2013

The tectonic evolution of a Neo-Tethyan (Eocene-Oligocene) island-arc (Walash and Naopurdan groups) in the Kurdistan region of the Northeast Iraqi Zagros Suture Zone

Sarmad A. Ali

University of Wollongong, sarmad@uow.edu.au

Solomon Buckman

University of Wollongong, solomon@uow.edu.au

K J. Aswad

Mosul University

Brian G. Jones

University of Wollongong, briangj@uow.edu.au

Sabah A. Ismail

Kirkuk University

See next page for additional authors

Follow this and additional works at: <https://ro.uow.edu.au/smhpapers>

Part of the [Medicine and Health Sciences Commons](#), and the [Social and Behavioral Sciences Commons](#)

Recommended Citation

Ali, Sarmad A.; Buckman, Solomon; Aswad, K J.; Jones, Brian G.; Ismail, Sabah A.; and Nutman, Allen P., "The tectonic evolution of a Neo-Tethyan (Eocene-Oligocene) island-arc (Walash and Naopurdan groups) in the Kurdistan region of the Northeast Iraqi Zagros Suture Zone" (2013). *Faculty of Science, Medicine and Health - Papers: part A*. 357.

<https://ro.uow.edu.au/smhpapers/357>

The tectonic evolution of a Neo-Tethyan (Eocene-Oligocene) island-arc (Walash and Naopurdan groups) in the Kurdistan region of the Northeast Iraqi Zagros Suture Zone

Abstract

The Walash and Naopurdan groups are incorporated into the lower allochthonous thrust sheet in the Iraqi Zagros Suture Zone (IZSZ). ^{40}Ar – ^{39}Ar dates on magmatic feldspar separates from both Walash and Naopurdan volcanic rocks indicate an Eocene–Oligocene age (43.01 ± 0.15 to 24.31 ± 0.60 Ma). The Walash and Naopurdan groups form a thrust sheet that is structurally overlain by an upper allochthon of Cretaceous arc-related rocks (106–92 Ma) now known as the Hasanbag igneous complex (formerly known as the Gemo–Qandil Group). The Walash and Naopurdan lower allochthon is thrust over the foreland basin Red Beds series. Volcanic and subvolcanic units in the Walash and Naopurdan groups were studied from the Mawat, Galalah–Choman, Leren, and Qalander–Sheikhan provinces. Most of these rocks are basaltic to andesitic for both the Naopurdan and Walash suites. The petrographic study shows that these rocks are affected by metamorphic alteration under greenschist facies conditions, but preserve primary porphyritic textures with some relict igneous plagioclase, pyroxene, and hornblende. The enrichments in LREE/HREE and high Th/Nb and Nb/Zr show that the Walash and Naopurdan rocks have distinct subduction-related signatures: specifically island-arc tholeiite for the Naopurdan and calc-alkaline to alkaline for the Walash suites. Hence the Walash and Naopurdan suites are back-arc and arc systems, respectively, that developed 43–24 Ma. Accordingly, the IZSZ contains a full record of Neo-Tethys pre-collision-related volcanism in dual subduction settings, from the Early Cretaceous (Hasanbag igneous complex) to the Eocene–Oligocene (Walash–Naopurdan suites). Final continent–continent collision started when the last of the Neo-Tethys Ocean was subducted beneath the Iranian continent, resulting in its collision with the Arabian Plate, probably during the Middle Miocene. This reinforces a continuity of events along the entire edge of the Arabian Plate from Turkey, through Iraq and Iran, and into Oman.

Keywords

neo, arc, tethyan, walash, evolution, naopurdan, region, tectonic, groups, eocene, kurdistan, oligocene, island, zone, suture, zagros, iraqi, northeast, GeoQuest

Disciplines

Medicine and Health Sciences | Social and Behavioral Sciences

Publication Details

Ali, S. A., Buckman, S., Aswad, K. J., Jones, B. G., Ismail, S. A. & Nutman, A. P. (2013). The tectonic evolution of a Neo-Tethyan (Eocene-Oligocene) island-arc (Walash and Naopurdan groups) in the Kurdistan region of the Northeast Iraqi Zagros Suture Zone. *Island Arc*, 22 (1), 104-125.

Authors

Sarmad A. Ali, Solomon Buckman, K J. Aswad, Brian G. Jones, Sabah A. Ismail, and Allen P. Nutman

The tectonic evolution of a Neo-Tethyan (Eocene-Oligocene) island-arc (Walash-Naopurdan Groups) in the Kurdistan region of the NE Iraqi Zagros Suture Zone

Ali^{a*}, S. A., Buckman^a, S., Aswad^b, K. J., Jones^a, B.G., Ismail^c, S.A., Nutman^a, A.P

^a School of Earth and Environmental Sciences, University of Wollongong, NSW, Australia

^b Department of Geology, College of Science, Mosul University, Iraq

^c Department of Applied Geology, College of Science, Kirkuk University, Iraq

Abstract

The Walash-Naopurdan Groups is incorporated into the lower allochthonous thrust sheet in the Iraqi Zagros Suture Zone (IZSZ). ⁴⁰Ar-³⁹Ar dates on magmatic feldspar separates from both the Walash and Naopurdan volcanic rocks indicate an Eocene-Oligocene age (43.01±0.15 to 24.31±0.60 Ma). It is overlain by an upper allochthon of Cretaceous arc related rocks (106-92 Ma) now known as the Hasanbag igneous complex (formerly known as the Gemo-Qandil group).

Volcanic and subvolcanic units in the Walash-Naopurdan Groups were studied from the Mawat, Galalah-Choman, Leren and Qalander-Sheikhan provinces. The majority of these rocks are basalt/andesitic basalt for the Naopurdan and basalt/basaltic andesite for the Walash suites. The petrographic study shows that these rocks are affected by post-magmatic metamorphic alteration under greenschist facies conditions, but preserve some relict primary porphyritic textures with phenocrysts of plagioclase and pyroxene. The enrichments in LREE/HREE and high Th/Nb and Nb/Zr show that the Walash and Naopurdan rocks have a distinct subduction-related signature –specifically island arc tholeiite for the Naopurdan and calc-alkaline to alkaline for the Walash suites.

Hence the Walash and Naopurdan suites are back-arc and arc systems respectively that developed between 43-24 Ma. Accordingly, the IZSZ contains a full record of pre-collision-related active volcanism in dual subduction settings in the Neo-Tethys, from the Early Cretaceous (Hasanbag igneous complex) to the Eocene-Oligocene (Walash-Naopurdan suites). Final continent-continent collision took place when the remnants of the Neo-Tethys Ocean were subducted beneath the Iranian continent resulting in collision with the Arabian plate, probably during the Middle Miocene. This reinforces a continuity of events along the entire edge of the Arabian plate, from Turkey, through Iraq and Iran into Oman.

Keywords; arc; Zagros; ^{40}Ar - ^{39}Ar geochronology; Iraq; Walash; Naopurdan.

*Corresponding author, E-mail: saaa952@uowmail.edu.au , Tel.; +61450355102; Fax; +6142214250.

1. Introduction

The Iraqi part of the Zagros Suture Zone in north and northeastern consists of many overriding nappes of ophiolite complexes, layered and pillow lavas and Tertiary sedimentary deposits (Buday, 1980), separated by crush zones and thrusts (Bolton, 1958). The Iraqi Zagros Suture Zone (IZSZ) contains the collision site between the Arabian and Iranian plates in the northeast, and the Arabian and Turkish plates in the north (Searle et al., 1980; Hall, 1980, 1982; Abbotts, 1981; Babaie et al., 2001; Omrani et al., 2008; Ismail et al., 2009, 2010; Aswad et al., 2011). However, there is uncertainty concerning late events in the Neo-Tethys ocean and the timing of collision of the Arabian and Iranian continental plates. Access to this part of Iraq during the past four decades has been limited due to ongoing war and landmine threats making some areas virtually inaccessible to study. Nevertheless, some previous work (e.g. Bolton, 1958; Buday, 1980; Buday and Jassim, 1987; Jassim and Goff, 2006) suggests that volcanosedimentary rocks occur in the Iraqi Zagros Suture Zone. In northeastern Iraq these rocks were named the Walash and Naopurdan Groups. Understanding the origin of the Paleogene (Walash-Naopurdan Groups) volcanic and subvolcanic rocks in the IZSZ will contribute greatly to resolving this.

