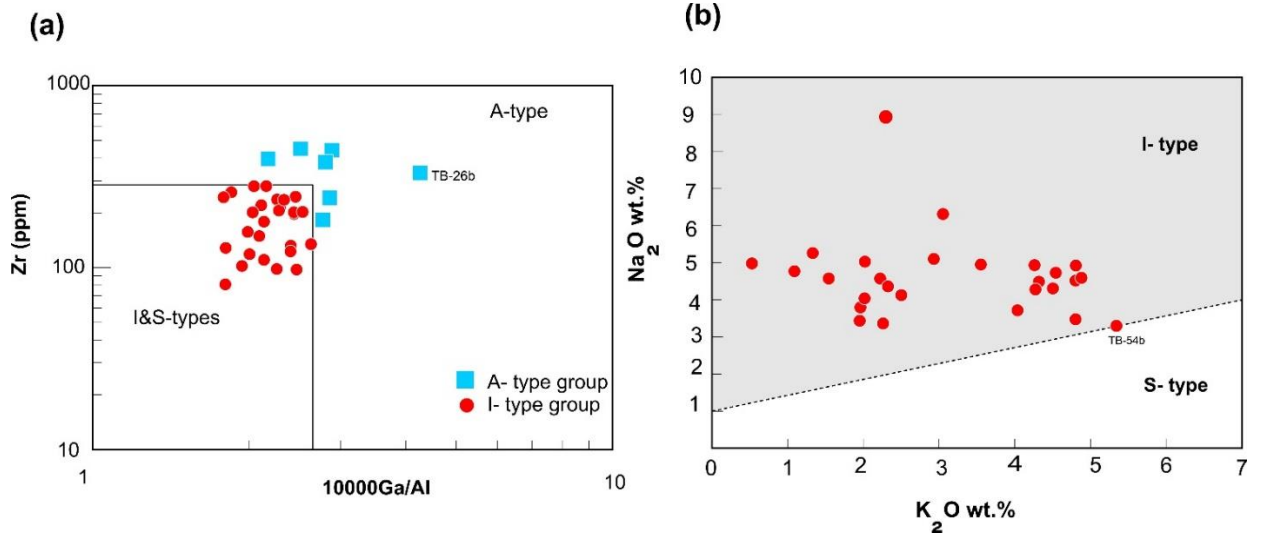


Figure. 17 (a) Distribution of granitoids types on the 10^4Ga/Al vs Zr plot (Whalen, 1986), and (b) Na_2O vs K_2O diagram. The line is the border of I- and S-type granites (after Chappell and White, 1974)

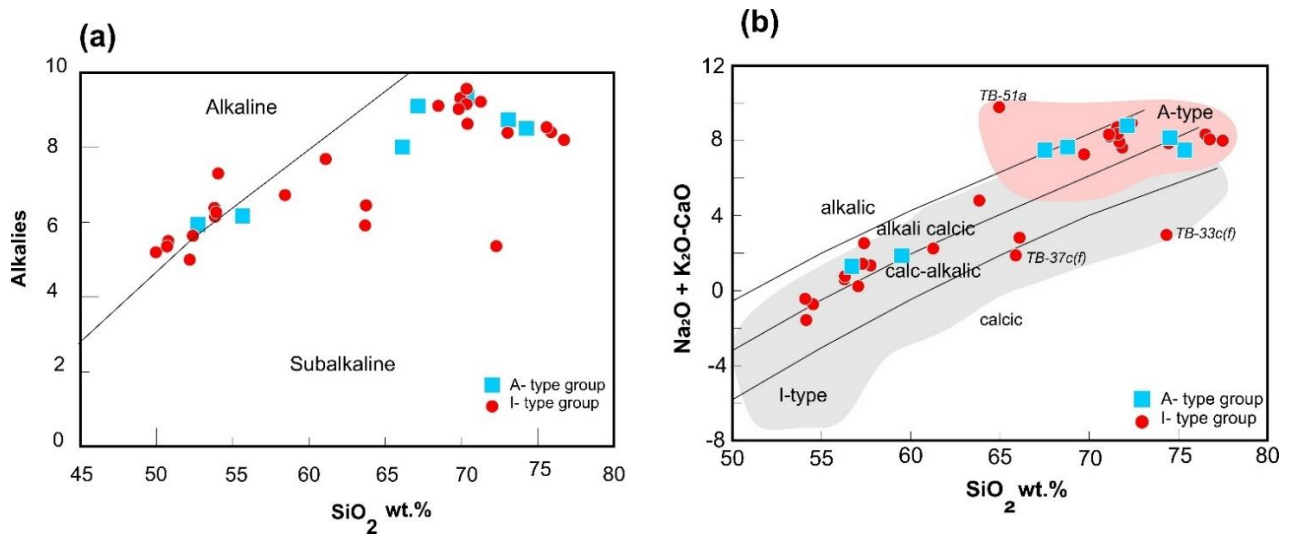


Figure. 18 (a) diagram of alkalis versus silica illustrates the sub-alkaline nature of the NW Midyan (from Irvine and Baragar, 1971), (b) Modified alkali lime index ($\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$) vs. SiO_2 (%) of the A-type and I-type granitoid group, (from Frost et al. 2011).

The NW Midyan granitoid displays similarities in major oxide characteristics (Fig. 19). Selected major elements are graphed against SiO_2 , which is utilized as a differentiation index. The nine oxides include TiO_2 , MnO , MgO , CaO , P_2O_5 , Na_2O , Al_2O_3 , Fe_2O_3 , and K_2O (Fig. 16b, Fig. 19, and Fig. 20). Most of these oxides show negative correlations with SiO_2 (Fig. 19). Decreasing MgO , Fe_2O_3 and CaO towards high silica content with progressive eliminate of mafic minerals (clinopyroxene, biotite, and amphibole) from a mantle-derived parent magma. In contrast, K_2O reveals a positive correlation, forming a data array that spans across the medium- to high-K divide (Gill, 1981) in samples with ≤ 65 wt% SiO_2 . Samples with higher silica abundances have K_2O abundances largely coincident with the high-K field (Fig.16b). The TiO_2 , P_2O_5 , MgO , and CaO concentrations vary considerably at lower SiO_2 abundances but scatter less and decrease to lesser values at greater SiO_2 contents. The Al_2O_3 abundances also decrease, with increasing SiO_2 and increasing with inflection at $\sim 65\%$ wt.% SiO_2 suggesting that feldspar fractionation may have played an important role during granite formation. Na_2O shows a linear correlation with increasing silica, except for two samples that show a high positive correlation (TB-51a and TB-55a, Fig. 20 b). In summary, the variation plots of the SiO_2 versus the major oxides of the A-type samples range from a maximum of 75.36 to a minimum of 56.69 wt.% SiO_2 , while the I-type range from 54.08 - to 77.48. wt% SiO_2 .

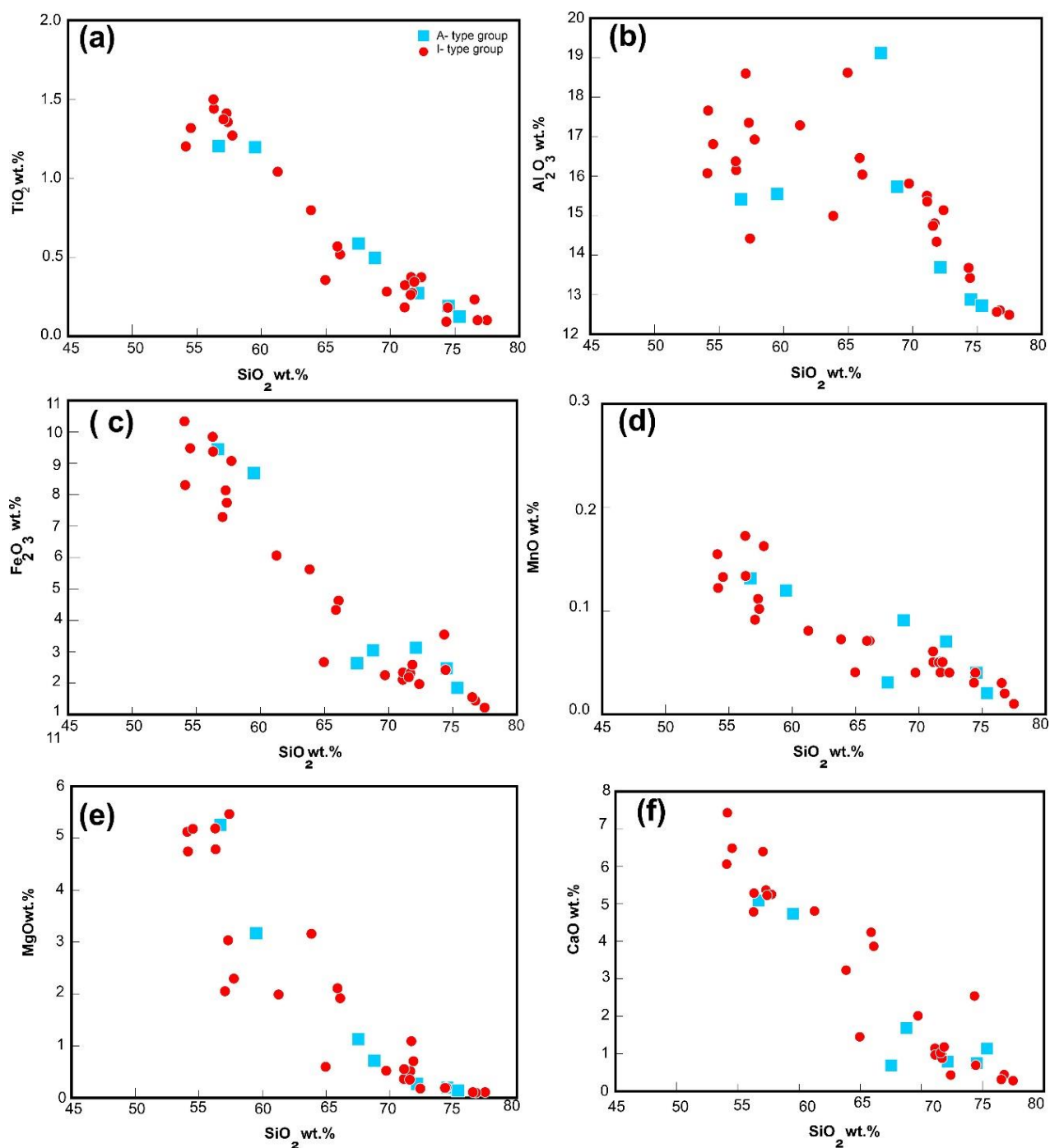


Figure. 19 Selected Harker diagrams for the NW Midyan terrane. (a to f), showing a clear negative correlation with SiO_2 .

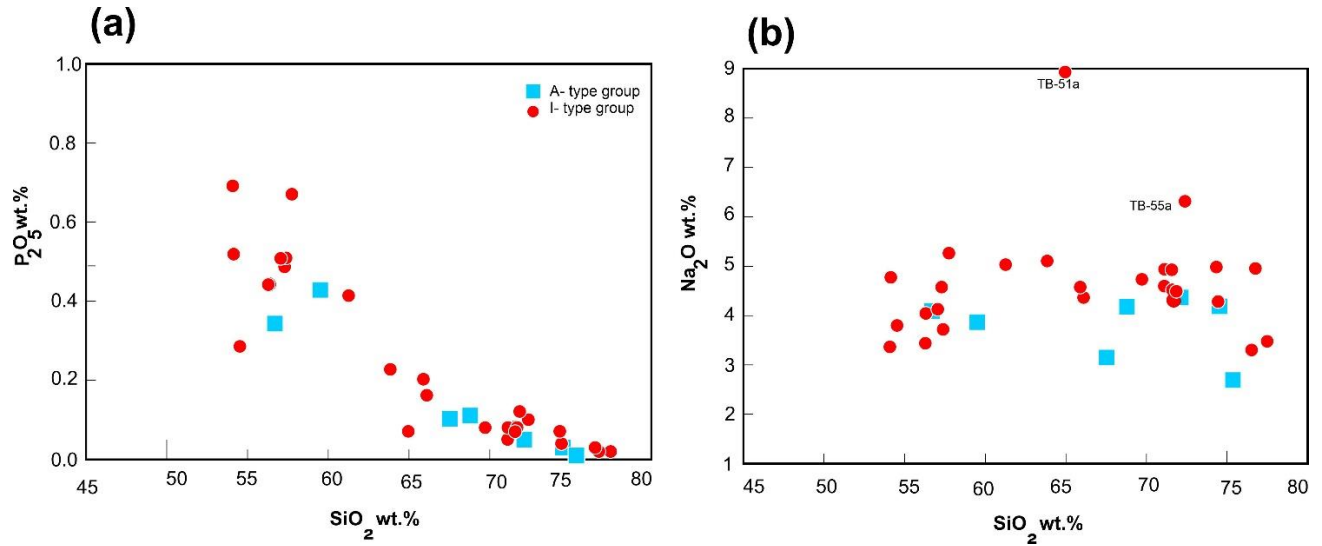


Figure. 20 Selected Harker diagrams for the NW Midyan (a) show a negative trend with increasing silica content, and (b) linear correlation Na_2O vs. silica.

According to the classification scheme of Maniar and Piccoli (1989) of ANK ($Al_2O_3/Na_2O + K_2O \geq 1.0$) versus ACNK ($Al_2O_3/CaO + Na_2O + K_2O \leq 1.1$) (Fig.21a), the I and A-type samples show strongly to moderately metaluminous signature >1.1 , except for one sample of the A-type group (TB- 18b) which shows a peraluminous behavior < 1.5 related to their high aluminon content. Moreover, on the ASI (molar $Al_2O_3/CaO + Na_2O + K_2O$) (Forest et al., 2001) classification, all the rock types are mainly metaluminous to slightly peraluminous. This high aluminum content is like Midyan granite in the western Midyan terrane (Lashin et al.,2023) (Fig. 21b).

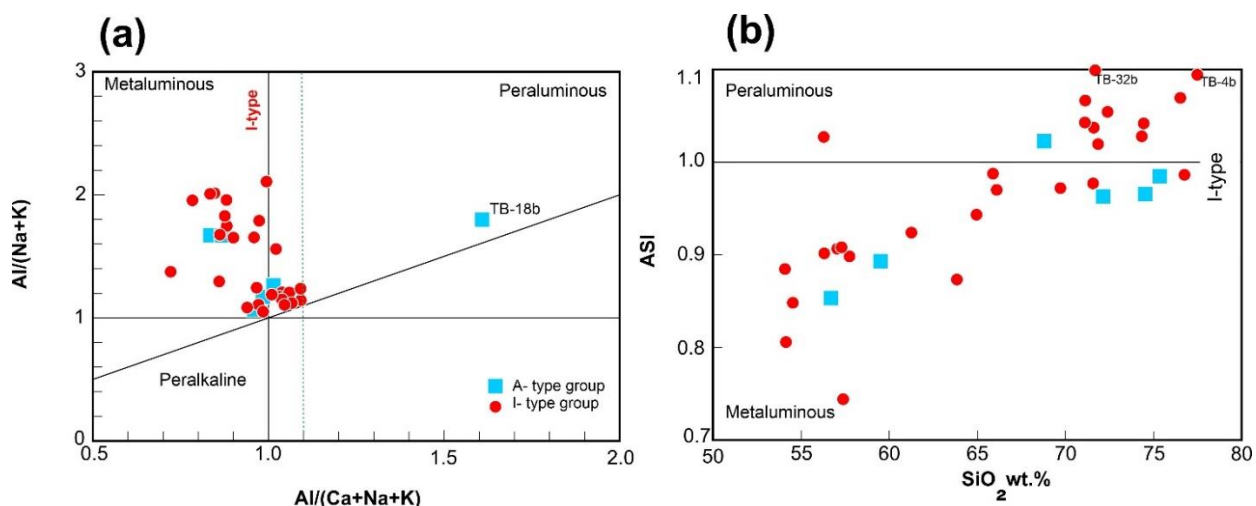


Figure. 21 (a) A/CNK (molar $Al_2O_3 / (CaO + (Na_2O + K_2O))$) vs. A/NK ($Al_2O_3 / (Na_2O + K_2O)$) diagram (Shand, 1943), showing major-element compositional variation, and metaluminous nature for the A and I-type samples, (b) Aluminum saturation index (ASI) versus SiO_2 plot portraying the A and I-type composition for NW Midyan region.

4.2.2 Trace Elements

Variations of selected trace elements Sr, Ba, Nb, La, and Rb against SiO_2 are shown in (Fig. 22). Sr exhibits a defined linear trend, and it decreases with increasing SiO_2 . Sr of I-type samples have concentrations from 30.4 ppm to 856.2 ppm, which is consistent with SiO_2 , which ranges from 54.08 to 77.48 wt%. Furthermore, the Sr of A-type has a concentration from 47.4 to 656 ppm, which is consistent with SiO_2 , which ranges from 75.36 to 56.50 wt%. This variable value might relate to fractional crystallization (Chappel, 1996). Nb, La, Rb, and Ta increase systematically with increasing silica (Fig. 22b, c, and e). The I and A- types groups are enriched with Ba (927 to 1585 ppm), reflecting the high percentage of micas and feldspars.

In addition, Th, U, Cs, Ce Y, and Pb are highly fluctuating but increase slightly with increasing silica content. In contrast, the concentrations of Co, Sc, V, and Zn decrease regularly with increasing silica. Cr, Ni, Ga, and Cu are highly variable but also decrease slightly with increasing silica content. Ni in I-type rocks ranges between 1.8 -85.4 ppm while in the A-type, Ni ranges from 1.3 – 4.3 ppm. The high Ni value reflects the mantle

source, while the low value indicates crustal contamination. Some elements, such as Hf, Mo, Sn, and W, display no consistent variation with varying SiO₂ content.

Abundances of Zr increase in A-type samples with increasing SiO₂, ranging from 183 to 450 ppm, and then show decreases with increasing silica content in I-type. Samples with lesser Zr content from 63.7 to 280.7 ppm.

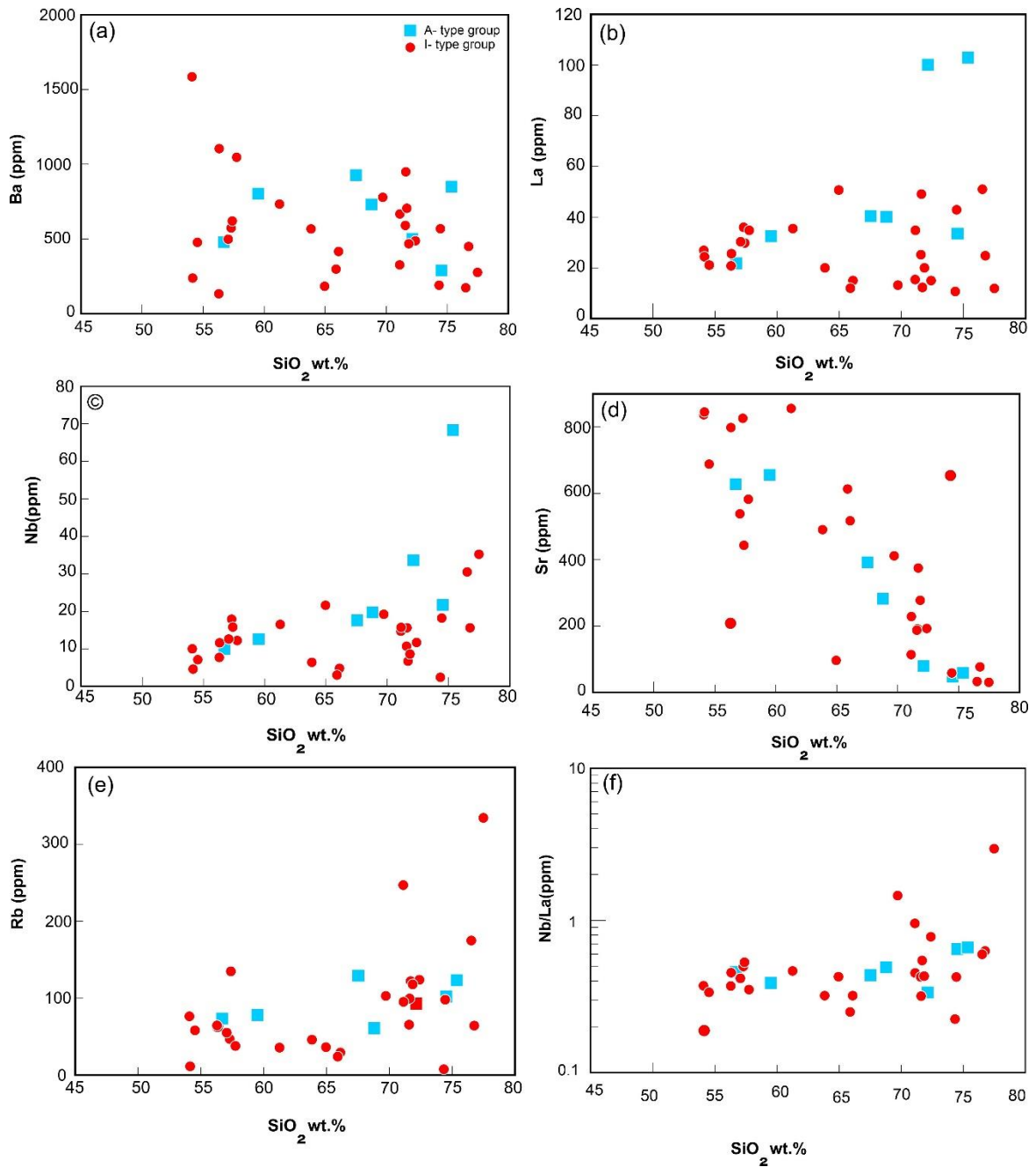


Figure. 22 Harker plots of selected trace element concentrations of the NW Midyan region.

