The early Eocene (48 Ma) Qaladeza trondhjemite formed by wet partial remelting of mafic crust in the arc-related Bulfat Igneous Complex (Kurdistan, Iraq): constraints on the timing of Neotethys closure

Allen Nutman1· Sarmad Ali1,2· Yousif Mohammad3· Brian G. Jones1· Qing Zhang1,4

Received: 4 January 2022 / Accepted: 23 March 2022 / Published online: 2 April 2022 © The Author(s) 2022

Abstract
Events in the tectono-magmatic framework of the Eocene Bulfat Igneous Complex in the Kurdistan region of northeastern Iraq are revealed through the integrated field, petrographic, geochemical and zircon petrography and U–Pb geochronology of the Qaladeza trondhjemite sheets that cut gabbros of the complex. The trondhjemite sheets are variably deformed, with the cataclasis of large plagioclase feldspars. The trondhjemites are albitic, and geochemical features such as strong enrichment of the light REE relative to the heavy REE and low Ti and REE content show that they did not form as late differentiates of a MORB-like source, but instead by hydrous partial melting of mafic rocks, possibly also involving some more evolved crustal source as well. Qaladeza trondhjemite oscillatory-zoned magmatic zircon has an age of 48.0 ± 0.6 Ma (95% confidence). These domains have been etched to form voids in the zircons, the walls of which have thin coatings of Th- and Ca-bearing species. Subsequent partial recrystallization of the zircons obliterated the voids and increased the Th/U of the recrystallized zircon, which mostly formed at 38.74 ± 0.74 Ma. The 48 Ma domains relate to recycling of mafic crust in a proto-arc tectonic setting and are congruent with Eocene proto-arc magmatic activity within the Neotethyan oceanic basin. The 39 Ma domains relate to later tectonic-induced recrystallisation events coeval with the closure of Neotethys resulting from the late Eocene collision between the Arabian plate and Eurasia in Kurdistan.

Keywords Neotethys · Kurdistan · Trondhjemite · Bulfat Igneous Complex · Iraq

Introduction

The Zagros Suture Zone in NE Iraq (Kurdistan) is a complex collage of predominantly arc-related rocks that were formed in the Neotethys Ocean, from the late Mesozoic and into the Cenozoic (see review by Ali et al. 2019 and references therein). With ocean closure, these arc-related rocks were obducted onto the eastern edge of the Arabian plate as several allochthons (Fig. 1A; Aswad et al. 2013; Ali et al. 2012, 2013, 2019). Recent studies are highlighting the temporal and lithological complexities of the Kurdish sector of the Zagros Suture zone with, most importantly, the recognition of Cretaceous as well as Cenozoic arc-related allochthons (Ali et al. 2012, 2019). In most cases the different Cenozoic and Mesozoic arc assemblages in the Zagros Suture Zone cannot be distinguished in the field, particularly because in most cases any associated sedimentary rocks are not suitable for biostratigraphic constraints (Aswad and Pashderi...
Fig. 1 (A) Geological map of the Zagros suture zone along the Iraq-Iran border, showing the location and tectonic division of the study areas (after Ali et al., 2013). (B) Geological map of the Bulfat Igneous Complex, Qaladeza, NE Iraq (after Aswad et al., 2016, and references therein).
Also, due to the dominance of mafic igneous rocks, there are limited targets for U–Pb zircon geochronology. Furthermore, due to minefields and recent conflict, fieldwork has in many instances to be based on rapid appraisal and limited sampling of roadside outcrops. Nonetheless, a growing amount of $^{40}$Ar/$^{39}$Ar mineral and U–Pb zircon geochronology is revealing two important periods of arc magmatism: in the Cretaceous (Albian-Cenomanian) and the Paleogene (Eocene–Oligocene; Aswad et al. 2011, 2013; Ali et al. 2013, 2016, 2019).