Tectonic remnants of the Walash-Naopurdan Groups are present in two major nappes in the study area (Fig.1). In this paper we investigate the origin of these rocks in these nappes. The Walash-Naopurdan Groups occurs with ophiolite complexes in the IZSZ and extends southeast into the Iran. Therefore, by understanding these Groups and its relationship with the ophiolite complexes, it will be possible to develop a regional tectonic model from Turkey to Oman that interprets these rocks in relation to the history and closure of the Neo-Tethys, the obduction of the ophiolite complexes, and determining the timing of collision of the Arabian and the Iranian plates.

2. Geological background

The study area is in Kurdistan Region of northeast Iraq, near the Iraqi-Iranian border (Fig. 1). The area is part of the Western Zagros Fold-Thrust Belt, which developed as a response to the collision of the Arabian and Iranian plates and filling of the Neo-Tethys basin with sediments (Alavi, 2004). The Walash and Naopurdan Groups crop out in nappes in four main areas in northeastern Iraq (Fig. 2).

The Walash samples were collected from three of these areas:

(1) Mawat (M samples) named after Mawat village; (2) Galalah to Haj-Omran area where the samples were collected from Choman (Ch) and Galalah (Ga) locations, and (3) Leren area (Lw), where the samples were collected from northwest of Hasanbag Mountain.

Naopurdan samples come from two areas: (1) The Qalander area where they were sampled from two sections located in Jabal Qalander (Q) in the Baradost area, and north of Sheikhan (Sh) village, and (2) the Leren (Ln) area, from northwest of Hasanbag Mountain.

2.1. Mawat

This area (between $45^{\circ} 24' 56.8''$ – $45^{\circ} 25' 33.2''$ E and $35^{\circ} 54' 3''$ – $35^{\circ} 54' 24.1''$ N) is located 25 km northeast of Sulaymaniyah city and 20 km southeast of Mawat town (Fig. 2). Here, the Walash succession starts with pillow lavas, pyroclastic rocks, slates and calcic schist. These are overlain by a gabbroic body about 50 m thick starting with the fine gabbro at the bottom grading to coarse gabbro at the top. A diorite dyke intrudes the upper part of the gabbroic body and is chilled against it (Fig. 3a). This sequence is unconformably overlain by metasedimentary rocks (slate and marble) and basaltic andesite and dacite showing deep weathering. Structurally overlying this is a unit of amphibole-rich rocks, probably derived from pyroxenite, followed by marble and slate overlain by pillow lavas and pyroclastic rocks interspersed with volcanic ash. All these rocks are faulted, thrust and sheared. In the Mawat area the contacts between post arc Red Beds, Walash volcanic rocks and Mawat ophiolite are tectonic and clearly exposed (Fig.3b).

2.2. Galalah-Choman area

The Galalah study area (between $44^{\circ} 50' 54.12''$ – $44^{\circ} 52' 7.49''$ E and $36^{\circ} 36' 45.59''$ – $36^{\circ} 36' 53.336''$ N) is situated within Galalah village, ca. 150 km from Erbil city, (Fig. 2). The area is mountainous, providing good cross sections through units. From bottom to top the Galalah section consists of brecciated, layered and pillowed lavas alternating with mafic and ultramafic volcanoclastic rocks reaching a total thickness of nearly 50 m. This is overlain by 40 m of massive serpentinite and then by marble which appears to be a *mélange* (a heterogeneous mixture of calcite, chlorite and serpentinite), together with phyllonite. This, in turn, is overlain by a thin layer of radiolarian chert (Fig. 3c). Above the radiolarian cherts is a crush zone, tectonically overlain by Red Beds.

The Choman study area (between $44^{\circ} 55' 12''$ – $44^{\circ} 56' 1.89''$ E and $36^{\circ} 39' 37.52''$ – $36^{\circ} 39' 47.68''$ N) is about 160 km from Erbil city (Fig. 2). In the Choman area the volcanic rocks are

mainly pillow lavas with variable thicknesses, sometimes reaching up to 200 m (Fig. 3d). The pillow exteriors are vesicular or amygdaloidal, with amount of vesicles decreasing inwards. The pillow lavas are intercalated with volcanic ash, tuff and volcanic breccias. The inter-pillow matrix is filled with ash while pyroclastic deposits envelop the pillow lava. There are also bands of layered metaclastic rocks (15 m thick) that represent the eroded products of the neighbouring volcanic rocks. The samples from this area were collected from outcrops along the main road between Choman and Darband.

2.3. Leren (Hasanbag Mountain)

The Leren area between $44^{\circ} 38' 17'' - 44^{\circ} 35' 21.58''$ E and $36^{\circ} 44' 10.23'' - 36^{\circ} 44' 54.57''$ N) is situated near Sidekan, 100 km northeast of Erbil city (Fig. 2). The Leren section starts with pillow lavas that are cross-cut by quartz, epidote and chlorite veins. The contact between the lower metavolcanic (pyroclastic) rocks in the Leren area and upper part of metasediment (slate, shale and sandstone) is sheared and highly weathered chlorite-slate due to intense deformation and low grade regional metamorphism that took place during continental collision (Aziz, 1993, see Fig 1.11).

The overlying metasediment is highly fossiliferous black shale alternating with lenses of sandstone about 20 cm thick, all cross-cut by veins of calcite (Fig.4a). These rocks are overlain by radiolarian chert (Fig.4b). A part of the section is folded and faulted (Fig.4c). The thickness of the Leren sequence is uncertain due to thrusting, but is probably about 1000-2000 m.

2.4. Qalander-Sheikhan area

The Qalander area is rugged and mountainous area between $44^{\circ} 28' 0'' - 44^{\circ} 28' 21.34''$ E and $36^{\circ} 46' 53.77'' - 36^{\circ} 47' 14.28''$ N) is located 100 km northeast of Erbil city and about 10 km to the east of Mirgasur (Fig. 2). The studied samples have been collected from the base of Qalander Mountain at Sardaw village (Fig. 4d).

The sampled section at Jabal Qalander (from bottom to top) consists of sedimentary rocks (Govanda Limestone of Early-Middle Miocene age overlain by Middle-Late Miocene Red Bed sandstones. The sedimentary rocks are sandwiched between the autochthonous Tanjero and Aqra Formations (Late Cretaceous) at the bottom and the metavolcanic Naopurdan rocks at the top. All contacts between the sedimentary rocks and the underlying or overlying rocks are tectonic and marked by crush and mélangé zones. The sedimentary sequence (Govanda

Limestone and Red Beds) is tilted parallel to the underlying Tanjero and Aqra Formations, whereas layering in the Naopurdan metavolcanic rocks is discordant with the underlying sedimentary sequence.

The Naopurdan rocks in this area can be divided into three parts: (a) The lower metavolcanic part which is mainly basalt flows. They constitute most of the sampled sequence. The layered lavas look very fresh and unaltered in the field, except for being jointed and veined. The veins are mostly made of calcite, although, in some places they comprise zeolite and/or epidote.

(b) The middle part is composed of pillow lavas, brecciated lavas and inter-pillow ash. The pillow lavas show variable thicknesses, sometimes reaching up to 50 m. The exterior of the pillows are more vesicular and amygdaloidal than the centres. This part of the sequence appears to have been greatly altered, to the extent that red clay replaces plagioclase in some places. These rocks are also crosscut by the same veins that affected the flow lavas. The contact between the pillowed and the flow lavas is not exposed in the field. Several dolerites dykes are found on Qalander Mountain. The whole igneous sequence (pillow and flow lavas) is nearly 450 m thick.

(c) The upper part is a coarsening upward sequence of fine sandstone at the bottom grading upwards into conglomerate. Because they contain pebbles of basalt, serpentinite and marble, strata appear to have been derived from the erosion and rapid deposition of the igneous rocks, probably the Naopurdan and Walash metavolcanic sequences (Aziz et al., 1993b). No sedimentary structures were noticed in the field apart from reverse graded bedding.

Sheikhan is located on the northwest of Qalander Mountain (between $44^{\circ} 25' 28''$ – $44^{\circ} 25' 31.89''$ E and $36^{\circ} 47' 54.47''$ – $36^{\circ} 48' 2.40''$ N). The contact between the Govanda Limestone and Naopurdan sequence ($44^{\circ} 25' 30''$ E; $36^{\circ} 47' 55''$ N) is obvious in the field. On the upper part of Sheikhan mountain there is a conglomerate (or tectonic breccia layer). The geology of the Sheikhan and Qalander areas is similar.

3. Analytical methods

3.1. Whole rock XRF, ICPMS and microprobe mineral analysis

X-ray fluorescence (XRF) analysis was carried out with a Spectro-Analytical Instrument (XEPOS) energy-dispersive spectrometer fitted with a Si-diode detector at School of Earth

and Environmental Sciences, University of Wollongong, following the methods of Norrish and Chappell (1977). Major elements were measured on samples fused with Li borate while trace elements were analysed from pellets bonded with PVA. Calibration was made against a wide range of international reference materials and laboratory standards previously calibrated against synthetic standards. Loss-on-ignition was determined by heating a separate aliquot of rock powder at 1000 °C. The samples were additionally analysed at the Australian Laboratory Services ALS at Brisbane, Australia for their REE and other trace element concentrations.