4.2.2 Chondrite-Normalized REE and Primitive-Mantle Normalized Diagrams

Multi-element spider diagrams have been shown to be an effective means for distinguishing the tectonic setting of granitoids (Moghazi, 2002). Chondrite-normalized rare earth element (REE) and primitive mantle-normalized diagrams for incompatible

elements in various granitoid groups are presented in (Fig. 23 and 24). The A and I-type granitoid group on the chondrite-normalized (REE) diagrams show enrichment in the LREE relative to the HREE, indicative of different geochemical signatures depending on accessory minerals that crystallized within the magma (Fig. 23). REE for all the samples show variation patterns, for example some rocks have strong to moderately developed negative europium anomalies which may indicate feldspar fractionation (McDonough, 1995). The generalization of TB.33c(f) of the I-type revealed a positive anomaly, as shown in (Fig 23c). A positive Eu anomaly in some samples (Rollinson, 1993) may indicate cumulates and unfractionated plagioclase and amphibole material remained in the residue, which is characterized by a flatter REE pattern. The Eu/Eu^* for the whole rock ranges from 0.22 to 3.44. In A-type samples Eu/Eu^* is 0.22-0.96, whereas in I-type samples Eu/Eu^* is 0.24-3.24. In contrast, some samples are characterized by a smooth negative slope and show a listric-shaped (or concave-shaped) pattern as the result of depletion in MREE (Sm – Ho, particularly Dy, and Ho) relative to LREE and HREE. These patterns of MREE depletion are attributable to amphibole fractionation (Davidson et al., 2007; Whattam et al., 2024).

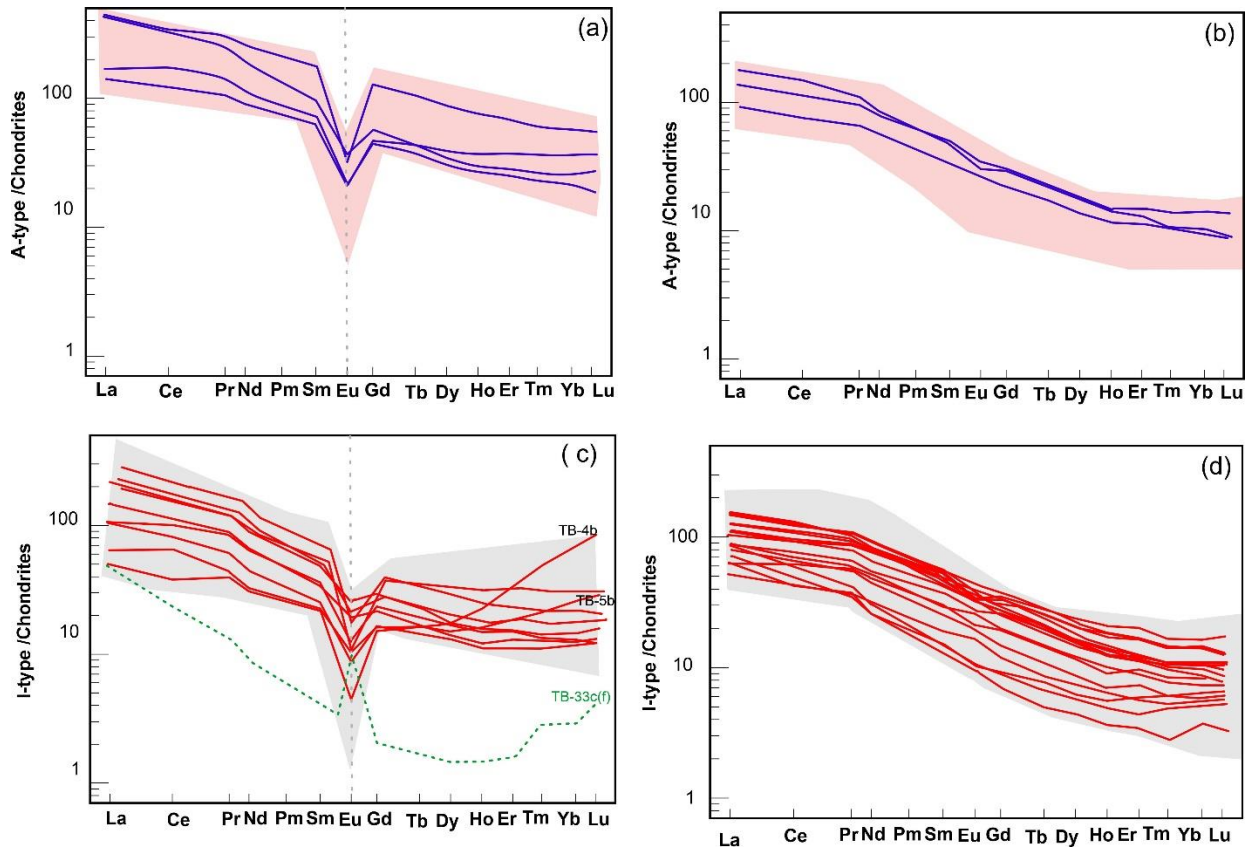


Figure. 23 (a, b) Chondrite-normalized REE patterns of the A-type granite, and (c, d) I-type granite (chondritic abundances from Sun and McDonough, 1989), the shaded area compared with (Robison et al.,2017).

The Sun & McDonough (1989) primitive mantle-normalized plots for the NW granitoids are presented in Fig. 24. The various granitic samples represent clear similarities in their patterns. They are enriched in some large ion lithophile elements (LILEs), alkali metals, and alkaline earth, such as Rb, K, Ba, and Cs. Meanwhile, samples show depletion in high field strength elements (HFSE) (Nb, Ta) average = 32.55 ppm of Gd, and enrichment in Rb (334.3 ppm), Ba (1585 ppm), and Th (29.9 ppm). This depletion represents the proprieties of subduction-related rocks and results in the chemical differentiation of arc-related magma (Taylor and McLennan,1995). Relative concentrations of K, Rb, and Sr in granitoid rocks are largely governed by feldspars (Hanson,1978) through degrees of fractional crystallization and partial melting. Nevertheless, some samples show strongly depleted in Sr, P, and Ti indicating extreme feldspar fractionation (Clarkson, 1980; Lee,

2016; Möller, 1984). Which is consistent with the geochemical signature of A-type granite (Jahn et al., 2000). The negative anomalies in Eu are related to feldspar fractionation during magma crystallization. Meanwhile, the very low Eu/Eu* in the granites can be attributed to melt-fluid interaction at the end phase of magma evolution (Irber, 1999; Jahn et al., 2001). Moreover, all samples revealed negative Nb anomalies of comparable depth, which are the quintessential signatures of subduction-related magmatism. (Fig. 24).

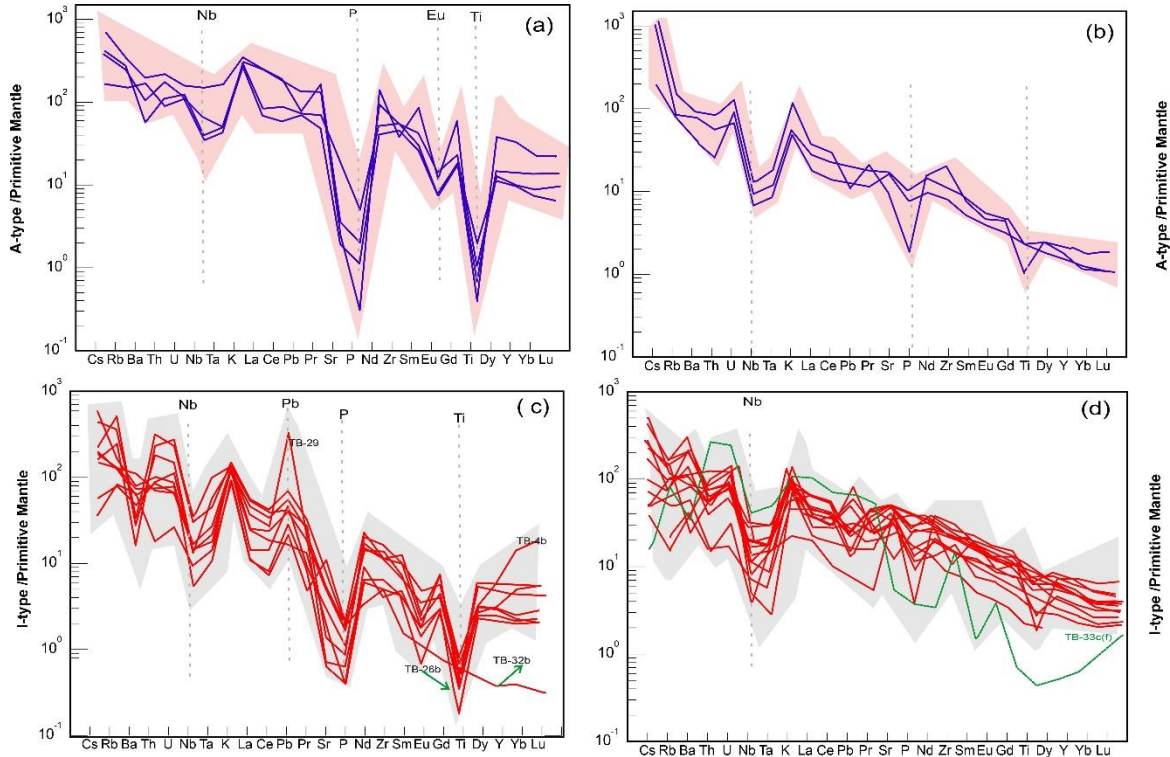


Figure. 24 primitive mantle (PM)-normalized plots of NW Midyan intrusive (after McDonough and Sun, 1995).

4.3 Whole Rock Isotopes

Ten samples were chosen for whole rock isotopic analysis of Sr, Nd, and Pb. The results of the $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios are listed in Table 6. The initial $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were calculated based on a SHRIMP zircon U–Pb age of 600 Ma. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ of our samples are mostly homogenous, ranging from +0.70291 to +0.9743 and +0.73016 to +0.70619 for the I and A-type groups, respectively (Fig. 25). The Nd values of the A-type granite (25.8 -116.9 ppm) are relatively high compared to those of I-type granite Nd values (4 -45.4 ppm). The $\epsilon\text{Nd}(t)$ isotope data of the A-type granites gave positive values

varying from +5.8 to +4.65 with T_{DM} ages from 849 to 947 Ma (Table 9), while I-type shows $\epsilon Nd(t)$ of +6.05 to +3.80 with T_{DM} age of 818- 984 Ma.

Initial $^{143}Nd/^{144}Nd$ ranges from +0.512506 to +0.512727 for the I-type granitoid, whereas initial $^{143}Nd/^{144}Nd$ ranges from 0.512515 to 0.512643 for the A-type granites. Generally, I-type has initial $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios of 21.5774 to 18.0826 and 39.4690 to 37.6790, respectively, and $^{207}Pb/^{204}Pb$ of 15.4734 to 15.6565. The A-type records $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios of 18.3666 to 18.6226 and 38.0571 to 38.5351, respectively, and $^{207}Pb/^{204}Pb$ of 15.4976 to 15.5922. The $^{207}Pb/^{204}Pb$ isotope ratios lie slightly above the Northern Hemisphere Regression NHRL, Hart (1984), (Fig.25). Studied granites are similar in terms of initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ to those of Arabian Shield Neoproterozoic arc terranes but extend to more radiogenic Pb isotope compositions (Fig. 25). Overall, the trends of $^{143}Nd/^{144}Nd_{(i)}$ ratios with SiO_2 and $1/Nd$ are both horizontal for the granite samples, which clearly demonstrate the magma differentiation trend for the granites and also shows that some samples have different sources.

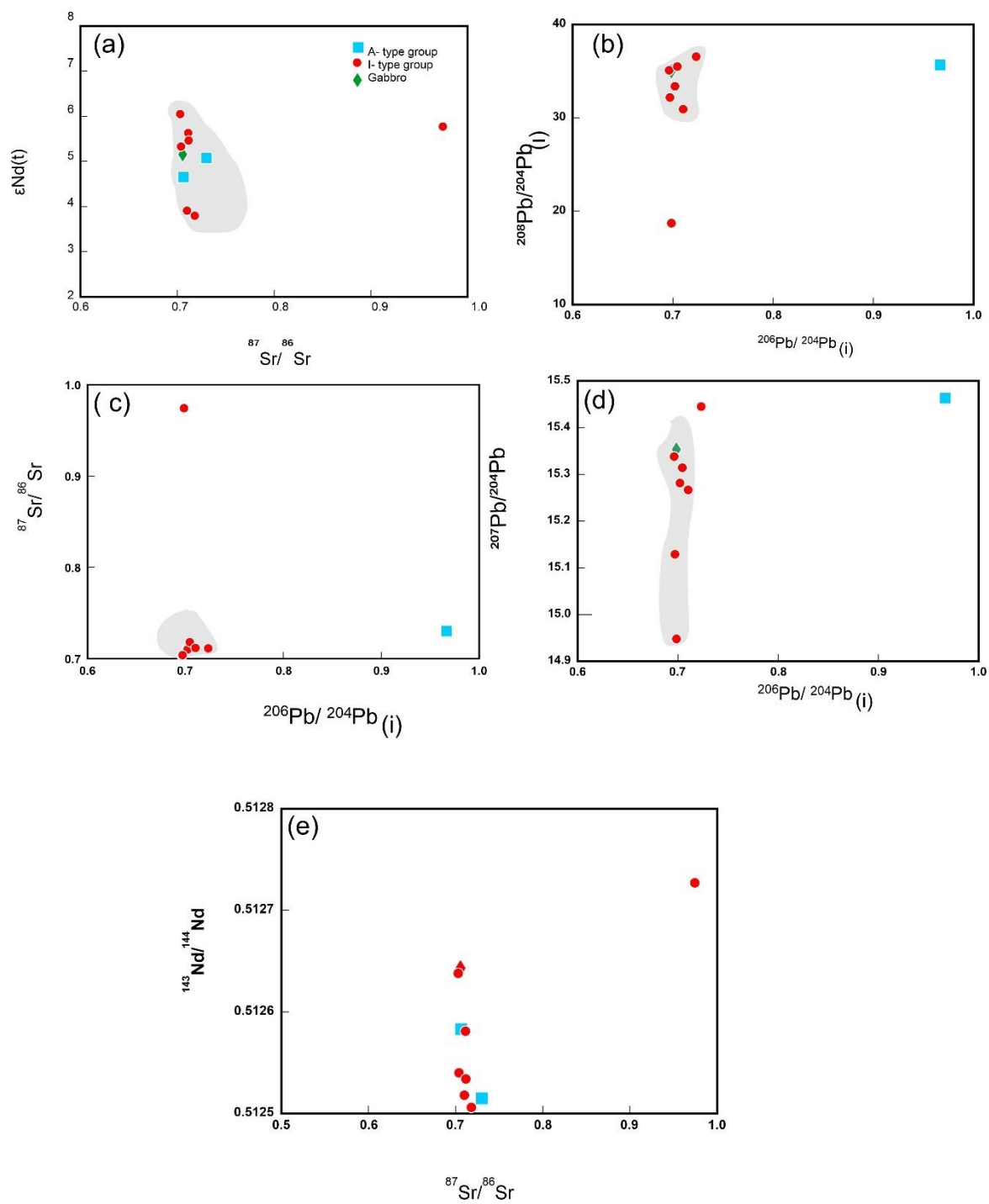


Figure. 25 Sr, Pb isotope correlations of A- and I-type granitoid rocks from the NW Midyan region.

4.4 U-Pb SHRIMP Zircon Dating

Zircon plays a crucial role in tectonic studies as it serves as a significant indicator of parent isotopes for age determination (Hoskin and Schaltegger, 2003). The significance of zircon in studies of crustal evolution is emphasized by its primary application in U-Th-Pb geochronology. Besides that, this mineral contains a considerable fraction of U, Th, Hf, and REEs (O'Hara et al., 2001). This study has selected nine samples of granites (samples TB-11b, TB-29, TB-39b, TB-51a, TB-55a, TB-55b, TB-20, TB-4b, TB-5b) for U-Pb SHRIMP zircon dating. To study the internal textures of zircon, we used cathodoluminescence (CL) imaging (Hanchar and Watson, 2003) (see Fig. 26,27).

Zircon grains exhibit distinct oscillatory zoning, 63 μm to 245 μm , and a 20–25 μm spot size which is the prevailing texture in igneous zircons. The majority of zircon grains are euhedral, elongated, and prismatic, displaying well-developed zoning that indicates a magmatic origin for the granitoids. However, some grains are subhedral. (Fig. 26). Some samples show zoning in the grains rim while the core shows elliptical, or circle-shaped cores mantled by overgrowth. However, some samples reveal xenocrystal cores with rim overgrowths, suggesting magmatic zircons (e.g., as in TB-55a) with different growth directions. Although, in some samples, zircon is elliptical and appears to have various degrees of roundness (TB-55b, Fig. 27). Some zircon grains also show cracks, small-scale zoning, and patchy textures.

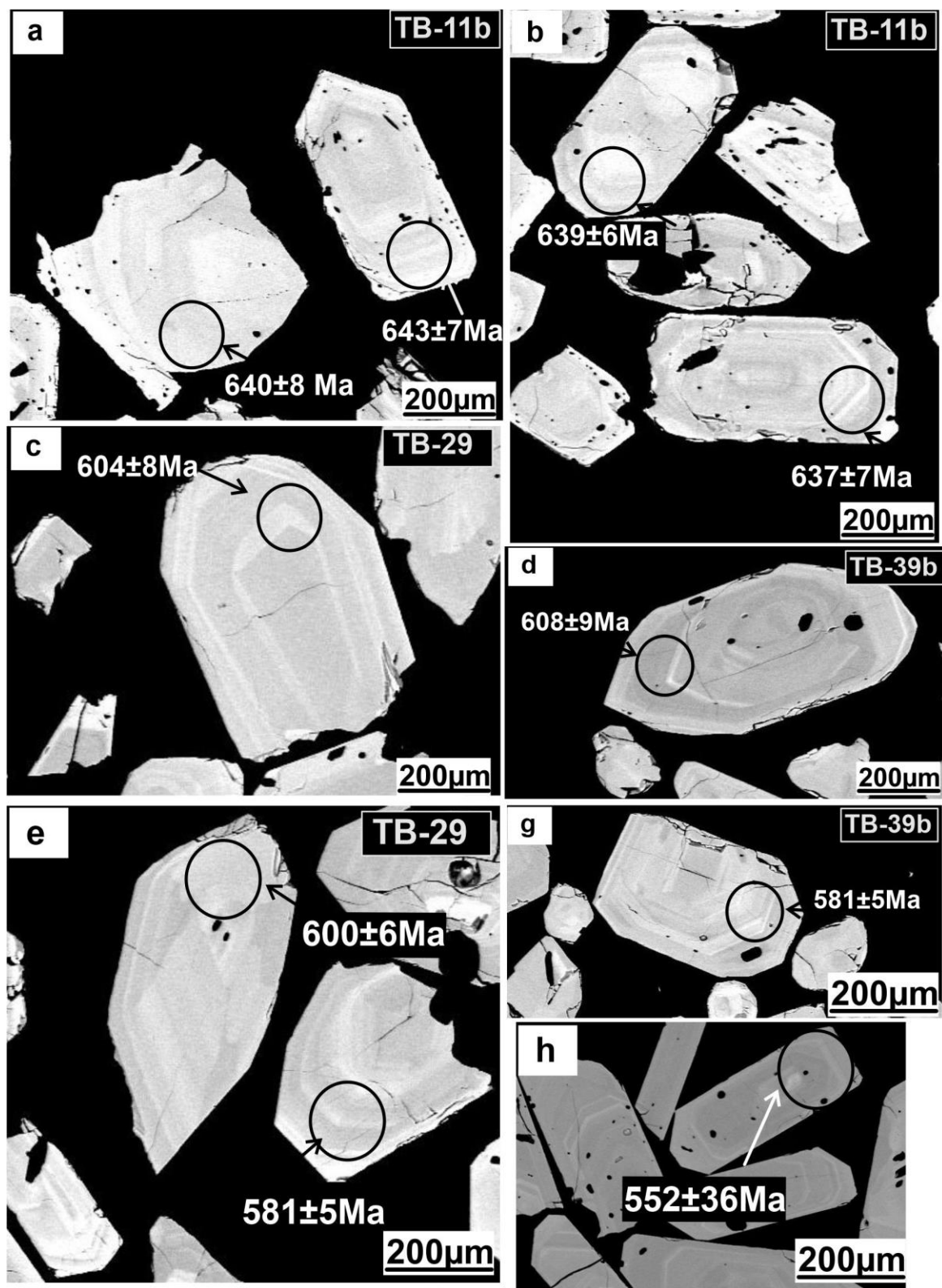


Figure. 26 Cathodoluminescence (CL) images of selected zircon crystals from the various rock types. Circles indicate the location of the analysed spots.

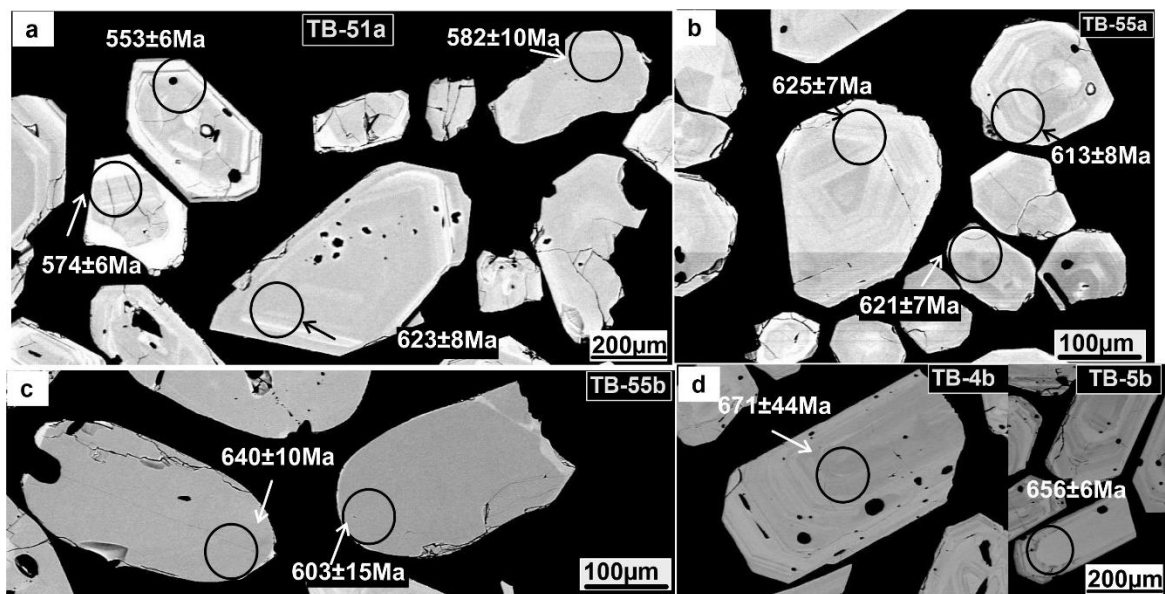


Figure. 27 Cathodoluminescence (CL) images of selected zircon crystals from the various rock types. Circles indicate the location of the analyzed spots.