In this paper we report on yet further complexities to these systems—the presence of Eocene trondhjemites indicative of low pressure partial melting of mafic rocks associated with the Eocene Bulfat Igneous Complex (Fig. 1B), which was emplaced into a Cretaceous intra-oceanic assemblage. As revealed by U–Pb zircon geochronology, these trondhjemites were emplaced at ~48 Ma but then underwent tectonothermal modification later in the Eocene at ~39 Ma. Geochemistry of the dated trondhjemite indicates partial melting of mafic rocks at pressures less than the stability of garnet. However, as supported by petrographic evidence, the plagioclase-phyric nature of the sample precludes more detail information on the conditions under which it was generated. Significance of the timing of trondhjemite formation and its tectonothermal modification for the closure of Neo-Tethys in the Middle East is discussed.

Regional geology

The Bulfat Igneous Complex occurs within the NW–SE trending Iraqi Zagros Suture Zone (Fig. 1A,B; Jassim et al. 2006). Within this zone are the allochthonous Albian-Cenomanian Gimo-Qandil sequence (upper Allochthon) and the Paleocene–Eocene Walash-Naopurdan volcanic-sedimentary sequence (Lower Allochthon; Aswad et al. 2011; Aziz et al. 2011). The Gimo-Qandil sequence used to be referred to as the Bulfat Group (Jassim et al. 1982). As a composite package, these allochthons now rest on the Arabian plate margin above molasse (Cenozoic Red Beds), neo-autochthonous flysch (Maastrichtian) and parautochthonous radiolarite (Albian-Cenomanian; Aswad 1999). Within the Upper Allochthon Gimo-Qandil sequence, magmatic arc activity began at ~100 Ma (Ali et al. 2012). Within the Lower Allochthon Walash-Naopurdan volcanic-sedimentary sequence, the magmatic arc activity was focussed at c. 40 Ma (Ali et al. 2013). The Cenozoic island-arc-affinity of the Walash-Naopurdan volcanic-sedimentary sequence implies that subduction of oceanic crust continued until the Miocene, when continental collision began with the final consumption of oceanic lithosphere (Aswad 1999; Ali et al. 2013, 2019).

The Eocene Bulfat Igneous Complex, cut by the trondhjemite dykes studied in this paper, consists of several intrusions emplaced into the Cretaceous Upper Allochthon Gimo-Qandil sequence. Voluminous gabbro-diorite intrusions and late stage differentiates of syenite and nepheline syenite crop out at Jabal Bulfat, 30 km east Qaladeza City (Fig. 1B).

The Bulfat Igneous Complex (Jassim et al. 2006) (Fig. 1B) has experienced medium-grade regional metamorphism, overprinted by a Paleogene contact metamorphic aureole (Jassim and Goff 2006). In this complex, voluminous and diverse Paleogene gabbro-diorite intrusions crop out at Jabal Bulfat. At least two types of intrusions are distinguished (Buda 1993). An older intrusion is composed predominantly of olivine-free gabbro and diorite intruded by younger, smaller bodies of olivine gabbro-diorite. A minor body of ultrabasic rocks and very limited occurrence of acid differentiates is also present (Buda 1993; Jassim and Goff 2006; Aswad et al. 2016). The Bulfat igneous bodies form sheet-like intrusions along lithological layering of the host sedimentary rocks, which are calcareous and argillaceous sediments of Late Cretaceous (Albian-Cenomanian) age (Jassim et al. 2006). Contact metamorphic rocks occur on the highest summits (~2340 m) forming roof pendants down into the Bulfat Igneous Complex (Buda 1993). Xenoliths of the country rocks with very high-grade thermal metamorphism up to the pyroxene hornfels facies are characteristic of the Bulfat complex (Buday 1980).

Trondhjemite field relationships and petrography

Trondhjemites occur as anastomosing sheets and dykes up to 1 m thick within the Eocene Bulfat complex gabbro. The studied trondhjemites occur at Qaladeza (36°04′59″ N, 45°17′26″ E; Fig. 1B). The gabbro was heterogeneously deformed since emplacement of the trondhjemites, such that in places the gabbro is devoid of fabric and the trondhjemites are not deformed (Fig. 2A), whereas elsewhere the gabbro has developed an LS tectonic fabric and the trondhjemite sheets are severely disrupted (Fig. 2B).