Microprobe analyses were carried out on polished thin sections utilizing a fully automated, Cameca SX100 Electron Microprobe at Macquarie University, fitted with 5 wavelength dispersive spectrometers (WDS) and a PGT energy dispersive system (EDS).

3.2. ^{40}Ar - ^{39}Ar analyses

Three samples were selected for $^{40}\text{Ar}/^{39}\text{Ar}$ analyses – M7 (Walash), Q13, and SH8 (Naopurdan). Samples Q13 and SH8 were crushed to ~2 cm chips using a jaw crusher. Individual chips were then screened for alteration, with acceptable chips crushed further using a steel piston crusher. Crushed samples were washed and sieved to 0.2-0.5 mm grain size. Approximately 200 mg of material was hand-picked from each sample and leached for 5 minutes in 10% HNO_3 to remove carbonate. Feldspar (M7, Q13) mineral separates were obtained from the remaining samples using standard crushing, de-sliming, sieving, magnetic and heavy liquid separation methods. Prior to irradiation, all samples were rinsed with deionised water in an ultrasonic bath.

Samples were loaded into aluminium foil packets and placed in quartz tubes (UM#43) along with the flux monitor GA1550 biotite (98.8 ± 0.5 Ma; Renne et al., 1998) and irradiated in cadmium-lined cans in position 5c of the McMaster University reactor, Hamilton, Canada.

$^{40}\text{Ar}/^{39}\text{Ar}$ step-heating analyses were conducted at the University of Melbourne generally following procedures described previously by Phillips et al. (2007) and Matchan and Phillips (2011). Irradiated aliquots of samples M7, Q13 and SH8 were loaded into tin-foil packets and step-heated using a tantalum-resistance-furnace, linked to a VG3600 mass spectrometer equipped with a Daly detector. Due to low potassium contents and limited mineral separate volumes, aliquots of feldspar from sample Q13 were step-heated using a CO_2 laser linked to a MM5400 mass spectrometer with a Daly detector.

Mass discrimination was calculated prior to the analyses by measuring multiple air aliquots from a pipette system, yielding weighted mean values of $1.0061 \pm 0.30\%$ (1σ) per atomic mass unit for the VG3600 and $1.0055 \pm 0.12\%$ (1σ) per amu for the MM5400. Argon isotopic results are corrected for system blanks, mass discrimination, radioactive decay, reactor-induced interference reactions and atmospheric argon contamination. Decay constants used are those reported by Steiger and Jäger (1977), Correction factors ($\pm 1\sigma$) for interfering isotopes were $(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 0.000280 \pm 3.6\%$, $(^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 0.000680 \pm 2.9\%$, $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}} = 0.000400 \pm 100\%$ and $(^{38}\text{Ar}/^{39}\text{Ar})_{\text{K}} = 0.0130 \pm 3.9\%$. System blank levels were monitored between analyses and found to be essentially atmospheric ($^{40}\text{Ar}/^{36}\text{Ar}_{\text{atm}} = 295.5 \pm 0.5$; Nier, 1950).

Plateau ages were calculated using ISOPLLOT (Ludwig, 2003) and are defined as including at least 50% of the ^{39}Ar , distributed over a minimum of 3 contiguous steps with $^{40}\text{Ar}/^{39}\text{Ar}$ ratios within agreement of the mean at the 95% confidence level. Inverse isochron plots were also constructed with ISOPLLOT (Ludwig, 2003), using the same data points included in the calculation of the weighted mean ages. The inverse isochron regressions show that the trapped argon component ($^{40}\text{Ar}/^{36}\text{Ar}_{\text{i}}$) is of atmospheric composition within the uncertainties, justifying the interpretation of weighted mean ages as crystallisation ages. Calculated uncertainties associated with mean and plateau ages include uncertainties in the J-values, but exclude errors associated with the age of the flux monitor and the decay constant.

4. Petrography and mineral chemistry

The studied rocks are divided into two groups; Walash samples have mostly gray to brownish gray weathering whereas Naopurdan samples have mostly greenish gray and brown weathering. Study of 108 thin sections shows that these two groups present some variation in texture and mineralogy. This following section is a condensation of detailed petrographic descriptions provided by Ali (2012).

The Walash samples comprise basalt, basaltic-andesite, trachy-basalt and some dolerite. They range from relatively fresh (Galalah samples) to highly altered (Choman samples). They display amygdaloidal, porphyritic, radiate, vesicular, pilotaxitic, spherulitic, and variolitic textures (Fig.5a-c). Phenocrysts include altered plagioclase, clinopyroxene, and iron oxide (mainly magnetite and illeminite with some pyrite only in Mawat area) up to 1 mm in size. Plagioclase phenocrysts are euhedral to subhedral laths or prismatic and partly altered to

calcite, sericite or epidote, whereas, the microcrystalline matrix is dominated by small microliths of plagioclase. Plagioclase forms 30-65% of Walash samples.

The clinopyroxene, which is 1-20% volume, occurs as fresh euhedral or subhedral augite grains (Fig5.d). Rare primary hornblende and biotite are also observed in these rocks. Secondary zeolite minerals and two types of chlorite are present in the voids (Fig.5e).

Naopurdan samples display all the same texture as the Walash rocks, plus glomeroporphyritic and seriate textures. This group comprises basalt, andesitic-basalt, and andesite. Plagioclase, K-feldspar, and clinopyroxene are the main minerals as phenocrysts and in the groundmass, but are mostly replaced with epidote, white mica, chlorite and clay minerals. Iron oxides (0.5% to 4%) are found as fine crystals randomly scattered in the groundmass. When the Naopurdan samples are compared with the studied Walash samples, they maintain higher volumetric percentages of epidote and quartz, reaching up to 10% and 24%, respectively (Fig.5f).

Online resource (see supplementary 1& 2) presents all mineral analyses and plots of the feldspar, pyroxene and amphibole compositions. Plagioclase is mostly albite in both Walash and Naopurdan samples because of superimposed greenschist facies alteration. Andesine is observed in one Qalander sample (Q2, An₃₁) and most Mawat samples (M18, M13, M7, M11, An₃₁₋₅₀). In addition, primary plagioclase composition was only detected in one Mawat area Walash volcanic rock (M11, An₅₅₋₇₃). The clinopyroxene is augite in both Walash and Naopurdan samples apart from two crystals of diopsidic composition in a Mawat area Walash sample (M12) and one iron-rich clinopyroxene (hedenbergite) in a Galalah area Walash sample. The Walash amphiboles are magnesio-hornblende and ferropargasite (i.e. CH24, M7 and M9) and the Naopurdan samples carry both primary and secondary amphiboles. The primary amphibole is magnesio-hornblende and is preserved in the volcanic sample (SH10). Generally this hornblende has exsolved into Ti-poor actinolite and ilmenite during superimposed alteration.

5. ⁴⁰Ar-³⁹Ar geochronology

5.1. Pyroclastic feldspar from Mawat area Walash sample M7

Sample M7 feldspar, a pyroclastic rock from the Walash in the Mawat area yields a well-defined age spectrum (Fig.6a). Due to low temperature alteration, the initial ~7% of the ³⁹Ar_{tot} released is disturbed (see supplementary 3 Table 1). Excluding the disturbed first five small fractions (i.e. ~7% of the ³⁹Ar_{tot}), the remaining 93% was used to calculate a weighted mean age of 43.01 ± 0.15 Ma. The Ca/K values reveal an overall increase from 0.96 to 0.98

(steps 1 and 2 in Fig. 6a and supplementary 3 Table 1) and then declines to 0.18. The high-temperature gas fractions display very small fluctuations in apparent Ca/K ratios (e.g. 0.02-0.06), suggesting that the release of $^{39}\text{Ar}_K$ occurred from compositionally uniform sites.

The plateau age of 43.01 ± 0.15 Ma and is within two standard deviations of each other (Mean Square Weighted Deviation MSWD) less than ~ 2.3 for 47% of the gas released (step 6 to step 10). Visually, there appear to be descending staircase age spectra and fairly minor “bump” on the plateau section at step 11 and step 12 (Fig. 6a). The latter suggests that there may have been a recoil of ^{39}Ar . Recoil has the affect of increasing the apparent ages of the parts of the spectrum to 44.45 Ma (step 11) controlled by site of low Ar retentivity of the studied feldspar that have lost ^{39}Ar and decreasing the apparent ages of the parts of the spectrum (step 13 to step 14) controlled by high retentive sites of the same mineral that have gained ^{39}Ar . The gases released from site of low Ar retentivity to high retentive sites of the same mineral.