The Tera–Wasserburg Concordia plots are illustrated in (Fig. 28), and all spot data analyses are given in (Table 7). In addition, all analyzed zircons of this study have high Th/U ratios ranging from 0.1 to 1.7% demonstrating their magmatic origin (Chen et al., 2007). Ages range from 597 to 640 Ma. The following sections provide more details.

4.4.1 Concordia Plots of A-type Group

Sample TB- 11b

The zircon grains have well-developed growth zoning representing prismatic and elongated crystals with good terminations, as well as subhedral to euhedral (Fig. 26 a and b). They show variable grain size. They have Pb^{206}/U^{238} ratios that range from 1.2- 2.5 (Table 10). The analyses involve 15 spots that plot on the Concordia diagram (Fig. 28), and varying age from 660 ± 11 to $596 \pm$ Ma (MSWD = 1.5). The Pb^{207} – corrected Pb^{206}/U^{238} age = 640.7 ± 5.3 Ma (Fig. 28), with Th/U ratios 0.43- 0.93. Spot TB-11B_4.1 shows a high of 1.7% of ^{206}Pb .

Sample TB-20

Grains show well-zoned euhedral and subhedral shapes. Some grains show overgrowth in the grain core. 25 spot analyses show an age range of 611 ± 5 to 586 ± 5 Ma. The Pb^{207} – corrected $\text{Pb}^{206}/\text{U}^{238}$ age yields an age of 597.6 ± 2.2 Ma (MSWD = 1.1), with Th/U ratios 0.27- 0.63 (Fig. 27 and 28).

Sample TB-55b

The zircon crystals show various degrees of roundness with ovoid shapes, and some do not present clear cores and rims (Fig. 27c). Eight spots were examined and are shown on the Concordia diagram in Fig.28. The age ranges from 668 ± 8 to 603 ± 15 Ma. The Pb^{207} – corrected $\text{Pb}^{206}/\text{U}^{238}$ age = 624.11 ± 1.4 Ma (MSWD = 1.4) (Fig.28), with Th/U ratios of 0.42 - 0.76.

4.4.2 Concordia Plots I- type Group

Sample TB-55a

Some zircons show subhedral with ovoid shapes. 15 spots were analyzed to calculate the samples age which ranges from 635 ± 9 to 556 ± 10 . Spot TB-51a_21.1 shows the highest ^{206}Pb (7.97%). The Pb^{207} – corrected $\text{Pb}^{206}/\text{U}^{238}$ age = 618.6 ± 5.7 Ma (MSWD = 1.6), with Th/U ratios 0.72- 1.96, typical of zircons crystallized from an igneous melt (Fig. 27 b and Fig. 28).

Sample TB- 29

The zircon grains here are euhedral to subhedral and prismatic, with well-developed zoning showing a magmatic origin. 20 spots were analyzed and the age ranges from 631 ± 8 to 517 ± 6 . The Pb^{207} – corrected $\text{Pb}^{206}/\text{U}^{238}$ shows an age of 604 ± 4.5 Ma (MSWD = 0.99), with Th/U ratios (0.40- 1.07), (Fig. 26c).

Sample TB- 39b

Some zircons are rounded and detrital whereas other samples show xenocrystal cores with rim overgrowths indicating a magmatic origin. 16 spots were analyzed, and it revealed ages from 616 ± 6 to 581 ± 5 Ma. The Pb^{207} – corrected $\text{Pb}^{206}/\text{U}^{238}$ age = $603.5 \pm$

6.0 Ma (MSWD = 1.9), with Th/U ratios 0.63 - 1.56, ideally of zircons crystallized from an igneous melt (Fig. 27, 28)

Sample TB-51a

Zircon crystals are euhedral to subhedral and vary in length. Some samples show zoning in the grain's rim, while the core shows elliptical or circle-shaped cores mantled by overgrowth. 15 spots analyses show an age range of $628. \pm 7$ - 327 ± 4 Ma. (Fig. 28). The Pb^{207} – corrected $\text{Pb}^{206}/\text{U}^{238}$ age = 598.9 ± 6.1 Ma (MSWD = 1.8) (Fig.28), with Th/U ratios (0.70 - 1.63).

Sample TB-4b

Some zircon grains show cracks. Moreover, other grains show small-scale zoning and patchy textures. 31 spots were analysed and the $^{206}\text{Pb}/^{238}\text{U}$ ages range from 582 ± 7 to 90.5 ± 2 with Th/U ratios of 0.37 to 1.93 (Fig. 28).

Sample TB- 5b

Some grains show oscillatory zoning. 29 spots were analysed and yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 669 ± 4 to 241 ± 3 with Th/U ratios of 0.26 to 0.85.

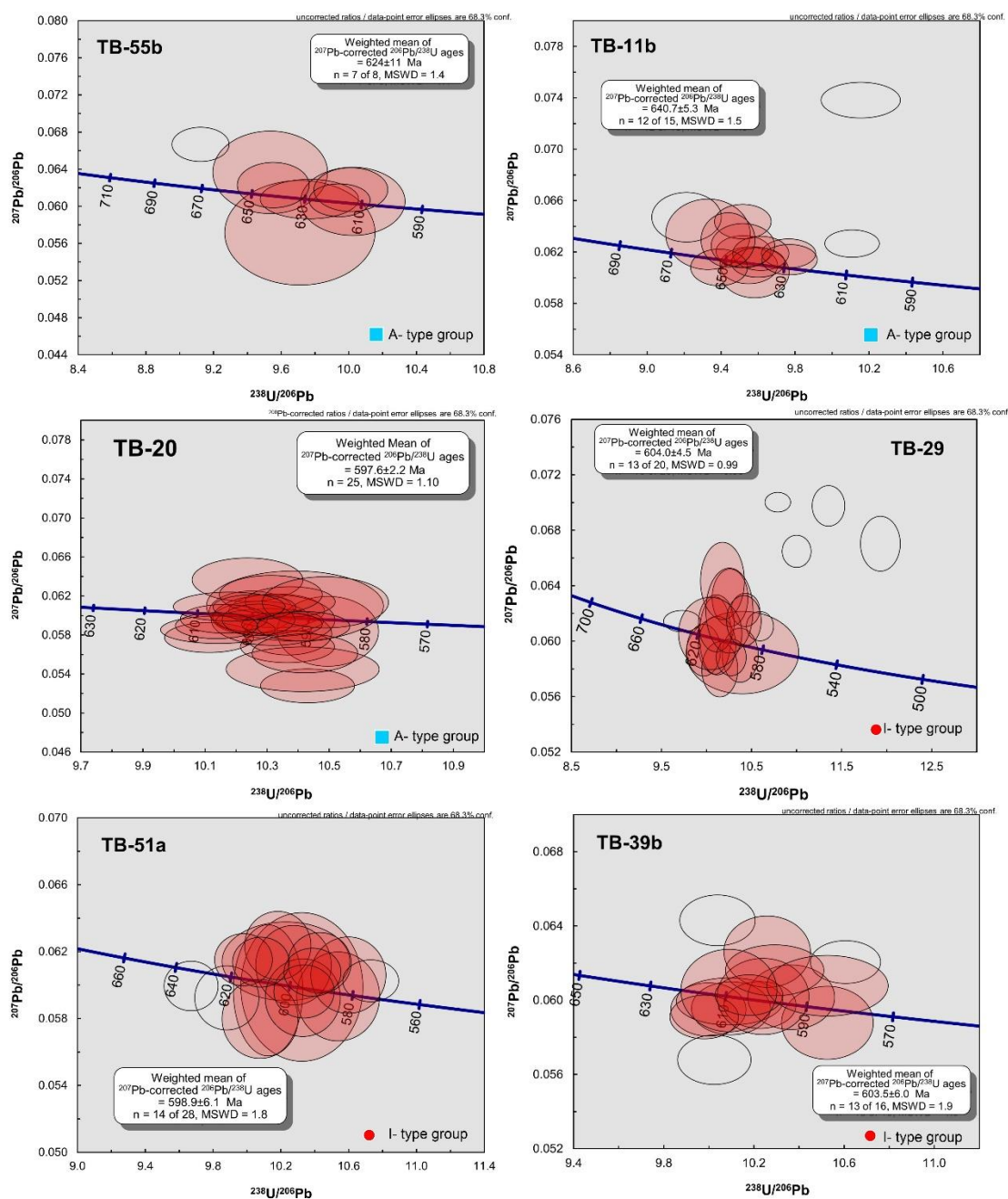


Figure. 28 Concordia plots of dated A-type samples TB-(55b, 11b, and 20) and I-type samples TB (29, 51a, and 39b).

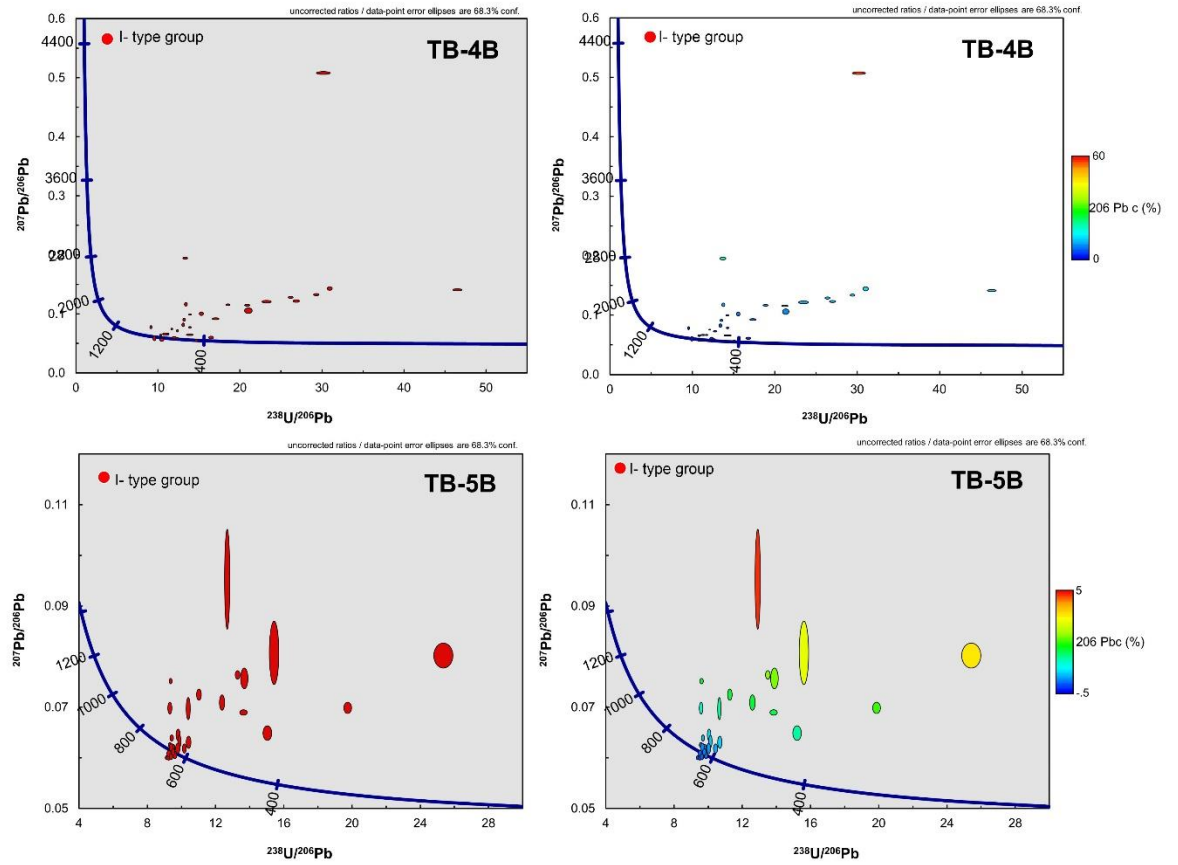


Figure. 29 Concordia plots of dated I-type TB-4b and TB-5b samples.

4.2 Temperature estimation

Zircon and apatite are two mineral phases for which saturation temperatures have been calibrated experimentally as a function of melt composition (Watson, 1984). The high Zr contents (see the Supplementary Material) and the presence of crystallized zircon grains in some granite samples suggest that the melt was saturated in Zr at the magma generation stage (Miller et al., 2003). The magmatic temperatures of metaluminous and peraluminous granitic rocks are estimated by zircon saturation thermometry (Crisp & Berry, 2022; Hanchar & Watson, 2003) on a diagram of whole rock Zr vs $M (\text{Na} + \text{K} + 2\text{Ca})/\text{Al}^*\text{Si}$. I-type granite yield temperatures of $\sim 650\text{--}800^\circ\text{C}$ (see Fig. 19) and A-type yield crystallization temperatures of $750\text{--}900^\circ\text{C}$ (Fig. 30). Most of the I-type granite formed at the lower magmatic temperature (Chappell et al., 2000). The significant Zr content in the

analyzed A-type granitoids (Table 4) suggests that they originated from a melt of notably high temperature (King et al., 1997).

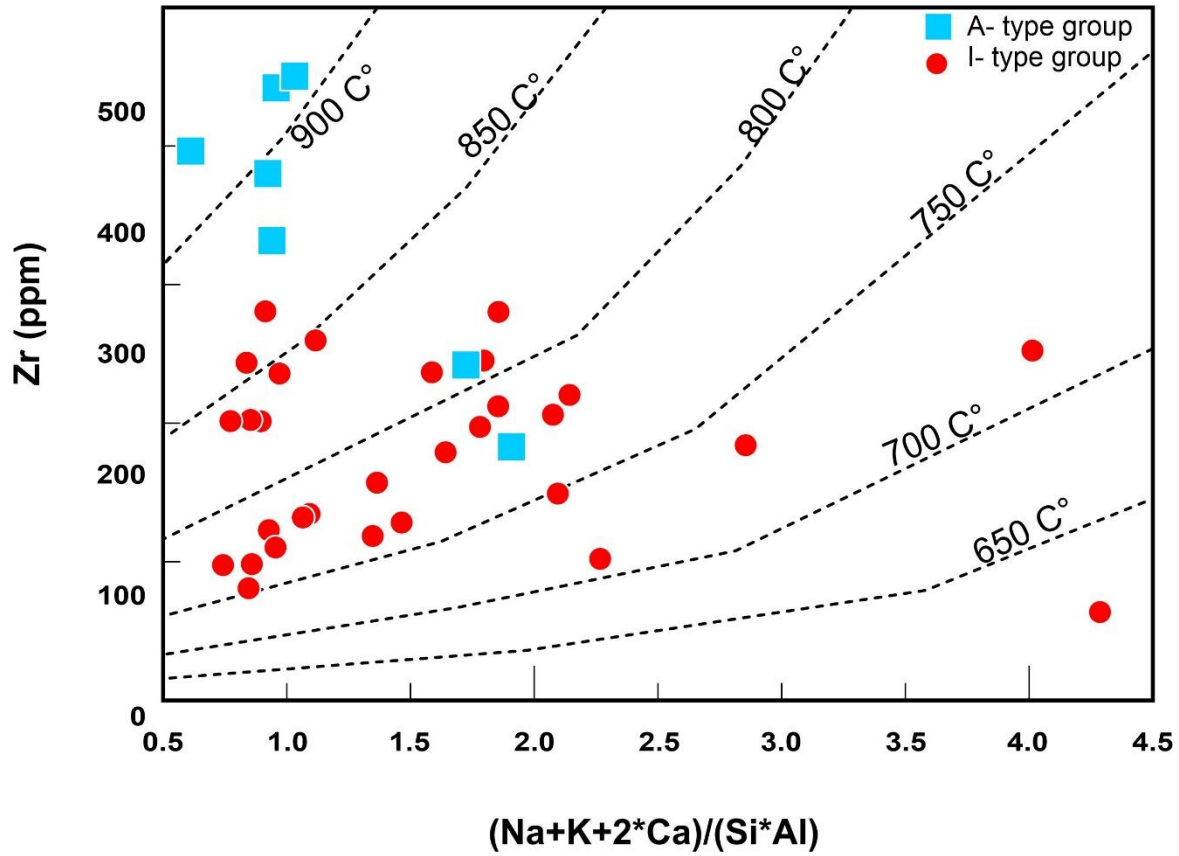


Figure. 30 Zircon saturation temperature of Midyan terrane A- and I-type granitoids of this NW Midyan region (from Watson & Harrison, 1983).

CHAPTER 5

DISCUSSION

The petrogenesis and tectonic history of the NW Midyan terrane is not well understood. Based on our results, this chapter provides a novel interpretation of the tectonic setting, environment, and magmatic source.

5.1 Tectonic Affinities

This study is the initial one to date on the granites in NW Midyan using modern, precise techniques (SHRIMP U–Pb zircon). Rocks were gathered from different localities across the study area (Fig. 3). According to Robinson et al. (2017), the forming of the granitoid complexes in the northern part of the Arabian-Nubian Shield happened in three different geological times starting at 650 to 600 called the Late Cryogenian. Followed by the 620–600 Ma period is characterized by alkali feldspar granite with alkaline/ferroan/A-type geochemistry. Around 599 Ma, granite cumulates (garnet-bearing) exhibit calc-alkaline/magnesian affinities, while from 584 to 566 Ma, alkali feldspar granite (aegirine-bearing) shows a distinct peralkaline/ferroan/A-type signature. The granitoid samples of this study of the NW Midyan region date from ~640 to 597 Ma. Based on that, two different ages of magmatism intrude the NW Midyan region (1) the ~600-645 Ma group classified as A-type granite, and (2) the ~597 to 620 Ma group classified as I- type and A-type granitoid, (Fig. 28). However, this is interpreted by several authors as a transition from late orogeny to post orogeny (Johnson and Katten, 2012; Fritz et al., 2013; Robinson et al., 2017).

5.1.1 Whole Rocks Chemistry

The chemistry of NW Midyan terrane granitoids is variable in the sense that each has rock types, which, based on chemistry, suggest differing tectonic environments. For example, on a $\text{FeO}^T / (\text{FeO}^T + \text{MgO})$ vs SiO_2 diagram, the samples with ferroan geochemistry composition are considered to be A-type granite due to mantle pulses toward

the lower crust including the youngest dated age in NW Midyan. Bonin (2007) considered that not all the A-type granite in the ANS is ferroan, which is formed by partial melting and fractionation. In some cases, it has been linked to a mantle source (Frost et al., 2001; Frost & Ronald Frost., 2011) (Fig. 31).

Trace Elements and Granitoid Discrimination

Delfour (1974) classified the middle and northern parts of the Arabian Shield and suggested that the Arabian Shield recycled continental crust to produce crystalline rocks (Al-Shanti, 2003). The Midyan terrane resulted in the formation of an island arc or continental marginal arc crust above the developing subduction system throughout the Late Proterozoic. Stoesser and Frost (2006) classified these terranes as Neoproterozoic oceanic affinity. In the Arabian Shield, numerous models have suggested that the origin of post-collisional A-type magma includes mantle and partial melting of the continental crust (Abuamarah, 2021; Frahay and Azer, 2011). To distinguish between these magmas, including I or A-type granite this study provides several diagrams showing their types and tectonic setting (Fig. 32). The A-type granites have been subdivided based on Nb–Y–3Ga and Nb–Y–Ce discrimination into two types, A1 and A2 (Eby 1992,1990). A1 is defined by element ratios similar to oceanic island basalts (OIB), and the other (A2) is similar to sources associated with granitic rocks originating from continental crust or underplated crust that has undergone continent-continent collision or island arc magmatism (Fig.31b, d). The Rb/Nb vs. Y/Nb discrimination diagram of Eby (1992), indicates that the A-type granites fall into the A2 group (Fig. 31c), suggesting a post-orogenic tectonic setting inconsistent with those from other parts of the ANS. The A-type granite granitoids are interpreted to have formed in a post-orogenic setting based on the discrimination diagrams. This interpretation is consistent with geological evidence indicating that these plutonic rocks in NW Midyan were emplaced during an extensional regime associated with the post-collisional collapse of the Pan-African Orogeny (Stern, 1994; Greiling et al., 1994).

The widely used trace element plots by Pearce et al. (1984), specifically the Rb vs (Y+Nb) and (Yb+Ta) vs Rb diagrams, are valuable tools for distinguishing different tectonic settings of granitoids. In this study, the chemical porosities of the studied granitoids are associated with volcanic arcs and within-plate settings (Fig 31 c, d), when compared

chemically with similar granitoids in the Arabian Shield, supporting the suggested interpretation. Notably, according to Pearce et al. (1984), the high Rb content of VAG and post-COLG comes from an enriched mantle or subducted crust and is possibly subduction-derived fluids. High Rb in the WPG comes from the combination of limited degrees of involvement of enriched lithospheric mantle. However, the changes in the Nb+Y composition of the differing granite types were considered by Pearce et al. (1984) to be mainly a partial melting effect of asthenosphere mantle origin. On the other hand, the (Y vs Nb), (Yb vs Ta) discrimination (Fig. 31a, b) of Pearce (1996) shows that all samples plot in VAG to WPG which is linked to the post-collisional setting. The integration of all samples is considered to be representative of a post-collisional granite environment.

Moreover, in Yb/Ta and Y/Nb versus Ce/Nb space (Fig. 31 e, f), most of the A and I-type granite samples fall in the OIB field. These samples have chemical behaviors like those observed for OIB and thus suggest formation as mantle-derived with an intraplate environment. This also suggests that the magma originated from an enriched mantle source with minimal crustal contamination through the ascent of the mantle. On the contrary, A2-type granites are like rocks of continental crust or island arc sources formed at collisional plate margins. Accordingly, the NW Midyan A -types fall in the A2 subgroup and overlapping the OIB field, align with an intraplate setting (Fig. 31 e, and f). If OIB is associated with A1, this contrasts with the Eby (1990) plot, which shows that they are A2.