In thin section, a ~10-cm wide, weakly deformed, trondhjemite intrusion is dominated by albitic plagioclase (~90%) together with minor quartz, amphibole and biotite. Biotite is secondary, replacing amphibole (Fig. 3A). Zircon occurs as an accessory phase and is abundant enough to be detected in thin section. One notable feature of the trondhjemite is its inequigranular texture, with domains of very coarse-grained plagioclase (up to 1 cm) surrounded by finer-grained domains, in which plagioclase and quartz display planar mutual boundaries, giving a granoblastic texture with ~120° triple junctions (Fig. 3B). These features indicate solid-state
recrystallization under directed stress. The interiors of the larger plagioclase grains display normal and occasionally oscillatory zoning which is locally cross-cut by grain boundaries. These textures indicate mild cataclasis of the original plagioclase grains, probably at conditions near the ductile–brittle transition.

**Whole rock geochemistry**

**Analytical methods**

A Qaladeza trondhjemite and a host gabbro sample (Table 1) were crushed using a chromium steel TEMA ring mill. The major elements were determined by X-ray fluorescence (Spectro-Analytical Instrument XEPOS XRF spectrometer) at the University of Wollongong (UOW), with uncertainties less than 3%. The loss-on-ignition was detected by a separate aliquot of powder heated at 1000 °C. A 57–43% flux mixture was used for the felsic sample, following Norrish and Chappell (1977). The trace elements (including the rare earth elements, REEs) were analysed by inductively coupled plasma-mass spectrometry (ICP-MS) in commercial ALS Mineral Division, Brisbane. The prepared samples were added to lithium flux for melting and then cooled and dissolved in an acid mixture containing nitric, hydrochloric and hydrofluoric acids (geochemical procedure ME-MS61r). Pulverized sample was added to lithium metaborate/lithium tetraborate flux and fused in a furnace to form beads. Each bead is cooled and dissolved in an acid mixture containing nitric, hydrochloric and hydrofluoric acids. The resulting solution is neutralized and diluted before being analysed by ICP-MS. Standards used were OREAS-120 and STSD-1, and results are within a 10% error tolerance. Further details of standards for monitoring drift can be obtained from the ALS laboratories.

**Results**

The host gabbro has ~ 50 wt% SiO₂ and ~ 3 wt% Na₂O + K₂O, which according to the TAS classification system confirms...
its gabbroic affinity. The gabbro has an MgO content of 6.7 wt%, in the range typical for arc-related mafic rocks. The gabbro shows mild enrichment in chondrite-normalised light rare earths (LREE) over the heavy rare earths (HREE; Fig. 4A) with La/Yb(N) = 2.9, with a positive Eu anomaly (Fig. 4A). The positive Eu anomaly is indicative of some plagioclase accumulation, as has been noted in leucogabbros (e.g., O’Nions and Pankhurst 1974). Some plagioclase accumulation is in accord with the rather high Al₂O₃ content of ~21 wt% in the gabbro. The gabbro shows a Ti/V ratio of 16.9, which is in the 10–20 range for arc-related mafic rocks (Shervais 1982). Given that the gabbro sample is homogeneous/isotropic, without cumulate layering, it is unlikely this value was distorted by magmatic accumulation of Fe-Ti oxide. The gabbro has a high La/Nb ratio of 5.0, typical for subduction-related mafic magmatism.