5.2. Volcanic rock Q13 and SH8 from Naopurdan arc at Qalander and Sheikhan

Low- and high-temperature gas fractions of sample Q13 basalt aliquot 'b' display clear fluctuations in apparent Ca/K ratios, suggesting that the release of $^{39}\text{Ar}_K$ occurred from compositionally non-uniform sites and/or due to recoil. The higher Ca/K ratio at ~ 0.54 - 1.35% ^{39}Ar release is probably due to partial rock decomposition in the step 1 and step 2 may reflect post-magmatic metamorphism. In the $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating studies, the plateau steps (3-7) released argon from the least altered sites the primary minerals (i.e. augite and Ca-rich plagioclase).

The high-temperature gas fractions (step 8 to step 12) suggest that the release of $^{39}\text{Ar}_K$ occurred from compositionally non-uniform sites and/or recoil. The latter has the affect of increasing or decreasing the apparent ages of the parts of the spectrum, controlled by either primary (i.e. pyroxene) that have lost ^{39}Ar and slightly decreased or increased the apparent ages (Fig. 6b). The change in plateau spectra shown by steps 8-12 are certainly related to the fluctuated Ca/K ratios. The high apparent age shown by sample Q13 within the first few percent of gas released may be due to the secondary mineral constituents during post-magmatic alteration. The Ca/K ratio remains relatively constant at about 3-7 for the initial $^{39}\text{Ar}_{\text{tot}}$ release of 42.6%. But then at 62.1 % and greater, the Ca/K ratio rapidly increases up to 28.77, indicating a phase with either a relatively larger calcium content or a relatively smaller potassium content. By means of microprobe analysis, the mineral giving a slightly fluctuating age plateau was either a low temperature high-Ca/K-ratio secondary phase or a high-

temperature high-Ca/K-ratio phase relict of the original igneous mineralogy (see supplementary 3 Table 2).

The SH8 basalt aliquot 'a' is characterized by a U-shaped (also called 'saddle-shaped') spectra of low confidence. The age spectra for this rock sample consists of three distinct parts, revealing that the older apparent ages occur in the lower temperature fractions and the minimum age occur in the middle temperature step. The first part, constituting the first ~30% of gas release, is characterized by down-stepping ages and low Ca/K ratios. The second part of the release is characterized by Ca/K ratios that increase to a value of ~7 (step 9; Fig. 6c and supplementary 3 Table 3). The last ~1% of gas released is characterized by low Ca/K ratios and older ages. The highly variable Ca/K ratios from step 6 to step 12 are consistent with argon degassing from different reservoirs of strongly varying retentivity and composition. These high values are probably caused by degassing from Ca-rich minerals, for example, clinopyroxene. The low temperature steps, however, are associated with low Ca/K, indicating contamination by a K-rich phyllosilicate or an alteration product. No definite plateau age was obtained for this age spectra.

The SH8 basalt aliquot 'b' yielded a slightly saddle-shaped age spectra using the $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating technique, and revealed a good plateau age spectra. The limited change in plateau spectra shown by steps 6-9 reveals a plateau age spectra of 24.31 ± 0.60 Ma (MSWD = 0.50) for the initial $^{39}\text{Ar}_{\text{tot}}$ release of 61% (Fig. 6d and supplementary 3 Table 4).

6. Geochemistry

6.1. Major elements

The Walsh–Naopurdan volcanic rocks are all mafic to intermediate. The Naopurdan volcanic and subvolcanic rocks show low to moderate loss-on-ignition (LOI) values ranging from 1.32 to 5.52 (with higher values in most Leren samples, that contain copious hydrous minerals such as chlorite). The LOI values in the Walsh samples are higher than in the Naopurdan samples, (see Table 1).

Silica (SiO_2) content in both the Walsh and Naopurdan rocks ranges between 43.36-61.65 wt% with an average of 51.61 wt% in the Leren and Mawat Walsh volcanic and subvolcanic rocks and 42.95-54.37 wt% with an average of 48.2 wt% in Galalah-Choman Walsh volcanic and subvolcanic rocks. The highest variation occurs for the Naopurdan rocks in the Qalander and Sheikhan areas, where the silica content is between 47.04-65.79 wt% with an average of 56.09 wt% (see Table 1). SiO_2 shows a significant negative correlation with MgO and this serves to separate the Walsh and Naopurdan samples (except two Walsh samples,

M1 and M7, which are more felsic with high values of silica; Fig. 7a). SiO_2 also shows a significant negative correlation with CaO (Fig. 7b) and a positive correlation with Na_2O . These relationships indicate that there has been an increase in silica content during secondary alteration when sodium replaced calcium particularly in plagioclase in both the Walsh and Naopurdan volcanic rocks.

The content Al_2O_3 in Naopurdan samples is less than Walsh ones (11.25-16.26 wt%, average 14.29 wt %). This value increases in the samples containing a high proportion of plagioclase and those that suffered epidotization.

The calcium content in the Walsh rocks ranges between 2.64-12.84 wt% (average 6.96 wt %) and 3.83-14.44 wt% (average 7.51 wt %), respectively. The Naopurdan samples show a lower variation in CaO content than Walsh samples (see Table 1). However, most of the plagioclase encountered in the present study is sodic, indicating secondary alteration, hence the relatively high CaO concentration in some studied samples is due to the presence of calcite and epidote in the groundmass (e.g. ChQ14) or in veins. Thus CaO shows a disordered relationship with most elements in the Walsh samples due to alteration. However in the Naopurdan rocks CaO shows a negative correlation with Zr, which is probably related to crystal fractionation of clinopyroxene (Cox, 1980). CaO shows a negative and positive correlation with SiO_2 and MgO, respectively (Fig. 7 b & c), in both the Walsh and Naopurdan rocks indicating crystallization of plagioclase, amphibole and formation of epidote during epidotization. Thus, some variation in SiO_2 concentration may be related to its mobility during secondary processes.

The MgO content in the Walsh rocks ranges between 2.39-6.35 wt% and 2.97-8.32 wt%, with averages of 4.66 wt% and 5.04 wt%, respectively. The MgO content in the Naopurdan rocks ranges from 1.68-17.45 w% (average 7.22 w %). Despite the high amount of chlorite in most of the Walsh and Naopurdan samples, the lower MgO in most samples is related to the absence of olivine and the low content of amphibole (Mg-hornblende). The higher MgO values in some Choman $\pm$ (Walsh) and Leren (Naopurdan) samples is due to the presence of olivine and amphibole respectively. Generally, MgO displays significant negative correlations with SiO_2 , TiO_2 , Na_2O , Zr, Th, Nb, Y and Ga, and positive correlations with CaO, Mg#, Ni, Cr, Co and Al_2O_3 (with minor scatter; see Fig. a- h except b). These correlations can be explained by the fractionation of plagioclase and ferromagnesian minerals (such as clinopyroxene, Ti-bearing opaques and olivine) from the liquid by fractional

crystallization. In addition, the increase in incompatible trace elements such as Zr, Y, and Nb with the decrease in MgO indicates that crystal fractionation is the dominant magmatic processes.

The range of Mg-numbers ($Mg\# = (Mg/Mg+Fe^{+2})$) is between 33 and 62 in Walash rocks, respectively. The Mg# in the Naopurdan rocks ranges from 31 to 79, with the high Mg# being observed in most of the Leren samples. The Leren samples have also high Cr and Ni values, and can be regarded as being close to the primary magma (Clague and Fery, 1982). However, as most Walash and Naopurdan rocks have $Mg\# < 60$, they must have suffered some differentiation (see Table 1).

The total Fe as Fe_2O_3 content in the Walash samples is higher than Naopurdan samples. The increased Fe_2O_3 percentage is probably a consequence of oxidation and other secondary alteration processes (Miyashiro et al., 1971). Fe_2O_3 contents in all studied rocks are scattered, but generally display a no weak or a negative correlation with MgO, which indicates that the Fe_2O_3 has not entered into the structure of the ferromagnesian silicates. However, Fe_2O_3 shows a positive correlation with TiO_2 in all studied samples which indicates the primary crystallization of Ti-Fe oxide minerals, which is consistent with petrographic evidence.