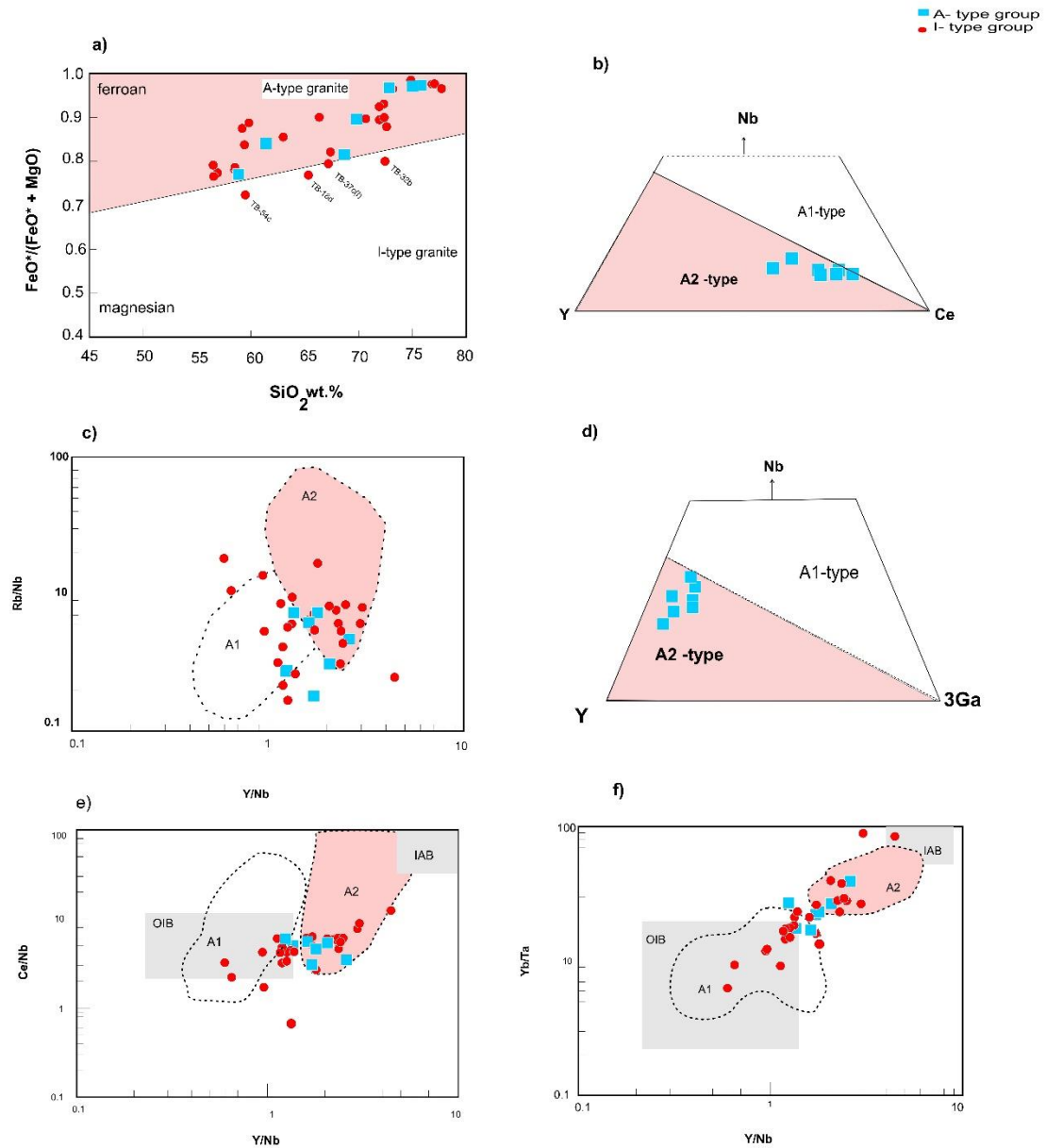


Figure. 31 a) $\text{FeO}^*/(\text{FeO} + \text{MgO})$ versus SiO_2 diagram after Frost et al. (2001) showing the distribution of the A – and I-type granitic rocks with respect to the ferroan and magnesian fields (e, f) Nb/Ta versus Y/Nb, Y/Nb versus Ce/Nb diagrams and Y/Nb versus Y/Nb, Y/Nb versus Ce/Nb diagrams and Y/Nb versus Rb/Nb for the NW Midyan region A-type granites (Eby, 1992). OIB = oceanic island basalt; IAB = island arc basalt.

The major and trace elements chemistry of igneous rocks bears a strong relationship to their tectonic formation setting. In the SiO_2 vs Rb/Zr, most of the granitoid types show a post-collisional to VAG signature (Harris et al. 1986). Moreover, the R1-R2 rock classification scheme of Batchelor and Bowden (1985) confirms that the sample straddles the post-collisional areas in this diagram (Fig. 32 a, b). This prominent alkaline signature of the studied granite is suitable with their affiliation (Petro et al. 1979). In the Arabian Shield, the I-type is associated with mantle-derivation in the island-arc stage, (Moghazi et al., 1999; El Sayed, 2003). This is in line with our findings.

Chondrite Normalized REE and Primitive-Mantle Normalized

Different batches of magma formed as confirmed by the Zr grains, which have variations in shape and zonation (Fig. 27) (Wang et al., 2010). The primitive mantle-normalized trace-element patterns of the post-collisional granitoids show enrichment in Sr, Pb, and Ta and depletions in Nd, Ti, LREE, and P (Fig. 24). These characteristics are considered to have been inherited from a mantle source (Keller, 2003), and thus indicate a mantle source for the NW Midyan A- type granitoid and most of the I type.

The continuing subduction processes during the Cryogenian~720- ~635 Ma to the Ediacaran period at 635- 570 Ma Kozdrój et al. (2017) are reported as within plate to volcanic arc chemical characteristics. This scenario is compatible with our samples (see Fig. 32), reflecting the post-collisional signature with a fractionation trend. Many signatures observed by the geochemistry and geochronology results, such as the ferroan alkali granite, negative Eu anomaly, enrichment in the LREE, and high depletion in the HREE, reflect the alkaline and calc-alkali fractionated composition (Fig. 24). The A- and I-type geochemistry is enriched by LILE and depleted in HFSE. According to Stern and Johnson (2010), most of the ANS granitoids are juvenile. One example of the A-type granites is the Katherina pluton in Sinai, Egypt, which is interpreted as generated from a “juvenile” crustal source, which is typical of the rocks formed most of the Arabian–Nubian Shield (Katzir et al. 2007). Furthermore, various similar crustal-source models were also recommended for other A-type granites of the Arabian–Nubian Shield (e.g., Stern and Hedge 1985; Beyth et al. 1994; Moghazi 1999).

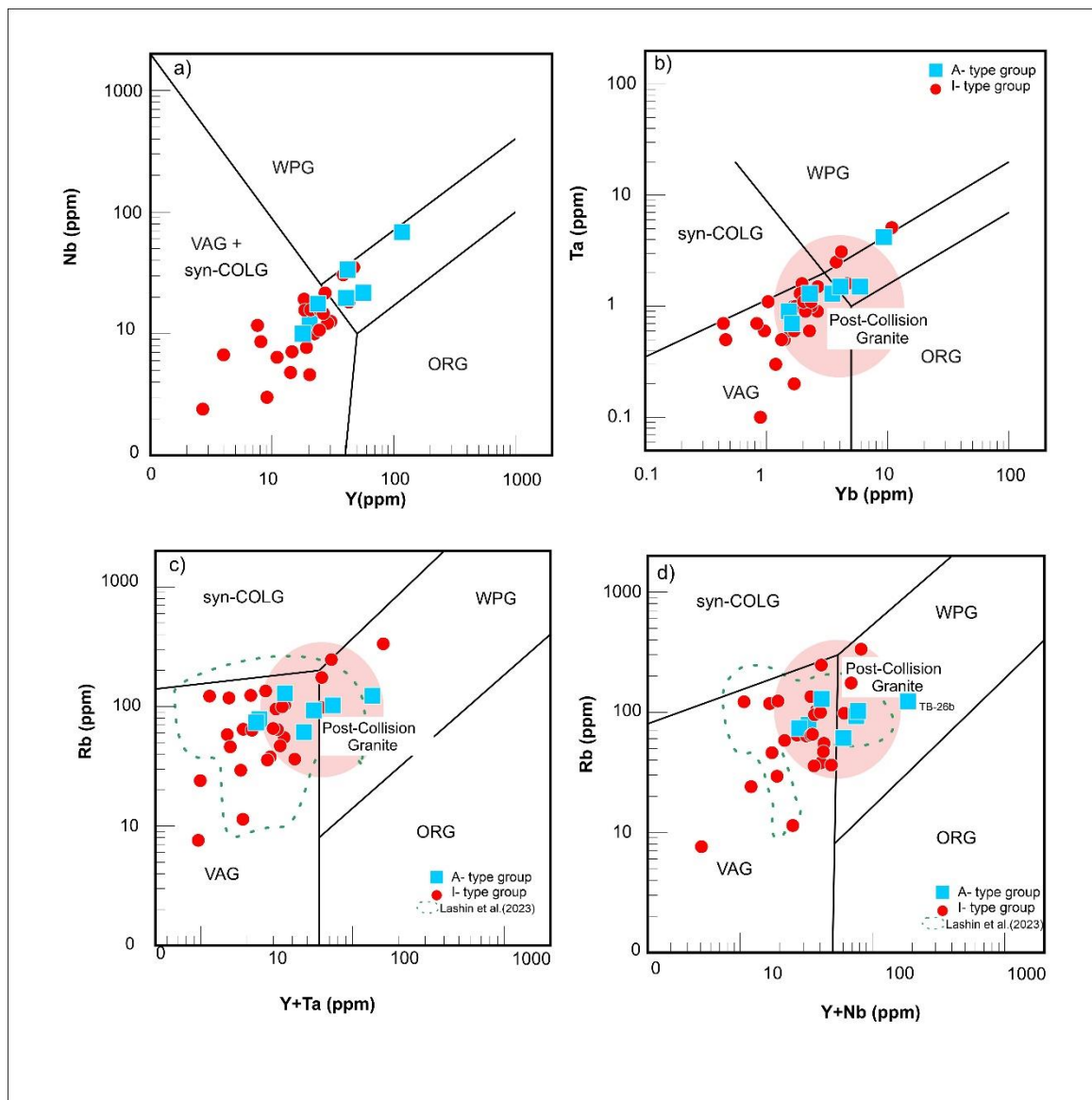


Figure. 31 Rb versus (Y + Nb), Y vs Nb, Yb vs Ta, and Yb+Ta versus Rb plots of Pearce et al. (1984) and Pearce (1996). Abbreviations: WPG – within-plate granitoid, ORG – ocean-ridge granitoid, VAG – volcanic arc granitoid, COLG – collisional granitoid

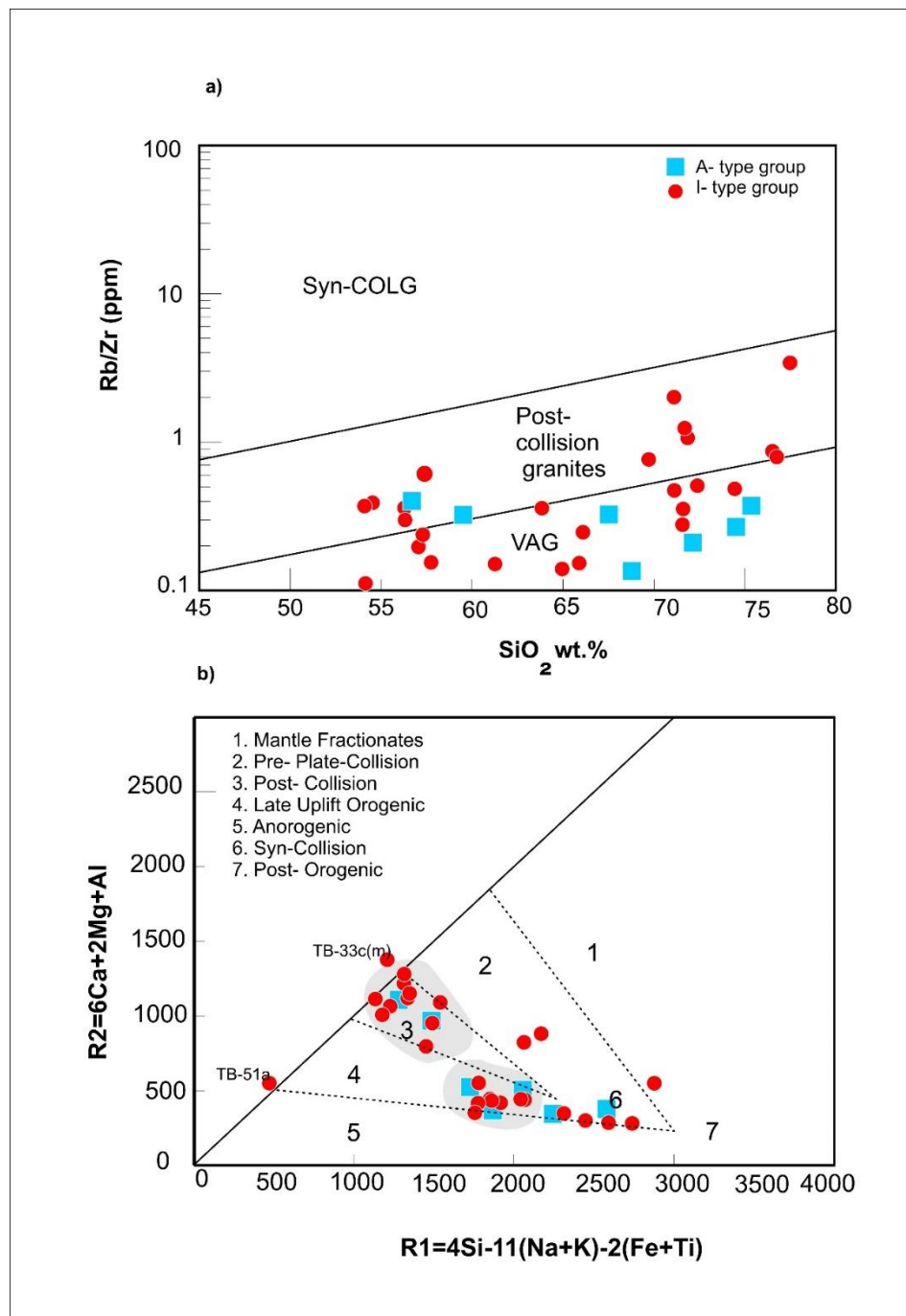


Figure. 32 (a) Rb/Zr vs SiO₂ discrimination diagram (Harris et al. 1986), (b) Geochemical discrimination diagrams of R1/R2 (after Batchelor and Bowden 1985) for the NW Midyan granites. R2 = 6Ca + 2Mg + Al; R1 = 4Si - 11(Na + K) - 2(Fe + Ti).

5.2 Magmatic Source from Isotope Constraints

Nd Isotope

The age data provided in Table 5 range from ~645 to ~597 Ma. The oldest sample is TB-11b, located in the south part of the study area, while the youngest is sample TB-20 (Fig.28). From the isotopic results, two phases of Neoproterozoic magmatism are identified in our study area. The phase of late Cryogenian~ 645 Ma may be evidence that the granitoid magma of this complex involved partial melting. The early to late Ediacaran pulse phase is identified by ages ~624 to ~597 Ma situated in the north and western part of the study area. This younger magma represents the I-type granite group; in contrast, the older pulse represents the A-type group of our study area. Magma is derived from different sources, such as mantle and crust, which are distinctive from the signatures of trace elements. These elements are (Sr, Nd, and Pb) (Leeman & Hawkesworth, 1986). To distinguish between these two phases, we addressed isotopic and geochemistry evidence. The ϵ Nd values of the A and I-type granitoids are isotopically juvenile, and most of them fall between +6.05 to +3.80 of the I-type to +5.8 to +4.65 of the A-type samples. These high positive values are defined by Stoesser and Frost (2006), and Johnson & Kattan (2012) as a mantle source and the juvenile nature of the Arabian Shield (Dickin, 2005; Stoesser and Camp,1985). Some low ϵ Nd value samples, TB-51a and TB-55a are found which belong to I-type granites. Chappell and White (2001) might be considered less juvenile or crustal contamination. All these features indicate that they originated from two different sources: the mantle source, as we found in the A-type granitoid, and the contaminated source in some I-type samples, as mentioned earlier.

Isotope data were obtained for ten samples dated by U-Pb SHRIMP. The result of ^{144}Nd vs age shows that all samples are juvenile and formed during post-orogenic processes. The southern segment of the Midyan terrane in the Al Wajh area shows an orogenic nature and specifically a transition from subduction to within-plate magmatism at 640 Ma (Whattam et al., 2024) (Fig. 33b). Our results show a further transition to a postcollisional environment by ~600 Ma comparing to the other terranes of the Arabian Shield (Robinson, 2014) (Fig. 34 c). Nd model ages vs. $^{143}\text{Nd}/^{144}\text{Nd}$ of all samples have

0.512 representing the mantle source and reflect juvenile nature with an age of ~600 Ma (Fig. 33a).

Sr Isotope

The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the studied rocks are generally low (0.705, 0.710, 0.703, 0.706, 0.730, 0.711, 0.718 to 0.974). Such low ratios are abundant in the Arabian Shield felsic plutons. These were suggested to have the source in the partial melting of mafic material in an island-arc tectonic setting over a subduction zone (Al-Shanti et al., 1984). Moreover, with an insignificant contribution from the crust (Harris et al., 1986). If the samples have these low ratios, it is interpreted that granitoids are derived from a mantle and juvenile crustal source with no, or only minimal contribution from the pre-Pan-African crust or an older continental component (Teklay et al. 2001; Kebede and Koeberl, 2003). Universally, many granite plutons show the same range of initial $^{87}\text{Sr}/^{86}\text{Sr}$ proportions from 0.705 to 0.709, for example as in in Scotland, Australia, eastern China, the United States, and East Africa (Chorowicz, 2005; Caritat et al., 2023; Sherrod et al. (2004). Meanwhile, the low $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is similar to a depleted and modified mantle origin (Bonin et al., 1998). Other examples, such as the Superior Province plutons in Canada show higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios > 0.709 (Mueller and Groves, 1993) indicative of a crustal source (Fig. 25). Also, the differences in the Nd and Pb isotopic compositions of the metaluminous granitoids can aid in the identification and understanding of the genesis processes involved in the formation of these rocks. In the Nubian Shield in Egypt, the source of magma for younger granite was interpreted by Sultan et al. (1992) as derived by mantle to crustal assimilation by their Pb isotopic composition.

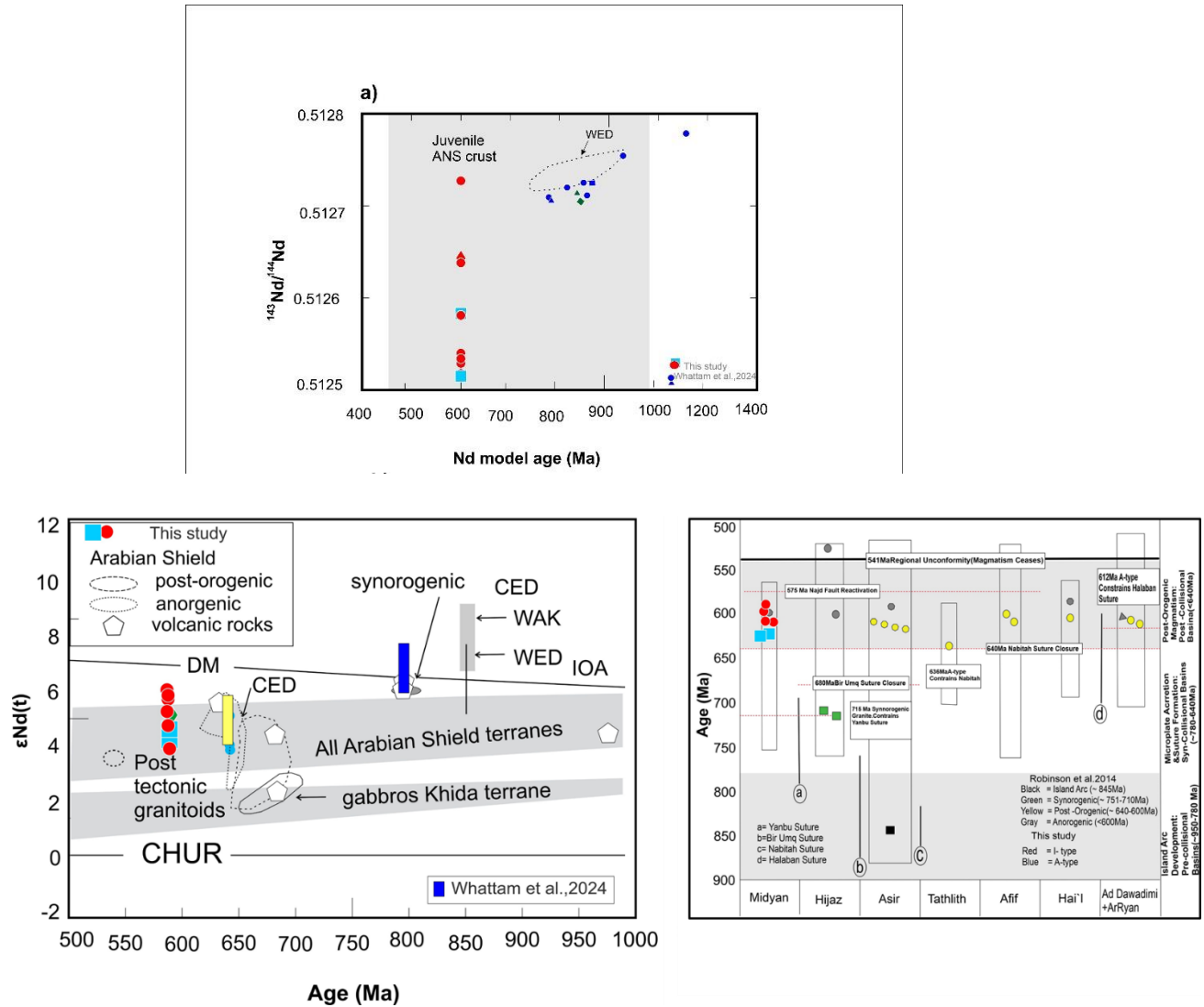


Figure. 33 a) Nd model age Samples of the NW Midyan occupy the post-orogenic interval between ~598 to 645 Ma reflecting the juvenile nature (b) Plot of epsilon Nd versus crystallization age Plot for all data of the Proterozoic rocks of the ANS from this and previous studies. The reference line for the chondritic uniform reservoir (CHUR) and the depleted mantle evolution curves of DM DePaolo (1981) and DM Goldstein et al. (1984), CED = central eastern desert, WED=West eastern desert(from) Ali et al. (2009) (c) our samples of the post-collisional magmas compared with the older terranes of the Arabian Shield (from Robinson et al. 2014)

5.3 Slab Failure Granitoid

Slab failure has recently gained prominence as an explanatory mechanism for various features of collisional orogens. This process occurs in all collisional orogens except those with young and hot subducting slabs (Hildebrand, 1999; Hildebrand et al., 2018). The failure of the subducting slab is associated with rapid uplift, syn-collisional magmatism, tomographic gaps in descending slabs, and seismic discontinuities (Regnier et al., 1992). Slab failure typically occurs when dense oceanic lithosphere descends into the mantle beneath the continental crust due to gravitational forces (Isacks et al., 1986; Davies and von Blanckenburg, 1995; Hildebrand, 1999). This process leads to the heating of the mantle lithosphere by upwelling asthenosphere, resulting in the melting of enriched layers and bimodal magmatism (Blanckenburg, 1995). The slab tail may sink into the mantle, undergo gradual heating, or accumulate at the boundary between the lower and upper mantle (Bercovici & Karato, 2003).