The Qaladeza trondhjemite with ~62.9 wt% SiO₂, ~9.3 wt% Na₂O + K₂O with a low K₂O/Na₂O of 0.06 and ~3.4 wt% CaO demonstrates the trondhjemitic nature with the albitic character of its plagioclase. The trondhjemite shows strong enrichment of the LREE over the HREE (La/Yb(N) = 58), but with almost flat HREE (Gd to Lu; Gd/Yb(N) = 1.2) and a marked positive Eu anomaly (Figs. 4A,B).
with this anomaly most readily explained by the sample containing accumulated plagioclase. The Qaladeza trondhjemite shows depletion of Nb and Ta relative to Th and La and, in accord with likely plagioclase accumulation, positive Sr and Eu anomalies (Fig. 4B). TiO$_2$ and La versus SiO$_2$ Harker diagrams are used for discriminants for ‘plagiogranites’ of different origins (here meaning simply felsic igneous rocks in oceanic crust or ophiolites). The Qaladeza trondhjemite has low TiO$_2$ for given SiO$_2$ wt% content, and falls well below the line marking the lower limit of experiments on MORB fractionation (Fig. 4C), as explained in detail by Koepke et al. (2004; 2007). In terms of La versus SiO$_2$, the Qaladeza trondhjemite falls in the field of low-La ‘plagiogranite’, appropriate for those involving hydrous partial melting of mafic rocks, as opposed to those such as from the East Pacific Rise that have much higher La and are concentrations of residual melt from the crystallisation of MORB magma (Fig. 4D; Brophy 2009).

The Qaladeza trondhjemite with its strong enrichment of the LREE over the HREE and its low K$_2$O/Na$_2$O and low CaO differs from ‘plagiogranites’ considered to have formed solely by hydrous anatexis of mafic rocks, such as the Jebbel Fayyad and Wadi Rajmi Oman plagiogranites (Fig. 4A; Rollinson 2009). On the other hand, the LREE enrichment and the low K$_2$O/Na$_2$O character of the Qaladeza trondhjemite resemble that of the Oman Hamaliya plagiogranites’ which Rollinson (2009) proposed contain both crust and mantle components and formed through a mixing or contamination process during, or immediately following, the emplacement of the Oman ophiolite.

Zircon U–Pb analyses and internal structure

Analytical methods

Zircons from the Qaladeza trondhjemite sample ‘trond’ were separated at the Australian National University (ANU) using density and magnetic methods. These were mounted with $^{238}$U-$^{206}$Pb calibration reference material TEMORA zircon grains, on a glass plate with double-sided tape, which were then cast with epoxy resin in a mould. The zircon mounts were then polished prior to cathodoluminescence (CL) imaging. The CL images were obtained via the scanning electron microscope at the UOW Centre for Electron Microscopy.

Zircon U–Pb dating on the SHRIMP RG instrument at ANU followed the analytical protocols of Williams (1998). The intensity of the primary O$^{2-}$ ion beam was 4–6 nA and spot size was ~15 µm, with each site rastered for 120 s prior to analysis. Six scans through the mass stations (nominal masses 196 = $^{90}$Zr $^{16}$O (2 s); 204 = $^{204}$Pb (10 s); 204.1 = background (10 s); 206 = $^{206}$Pb (15 s); 207 = $^{207}$Pb (20 s); 208 = $^{208}$Pb (5 s); 238 = $^{238}$U (7 s); 248 = $^{232}$Th $^{16}$O (2 s); 254 = $^{238}$U $^{16}$O (2 s)) were made for each age determination. The SHRIMP RG’s magnet is extremely stable, requiring a settling time of only 2 s before peak centering mass 196 after moving from mass 254 between scans. The raw data were reduced using the new application POXI-SC developed by ANU, which combines the functionality of the previous two ANU applications PRAWN and LEAD. Quoted errors on isotope ratios also take into account non-linear fluctuations in ion count rates above that expected from counting statistics alone (Williams 1998). Correction for common Pb using the composition of Broken Hill lead was made according to the 207-method (Compston et al. 1984), applicable to young zircons where concordancy can be assumed. U-Th elemental abundance was calibrated based on the reference zircon SL13 (U = 238 ppm), which was in a set-up mount and $^{206}$Pb/$^{238}$U were calibrated using the TEMORA reference material with a concordant age at 416.8 ± 1.1 Ma (Black et al. 2003). To increase confidence in the calibration of U–Pb, Temora was distributed as several clusters of grains in different parts of the epoxy mount. These were visited in a random fashion during the analytical session. This allows the best estimate across the mount of the U–Pb calibration and uncertainty with it. In order to allow accurate comparison with other data, the calibrated mean $^{206}$Pb/$^{238}$U ages in this paper are quoted with the Temora U–Pb calibration error (~1.5%) added in quadrature. The reduced and calibrated data were then assessed and plotted using Isoplot (Ludwig 2003). Calculated ages below are given at the 95% confidence level.