Na_2O contents in calc-alkaline and alkaline Walash samples are very similar ranging between 2.88-5.58 wt% and 2.77-5.84 wt% with averages of 4.15 wt% and 4.25 w%, respectively (Table 1). The Naopurdan samples show a wider range of Na_2O contents from 0.34-7.44 wt% with average 3.7 wt%. In one Naopurdan sample (SH4), it reaches 7.44 wt%. When correlated with MgO, it displays a negative correlation in both the Walash and Naopurdan samples, but it shows more scatter with decreasing MgO (less than 6%) which indicates that Na_2O was mobile during secondary processes (see Fig. 7e). The percentage of Na_2O increases with albitization and this possibly explains the negative correlation with calcium oxide in all Walash and Naopurdan volcanic rocks.

K_2O content in Walash samples is higher than Naopurdan samples where in some it is below the detection limit (e.g. Qalander samples, see Table 1). The high values of K_2O in some Walash and Naopurdan samples reflect the higher modal contents of K-feldspar (e.g., M7, M14 and L21) and/or biotite (Ch24). K_2O shows a variable distribution against MgO indicating its mobility. K_2O displays a significant correlation with Rb and Ba in both the Walash and Naopurdan volcanic rocks.

The Walsh samples have higher TiO_2 values than Naopurdan samples. The contrasting TiO_2 content is due to different tectonic setting of basalts the Naopurdan versus the Walsh basalts (Woodhead et al., 1993, Gürsu and Göncüoğlu, 2005). Ti shows significant positive and negative correlations with Zr and MgO, respectively, in all the studied samples indicating the increase of TiO_2 with evolving fractional crystallization (Fig. 7d).

6.2 Trace elements

Chromium abundance in the Naopurdan rocks is higher than in the Walsh rocks, excluding Choman area ones rocks which have higher Cr values than other Walsh samples, reflecting the higher modal content of olivine in these rocks (Table 1). Cr is highly compatible and is concentrated in clinopyroxene, olivine and spinel (Wilson, 1989), and hence it shows a significant positive correlation with MgO in both the Naopurdan and Walsh rocks.

Ni shows a significant positive correlation with MgO (Fig. 7f) in all samples. Those with low Ni is due to the fractionation of olivine. However, some Walsh samples from Choman and the Leren area Naopurdan samples have high Ni values which reflected the presence of olivine in them (Table 1).

The Walsh samples contain vanadium in the range from 110-471 ppm and 34-416 ppm with averages of 261 ppm and 223 ppm, respectively. Vanadium values in the Naopurdan rocks are similar to those in the Walsh rocks. It ranges from 126-354 ppm with an average of 242 ppm (see Table 1). Vanadium shows a strong fractionation into Fe-Ti oxides (Wilson, 1989). In addition, vanadium is incorporated into pyroxene, amphibole and biotite (Mason and Moore, 1982). It shows a significant positive correlation with Fe_2O_3 in both the Walsh and Naopurdan samples, which is related to the similarity in chemical behavior between V and Fe.

Strontium, rubidium and barium concentrations in Naopurdan rocks are lower than in the Walsh rocks. The high rubidium and barium content in the Walsh samples might be a primary igneous feature. Sr exhibits no significant correlation with CaO as Sr may be either depleted or enriched due to secondary processes. In addition, Walsh samples Ch24 and M7 have the highest Rb contents and the highest modal contents of biotite and sanidine, respectively (see Table 1).

Lead values are low in most Walash and Naopurdan samples due to hydrothermal alteration particularly being leached out of altered feldspars. No marked correlation was observed between Pb and MgO, which is related to the mobility of Pb.

Zr, Y, Nb, and Th content in the Walash rocks is higher than in the Naopurdan rocks, and is highest those from the Galalah-Choman area. This contrast in Zr, Y, Nb, and Th content between the Walash and Naopurdan samples confirms the difference in tectonic setting and degree of partial melting that controls Zr abundance (Woodhead et al., 1993). Zr, Y, Nb, and Th show a negative correlation with MgO in the Walash samples, whereas a similar relationship was not seen in the Naopurdan samples (Fig.7g & h).

6.3 Rare earth elements and spider diagrams

The overall REE patterns for the Naopurdan rocks are overall flat-lying (Fig.8 a, c & e). Such flat-lying patterns resemble the rocks formed in island arc tholeiitic (IAT) and subduction relating settings with $La_N/Yb_N = 0.8$ to 7.17 . The Walash samples are characterised by more enrichment in LREEs than the Naopurdan samples. No Eu anomaly is apparent in the Walash samples, whereas a moderate to strong negative Eu anomaly is observed in some Naopurdan samples ($Eu/Eu^* = 0.43-1.12$, e.g. L2 and Q13; see Table 5.4a) which is normally interpreted as resulting from removal of plagioclase. The Naopurdan rocks show prominent depletions in high field strength elements relative to fluid-mobile elements (e.g. negative Ta and Nb anomalies with respect to the neighbouring incompatible elements) on a N-MORB-normalized plot, whereas, the Walash samples mostly fall between those of E-MORB and the average ocean island basalt (OIB) (Fig.8 b, d & f). However, the some Walash samples show REE patterns typical of OIB but with slightly greater enrichments in incompatible elements due to the effects of fractionation and subduction component addition.

6.4 Geochemical classification rocks

The Nb/Y of <0.67 for the Walash and Naopurdan rocks indicates their sub-alkaline nature (c.f. Pearce, 1996). However, the Zr/TiO₂ ratio increases from the mafic to the felsic rocks as fractionation progresses. All of the Walash and Naopurdan rocks plot in the sub-alkaline basalt and andesitic basalt fields, except for the some Walash samples from the Galalah-Choman area, that plot in alkaline field (Fig. 9a & b; c.f. Winchester and Floyd, 1977).

6.5 Tectonic affinity

As shown in the Zr-Y diagram (Muller et al. 2001; Figure 10a) all the Walash and Naopurdan volcanic rocks are located in arc-related fields, except one Galalah sample (GA13), due to its high contents of both Zr and Y (see Table 1).

The Zr-Zr/Y diagram proposed by Pearce and Norry (1979) discriminates between MORB, within plate basalt, subduction related tholeiitic basalts such as back-arc basin basalts, and IAT (modified by Floyd et al., 1991). Most of the Walash volcanic samples are located in the back-arc basin field except those with very high Zr values (the more alkaline Galalah-Choman samples), while the majority of Naopurdan samples are situated in the subduction – related volcanic arc field (Fig. 10b).

According to the Shervais (1982) Ti-V diagram, if the value of Ti/V is close to 20, it will indicate crystallization of clinopyroxene and plagioclase. However, if this ratio is < 20 , it will indicate the crystallization of olivine in addition to clinopyroxene and plagioclase minerals. If this ratio is > 20 , it means crystallization of iron oxide (ilmenite, magnetite). The Naopurdan samples dominantly fall in island arc tholeiites (IAT) with Ti/V of < 20 , whereas most of the Walash samples fall in the back arc basin (BAB) field as their Ti/V ratio is higher, (i.e. 20 to 50, fig.10c). The V/Ti versus Zr diagram proposed by Woodhead et al. (1993) discriminates between island arc tholeiites (IAT), normal mid oceanic ridge basalt (N-MORB) and back-arc basin basalt (BABB). This diagram indicates the back-arc basin affinity of the Walash rocks and the island arc tholeiite affinities of the Naopurdan rocks (Fig. 10d).

The Ti/Zr-Zr diagram proposed by Woodhead et al. (1993) discriminates between island arc and back-arc basin environments. According to this diagram (Fig.11a), most of the Walash samples fall in the BAB field. However, the majority of the Naopurdan samples indicate a volcanic arc, except for five samples from the Leren area which have low Ti and high MgO values and fall out of the arc field (see Fig. 11a).

According to the Zr-Nb diagram, Naopurdan rocks fall within the arc field (Fig.11b). However, due to enrichments of incompatible elements the Walash calc-alkaline rocks fall in the back-arc field (Fig.5.17), and are comparable with rocks in back-arc settings in New Zealand and Patagonia (Tatsumi et al., 1983). However, all the alkaline Walash samples are off the scale of this discrimination diagram (except two samples, Ga17 and Ga20, which fall with the Naopurdan arc samples).

In the Zr-Th-Nb plot (after Wood, 1980), the Naopurdan samples show relative enrichment in Th and depletion in Nb, thus they plot in the field of volcanic arc basalts (Fig. 11c). Excluding two samples SH4 and SH7 which plot in E-MORB field because they have higher Zr and Nb values than other Naopurdan samples. The Walash samples form two distinct trends coinciding with E-MORB and OIB. Exceptions are two alkaline (Ga17 and Ga20 – with low Nb) and two calc-alkaline samples (with high Th) that plot with the Naopurdan samples in the arc basalt field (Fig. 11c).