5.3.1 Mechanisms and Geochemical Evidence

Several mechanisms suggest continuous recycling of the crust through processes such as subduction and seafloor spreading, with a significant portion of the continental crust regularly recycled into the mantle (Wortel et al., 1992; Armstrong, 1986; Hildebrand, 1999; Straub et al., 2015). The subducting slab plays a crucial role in earthquake and volcanic activities (Delbridge et al., 2024). The concept of slab detachment, expected by tectonic models for the last sixty years, explains syn-collisional magmatism such as that observed in the Alpine Miocene-Eocene period (von Blanckenburg and Davies, 1995). This model has been widely accepted and applied to various geological phenomena, including ore mineralization, seismicity distribution, sediment supply, metamorphic rock formation, volcanic surges, topographic uplift, and subduction polarity inversion (Garzanti et al., 2018; Zhu et al., 2015; Lippitsch et al., 2003; Sacks et al., 1968; Spakman, 1988; Sue et al., 1999; Teng et al., 2000; O'Brien, 2001). Seismic evidence supports collision-related slab-breakoff events in the Mediterranean, Anatolia-Zagros orogen, Himalaya, Tibet, and around the Pacific Ocean (Rosenbaum et al., 2008; Handy et al., 2010; Molli and Malavieille, 2011; Keskin, 2003; Mutlu and Karabulut, 2011; Ma et al., 2014; Vargas and Mann, 2013). Additionally, ore mineralization types such as Zn-Cu, Au, Ag, Pb, and alkaline and calc-alkaline magmatism have been associated with collisional slab failure (Neubauer et al.,

2005; Seghedi et al., 2011). Despite its widespread acceptance, the break-off model has not been applied to magmatism events in the Arabian Shield. This study compiles evidence of slab failure in the NW Midyan region, outlining the foundational concept of slab failure in a scenario like that advocated for Caledonian magmatism and worldwide. Usually, convergence environments show changes in their magmatic compositions due to geodynamic changes such as subduction angle or slab buoyancy, which are interpreted as slab failure post-collision (Gutscher et al., 2000).

The northern segment of the Arabian Shield developed via various geological and structural events. Previous studies suggest an intra-oceanic volcanic arc setting during the Neoproterozoic era, around 900 to 550 Ma (Duyverman, 1982). The magma source of the Arabian Shield involved crustal melt, fractional crystallization, and hybrid mantle-derived and crustal-derived partial melting. Two prevailing hypotheses regarding granitic magma in the Caledonian suggest either a juvenile origin linking felsic and mafic granitoids (Fowler et al., 2008) or mafic compositions derived from the mantle with granites as crustal melts interacting with mafic magmas (Neilson et al., 2009). Both models align with the concept of slab failure.

5.3.2 Slab Failure Magma Sources

Geochemical evidence from the NW Midyan region supports the slab breakoff model, explaining the pulse of granite magma between 645 to 598 Ma as a response to asthenosphere upwelling following the breakoff of the long subducting slab (Atherton and Ghani, 2002). High Ba–Sr contents are due to initial melting at the base of the enriched underplate, while low Ba–Sr derive from a less-enriched source contaminated with older crustal material (Atherton and Ghani, 2002). Felsic samples with SiO₂ concentrations between 55 and 77 wt% and an alumina saturation index (ASI) of <1.1 falls within the tectonomagmatic discrimination field reflective of slab failure (Lawrence et al., 2023; Hildebrand and Whalen, 2017; Whalen and Hildebrand, 2019).

Slab failure magmas may be derived from partial melting of the upper portion of the slab, consisting of metabasaltic or gabbroic rocks, resulting in a residue rich in garnet but lacking plagioclase, characterized as eclogitic (Hildebrand et al., 2018). In contrast, arc magmas produce volatiles from the subducting slab, leading to partial melting of source

rocks containing spinel and plagioclase, leaving behind residues of plagioclase, pyroxene, and rutile (Till et al., 2012). In the NW Midyan region, magmatic rocks are categorized into arc and slab failure types based on trace element discrimination of granite. Our study suggests that high silica content (~60%) in the continental crust, traditionally attributed to arc magmatism, developed during the late phases of tectonic collision due to slab failure.

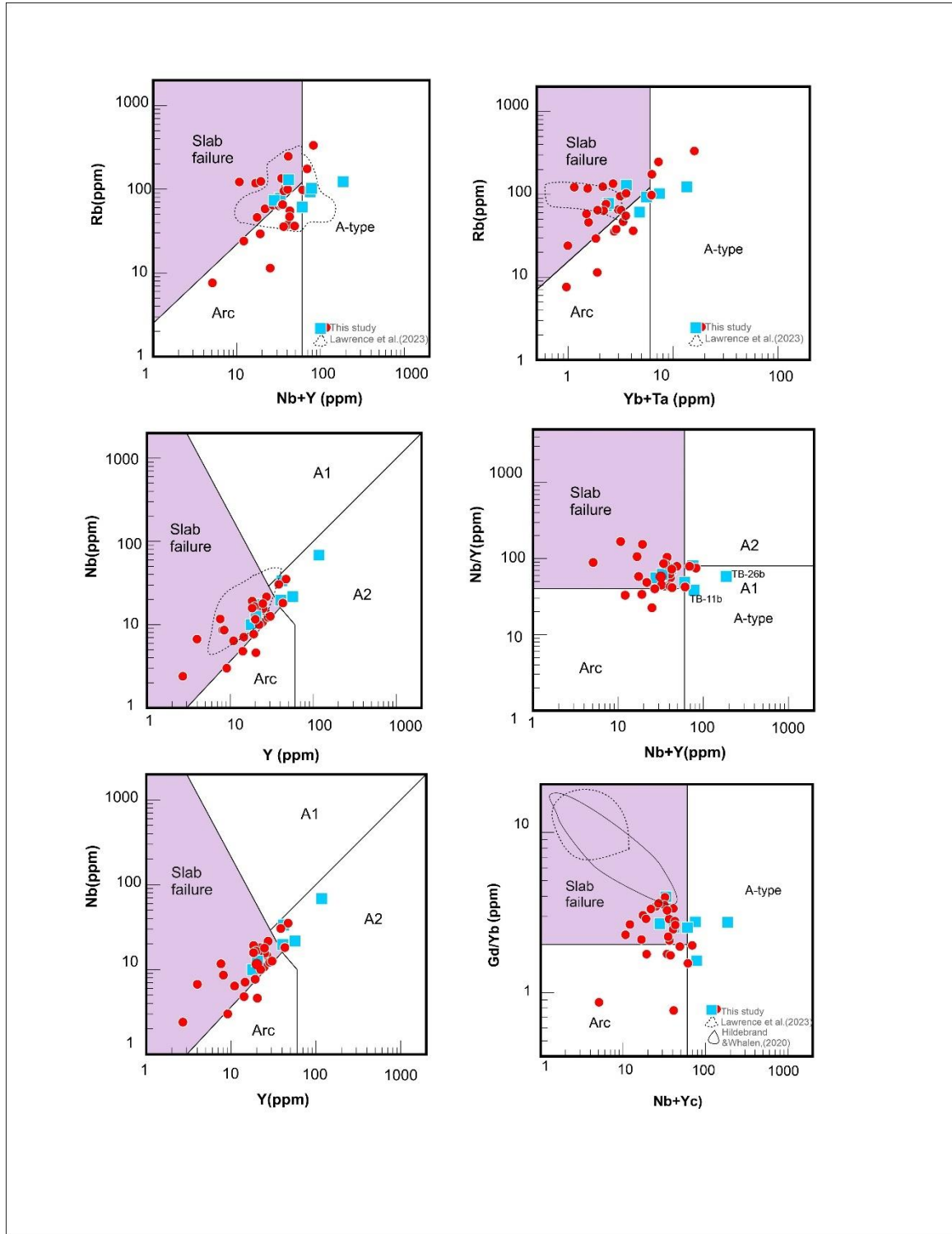
5.3.3 Slab Failure Model of NW Midyan Region

This study investigates the formation of the continental crust of the Arabian Shield through the lens of slab failure in the NW Midyan terrane. Previous models for the tectonic evolution of the NW Midyan terrane do not provide comprehensive details about its evolutionary history (Genna et al., 2002; Duyverman, 1982). Convergence between the Midyan and Hijaz arcs formed the Yanbu suture (~700 Ma). Various models propose enriched asthenosphere moving into the back-arc setting as the origin for A-type magmas (Stein and Goldstein, 1996; Stern and Johnson, 2010; Avigad and Gvirtzman, 2009). However, these models do not fully explain the transition of magma chemistry from A-type to I-type in the NW Midyan. This study suggests that this transition is associated with the slab failure of the subduction slab.

In the Midyan terrane, convergence between the Midyan and Hijaz arcs developed the Yanbu suture ~700Ma. The transition from late orogenic to post-orogenic magmatism and the source of magma is discussed by several authors as mantle plume enriched (Stein and Goldstein,1996), slab subduction rollback, mafic underplating (Stern and Johnson, 2010), or delamination (Avigad and Gvirtzman,2009). These models propose that enriched asthenosphere moves into the back-arc setting and serves as the origin for all A-type magmas. Nevertheless, Robinson et al. (2017) suggest that the late-orogenic A-type magmatism in the Ha'il terrane of the northeastern Arabian Shield might be linked to slab tear or rollback toward the east of the subducting Hijaz plate. However, none of these fully explained the transition of magma chemistry from A-type to I-type in the NW Midyan.

This study presents a new perspective on the source of the post-collisional NW Midyan granitoid complexes, suggesting that besides the two arc magmatism events (A and I) which were described by Johanson and Kattan (2012), there is another granitic type. This new granitic magma called slab failure magmatism was generated by slab failure in the

subduction zone, in the NW Midyan region, Arabian Shield, providing an alternative evolution concept to magmas in the Arabian Shield which dates back between 645 to 598 Ma from the Late Cryogenian to the Early Ediacaran (see Figs. 35, 36).



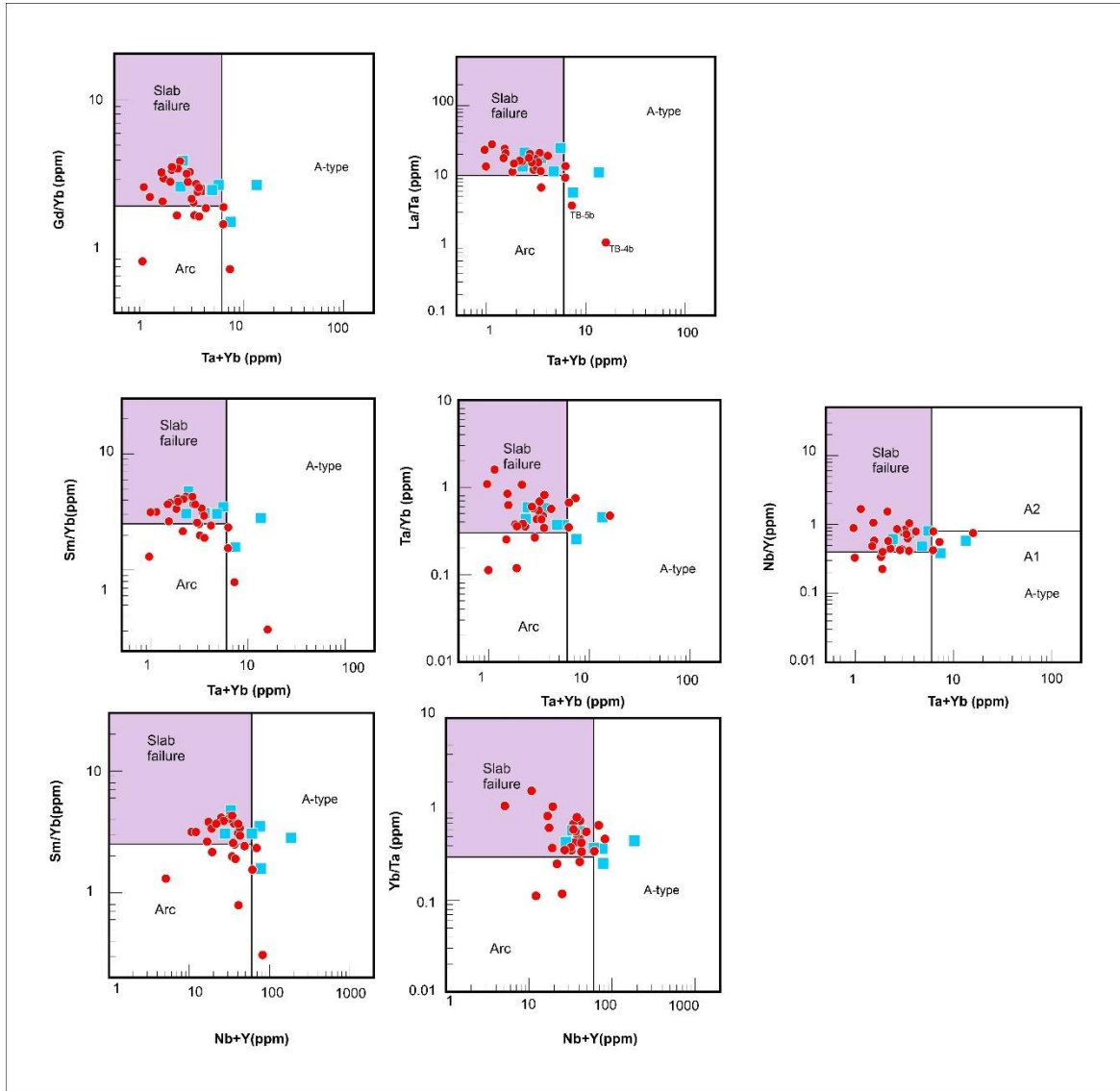
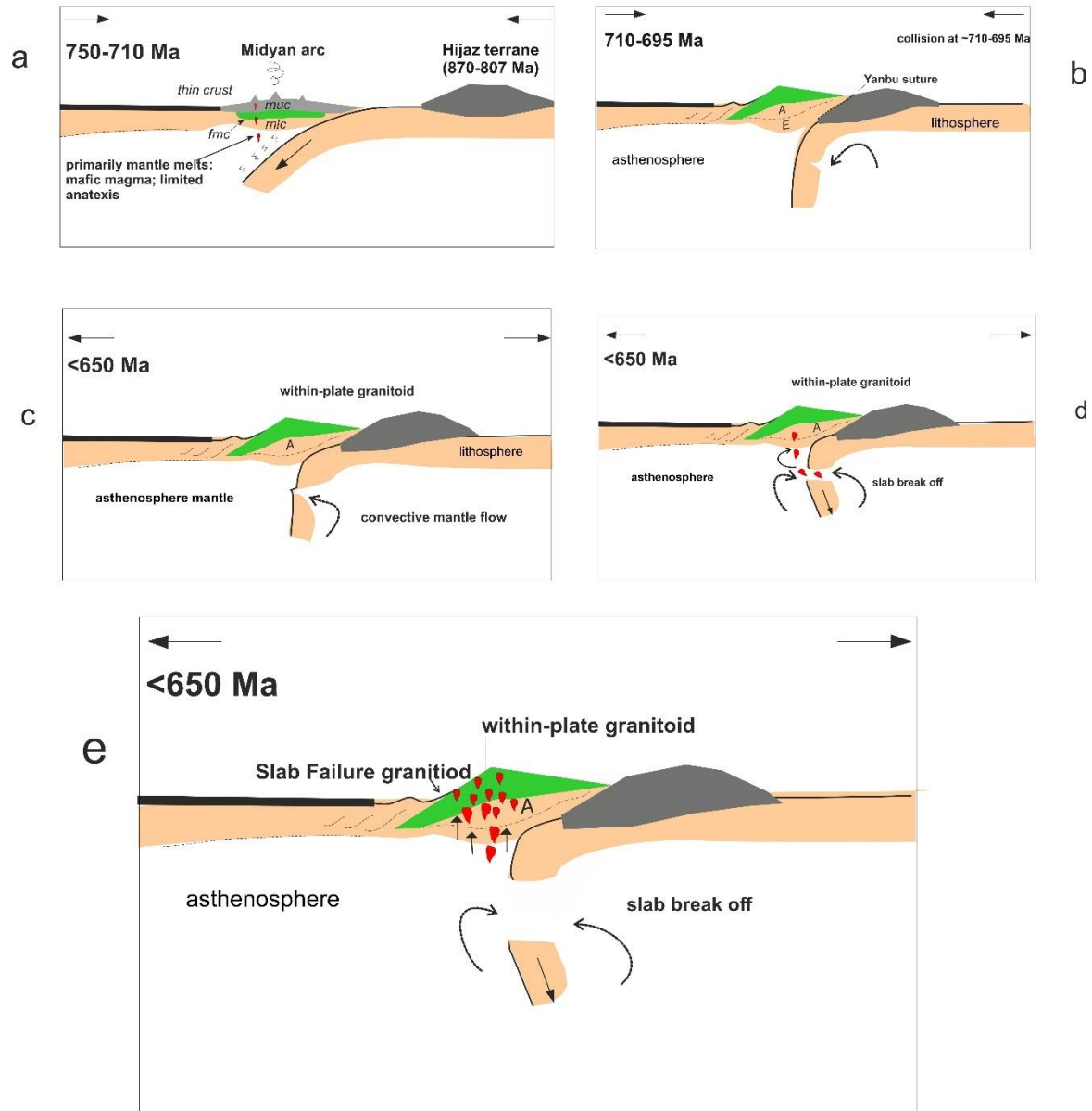


Figure. 34 granitoid rock discrimination plots modified to better discriminate between I-type arc, slab failure, and A1- and A2-type granitoid compositions. Tectonomagmatic discrimination diagrams (Hildebrand and Whalen, 2017; Whalen and Hildebrand, 2019) for our study area

present day NW

present day SE



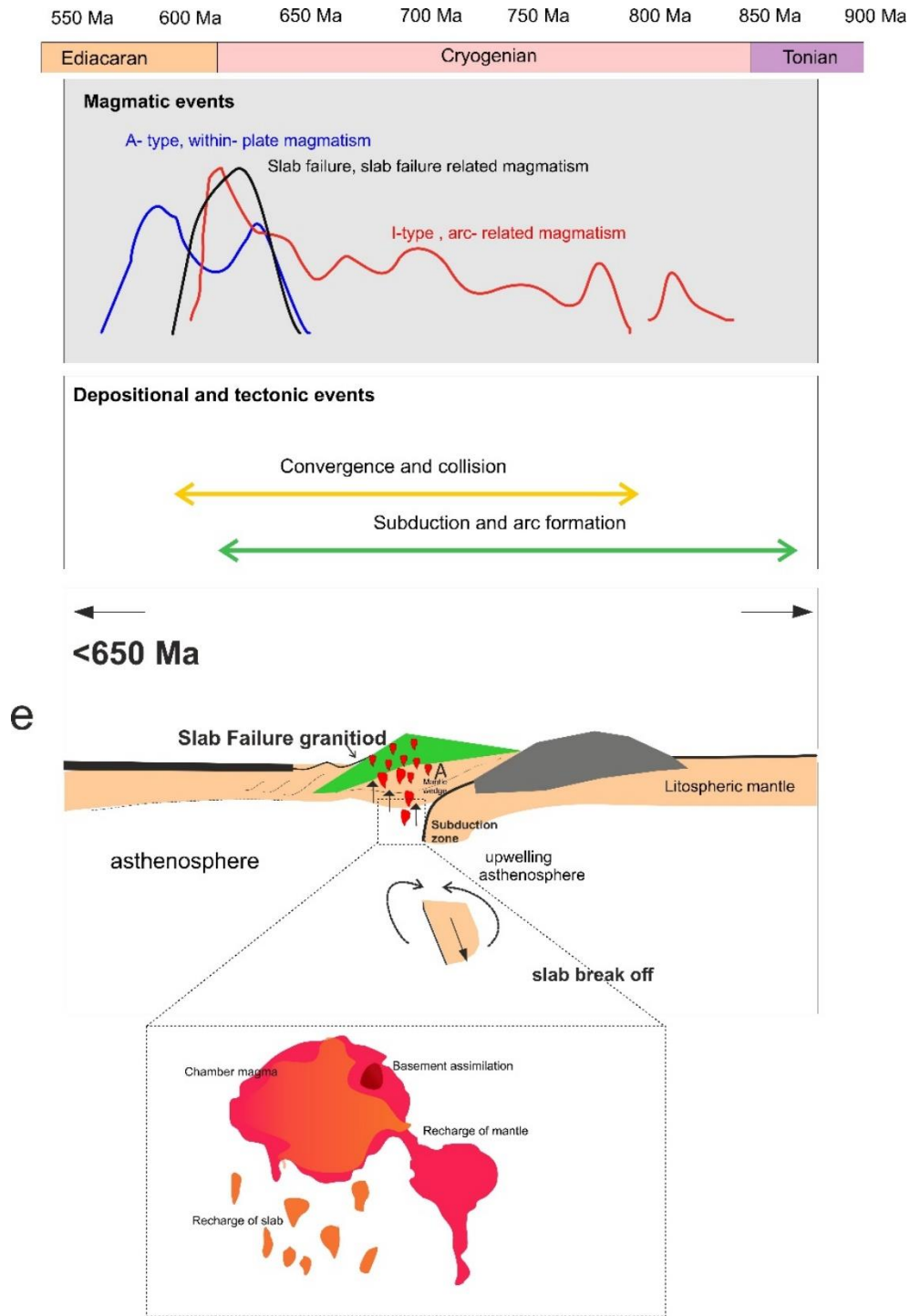


Figure. 35 Cartoon diagram illustrating slab failure mechanism in the NW Midyan, Arabian Shield (after Whattam et al.,2024; Johnson and Kattan, 2012; Bastos et al., 2024)

CHAPTER 6

CONCLUSIONS AND FUTURE RECOMMENDATION

6.1 Research Conclusions

1. Geochronological, geochemical data and Sr-Nd-Pb isotopic compositions from the NW Midyan region in the northern part of Saudi Arabia allow us to summarize the following conclusions:
2. Granitoids can host economically important mineral deposits, such as rare earth elements (REEs), uranium, and other metallic minerals.
3. Besides the A, I, and S-type granitoid magma in the Arabian Shield this study addresses new granitoid of slab failure source.
4. The whole chemical data revealed sub alkaline signature.
5. Zircon U-Pb SHRIMP dating reveals that granite has Ediacaran- Cryogenian ages (~597- 645 Ma), similar to many post-collisional granites in the ANS.
6. The isotope initial ϵ_{Nd} positive values for the granites are within the range of the ANS juvenile crust.

6.2 Research Recommendations

1. Further investigations are required to determine why the slab failure occurred in the NW Midyan terrane compared to the other complexes and suites in the same terrane and within the ANS.
2. Each suite and complex needs individual and comprehensive study.
3. Regional and local comparisons will serve the slab failure model by utilizing geophysical methods.

REFERENCES

- Abd El-Wahed, M., & Attia, M. (2023). Structural and tectonic evolution of suture-related belts and post-accretionary systems in the Arabian-Nubian Shield. In *Geological Journal* (Vol. 58, Issue 5, pp. 1776–1809). John Wiley and Sons Ltd. <https://doi.org/10.1002/gj.4693>
- Aboud, E., Alqahtani, F., Abdulfarraj, M., Abraham, E., El-Masry, N., & Osman, H. (2023). Geothermal Imaging of the Saudi Cross-Border City of NEOM Deduced from Magnetic Data. *Sustainability (Switzerland)*, 15(5). <https://doi.org/10.3390/su15054549>
- Aboud, E., Lashin, A., Zaidi, F., Al-Bassam, A., Al Arifi, N., Abu Anbar, M., & Al-Homadhi, E. (2023). Audio Magnetotelluric and Gravity Investigation of the High-Heat-Generating Granites of Midyan Terrane, Northwest Saudi Arabia. *Applied Sciences (Switzerland)*, 13(6). <https://doi.org/10.3390/app13063429>
- Abuamarah, B. A., Alzahrani, H., Matta, M. J., Azer, M. K., Asimow, P. D., & Darwish, M. H. (2023). Petrological, geochemical and geodynamic evolution of the Wadi Al-Baroud granitoids, north Arabian-Nubian shield, Egypt. *Journal of African Earth Sciences*, 207. <https://doi.org/10.1016/j.jafrearsci.2023.105044>
- Aleinikoff, & Stoeser. (1988). Zircon morphology and U-Pb geochronology of seven metaluminous and peralkaline post-orogenic granite complexes of the Arabian Shield, Kingdom of Saudi Arabia Open-File Report.
- Alharbi, W. R. (2016). Mineral determination and radiological risk caused by geological formations from Iron Ore in Wadi Sawawin, Duba, Saudi Arabia. *International Journal of Physical Sciences*, 11(16), 209–216. <https://doi.org/10.5897/ijps2016.4530>
- Al-Husseini. (2015). EDIACARAN-CAMBRIAN MIDDLE EAST GEOLOGIC TIME SCALE 2015 Spatio-temporal position of the Ediacaran Thalbah Basin in the Najd Fault System, Arabian Shield (Vol. 20, Issue 1). <http://pubs.geoscienceworld.org/geoarabia/article-pdf/20/1/17/5447694/al-husseini.pdf>
- Ali et al. (2022). Earthquake Occurrences of the Major Tectonic Terranes for the Arabian Shield and Their Seismic Hazard Implications. *Frontiers in Earth Science*, 10. <https://doi.org/10.3389/feart.2022.851737>

- Ali, K. A., Stern, R. J., Manton, W. I., Kimura, J. I., Whitehouse, M. J., Mukherjee, S. K., Johnson, P. R., & Griffin, W. R. (2010). Geochemical, U-Pb zircon, and Nd isotope investigations of the Neoproterozoic Ghawjah Metavolcanic rocks, Northwestern Saudi Arabia. *Lithos*, 120(3–4), 379–392. <https://doi.org/10.1016/j.lithos.2010.08.024>
- Ali, K. A., Zoheir, B. A., Stern, R. J., Andresen, A., Whitehouse, M. J., & Bishara, W. W. (2016). Lu-Hf and O isotopic compositions on single zircons from the North Eastern Desert of Egypt, Arabian-Nubian Shield: Implications for crustal evolution. *Gondwana Research*, 32, 181–192. <https://doi.org/10.1016/j.gr.2015.02.008>
- Aseri&Linnen. (2020). Rare-metal Alkaline Granite from The Arabian Shield, Saudi Arabia. <https://ir.lib.uwo.ca/etdhttps://ir.lib.uwo.ca/etd/6822>
- Atherton, M. P., & Ghani, A. A. (2002). Slab breakoff: a model for Caledonian, Late Granite syn-collisional magmatism in the orthotectonic (metamorphic) zone of Scotland and Donegal, Ireland. www.elsevier.com/locate/lithos
- Azer, M. K., & Asimow, P. D. (2021). Petrogenetic Evolution of the Neoproterozoic Igneous Rocks of Egypt (pp. 343–382). https://doi.org/10.1007/978-3-030-49771-2_13
- Bakhsh. (2013). Granites from the Midyan terrain, NW Saudi Arabia: Petrology, geochemistry and geochronology.
- Balcaen, De Schrijver, I., Moens, L., & Vanhaecke, F. (2005). Determination of the $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio in USGS silicate reference materials by multi-collector ICP-mass spectrometry. *International Journal of Mass Spectrometry*, 242(2–3), 251–255. <https://doi.org/10.1016/j.ijms.2004.10.025>
- Barbarin, B. (1990). Granitoids: Main petrogenetic classifications in relation to origin and tectonic setting. *Geological Journal*, 25(3–4), 227–238. <https://doi.org/10.1002/gj.3350250306>
- Billen. (2008). Modeling the dynamics of subducting slabs. *Annual Review of Earth and Planetary Sciences*, 36, 325–356. <https://doi.org/10.1146/annurev.earth.36.031207.124129>

- Bonin. (2007). A-type granites and related rocks: Evolution of a concept, problems and prospects. *Lithos*, 97(1–2), 1–29. <https://doi.org/10.1016/j.lithos.2006.12.007>
- Bonin, Azzouni-Sekkal, Bussy, & Ferrag. (1998). Alkali-calcic and alkaline post-orogenic (PO) granite magmatism: Petrologic constraints and geodynamic settings. *Lithos*, 45(1–4), 45–70. [https://doi.org/10.1016/S0024-4937\(98\)00025-5](https://doi.org/10.1016/S0024-4937(98)00025-5)
- Bonin, Janoušek, & Moyen. (2019). Chemical variation, modal composition and classification of granitoids. 10. <https://doi.org/10.1144/SP491-2019-138i>
- Brown. (1989). The Earth from space. GEOLOGY OF THE ARABIAN PENINSULA SHIELD AREA OF WESTERN SAUDI ARABIA.
- Brown. (2013). Granite: From genesis to emplacement. *Bulletin of the Geological Society of America*, 125(7–8), 1079–1113. <https://doi.org/10.1130/B30877.1>
- Burton. (1878). The gold-mines of Midian and the ruined Midianite cities: a fortnight's tour in North-Western Arabia.
- Carr, & Gazel, E. (2017). Igpert software for modeling igneous processes: examples of application using the open educational version. *Mineralogy and Petrology*, 111(2), 283–289. <https://doi.org/10.1007/s00710-016-0473-z>
- Chappell, & White. (1992). I-and S-type granites in the Lachlan Fold Belt. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 83(1-2), 1-26.
- Chappell, & White. (2001). chappell& white 2001.
- Clark, M. D. (1985). Late Proterozoic crustal evolution of the Midyan region, northwestern Saudi Arabia. <http://pubs.geoscienceworld.org/gsa/geology/article-pdf/13/9/611/3508349/i0091-7613-13-9-611.pdf>
- Clarkson, H. (1980). The mineral nutrition of higher plants.
- Clemens, Holloway, & White. (1986). Origin of an A-type granite: Experimental constraints. In *American Mineralogist* (Vol. 71). http://pubs.geoscienceworld.org/msa/ammin/article-pdf/71/3-4/317/4212736/am71_317.pdf

- Clemens, J. D., Stevens, G., & Farina, F. (2011). The enigmatic sources of I-type granites: The peritectic connexion. *Lithos*, 126(3–4), 174–181. <https://doi.org/10.1016/j.lithos.2011.07.004>
- Collins, W. J., Beams, S. D., White, A. J. R., & Chappell, B. W. (1982). Nature and origin of A-type granites with particular reference to southeastern Australia. *Contributions to Mineralogy and Petrology*, 80(2), 189–200. <https://doi.org/10.1007/BF00374895>
- Collins, W. J., Huang, H. Q., Bowden, P., & Kemp, A. I. S. (2020). Repeated S–I–A-type granite trilogy in the lachlan orogen and geochemical contrasts with a-type granites in Nigeria: Implications for petrogenesis and tectonic discrimination. *Geological Society Special Publication*, 491(1), 53–76. <https://doi.org/10.1144/SP491-2018-159>
- Condie KG (1973) Archean magmatism and crustal thickening. *Geol Soc Am Bull* 84:2981–2992
- Crisp, L. J., & Berry, A. J. (2022). A new model for zircon saturation in silicate melts. *Contributions to Mineralogy and Petrology*, 177(7). <https://doi.org/10.1007/s00410-022-01925-6>
- Davidson, Turner, Handley, Macpherson, & Dosseto. (2007). Amphibole ‘sponge’ in arc crust? *Geology*, 35(9), 787–790. <https://doi.org/10.1130/G23637A.1>
- Dawood, Y. H., & Abd El-Naby, H. H. (2022). Genesis of uranyl mineralization in the Arabian Nubian Shield: A review. *Journal of Asian Earth Sciences*, 225. <https://doi.org/10.1016/j.jseaes.2021.105047>
- DeCelles, Robinson, & Zandt. (2002). Implications of shortening in the Himalayan fold-thrust belt for uplift of the Tibetan Plateau. *Tectonics*, 21(6), 12-1-12–25. <https://doi.org/10.1029/2001TC001322>
- Dickin, A. P., McNutt, R. H., Martin, C., & Guo, A. (2010). The extent of juvenile crust in the Grenville Province: Nd isotope evidence. *Bulletin*, 122(5-6), 870-883.

- Dostal, J. (2023). Jurassic Uranium-Thorium Deposit of Peralkaline Granitic Rocks, Bokan Mountain, Prince of Wales Island, Southeastern Alaska. *Minerals*, 13(8). <https://doi.org/10.3390/min13081032>
- Duretz, T., & Gerya, T. V. (2013). Slab detachment during continental collision: Influence of crustal rheology and interaction with lithospheric delamination. *Tectonophysics*, 602, 124–140. <https://doi.org/10.1016/j.tecto.2012.12.024>
- Duyverman, H. J., Harris, N. B., & Hawkesworth, C. J. (1982). Crustal accretion in the Pan African: Nd and Sr isotope evidence from the Arabian Shield. *Earth and Planetary Science Letters*, 59(2), 315-326.
- Eby. (1990). The A-type granitoids: A review of their occurrence and chemical characteristics and speculations on their petrogenesis.
- Eby. (1992). Chemical subdivision of the A-type granitoids: Petrogenetic and tectonic implications. <http://pubs.geoscienceworld.org/gsa/geology/article-pdf/20/7/641/3514251/i0091-7613-20-7-641.pdf>
- Edward. (1986). Jabal Silsilah tin prospect, Najd region, Kingdom of Saudi Arabia. *Journal of African Earth Sciences*, Volume 4, 1.
- El-Desoky, H. M., El-Awny, H., Fahmy, W., El-Naggar, I. M., Abdel-Rahman, A. M., & Khalil, A. E. (2024). Geochemistry and Tectonic Evolution of Neoproterozoic Wadi Kid Dokhan volcanics, Southeast Sinai, Egypt. <https://doi.org/10.21203/rs.3.rs-3851006/v1>
- El-Fakharani, A., AlKashghari, W. A., Baggazi, H. M., El-Shafei, M. K., & Matsah, M. (2020). Microstructural analyses of the Najd Fault System in Midyan Terrane, NW Arabian Shield, Saudi Arabia. *International Journal of Earth Sciences*, 109(1), 301–316. <https://doi.org/10.1007/s00531-019-01803-w>
- Fnais, M., Ibrahim, E., El-Motaal, E. A., Abdelrahman, K., Al-Heniedi, A., & Al-Kahtany, K. (2016). Structural development of northwest Saudi Arabia using aeromagnetic and seismological data. *Journal of Earth Science*, 27(6), 998–1007. <https://doi.org/10.1007/s12583-016-0904-0>

- Fowler, M. B., Kocks, H., Darbyshire, D. P. F., & Greenwood, P. B. (2008). Petrogenesis of high Ba-Sr plutons from the Northern Highlands Terrane of the British Caledonian Province. *Lithos*, 105(1–2), 129–148. <https://doi.org/10.1016/j.lithos.2008.03.003>
- Freeburn, R., Bouilhol, P., Maunder, B., Magni, V., & van Hunen, J. (2017). Numerical models of the magmatic processes induced by slab breakoff. *Earth and Planetary Science Letters*, 478, 203–213. <https://doi.org/10.1016/j.epsl.2017.09.008>
- Fritz, H., Abdelsalam, M., Ali, K. A., Bingen, B., Collins, A. S., Fowler, A. R., Ghebreab, W., Hauzenberger, C. A., Johnson, P. R., Kusky, T. M., Macey, P., Muhongo, S., Stern, R. J., & Viola, G. (2013). Orogen styles in the East African Orogen: A review of the Neoproterozoic to Cambrian tectonic evolution. In *Journal of African Earth Sciences* (Vol. 86, pp. 65–106). Elsevier Ltd. <https://doi.org/10.1016/j.jafrearsci.2013.06.004>
- Frost, Barnes, C. G., Collins, W. J., Arculus, R. J., Ellis, D. J., & Frost, C. D. (2001). A Geochemical Classification for Granitic Rocks. In *JOURNAL OF PETROLOGY* (Vol. 42).
- Frost, & Ronald Frost. (2011). On ferroan (A-type) granitoids: Their compositional variability and modes of origin. *Journal of Petrology*, 52(1), 39–53. <https://doi.org/10.1093/petrology/egq070>
- Gan, C., Wang, Y., Qian, X., Lu, X., Mustapha, K. A., Zhang, Y., & Wu, S. (2022). Diorite enclaves and host granite of the early Miocene Gorontalo pluton in the North Sulawesi Arc, Indonesia: Implications for recycled oceanic crust and crust-mantle interaction. *Journal of Asian Earth Sciences*, 227. <https://doi.org/10.1016/j.jseaes.2022.105101>
- Gao, H., Tong, X., Wen, Z., & Wang, Z. (2019). The tectonic evolution of the eastern Mediterranean basin and its control on hydrocarbon distribution. *Journal of Petroleum Science and Engineering*, 178, 389–407. <https://doi.org/10.1016/j.petrol.2019.03.029>
- Garzanti, Radeff, & Malusà, . (2018). Slab breakoff: A critical appraisal of a geological theory as applied in space and time. In *Earth-Science Reviews* (Vol. 177, pp. 303–319). Elsevier B.V. <https://doi.org/10.1016/j.earscirev.2017.11.012>

- Genna, A., Nehlig, P., Le Goff, E., Guerrot, C., & Shanti, M. (2002). Proterozoic tectonism of the Arabian Shield. In *Precambrian Research* (Vol. 117). www.elsevier.com/locate/precamres
- Ghrefat, Batayneh, A., Zaman, H., Zumlot, T., Elawadi, E., & Nazzal, Y. (2013). Major ion chemistry and weathering processes in the Midyan Basin, northwestern Saudi Arabia. *Environmental Monitoring and Assessment*, 185(10), 8695–8705. <https://doi.org/10.1007/s10661-013-3205-4>
- Gill. (1981). *Orogenic Andesites and Plate Tectonics* (Vol. 16). Springer Berlin Heidelberg. <https://doi.org/10.1007/978-3-642-68012-0>
- Grebennikov, A. V. (2014). A-type granites and related rocks: Petrogenesis and classification. In *Russian Geology and Geophysics* (Vol. 55, Issue 11, pp. 1353–1366). Elsevier B.V. <https://doi.org/10.1016/j.rgg.2014.10.011>
- Gutscher, M. E. B. (2000). Can slab melting be caused by flat subduction?
- Hanchar, & Watson. (2003). 4 Zircon Saturation Thermometry. <http://pubs.geoscienceworld.org/msa/rimg/article-pdf/53/1/89/2943372/89.chapter4finalnew-zircon.pdf>
- Harris & Marriner. (1980). Geochemistry and petrogenesis of a peralkaline granite complex from the Midian Mountains, Saudi Arabia. *LITHOS*, Volume 13, Issue 4, p. 325-337.
- Harris, N. B. W., Pearce, J. A., & Tindle, A. G. (1986). Geochemical characteristics of collision-zone magmatism. *Geological Society Special Publication*, 19, 67–81. <https://doi.org/10.1144/GSL.SP.1986.019.01.04>
- Hart. (1984). A large-scale isotope anomaly in the Southern Hemisphere mantle.
- Hassan, M., Abu-Alam, T. S., Hauzenberger, C., & Stüwe, K. (2016). Geochemical signature variation of pre-, syn-, and post-shearing intrusives within the Najd Fault System of western Saudi Arabia. *Lithos*, 263, 274–291. <https://doi.org/10.1016/j.lithos.2016.06.024>

- Hildebrand, & Bowring. (1999). Crustal recycling by slab failure. *Geology*, 27(1), 11–14.
[https://doi.org/10.1130/0091-7613\(1999\)027<0011:CRBSF>2.3.CO;2](https://doi.org/10.1130/0091-7613(1999)027<0011:CRBSF>2.3.CO;2)
- Hildebrand, R. S., Whalen, J. B., & Bowring, S. A. (2018). Resolving the crustal composition paradox by 3.8 billion years of slab failure magmatism and collisional recycling of continental crust. *Tectonophysics*, 734–735, 69–88.
<https://doi.org/10.1016/j.tecto.2018.04.001>
- Hildebrand, & Whalen. (2021). ARC and slab-failure magmatism of the taconic orogeny, Western new England, USA. In *Geological Society Special Publication* (Vol. 503, Issue 1, pp. 409–422). Geological Society of London. <https://doi.org/10.1144/SP503-2019-247>
- Hinchey, A. M., Sandeman, H. A., & Butler, J. P. (2024). The Paleoproterozoic granite factory: Voluminous post-collisional, ferroan, A-type granites and implications for crust formation and metallogenic tenor, Labrador, Canada. *Bulletin of the Geological Society of America*, 136(1–2), 893–916. <https://doi.org/10.1130/B36727.1>
- Hoskin, P. W., & Schaltegger, U. (2003). The composition of zircon and igneous and metamorphic petrogenesis. *Reviews in mineralogy and geochemistry*, 53(1), 27–62.
- Hughes. (1999). ASPECTS O F MIDYAN GEOLOGY, SAUDI ARABIAN RED SEA.
<https://www.researchgate.net/publication/265363508>
- Irber. (1999). The lanthanide tetrad effect and its correlation with K/Rb, Eu/Eu*, Sr/Eu, Y/Ho, and Zr/Hf of evolving peraluminous granite suites. *Geochimica et Cosmochimica Acta*.
- Jackson, N. J. (1986). Mineralization associated with felsic plutonic rocks in the Arabian Shield. In *Journal of African Earth Sciences* (Vol. 4).
- Jacob, J. B., Moyen, J. F., Fiannacca, P., Laurent, O., Bachmann, O., Janoušek, V., Farina, F., & Villaros, A. (2021). Crustal melting vs. fractionation of basaltic magmas: Part 2, Attempting to quantify mantle and crustal contributions in granitoids. *Lithos*, 402–403.
<https://doi.org/10.1016/j.lithos.2021.106292>

- Jacobs, J., & Thomas, R. T. (2007). East African-Antarctic Orogen and initial Gondwana break-up: the role of structural inheritance during East Africa's passive margin formation. In *Geophysical Research Abstracts* (Vol. 9).
- Jahn, Wu, F., Capdevila, R., Martineau, F., Zhao, Z., & Wang, Y. (2001). Highly evolved juvenile granites with tetrad REE patterns: the Woduhe and Baerzhe granites from the Great Xing'an Mountains in NE China. In *Lithos* (Vol. 59). www.elsevier.com/locate/lithos
- Jamal, R., & Sc, T. B. (1991). STRATIGRAPHY A N D SEDIMENTOLOGY OF THE COVER ROCKS OF THE M AQNA AREA, SAUDI ARABIA.
- 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(2), 157–178. <https://doi.org/10.1002/gj.950>
- Johnson. (2006). EXPLANATORY NOTES TO THE MAP OF PROTEROZOIC GEOLOGY OF WESTERN SAUDI ARABIA. www.sgs.org.sa
- Johnson, P. R. (2014). Send Orders for Reprints to reprints@benthamscience.net An Expanding Arabian-Nubian Shield Geochronologic and Isotopic Dataset: Defining Limits and Confirming the Tectonic Setting of a Neoproterozoic Accretionary Orogen. In *The Open Geology Journal* (Vol. 8, Issue 1).
- Johnson, P. R. (2021). The Arabian–Nubian Shield, an Introduction: Historic Overview, Concepts, Interpretations, and Future Issues (pp. 1–38). https://doi.org/10.1007/978-3-030-72995-0_1
- Johnson, P. R., Andresen, A., Collins, A. S., Fowler, A. R., Fritz, H., Ghebreab, W., Kusky, T., & Stern, R. J. (2011). Late Cryogenian-Ediacaran history of the Arabian-Nubian Shield: A review of depositional, plutonic, structural, and tectonic events in the closing stages of the northern East African Orogen. In *Journal of African Earth Sciences* (Vol. 61, Issue 3, pp. 167–232). <https://doi.org/10.1016/j.jafrearsci.2011.07.003>
- Johnson, P. R., & Kattan, F. H. (2012a). KINGDOM OF SAUDI ARABIA GEOLOGY OF THE ARABIAN SHIELD The Geology of the Arabian Shield i Contents.