Clinopyroxene analyses were plotted onto Beccaluva et al.'s (1989) tectono-magmatic discrimination ternary diagram $\text{SiO}_2/100\text{-TiO}_2\text{-Na}_2\text{O}$ (not shown). All Walash clinopyroxenes follow a trend encompassing the MORB field, while most of the Naopurdan ones fall in the IAT and a few in the boninite field.

7. Discussion

7.1 Arc-backarc- related origin of the Walash-Naopurdan rocks

Despite superimposed secondary alteration, clear igneous geochemical trends are preserved. Thus the Walash-Naopurdan are all mafic to intermediate, with MgO showing significant negative correlations with SiO_2 , TiO_2 , Na_2O , Zr, Th, Nb, Y and Ga, and positive correlations with CaO, Mg#, Ni, Cr, Co and Al_2O_3 . These correlations can be explained by the fractionation of plagioclase, clinopyroxene, olivine and Fe-Ti oxides. Furthermore, relict igneous amphiboles in some samples indicate hydrous melting giving rise to amphibole as well as olivine and clinopyroxene fractionation.

The contrast in HFSE (i.e. Zr, Y, and Hf) abundances between the Walash and Naopurdan samples confirms the difference in their tectonic setting and degree of partial melting (c.f., Woodhead et al., 1993). The low concentrations of incompatible elements and low Nb/Yb for most of Naopurdan samples imply that the primary melts issued from a depleted N-MORB mantle source. In contrast, the trace element characteristics of the Walash samples, particularly, the Walash alkaline rocks are characterized by strong enrichments in highly incompatible elements relative to less incompatible elements (e.g. higher LREE/HREE ratios than that of MORB; see Fig. 8b & e). Hence these exhibit strong resemblances to modern suites formed in back-arc basins, where the influence of a marked subduction component modifies the geochemical characteristics of the source mantle (e.g., Taylor and Martinez, 2003; Pearce et al., 2005).

All tectonic diagrams confirm the backarc and arc affinities for Walash and Naopurdan rocks (Figs 10 & 11). Additionally, the Th/Yb vs. Nb/Yb diagram after Pearce (2008) is useful for

examining the melt source and contaminants. This is because normalising both axes to Yb eliminates most effects of partial melting and fractional crystallization (Pearce, 1983), so that the MORB–OIB field forms a diagonal array with a slope close to unity (see diagonal arrow in Fig. 11d). On this diagram, the studied rocks display an array showing higher Th/Yb ratios than the MORB–OIB array. This is most likely because of the enrichment in slab-derived fluids/melts (Pearce et al., 1995; Hawkesworth et al., 1997), then with subsequent fractional crystallisation.

Simultaneous variations in both Th/Yb and Nb/Yb ratios are related to enrichment or depletion of the mantle wedge. However, an increase in these ratios can also be recognized during the evolution of some subduction zone settings (increasing arc maturity). All nine Galalah and Choman alkaline Walash rocks plot next to the shoshonitic field of this diagram, suggesting that they formed in a mature back-arc setting (Fig. 11d). Age relationships can be resolved, with the Walash back-arc related lavas usually being older (43.01 ± 0.15 Ma) and Naopurdan arc-like lavas younger (24.31 ± 0.60 Ma).

7.2. Geodynamic framework

The Tertiary Walash-Naopurdan assemblage in the northwest Zagros Suture Zone preserves a series of magmatic suites and sedimentary rocks which contain a record of subduction initiation, rifting and back-arc basin formation. The various hypotheses for driving back–arc basin extension include slab roll-back (Dvorkin et al., 1993; Elsassser, 1971; Malinverno and Ryan, 1986; Molnar and Atwater, 1978; Schellart et al., 2007), induced mantle wedge flow (corner flow; Sleep and Toksoʻz, 1971) and relative motion of the overriding plate with respect to the subduction trench (Dewey, 1980; Jarrard, 1986; Heuret and Lallemand, 2005; Volti et al., 2006). Back-arc extension preferentially occurs with a steeper subduction angle. Based on the age progression (i.e. the 43 Ma age of Walash back-arc rocks and 24–34 Ma for the Naopurdan arc rocks; Figure 12 d & e), subducting slab steepening or “roll-back” may have resulted in trenchward migration of the arc system prior to the final continent–continent collision. Formation of the younger Naopurdan IAT trenchward of the slightly older Walash back-arc assemblage is analogous with the Tonga–Kermadec and Izu–Bonin–Marianas island arcs (Taylor, 1992; Macpherson and Hall, 2001; Taylor and Martinez, 2003). In the Iraqi case, this would have resulted in progressively younger arc volcanic rocks towards the retreating trench, prior to the continental–continental collision in Miocene.

7.3 Tectonic model and chronology of arc magmatism

The Walash-Naopurdan rocks display a consistent sequence of events during their formation, which can be combined with previously published results to produce new tectonic model for Neo-Tethys from the Permian until its disappearance in the Miocene:

- 1- Rifting along the present Zagros fold and thrust belt took place in Permian to Triassic time, resulting in the opening of the Neo-Tethys Ocean (Saidi et al., 1997; Ali et al., in press, see Fig.12a).
- 2- During the Early Cretaceous, subduction of part of the Neo-Tethyan oceanic crust towards the east and northeast developed an ophiolites/arc complex (basaltic andesites and andesites) represented by the Hasanbag rocks (106-92 Ma; see Fig. 12b). This was distal from Eurasia, which lay at the northeastern margin of Neo-Tethys.
- 3- Collision of the Hasanbag ophiolite/arc complex onto the Arabian passive margin occurred during the Late Cretaceous. This coincides with obduction of other ophiolites, including the Kermanshah-Penjween ophiolites, over the northeastern margin of the Arabian plate (Mohajjel et al. 2003; Jassim and Goff, 2006, Ali et al., in press, Fig. 12c).
- 4- Initiation of new Neo-Tethyan intra-oceanic subduction probably occurred in the Late Maastrichtian-Early Paleocene? (see Fig. 12c) following collision and obduction of the Hasanbag arc complex.
- 5- Walash calc-alkaline backarc magmatism commenced in the Eocene (43-34 Ma, Fig. 12d).
- 6- Slab rollback resulted in trenchward migration of island arc tholeiitic volcanism represented by the Naopurdan volcanic rocks (33-24 Ma). Limited alkaline volcanism continued within the Walash back arc region and is represented by the Galalah-Choman volcanic rocks (see Fig.12e).
- 7- Collision of the Walash-Naopurdan arc-back-arc system with the Arabian continental passive margin during the Early Miocene (23-16? Ma), resulted in cessation of magmatism (see Fig. 12f).
- 8- Final continent-continent collision between the Iranian-Turkish and Arabian continents occurred during the Middle? Miocene (see Fig. 12g).

8. Conclusions

Detailed field, geochronological, petrographical, geochemical and petrogenetic studies of the Walash-Naopurdan igneous rocks within the Iraqi sector of the Zagros thrust zone, has led to the following conclusions:

- 1- ^{40}Ar - ^{39}Ar ages of 43.01 ± 0.15 Ma for one feldspar from a pyroclastic Walash back-arc rock (Mawat area), and 33.42 ± 0.44 , and 24.31 ± 0.60 Ma for two feldspars from Naopurdan arc basaltic rocks (Qalander and Sheikhan areas) were obtained.
- 2- The Walash rocks are basalt to basaltic andesites and alkali basalts to trachytic andesites with calc-alkaline and alkaline character. The Naopurdan samples include basalts, andesitic basalts and andesites of sub-alkaline, low-k tholeiitic character.
- 3- Tectonic discrimination diagrams indicate that the Naopurdan rocks are an island-arc tholeiitic suite whereas the Walash rocks are a back-arc, calc-alkaline and alkaline suite.
- 4- The results clarify a tectonic model for the region with distinct Cretaceous and Tertiary arc systems existing during closure of Neotethys.

Acknowledgements

This paper is a part of the first author's PhD thesis undertaken at School of Earth and Environmental Sciences, University of Wollongong, and was supported financially by the Ministry of Higher Education and Scientific Research, Iraqi Government and the University of Wollongong's GeoQuest research centre.