- Johnson, P. R., & Kattan, F. H. (2012b). KINGDOM OF SAUDI ARABIA GEOLOGY OF THE ARABIAN SHIELD The Geology of the Arabian Shield i Contents.
- Johnson, & Robert. (1968). laucil Arabia Investigation Report RECONNAISSANCE MINERAL AND GEOLOGIC INVESTIGATIONS IN THE AL BAD 1 QUADRANGLE, AQABA AREA, SAUDI ARABIA.
- Jweda, Bolge, L., Class, C., & Goldstein, S. L. (2016). High Precision Sr-Nd-Hf-Pb Isotopic Compositions of USGS Reference Material BCR-2. *Geostandards and Geoanalytical Research*, 40(1), 101–115. <https://doi.org/10.1111/j.1751-908X.2015.00342.x>
- Kahal. (2020). Geological assessment of the Neom mega-project area, northwestern Saudi Arabia: an integrated approach. *Arabian Journal of Geosciences*, 13(10). <https://doi.org/10.1007/s12517-020-05345-3>
- Khalil, A. E. S., Obeid, M. A., Azer, M. K., & Asimow, P. D. (2018). Geochemistry and petrogenesis of post-collisional alkaline and peralkaline granites of the Arabian-Nubian Shield: a case study from the southern tip of Sinai Peninsula, Egypt. In *International Geology Review* (Vol. 60, Issue 8, pp. 998–1018). Taylor and Francis Inc. <https://doi.org/10.1080/00206814.2017.1364672>
- Kozdrój, W., Kennedy, A. K., Johnson, P. R., Ziółkowska-Kozdrój, M., & Kadi, K. (2018). Geochronology in the southern Midyan terrane: a review of constraints on the timing of magmatic pulses and tectonic evolution in a northwestern part of the Arabian Shield. *International Geology Review*, 60(10), 1290–1319. <https://doi.org/10.1080/00206814.2017.1385425>
- Lashin, A., Anbar, M. A., Aboud, E., Zaidi, F., Al-Bassam, A., Al Arifi, N., & Al-Homadhi, E. (2023). Geochemistry and Petrogenesis of the Ediacaran Post-Collisional Granitoid Rocks in the Midyan Terrain, Northern Arabian Shield, Saudi Arabia. *Minerals*, 13(3). <https://doi.org/10.3390/min13030379>
- Lawrence, A., Fowler, M., Kingsbury, C. G., Knott, T., Mark, D., & Stevenson, C. T. E. (2023). Slab-failure or Slab-success? Examining the contributions of crust and mantle to post-

- subduction magmatism in the Ratagain Complex, NW Scotland. *Lithos*, 448–449. <https://doi.org/10.1016/j.lithos.2023.107139>
- Lawrence, A., Maffione, M., & Stevenson, C. T. E. (2022). Mush ado about the Ratagain Complex, NW Scotland: insights into Caledonian granitic magmatism and emplacement from magnetic fabric analyses. <https://doi.org/10.6084/m9.figshare.c.5941375>
- Lee, C.-H. L. S. R. P. & C.-E. H. (2016). Integrated process development for the recovery of Europium and Yttrium from waste fluorescent powder. *Journal of Material Cycles and Waste Management*.
- Liddicoat, Ramsay, & Hedge. (1983). Cambrian nepheline syenite complex at Jabal Sawda, Midyan region, Kingdom of Saudi Arabia.
- Louis Vigneresse. (1995). Control of granite emplacement by regional deformation. In *Tectonophysics* (Vol. 249).
- Maniar, & Piccoli. (1979). Tectonic discrimination of granitoids. In Bonin and Giret (Vol. 101). *Geological Society of America Bulletin*. <http://pubs.geoscienceworld.org/gsa/gsabulletin/article-pdf/101/5/635/3380532/i0016-7606-101-5-635.pdf>
- Massari, S., & Ruberti, M. (2013). Rare earth elements as critical raw materials: Focus on international markets and future strategies. *Resources Policy*, 38(1), 36–43. <https://doi.org/10.1016/j.resourpol.2012.07.001>
- McDonough, S. (1995). The composition of the Earth.
- Meert, J. G., & Torsvik, T. H. (2003). The making and unmaking of a supercontinent: Rodinia revisited. *Tectonophysics*, 375(1–4), 261–288. [https://doi.org/10.1016/S0040-1951\(03\)00342-1](https://doi.org/10.1016/S0040-1951(03)00342-1)
- Miller, C. F., Mcdowell, S. M., & Mapes, R. W. (2003). Hot and cold granites? Implications of zircon saturation temperatures and preservation of inheritance. In *Geology* (Issue 6).

- Möller, M. (1984). Significance of Europium anomalies in silicate melts and crystal-melt equilibria: a re-evaluation.
- Moyen, J. F., Laurent, O., Chelle-Michou, C., Couzinié, S., Vanderhaeghe, O., Zeh, A., Villaros, A., & Gardien, V. (2017). Collision vs. subduction-related magmatism: Two contrasting ways of granite formation and implications for crustal growth. *Lithos*, 277, 154–177. <https://doi.org/10.1016/j.lithos.2016.09.018>
- Nandedkar, R. H., Ulmer, P., & Müntener, O. (2014). Fractional crystallization of primitive, hydrous arc magmas: an experimental study at 0.7 GPa. <https://doi.org/10.3929/ethz-b-000087224>
- Nehlig, P., Genna, A., & Asfirane, F. (2002). A review of the Pan-African evolution of the Arabian shield. *GeoArabia*, 7(1), 103–124. <https://doi.org/10.2113/geoarabia0701103>
- Neilson, J., Kokelaar, B., & Crowley, Q. (2009). Timing, relations and cause of plutonic and volcanic activity of the Siluro-Devonian post-collision magmatic episode in the Grampian. <http://www.geolsoc.org.uk/SUP00000.38>
- Pearce, Harris, N. B. W., & Tindle, A. G. (1984). Trace Element Discrimination Diagrams for the Tectonic Interpretation of Granitic Rocks. <http://petrology.oxfordjournals.org/>
- Peter Bird. (1978). Initiation of intracontinental subduction in the Himalaya. *JGR Solid Earth*.
- Ramsay. (1983). Felsic plutonic rocks of the Midyan region, Kingdom of Saudi Arabia—I. Distribution, classification and resource potential. *Journal of African Earth Sciences*.
- Roberts, M. P., & Clemens, J. D. (1993). Origin of high-potassium, calc-alkaline, I-type granitoids. <http://pubs.geoscienceworld.org/gsa/geology/article-pdf/21/9/825/3514832/i0091-7613-21-9-825.pdf>
- Robinson, F. A. (2014a). Geochronological and Geochemical Constraints on the Lithospheric Evolution of the Arabian Shield, Saudi Arabia: Understanding Plutonic Rock Petrogenesis in an Accretionary Orogen.

- Robinson, F. A. (2014b). Geochronological and Geochemical Constraints on the Lithospheric Evolution of the Arabian Shield, Saudi Arabia: Understanding Plutonic Rock Petrogenesis in an Accretionary Orogen.
- Sami, M., Adam, M. M. A., Lv, X., Lasheen, E. S. R., Ene, A., Zakaly, H. M. H., Alarifi, S. S., Mahdy, N. M., Abdel Rahman, A. R. A., Saeed, A., Farahat, E. S., Fathy, D., & Ali, S. (2023). Petrogenesis and Tectonic Implications of the Cryogenian I-Type Granodiorites from Gabgaba Terrane (NE Sudan). *Minerals*, 13(3). <https://doi.org/10.3390/min13030331>
- Sharland, P. R., Archer, R., Casey, D. M., Davies, R. B., Hall, S. H., Heward, A. P., Horbury, A. D., & Simmons, M. D. (2001). ARABIAN PLATE SEQUENCE STRATIGRAPHY Special Publication 2. www.gulfpetrolink.com
- Sisson, T. W., Ratajeski, K., Hankins, W. B., & Glazner, A. F. (2005). Voluminous granitic magmas from common basaltic sources. *Contributions to Mineralogy and Petrology*, 148(6), 635–661. <https://doi.org/10.1007/s00410-004-0632-9>
- Stern. (2004). Arc Assembly and continental collision.
- Stern, R. J., Ali, K. A., Liégeois, J. P., Johnson, P. R., Kozdroj, W., & Kattan, F. H. (2010). Distribution and significance of pre-neoproterozoic zircons in juvenile neoproterozoic igneous rocks of the arabian-nubian shield. *American Journal of Science*, 310(9), 791–811. <https://doi.org/10.2475/09.2010.02>
- Stern, R. J., & Gottfried, D. (1986). Contributions to Mineralogy and Petrology Petrogenesis of a Late Precambrian (575-600 Ma) bimodal suite in Northeast Africa.
- Stern, R. J., & Johnson, P. (2010). Continental lithosphere of the Arabian Plate: A geologic, petrologic, and geophysical synthesis. In *Earth-Science Reviews* (Vol. 101, Issues 1–2, pp. 29–67). <https://doi.org/10.1016/j.earscirev.2010.01.002>
- Stoeser. (1986). Distribution and tectonic setting of plutonic rocks of the Arabian Shield. In *Journal of African Earth Sciences*.
- Stoeser, D. B., & CAMP Saudi, V. E. (n.d.). Pan-African microplate accretion of the Arabian Shield. <http://pubs.geoscienceworld.org/gsa/gsabulletin/article->

pdf/96/7/817/3434450/i0016-7606-96-7-

817.pdf?casa_token=aJm6ctQVOIYAAAAA:h4U65WgQllJ5pL4U7lbSQVbkBApSuoIFn
wAk81-iZgFpcXmhccEIda-no

Stoeser, D. B., & Elliott, J. E. (n.d.). Open-File Report 85-665* Report prepared for Ministry of Petroleum and Mineral Resources, Deputy Ministry for Mineral Resources, Saudi Arabia.

Stoeser, D. B., & Frost, C. D. (2006). Nd, Pb, Sr, and O isotopic characterization of Saudi Arabian Shield terranes. *Chemical Geology*, 226(3–4), 163–188.
<https://doi.org/10.1016/j.chemgeo.2005.09.019>

Sultan, M., Becker, R., Arvidson, R. E., Shore, P., Stern, R. J., El Alfy, Z., & Guinness, E. A. (1992). Nature of the Red Sea crust: a controversy revisited. *Geology*, 20(7), 593-596.

Sun, & McDonough, W. F. (1989). Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. *Geological Society Special Publication*, 42(1), 313–345. <https://doi.org/10.1144/GSL.SP.1989.042.01.19>

Sylvester, P. J., & Sylvester2, P. J. (1998). Post-collisional alkaline granites LA-ICP-MS Method Development View project POST-COLLISIONAL ALKALINE GRANITES'. In Article in *The Journal of Geology*. <https://www.researchgate.net/publication/313105535>

Till, C. B., Grove, T. L., & Krawczynski, M. J. (2012). A melting model for variably depleted and enriched lherzolite in the plagioclase and spinel stability fields. *Journal of Geophysical Research: Solid Earth*, 117(6). <https://doi.org/10.1029/2011JB009044>

Tubbs, R. E., Fouda, H. G. A., Afifi, A. M., Raterman, N. S., Hughes, G. W., & Fadolkareem, Y. K. (2014). Midyan Peninsula, northern Red Sea, Saudi Arabia: Seismic imaging and regional interpretation (Vol. 19, Issue 3). <http://pubs.geoscienceworld.org/geoarabia/article-pdf/19/3/165/5447502/tubbs.pdf>

Vander Auwera, J., Bogaerts, M., Liégeois, J. P., Demaiffe, D., Wilmart, E., Bolle, O., & Duchesne, J. C. (2003). Derivation of the 1.0-0.9 Ga ferro-potassic A-type granitoids of southern Norway by extreme differentiation from basic magmas. *Precambrian Research*, 124(2–4), 107–148. [https://doi.org/10.1016/S0301-9268\(03\)00084-6](https://doi.org/10.1016/S0301-9268(03)00084-6)

- Vanderhaeghe, O. (2012). The thermal-mechanical evolution of crustal orogenic belts at convergent plate boundaries: A reappraisal of the orogenic cycle. *Journal of Geodynamics*, 56–57, 124–145. <https://doi.org/10.1016/j.jog.2011.10.004>
- Van der Voo, S. , B. (1999). Tethyan subducted slabs under India. *Earth and Planetary Science Letters*.
- Von Blanckenburg, & Davies. (1995). Slab breakoff: A model for syncollisional magmatism and tectonics in the Alps. In *TECTONICS* (Vol. 14, Issue 1).
- Wang, Pandit, Zhao, Chen, & Zheng. (2018). Slab break-off triggered lithosphere - asthenosphere interaction at a convergent margin: The Neoproterozoic bimodal magmatism in NW India. *Lithos*, 296–299, 281–296. <https://doi.org/10.1016/j.lithos.2017.11.010>
- Watson, T. M. H. (1984). Accessory minerals and the geochemical evolution of crustal magmatic systems: a summary and prospectus of experimental approaches. *Physics of the Earth and Planetary Interiors*, Volume 35,(Issues 1–3,), 19–30.
- Whalen. (n.d.). A-type granites: Geochemical characteristics. <https://www.researchgate.net/publication/281390425>
- Whalen, J. B., Currie, K. L., & Chappell, B. W. (1987). Contributions to Mineralogy and Petrology A-type granites: geochemical characteristics, discrimination and petrogenesis*. In *Contrib Mineral Petrol* (Vol. 95).
- Whalen, J. B., & Hildebrand, R. S. (2019). Trace element discrimination of arc, slab failure, and A-type granitic rocks. *Lithos*, 348–349. <https://doi.org/10.1016/j.lithos.2019.105179>
- Whattam, S. A., Stern, R. J., Azizi, H., Yi, K., Baggazie, H. M., Alquabalee, A., Nouri, F., Lemdjou, Y. B., & Fakharanie, A. E. (2024). Shift from arc to within-plate magmatism at 635 Ma as recorded by Neoproterozoic dikes, southern Midyan terrane, NW Arabian Shield. *Precambrian Research* (in press).
- Whattam, S.A., Torro, L. Carrasco, C., Azizi, H., Jeong, Y-J., Chattopaghyay, S., & Ireland, T. (2023). Arc adakitic-like signatures caused by amphibole fractionation: An example from

20 Ma granitoids, Charco Rico district, Panama. *Lithos* 107363.
<https://doi.org/10.1016/j.lithos.2023.107363>

Williams. (1997). U-Th-Pb Geochronology by Ion Microprobe.

Winter. (2014). Principles of igneous and metamorphic petrology.

Zaidi, F. K., Lashin, A., Aboud, E., Al Arifi, N., Al-Bassam, A., Al-Homadhi, E., & Anbar, M. A. (2022). Silica geothermometry and multi indices approach to characterize groundwater from Midyan region in Northwestern Saudi Arabia. *Journal of African Earth Sciences*, 192.
<https://doi.org/10.1016/j.jafrearsci.2022.104557>

LIST OF TABLES

Table 1 . *Plutonic rocks from the Midyan region, Northwestern Saudi Arabia (after Clark 1985).*

Age (Ma)	Method	Rock	Pluton	Suite
553±4	U-Pb	Nepheline syenite	Sawda	
574± 5	Rb-Sr	Alkali-feldspar granite	Ratamah	Haql
575±5	Rb-Sr	Alkali-feldspar granite	Buwarah	Haql
575± 5	Rb-Sr	Quartz syenite	(Dikes)	Midyan (?)
570± 7	Rb-Sr	Alkali granite	Dabbagh	Midyan
577± 4	U -Pb	Alkali granite	Dabbagh	Midyan
586±11	Rb-Sr	Alkali granite	Dabbagh	Midyan
598± 30	Rb-Sr	Monzogranite	Sadr area	Atiyah (?)
599± 5	U-Pb	Monzogranite	Sadr area	Atiyah (?)
625	U-Pb	Granodiorite	Amq	Ifal(?)

710±5	U-Pb	Tonalite	Duba	south Muwaylih
--------------	------	----------	------	----------------

Table 2. The mineral chemistry of the NW Midyan shows the different rock groups and the different ratios of major and minor minerals.

Unit	Minerals chemistry	Quartz	K-Feldspar	Plagioclase	Amphibole	Pyroxene	Epidote	Apatite	Sphene	Garnet	Chlorite	Muscovite	Biotite	Pyrite	Calcite	Iron Oxides	Others
A-type I- type granitoid group	TB-33b	17	11.1	51.1	8	0	1	0.4	0.6	0.9	2.9	3.1	0.5	0	0	2	1.4
	TB-33cf	20.9	5.1	51.2	10.6	0.1	0.5	0.5	0.7	0.3	1.7	2.9	3.7	0	0	1	0.8
	TB-33cm	2.9	5.4	52.4	28.6	0.1	0.7	1	1	0.6	3.7	0.9	1.7	0	0	0.5	0.5
	TB-37a	8.4	3.9	62.8	7.5	0	0.1	0.8	0.7	0.1	0.5	1.4	11.1	0	0.1	1.5	1.1
	TB-37b	11.7	1.9	59.3	6.1	0	0.8	0.7	1.3	0.2	1.7	1.7	12.5	0	0	1.1	1
	TB-37c(f)	40.5	2.1	47.3	0.1	0	0	0	0.1	0	0.5	7.1	0.8	0	0	0.3	1.1
	TB-39b	40.5	22.7	13.9	0.9	0	0	0.1	0.3	0	1.4	9.9	0.1	0	0	0.6	9.6
	TB-51a	4.5	26.1	63.6	0	0	0	0	0.1	0.1	1.1	1.2	0.2	0	0.6	0.3	2.2
	TB-39c(m)	9	6.6	52.3	6.4	0.1	0.1	1.3	3.2	0.6	3.2	2.6	8.8	0	0	2.4	3.3
	TB-51b	10.8	17	32.5	13	0.3	1.1	0.7	3.6	4.2	6.6	6.5	0.6	0	0.2	1.1	1.8
	TB-52a	30.5	22.3	32.1	0	0	0	0	0	0.2	0.2	12.7	0.4	0	0	0.4	1
	TB-52b	17.4	9.1	20.6	0.9	2	0.1	0.6	3.2	12.9	11.2	12	3	0	2.6	0.6	4
	TB-54a	14.1	53.7	27.9	0	0	0	0	0.1	0.2	0.1	3.1	0.2	0	0	0.1	0.4
	TB-54b	31	37	20.6	0.2	0	0	0.1	0.2	0.2	0.4	7.8	0.8	0	0	0.1	1.6
	TB-54c	5.8	31.1	27.8	22.4	0.1	1.1	0.7	1.9	2.7	2.7	2	0.5	0	0	0.4	0.9
	TB-55a	27.4	17.6	41.5	0.1	0.1	0	0.1	0.6	0.9	0.8	7	0.2	0	0	1.1	2.7
A-type I- type granitoid group	TB-56a	10.7	43.3	31.2	0.3	0.2	0.4	0.2	1.1	0.8	3	2	1.2	0	0	0.7	4.9
	TB-56	0.2	58.6	36.2	0	0	0.4	0	0.6	0.1	0.1	2.9	0.2	0	0	0.3	0.4
	TB-56b	9.2	15.3	45.6	7.7	0.3	2.5	1.1	2.6	2.1	2.5	2.9	6.1	0	0	0.3	1.6
	TB-58	7.2	55	28.6	0.3	0	0	0.1	0.5	0.3	0.7	2.1	1.1	0	0	0.2	3.8
A-type I- type granitoid group	TB-37c(m)	9.5	8.7	40.7	18.8	0.1	0.1	0.4	1.3	0.3	2.5	1.4	14.9	0	0.1	0.4	0.9

	TB-39c	21.5	44.5	27.2	0.2	0	0.1	0.1	0.1	0.4	0.8	3.9	0.6	0	0	0.2	0.5
	TB-55b	11.7	20	34.3	14.2	0.2	1.7	0.7	2.2	3	2.1	6.8	0.4	0	0	0.9	1.8
Gabbro	TB-40	0.2	4	5.5	72.8	0	9.9	0.1	2.5	0.3	1.4	2	0.1	0	0	0	2.4
	TB-33a	0	3.9	33.9	16	3.6	1.8	1.4	4.5	7.4	15.5	3.7	0.2	1.7	0.1	3.7	1.1

Table 3.Major oxides of the NW Midyan region.