References

- Abbotts, I. L., 1981. Masirah (Oman) ophiolite sheeted dykes and pillow lava: geochemical evidence of the former ocean ridge environment. *Lithos*, 14, 283-294.
- Alavi, M., 2004. Regional stratigraphy of the Zagros Fold-thrust Belt of Iran and its proforeland evolution. *American Journal of Science*, 304, 1-20.
- Ali, S.A, 2012. Geochemistry of Tethyan-arc related volcanic rocks, NE Iraq. PhD. Thesis, University of Wollongong, 326 p (unpublished).
- Asawd, K. J. A., Aziz, N. R. H., and Koyi, H. A., 2011. Cr-spinel compositions in serpentinites and their implications for the petrotectonic history of the Zagros Suture Zone, Kurdistan Region, Iraq. *Geological Magazine*, 148, 802-818.
- Aziz, R., Al-Hafdh, N., and Al-Ghadanfary, E., 1993a. Geochemistry and petrogenesis of the Walash volcanics in Draband, NE Iraq. *Abhath-Al-Yarmouk Pure Science and Engineering Series*, 2, 135-155.
- Aziz, R. M., Elias, E. M., and Al-Hafdh, N. M., 1993b. The igneous and metamorphic metaclastics of Naupordan Group and their relation to the tectonic regime in NE-Iraq. *Mu'tah Journal Research Study*, 8, 155-172.

- Babaie, H. A., Ghazi, A. M., Babaei, A., La Tour, T. E., and Hassanipak, A. A., 2001. Geochemistry of arc volcanic rocks of the Zagros Crush Zone, Neyriz, Iran. *Journal of Asian Earth Sciences*, 19, 61-76.
- Beccaluva, L., Macciotta, G., Piccardo, G., and Zeda, O., 1989. Clinopyroxene composition of ophiolite basalts as petrogenetic indicator. *Chemical Geology*, 77, 165-182.
- Bolton, C. M. G., 1958. The geology of the Rania area, Manuscript report No.271, GEOSURV, Baghdad.
- Buday, T., 1980. *The Regional Geology of Iraq. Vol. 1: Stratigraphy and Palaeogeography*. Publications of GEOSURV, Baghdad, 445 pp.
- Buday, T., and Jassim, S. Z., 1987. *The Regional Geology of Iraq. Tectonism, Magmatism and Metamorphism*. Publications of GEOSURV, Baghdad, 1, 352 pp.
- Clague, D. A., and Frey, F. A., 1982. Petrology and trace element geochemistry of the Honolulu Volcanics, Oahu: implications for the oceanic mantle below Hawaii. *Journal of Petrology*, 23, 447-504.
- Cox, K., 1980. A model for flood basalt vulcanism. *Journal of Petrology*, 21, 629-638.
- Dewey, J., 1980. Episodicity, sequence and style at convergent plate boundaries. *Geological Society of Canada*, in honour of J. Tuzo Wilson.
- Dvorkin, J., Nur, A., Mavko, G., and Ben-Avraham, Z., 1993. Narrow subducting slabs and the origin of backarc basins. *Tectonophysics*, 227, 63-79.
- Elsasser, W. M., 1971. Sea-floor spreading as thermal convection. *Journal of Geophysical Research*, 76, 1101-1112.
- Floyd, P.A., Kelling, G., Gokcen, S. L., and Gokcen, N., 1991. Geochemistry and tectonic environment of basaltic rocks from the Miss ophiolitic melange, south Turkey. *Chemical Geology*, 89, 263-280.
- Gürsu, S., and Göncüoğlu, M., 2005. Early Cambrian back-arc volcanism in the western Taurides, Turkey: implications for rifting along the northern Gondwanan margin. *Geological Magazine*, 142, 617-631.
- Hall, R., 1980. Contact metamorphism by an ophiolite peridotite from Neyriz, Iran. *Science*, 208, 1259-1262.
- Hall, R., 1982. Ophiolites and passive continental margins. *Ophioliti*, 2/3, 279-298.
- Hawkesworth, C. J., Turner, S. P., Mcdermott, F., Peate, D. W., and Van Calsteren, P., 1997. U-Th isotopes in arc magmas: implications for element transfer from the subducted crust. *Science*, 276, 551-555.

- Heuret, A., and Lallemand, S., 2005. Plate motions, slab dynamics and back-arc deformation. *Physics of the Earth and Planetary Interiors*, 149, 31-51.
- Omrani, J., Agard, P., Whitechurch, H., Benoit, M., Prouteau, G., and Jolivet, L., 2008. Arc-magmatism and subduction history beneath the Zagros Mountains, Iran: a new report of adakites and geodynamic consequences. *Lithos*, 106, 380-398.
- Ismail, S. A., Arai, S., Ahmed, A. H., and Shimizu, Y., 2009. Chromitite and peridotite from Rayat, northeastern Iraq, as fragments of a Tethyan ophiolite. *Island Arc*, 18, 175-183.
- Ismail, S. A., Mirza, T. M., and Carr, P. F., 2010. Platinum-group elements geochemistry in podiform chromitites and associated peridotites of the Mawat ophiolite, northeastern Iraq. *Journal of Asian Earth Sciences*, 37, 31-41.
- Jarrard, R. D., 1986. Relations among subduction parameters. *Reviews of Geophysics*, 24, 217-284.
- Jassim, S. Z., and Goff, C., (eds), 2006. *Geology of Iraq*. Dolin Prague and Moravian Museum, Brno, 341 pp.
- Ludwig, K. R., 2003. User's manual for Isoplot /Ex v3.0, a geochronological toolkit for Microsoft Excel. *Berkeley Geochronology Centre Special Publication*, 4, 25-31.
- Macpherson, G. C., and Hall, R., 2001. Tectonic setting of Eocene boninite magmatism in the Izu-Bonin-Mariana forearc. *Earth and Planetary Science Letters*, 186, 215-230.
- Malinverno, A., and Ryan, W. B. F., 1986. Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere. *Tectonics*, 5, 227-245.
- Mason, B. and Moore, C. B., 1982. *Principles of Geochemistry*. John Wiley and Sons, Hong Kong, 344 pp.
- Matchan, E., and Phillips, D., 2011. New $^{40}\text{Ar}/^{39}\text{Ar}$ ages for selected young (< 1 Ma) basalt flows of the Newer Volcanic Province, southeastern Australia. *Quaternary Geochronology*, 6, 356-368.
- Miyashiro, A., Shido, F., and Ewing, M., 1971. Metamorphism in the mid-Atlantic Ridge near 24 degrees and 30 degrees N. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 268, 589-603.
- Mohajjel, M., Fergusson, C. L., and Sahandi, M. R., 2003. Cretaceous-Tertiary convergence and continental collision, Sanandaj-Sirjan Zone, western Iran. *Journal of Asian Earth Sciences*, 21, 397-412.
- Molnar, P., and Atwater, T., 1978. Interarc spreading and Cordilleran tectonics as alternates related to the age of subducted oceanic lithosphere. *Earth and Planetary Science Letters*, 41, 330-340.

- Muller, D., Franz, L., Herzig, P. M., and Hunt, S., 2001. Potassic igneous rocks from the vicinity of epithermal gold mineralization, Lihir Island, Papua New Guinea. *Lithos*, 57, 163-186.
- Nakamura, N., 1974. Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. *Geochimica et Cosmochimica Acta*, 38, 757-775.
- Nier, A. O., 1950. A redetermination of the relative abundances of the isotopes of carbon, nitrogen, oxygen, argon and potassium. *Physical Review*, 77, 789-793.
- Norrish, K., and Chappell, B., 1977. X-ray fluorescence spectrometry. *Physical Methods in Determinative Mineralogy*, pp. 201-272. Academic press, London.
- Pearce, J. A. 1983. Role of the sub-continental lithosphere in magma genesis at active continental margins. *Continental Basalts and Mantle Xenoliths*, 230-249.
- Pearce, J. A., Baker, P. E., Harvey, P. K., and Luff, I. W., 1995. Geochemical evidence for subduction fluxes, mantle melting and fractional crystallization beneath the South Sandwich island arc. *Journal of Petrology*, 36, 1073-1109.
- Pearce, J., 1996. A user's guide to basalt discrimination diagrams. Trace element geochemistry of volcanic rocks: Applications for massive sulphide exploration: *Geological Association of Canada, Short Course Notes*, 12, 79-113.
- Pearce, J. A., Stern, R. J., Bloomer, S. H., and Fryer, P., 2005. Geochemical mapping of the Mariana arc-basin system: Implications for the nature and distribution of subduction components. *Geochemistry, Geophysics, Geosystems*, 6, Q07006, doi:10.1029/2004GC000895.
- Pearce, J. A., 2008. Geochemical fingerprinting of oceanic basalts with applications to ophiolite classification and the search for Archean oceanic crust. *Lithos*, 100, 14-48.
- Phillips, G., Wilson, C. J. L., Phillips, D., and Szczepanski, S. K., 2007. Thermochronological ($^{40}\text{Ar}/^{39}\text{Ar}$) evidence of Early Palaeozoic basin inversion within the southern Prince Charles Mountains, East Antarctica: implications for East Gondwana. *Journal of the Geological Society of London*, 164, 771-784.
- Renne, P. R., Swisher, C. C., Deino, A. L., Karner, D. B., Owens, T. L., and Depaolo, D. J., 1998. Intercalibration of standards, absolute ages and uncertainties in $^{40}\text{Ar}/^{39}\text{Ar}$ dating. *Chemical Geology*, 145, 117-152.
- Saidi, A., Brunet, M.-F., and Ricou, L.-E., 1997. Continental accretion of the Iran Block to Eurasia as seen from Late Paleozoic to Early Cretaceous subsidence curves. *Geodinamica Acta (Paris)*, 10, 189-208.
- Schellart, W., Freeman, J., Stegman, D., Moresi, L. and May, D., 2007. Evolution and diversity of subduction zones controlled by slab width. *Nature London*, 446, 308.
- Searle, M. P., Lippard, S. J., Smewing, J. D., and Rex, D. C., 1980. Volcanic rocks beneath the Semail Ophiolite nappe in the northern Oman Mountains and their significance in the Mesozoic evolution of Tethys. *Journal of the Geological Society*, 137, 589-604.

- Shervais, J. W., 1982. Ti-V plots and the petrogenesis of modern and ophiolitic lavas. *Earth and Planetary Science Letters*, 59, 101-118.
- Sleep, N., and Toksöz, M. N., 1971. Evolution of marginal basins. *Nature*, 233, 548-550.
- Steiger, R. H., and Jager, E., 1977. Subcommittee on geochronology: convention on the use of decay constants in geo- and cosmochemistry. *Earth and Planetary Science Letters*, 36, 359-362.
- Sun, S. S., and McDonough, W., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A. D., and Norry, M. J. (Eds.), *Magmatism in the Ocean Basins. Geological Society of London, Special Publication*, 42, 313-345.
- Tatsumi, Y., Sakuyama, M., Fukuyama, H., and Kushiro, I., 1983. Generation of arc basalt magmas and thermal structure of the mantle wedge in subduction zones (Japan arc). *Journal of Geophysical Research*, 88, 5815-5825.
- Taylor, B., and Martinez, F., 2003. Back-arc basin basalt systematics. *Earth and Planetary Science Letters*, 210, 481-497.
- Taylor, B., 1992. Rifting and the volcanic-tectonic evolution of the Izu-Bonin-Mariana Arc, *Proc. ODP Sciences Results*, 126, 627-651.
- Volti, T., Gorbatov, A., Shiobara, H., Sugioka, H., Mochizuki, K. and Kaneda, Y. 2006. Shear-wave splitting in the Mariana trough--a relation between back-arc spreading and mantle flow? *Earth and Planetary Science Letters*, 244, 566-575.
- Wilson, M. 1989. *Igneous Petrogenesis*. Springer, 466p.
- Winchester, J. A., and Floyd, P. A., 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chemical Geology*, 20, 325-343.
- Woodhead, J., Eggins, S., and Gamble, J., 1993. High field strength and transition element systematics in island arc and back-arc basin basalts: evidence for multi-phase melt extraction and a depleted mantle wedge. *Earth and Planetary Science Letters*, 114, 491-504.
- Wood, D. A., 1980. The application of a ThHfTa diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary Volcanic Province. *Earth and Planetary Science Letters*, 50, 11-30.
- Ali, S. A., Buckman, S., Aswad, K. J., Jones, B. G., Ismail, S. A., and Nutman, A. P., in submission a. Recognition of Late Cretaceous Hasanbag ophiolite-arc rocks in the Kurdistan region of the Iraqi Zagros Thrust Zone: a missing link in the paleogeography of the closing Neo-Tethys Ocean. *The Geological Society of America, Journal of Lithosphere*

Caption for figures

Figure 1 Location of study areas within the Zagros Thrust zone.

Figure 2 Geological map of the Zagros Suture Zone along the Iraq-Iran border, showing the location and tectonic division of the study area.

Figure 3 Field photos

- a) diorite dyke (M14) with chilled margins intruding the upper part of the gabbroic body of Walash calc-alkaline rocks in the Mawat area, see Figure 2 for location area.
- b) Field photograph of the contact area between the Walash-Naopurdan lower Allochthon thrust sheets (in Mawat), the Red Bed series and other autochthon sedimentary rocks (Mawat Province).
- c) Thin layer of radiolarian chert in the Galalah area.
- d) Most of Choman alkaline Walash samples consist of pillow lavas with variable sizes.

Figure 4 Field photos

- a) The metasediment in the Leren-Hasnabg area consists of highly fossiliferous black shale alternating with lenses of sandstone.
- b) The Walash volcanic rocks are overlain by radiolarian chert in the Leren-Hasanbag area.
- c) Veins and faults in the Leren-Hasanbag area.
- d) Field photograph of the contact area between the Naopurdan island arc (Qalander Mountain) and the Red Bed series (Qalander Province).

Figure 5 Photomicrographs and field photos of Walash and Naopurdan rocks

- (A) Amygdaloidal texture in Choman volcanic rocks, sample Ch1; XPL.
- (B) Vesicular texture in basaltic rocks, sample Ch19.
- (C) Radiate texture in Galalah samples (Ga20); XPL.
- (D) Subhedral fresh clinopyroxene (Cpx) grains showing two perfect sets of cleavage; XPL; M7
- (E) Two types of chlorite fill a vug in Choman samples (Ch3); XPL.
- (F) Epidote and calcite are amygdales in Q6; XPL.

Figure 6 ^{40}Ar - ^{39}Ar dating results (A) $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra and Inverse Isochron diagrams for Walash calc-alkaline sample M7 in Mawat area, (B) $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for Naopurdan sample Q13 in Qalander area, (C) $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for Naopurdan sample SH8 basalt aliquot 'a' in Sheikhan area, (D) $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for Naopurdan sample SH8 basalt aliquot 'b' in Sheikhan area.

Figure 7 Selected binary diagrams showing major and trace elements variation of both Walash and Naopurdan rocks. Symbols: filled red square = Walash calc-alkaline samples; filled red triangle = Walash alkaline samples; blue cross = Naopurdan arc samples.

Figure 8 Chondrite and NMORB normalized plots (A&D) for Naopurdan samples, (B&E) for Walash alkaline samples, (C&F) for Walash calc-alkaline samples. Chondrite values are from Nakamura (1974) and NMORB values are from Sun and McDonough (1989), Symbols as in Figure 7

Figure 9 Diagrams to discriminate different rock type in the Walash and Naopurdan volcanic rocks: (a) Nb/Y versus Zr/Ti (after Pearce, 1996); (b) Nb/Y versus Zr/TiO₂ (after Winchester and Floyd, 1977). Symbols as in Figure 7.

Figure 10 Tectonic discrimination diagrams, (A) Zr versus Y binary discrimination diagram to separate between arc and within-plate environments for the Walash and Naopurdan rocks (after Muller et al., 2001), (B) Zr/Y versus Zr diagram to identify the tectonic environments for the Walash and Naopurdan volcanic rocks (after Pearce and Norry, 1979; back-arc basin basalt discrimination from Floyd et al., 1991), (C) V and Ti/1000 for the Walash and Naopurdan volcanic rocks (after Shervais, 1982). IAT = island-arc tholeiitic, BAB = back-arc basin basalts, CFB = continental flood basalts, and OIB = oceanic island basalts, (D) Zr versus V/Ti showing back-arc affinity for the Walash volcanic rocks and arc affinity for the Naopurdan volcanic rocks (after Woodhead et al., 1993) Symbols as in Figure 7.

Figure 11 Tectonic discrimination diagrams, (A) Ti/Zr versus Zr showing back-arc affinity for the Walash volcanic rocks and arc affinity for the Naopurdan volcanic rocks (after Woodhead et al., 1993), (B) Variation diagram of Nb versus Zr for Naopurdan basalts and basaltic andesites showing arc affinities while most Walash calc-alkaline samples show back-arc affinities. Most Walash alkaline samples are beyond the scale of this diagram, because of high Nb and Zr values that indicate a compositional field of intraplate rocks in a back-arc setting similar to that of New Zealand and Patagonia (Tatsumi et al., 1995), (C) Composition of Naopurdan and Walash samples (after Wood, 1980), (D) Th/Yb versus Nb/Yb diagram indicates an island arc character for all samples, although Walash samples actually belong to a back-arc basin, Symbols as in Figure 7.

Figure 12 Schematic diagram presents tectonic evolution model of Walash-Naopurdan arc-back arc within Zagros Suture Zone.

Caption for Table

Table 1 Major (wt%) and trace element (ppm) data of Eocene-Oligocene Walash-Naopurdan rocks

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12