	Sample name	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5	Cr2O3	LOI	Total
Major oxides and normative compositions (wt%) of NW Midyan samples	Rock type													
	TB-4b	77.48	0.10	12.48	1.22	0.01	0.11	0.28	3.48	4.80	0.02	0.00	1.00	99.99
	TB-5b	71.10	0.18	15.50	2.11	0.06	0.37	1.15	4.60	4.88	0.05	0.00	1.30	100
	TB-18c	71.61	0.37	14.81	2.28	0.05	0.51	0.96	4.52	4.80	0.08	0.00	0.70	100
	TB-29	71.12	0.32	15.36	2.34	0.05	0.56	0.97	4.94	4.26	0.08	0.00	0.80	100
	TB-32b	71.69	0.27	14.81	2.32	0.04	1.09	0.88	4.31	4.50	0.08	0.01	1.00	100
	TB-39b	71.57	0.26	14.74	2.19	0.05	0.35	1.03	4.93	4.81	0.07	0.00	0.40	100
	TB-52a	76.75	0.10	12.60	1.44	0.02	0.10	0.44	4.95	3.55	0.02	0.01	0.80	100
	TB-54a	74.44	0.18	13.42	2.42	0.04	0.20	0.69	4.28	4.27	0.04	0.00	0.40	100
	TB- 54b	76.52	0.23	12.56	1.56	0.03	0.11	0.31	3.30	5.34	0.03	0.00	0.90	100
	TB-55a	72.39	0.37	15.14	1.97	0.04	0.18	0.43	6.32	3.05	0.10	0.00	0.60	100
	TB-56a	71.85	0.34	14.34	2.59	0.05	0.71	1.18	4.49	4.32	0.12	0.00	1.00	100
	TB-58	69.71	0.28	15.81	2.26	0.04	0.52	2.01	4.73	4.54	0.08	0.00	0.50	100
	TB-33c (f)	74.33	0.09	13.68	3.55	0.03	0.19	2.54	4.98	0.53	0.07	0.00	- 0.26	100
	TB- 18d	63.84	0.80	14.99	5.62	0.07	3.16	3.23	5.11	2.93	0.23	0.02	3.20	100
	TB-33b	66.10	0.52	16.04	4.63	0.07	1.92	3.87	4.37	2.32	0.16	0.00	1.30	100
	TB-51a	64.95	0.36	18.62	2.67	0.04	0.60	1.45	8.93	2.30	0.07	0.00	1.50	100
	TB-37c(f)	65.89	0.57	16.46	4.33	0.07	2.11	4.24	4.58	1.54	0.20	0.00	1.30	100
	TB- 26a	54.09	1.84	16.07	10.33	0.15	5.12	6.06	3.37	2.26	0.69	0.02	2.70	100
	TB- 33c(m)	54.14	1.20	17.66	8.31	0.12	4.74	7.43	4.77	1.09	0.52	0.01	1.50	100
	TB-37a	61.26	1.04	17.29	6.06	0.08	1.99	4.81	5.03	2.02	0.41	0.00	0.70	100
	TB-37b	57.30	1.41	17.35	8.14	0.11	3.03	5.37	4.58	2.22	0.49	0.00	1.10	100
	I-type granite													

A-type granite	TB-39c(m)	57.75	1.27	16.93	9.07	0.16	2.30	5.25	5.26	1.33	0.67	0.00	1.30	100
	TB-51b	56.32	1.44	16.15	9.37	0.13	4.78	5.29	4.04	2.02	0.44	0.01	2.40	100
	TB- 52b	56.29	1.50	16.38	9.84	0.17	5.19	4.79	3.44	1.95	0.44	0.02	7.00	100
	TB-54c	57.39	1.36	14.42	7.75	0.10	5.46	5.23	3.72	4.04	0.51	0.03	1.50	100
	TB- 56b	57.05	1.37	18.60	7.29	0.09	2.05	6.40	4.13	2.50	0.51	0.00	1.40	100
	TB-18a	54.53	1.32	16.81	9.48	0.13	5.18	6.49	3.80	1.96	0.29	0.02	1.80	100
	TB-11b	74.52	0.19	12.87	2.48	0.04	0.20	0.75	4.19	4.72	0.03	0.00	0.50	100
	TB-20	72.13	0.27	13.69	3.13	0.07	0.27	0.79	4.37	5.22	0.05	0.00	0.40	100
	TB- 26b	75.36	0.12	12.72	1.85	0.02	0.14	1.14	2.69	5.94	0.01	0.00	2.10	100
	TB-39c(f)	68.79	0.49	15.73	3.05	0.09	0.72	1.69	4.18	5.15	0.11	0.00	0.70	100
	TB- 18b	67.52	0.59	19.11	2.64	0.03	1.13	0.69	3.15	5.03	0.10	0.00	2.60	100
	TB-37c	56.70	1.20	15.41	9.45	0.13	5.26	5.09	4.09	2.29	0.34	0.03	0.78	100
	(m)													
	TB- 55b	59.50	1.20	15.55	8.69	0.12	3.17	4.73	3.87	2.73	0.43	0.01	1.19	100

Table 4. Trace element contents ($\mu\text{g/g}$) of NW Midyan samples.

Rock type	Sampl e name	S c	V	C o	N i	C u	Z n	G a	R b	Sr	Y	Zr	N b	C s	B a	H f	T a	P b	T h	U	S n	W o	M o	A s	C d	S b	B i	A g	A u	H g	T l	S e	
I- type granite	TB-4b	3	1	0.	2.	11	1	1	33	30	46	97	3	2	27	5.	5	2.	2	5.	8	1.	3.	1			0		0				
			2	9	2	.1	0	6.	4.	.4	.9	.6	5.		6	5	.	8	9.	5		6	8	.		.	.						
								3	3				2				1		9				4			4		7					
	TB-5b	4	1	2.	4.	4.	3	1	24	11	26	12	1	3.	32	5.	3	4.	1	3.	1	0.	1.				0					0	
			7	3	5	2	2	9.	6.	4	.4	2.	4.	6	6	3	.	5	7.	7	0	9	9			.					.		
								7	9			8	7				1		9							2					1		
	TB-18c	4	1	1.	1.	5.	3	1	99	18	24	28	1	1.	94	7.	1	4.	7.	1.	2		2.										
			0	8	8	2	7	6.	.5	8.	.9	0.	5.	4	9	3	.	1	7	8			8										
								9		9		7	6				1																
	TB-29	3	1	1.	4.	3.	5	1	95	22	20	20	1	1.	66	6	1	2	8.	2.	2	0.	2.	0		0							
			2	8	2	8	2	6.	.2	8.	.8	1.	5.	8	7		.	5.	1	1		7	6	.		.							
								5		7		4	7				1	6					6		1								
	TB-32b	2	2	4.	1	12	6	1	12	37	4	98	6.	4.	70	3.	0	2.	1	2.	1	0.	2.	0		0	0					0	
			3	7	6.	.8	1	7.	2.	4.		.3	7	7	5	1	.	3	0.	3		5	8	.		.	.				.		
				9				7	1	9							7		6				7		1	2					1		
	TB-39b	3	1	2.	4.	4	3	1	65	18	24	23	1	0.	59	5.	0	3.	2.	0.	2		2.	0									
			9	7	4		4	8.	.5	7.	.5	5.	0.	4	0	7	.	9	3	8			4	.									
							2		6			8	7				9						7										
	TB-52a	2	9	1.	3.	5.	9	1	64	77	18	80	1	0.	44	3.	1	1.	9.	2.	1	0.	1.	0									
				1	8	2		2	.3		.6	.9	5.	6	9	4	.	8	5	9		9	6	.									
												6					3						6										
	TB-54a	3	1	1.	3.	3.	3	1	98	58	43	20	1	1.	56	7	1	5.	9.	1.	4	1.	3.	0		0					0		
			0	6	7	3	0	8		.5		2.	8.	7	8		.	2	1	8		7	7	.		.				.			
												3	2				6						8		1					9			
	TB-54b	3		1	3.	2.	7	1	17	32	38	20	3	1.	17	7	2	6.	2	6.	3	1.	2.										
					3	4		6.	4.	.7	.5	1.	0.	5	3		.	4	2	4		4	2										
								2	9			5	5				5																

TB-55a	2	1	1.	3.	5.	6	1	12	19	7.	24	1	4.	48	7	1	6.	9.	4.		1	2.	0		0	0
		4	6	4	6		4.	3.	2.	6	3.	1.	1	7		.	1	1	7		1.	9	.		.	.
							3	9	7		6	7				1					4	7		3	6	
TB-56a	3	3	4.	7	8.	3	1	11	27	8.	11	8.	1	46	3.	0	8.	8.	2.	3		2.	0			
		2	5		1	1	6.	7.	7.	1	0.	6		8	4	.	1	2	3			5	.			
							2	9	7		3					7						6				
TB-58	2	2	3.	4.	5	5	2	10	41	18	13	1	1.	77	4	1	2.	7.	2.	2		1				0
		3	4	4		5	2	2.	1.	.4	4.	9.	6	8		.	9	6	3						.	
								9	7		5	2				6									1	
TB-33c (f)		1					1	7.	65	2.	13	2.	0.	19	3.	0		6.	2.	1	1					
		9					7.	6	4	7	2	4	2	0	9	.		1	1							
							4						2			5		8	1							
TB-18d	1	5	1	4	3.	5	1	46	49	11	12	6.	0.	56	3.	0	4.	7.	1.		0.	1.	7		1	
	0	3	7.	5.	6	3	4.		0.		8.	4	3	7	7	.	2	4	8		9	9	.			
			3	2			3		7		3					6						7				
TB-33b	8	7	1	1	4.	3	1	29	51	14	11	4.	0.	41	3.	0	1.	3.	1.			1.				
		2	0.	5.	3	2	7	.3	7.	.2	8.	8	3	6	6	.	7	2	7			7				
			1	3					4		6					5										
TB-51a	5	1	2.	3.	2.	3	1	36	96	27	25	2	0.	18	7.	1	3.	1	3.	2	0.	1			0	
		9	5	1	3	0	8.	.3	.5	.3	9.	1.	1	3	7	.	5	5.	5		7				.	
							2				7	6				5		4							2	
TB-37c(f)	8	6	1	2	5.	3	1	24	61	9.	15	3	0.	29	3.	0	0.	1	0.			2.	0		0	
		9	1.	1	5	5	7.		3.	1	7.		4	8	9	.	9		5			9	.	.	.	
			1				3		3		1					1						8	1			
TB-26a	1	1	3	4	48	1	1	76	83	22	20	1	2.	15	5.	0	1.	3.	1.	1	1.	1.	0	0	0	0
	6	9	2.	5.	.3	0	9.	.4	7.	.3	6.	0	4	85	1	.	3	8	3		8	1	.	.	.	.
		1	5	5		6	4		1		1					6						9	2	2	9	

TB-33c(m)	1	1	2	3	16	4	1	11	84	20	10	4.		23	2.	0	0.	1.	0.		1.	0			
	7	6	3.	5.	.1	1	8.	.4	5.	.4	2.	6		8	5	.	8	1	3		4	.			
		0	5	3			1		4		1					2					5				
TB-37a	6	9	1	2.	13	6	2	35	85	19	23	1	0.	73	5.	1	0.	2.	1	1	1.		0		
		5	2.	3	.3	5	0.	.7	6.	.7	6.	6	6	3	5		9	7			7	.			
			8				7		2		7	5										1			
TB-37b	1	1	1	7.	10	8	2	46	82	24	19	1	1	57	4.	1	0.	3.	1.	2	1.		0		
	1	4	9.	2	.6	7	2.	.9	6.	.7	7.	7.		3	8		9	7	5		1	.			
		1	9				4		4		3	9										2			
TB-39c(m)	1	1	1	2	23	1	2	37	58	28	24	1	1.	10	5.	0	1.	5	1.	2	0.	1.	0	0	
	1	1	8.		.3	0	2	.9	2.	.6	5.	2.	6	46	9	.	4		5		7	3	.	.	
		6	3			4			4		2	2				6						8		2	
TB-51b	1	1	2	3	8.	9	1	63	79	20	21	1	1.	11	5	0	1.	4.	1.	2	3.	1.	0	0	
	4	6	8.	9.	7	3	9.	.4	8.	.1	2.	1.	5	04		.	3	3	4		6	8	.	.	
		8	8	2			6		5		2	6				6						7	2		
TB-52b	1	1	2	4	26	1	1	64	20	19	17	7.	1.	13	4.	0	3.	3.	1.		1.	1		0 0 0 3	
	7	8	7.	9.		0	8.	.5	8.	.2	9	7	2	3	6	.	1	8	2		9		.		
		0	9	9		3	5		4							5							1 1 4 7		
TB-54c	1	1	2	8	56	4	1	13	44	18	22	1	1.	62	5.	1	2.	9.	3	3	2.	2		0	
	4	3	4.	5.	.7	4	6.	4.	3.	.4	0.	5.	4	0	8		9	2			7		.		
		7	3	4			1	8	5		4	8											1		
TB-56b	1	1	1	1	10	5	2	55	53	30	28	1	2.	49	7.	0	5	4.	1.	2	0.	1.	0	0	0
	2	4	7	8.	7.	6	0.	.1	8.	.4	0.	2.	8	8	2	.		9	6		8	8	.	.	
		5		9	3		1		4		3	6				9						6	1		7 1
TB-18a	1	2	3	2	40	4	1	58	68	14	14	7.	2.	47	3.	0	2.	5	1.	1	0.	2	1		0
	7	0	0.	7.	.9	8	8.	.2	8.	.6	9.	1	8	7	7	.	8		5		6		.		.
		5	9	6			6		2		2					3								1	

A-type granite	TB-11b	2	9	2.	4.	2.	4	1	10	47	56	38	2	1.	28	1	1	3.	6.	1.	3	2.	0	0	
				2	3	9	6	9.	2.	.4	.4	0.	1.	8	9	1	.	5	2	7	3	.	.		
								1	2			1	7				5				6	1			
	TB-20	4		1.	1.	10	2	2	92	79	41	44	3	1.	50	1	1	6.	9.	1.	1	0.	4	0	
				2	3	.2	6	0.	.9		.8	2	3.	6	1	0.	.	1	1	6	5		.		
							9						6			3	5						1		
	TB-26b			0.	1.	4.	4	2	12	58	11	33	6	2.	85	1	4	3.	1	2.	3	1.	2.	0	0
				7	9	7	0	8.	3.	.7	7.	1.	8.	8	0	2.	.	8	1.	1	1	7	.	.	
							7	3			1	7	3			6	2		2				1	1	
																								6	
TB-39c(f)	5	2	4.	3.	4.	5	2	60	28	40	45	1	0.	73	1	1	3.	5.	1.	2	1.				
		5	2	1	9	6	0.	.9	2.	.7	0.	9.	8	0	0.	.	6	2	5		3				
						9			2		4	7			9	3									
TB-18b	5	2	1.	3.	2.	3	2	12	39	23	39	1	9.	92	9.	1	1.	1	3.	2	1	2	0		
		5	7	7	3	1	2	9.	2.	.9	6.	7.	1	7	8	.	5	0.	7		0.		.		
								2	4		4	6				3		4		3		6			
TB-37c	1						2	73	62	17	18	1	2.	47	4.	0		3.	2.	2	1				
	4						2.	.4	8	.9	3	0	0	8	5	.		8	8						
(m)	5						6						3			7		9	4						
TB-55b	1						2	78	65	20	24	1	8.	80	5.	0		7.	2.	2	1				
	4						3.	.2	6	.4	2	2.	3	3	7	.		3	1						
	5						5					6	3			9		4	2						

Table 4. Rare earth element contents (μmg) of NW Midyan samples.

Rock type	Sample name	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	TOT/C	TOT/S	Ni
I- type granite	TB-4b	11.9	23.6	3.65	13.9	3.32	0.25	3.01	0.58	4.24	1.22	5.42	1.2	10.8	2.03	0.03		
	TB-5b	15.4	39.5	4.1	14.9	3.26	0.58	3.2	0.58	3.7	0.88	3.03	0.52	4.14	0.69	0.05		
	TB-18c	49.1	95.3	11	40.8	7.18	1.43	5.78	0.84	4.29	0.86	2.45	0.35	2.33	0.38	0.03		
	TB-29	34.8	69.9	8.24	31.2	5.02	1.08	4.27	0.61	3.45	0.67	2.05	0.31	2.02	0.32	0.02		
	TB-32b	12.3	21.7	2.33	8.4	1.39	0.39	1.01	0.13	0.78	0.14	0.41	0.05	0.44	0.06	0.04	0.04	
	TB-39b	25.2	61.8	7.84	29.7	5.35	0.69	4.67	0.7	4.14	0.81	2.4	0.33	2.09	0.3	0.04		
	TB-52a	24.8	50.1	5.66	20.3	3.75	0.49	3.29	0.52	3.22	0.61	1.79	0.27	1.89	0.3	0.04	0.15	
	TB-54a	42.9	84.4	9.85	35.9	7.11	0.59	7.02	1.16	7.33	1.55	4.81	0.7	4.61	0.7	0.03		
	TB- 54b	51	102.4	12.61	45.4	8.73	0.79	7.39	1.13	6.83	1.34	3.86	0.56	3.75	0.55	0.08	0.02	
	TB-55a	15	26	3.46	11.8	2.22	0.58	1.79	0.28	1.53	0.3	0.94	0.15	1.03	0.16			
	TB-56a	20	36.5	3.88	13.9	2.18	0.61	1.78	0.24	1.4	0.26	0.7	0.12	0.83	0.13	0.02		
	TB-58	13.2	32.9	4.42	17.7	3.71	0.85	3.35	0.52	3.09	0.63	1.95	0.27	1.96	0.3	0.08		
	TB-33c	10.7	14.5	1.25	4	0.6	0.55	0.4	0.06	0.36	0.08	0.25	0.07	0.46	0.1			
	(f)																	
	TB- 18d	20	40.6	5.13	20.4	3.66	1.1	2.92	0.39	2.12	0.38	1.18	0.15	0.96	0.15	0.41		
	TB-33b	15	37.3	5.31	22.3	4.47	1.19	3.84	0.52	2.86	0.49	1.54	0.21	1.33	0.2	0.05		46
	TB-51a	50.7	91.5	10.83	39	6.4	1.3	5.14	0.75	4.39	0.88	2.71	0.39	2.65	0.41	0.21		77
	TB- 37c(f)	12	26.8	3.44	14.4	2.8	0.93	2.37	0.31	1.82	0.35	0.9	0.13	0.89	0.14	0.04		28
	TB- 26a	26.9	59.2	8.22	36.3	7.27	2.2	6.66	0.86	4.35	0.79	2	0.27	1.69	0.24	0.03	0.07	54

A-type granite	TB-33c(m)	24.4	57.3	8.12	35.7	6.97	2.04	5.83	0.77	4.05	0.76	1.98	0.27	1.69	0.25	0.03	
	TB-37a	35.5	79.8	9.54	37.9	6.42	1.84	5.01	0.67	3.64	0.68	1.94	0.27	1.74	0.27	0.06	66
	TB-37b	36	76.9	9.91	41.8	7.93	1.87	6.51	0.92	5.01	0.93	2.63	0.35	2.33	0.32	0.05	
	TB-39c(m)	34.8	74.9	10.01	41.9	8.31	2.44	7.57	1.03	5.46	1.01	2.69	0.36	2.26	0.31	0.03	0.03
	TB-51b	25.6	57.5	7.34	30.1	6.4	1.81	5.53	0.75	3.99	0.73	1.89	0.25	1.57	0.21	0.09	
	TB- 52b	20.8	47.1	6.16	25.7	5.44	1.56	5.05	0.71	3.77	0.67	1.8	0.24	1.4	0.19	0.83	47
	TB-54c	29.8	66.1	8.62	37.5	7.16	1.78	5.45	0.72	3.84	0.69	1.77	0.26	1.67	0.25	0.03	57
	TB- 56b	30.3	69.3	8.94	37.1	7.73	1.91	6.95	1	5.84	1.14	3.2	0.41	2.63	0.42	0.03	121
	TB-18a	21.1	42.8	5.6	23.2	4.38	1.44	3.96	0.54	2.93	0.55	1.42	0.19	1.19	0.18	0.02	24
	TB-11b																
	TB-20																
	TB- 26b	102.9	208.6	28.71	116.9	26.08	1.87	25.48	3.8	21.5	4.12	11.09	1.46	9.28	1.35	0.16	0.07
	TB-39c(f)	40.1	106.5	13.57	50.5	10.63	1.18	8.86	1.35	7.39	1.46	4.04	0.56	3.48	0.47	0.04	
	TB- 18b	40.4	88.2	10.14	39	7.01	1.7	5.81	0.78	4.31	0.8	2.36	0.34	2.27	0.34	0.03	
	TB-37c (m)	21.8	46.2	6.07	25.8	4.96	1.47	4.36	0.62	3.36	0.63	1.8	0.26	1.62	0.22		24
	TB- 55b	32.5	70.2	8.88	36	7.28	1.95	6.07	0.79	4.36	0.76	2.06	0.26	1.53	0.22		

Table 5. *Nd isotopes analyses*

Samples ID	T(Ma)	Sm	Nd	¹⁴⁷Sm/¹⁴⁴Nd	¹⁴³Nd/¹⁴⁴Nd	2σ	Sm/Nd	INd	εNd(0)	εNd(t)	2σ	TDM	TDMC
TB-11a	600	9.11	42.10	0.130744	0.512643	0.000006	0.216390	0.512128	0.09	5.15	0.059	935	1036
TB -33c(m)	600	6.97	35.70	0.117964	0.512638	0.000007	0.195238	0.512174	0.00	6.05	0.069	818	927
TB -54c	600	7.16	37.50	0.115363	0.512518	0.000007	0.190933	0.512065	-2.34	3.91	0.066	982	1188
TB -37a	600	6.42	37.90	0.102348	0.512540	0.000007	0.169393	0.512137	-1.92	5.33	0.070	838	1015
TB -55b	600	7.28	36.00	0.122184	0.512583	0.000007	0.202222	0.512103	-1.07	4.65	0.071	947	1097
TB -4b	600	3.32	13.90	0.144314	0.512727	0.000008	0.238849	0.512160	1.75	5.77	0.078	932	961
TB -20	600	14.22	86.40	0.099442	0.512515	0.000007	0.164583	0.512124	-2.39	5.08	0.067	849	1046
TB -39b	600	5.35	29.70	0.108838	0.512581	0.000008	0.180135	0.512153	-1.12	5.63	0.075	830	978
TB -55a	600	2.22	11.80	0.113672	0.512506	0.000010	0.188136	0.512059	-2.58	3.80	0.098	984	1202
TB -51a	600	6.40	39.00	0.099152	0.512534	0.000006	0.164103	0.512144	-2.03	5.46	0.058	822	998

LIST OF ABBREVIATIONS

LREE: Light Rare Earth Elements
WPG: Within-Plate Granitoids
COLG: Collision-Related Granitoids
ORG: Orogenic Granitoids
VAG: Volcanic Arc Granitoids
LILEs: Large Ion Lithophile Elements
HFSE: High Field Strength Elements
EAAO: East African Orogen

VITAE

Name : Wafa Abdalnaser AL-Hakimi

Nationality : Yemeni

Date of Birth :12/21/1992

Email : alhakimiwafaa@gmail.com

Address : AlRawdah, Zaid Almoshiki Street, Taiz, Yemen

Academic Background

- Masters in Geology, 2022 - 2024
Geoscience Department, King Fahd University of Petroleum & Minerals, Saudi Arabia.
- Bachelor in Geology, 2011 - 2015
Geology Department, Taiz University, Yemen.

Academic and Research Experiences

- Poster presentation, EGU conference, Austria, April 2024
- Teaching assistant King Fahd University of Petroleum and Minerals (KFUPM), Principles of Geology (GEOL- 103), January 2022 to present.
- Teaching assistant at Taiz University, lab courses including: Optical Mineralogy, Principle of Geochemistry, Economic Geology, Advanced Mineralogy, Industrial Rocks, Minerals and Rocks, October 2017 to May 2020 Taiz, Yemen. |