Back scatter electron imaging (BSE) and energy dispersive spectra (EDS) analysis of zircon inclusions and structure was undertaken on a Phenom benchtop scanning electron microscope at UOW operating at 15 kV. The EDS analyses undertaken on the inclusions of the zircons are very thin, and therefore have Zr and Si from the underlying zircon (supplementary document).

Trondhjemite zircon U–Pb geochronology and internal structure

Sample ‘trond’ yielded zircons that are 200–300 µm long, euhedral, equant to stubby prisms. In CL images, they display diverse internal textures, which can be correlated with the measured $^{206}$Pb/$^{238}$U ages (below). Domains with the oldest ages (~48 Ma) show well-developed igneous-style oscillatory zoning with straight internal boundaries but are transected by elongate domains that appear dull in CL images (Fig. 5) and bright in BSE images and are mostly orientated
parallel to the long axes of prisms (grain #9 on Fig. 6). BSE imaging and EDS analyses of the domains that appear dull in CL images reveal that they are voids in the zircons, the walls of which have thin, estimated at one micrometre-scale, coatings of Ca or Th phosphates (Fig. 6, supplementary document). Grains with younger $^{206}\text{Pb}/^{238}\text{U}$ ages show a reduction, or lack, of the voids and obliteration or blurring of oscillatory zoning. Examples are grain #6 with an apparent age of $\sim 45$ Ma with few voids and irregular/blurred interior boundaries indicating some recrystallisation, whereas grain #13, with an apparent age of $\sim 41$ Ma, has a homogeneous void-free interior but with blurred irregular zoning towards the margins. Grains 1 and 5, with apparent ages of $\sim 39$ Ma, show blurred and irregular zoning and complex internal structures, respectively (Fig. 5).

Seventeen U-Th-Pb analyses were undertaken on 16 grains (Table 2). All sites have minimal content of
common Pb and even prior to correction for it, they plot within analytical error of concordia (Fig. 7A). The $^{206}\text{Pb}/^{238}\text{U}$ ages of the sites scatter well-beyond analytical error (44.70 ± 2.10 Ma MSWD = 24) as several clusters (Fig. 7B). The cluster of oldest ages are those with best preserved igneous oscillatory zoning and with most grains showing a high density of (irregularly-distributed) micron-scale voids with mineralized surfaces that appear dull in CL and bright in BSE images. These analyses yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 48.00 ± 0.57 Ma (95% confidence; MSWD = 0.15; probability of fit = 0.98) and are interpreted as giving the time of igneous crystallisation of the trondhjemite (Ypresian, early Eocene). Sites with younger $^{206}\text{Pb}/^{238}\text{U}$ ages are those in CL images showing less, or no, micron-scale voids and variable internal structures, particularly blurred irregular zoning. These sites also show an increase in Th/U (Fig. 7A inset). Together, these features indicate recrystallisation within the ~48 Ma grains, leading to the eradication of the micron-scale voids. With one exception (analysis 13.1), analyses of these grains cluster into two age groups, with weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages of 45.16 ± 0.82 Ma (MSWD = 0.49; probability of fit = 0.63) and 38.74 ± 0.74 Ma (MSWD = 0.61; probability of fit = 0.72). This indicates pulses of recrystallisation later in the Eocene (Lutetian and Bartonian).

### Discussion

#### Zircon igneous growth, corrosion and recrystallisation

The zircon petrology and dating indicate that the trondhjemite magma crystallised at ~48 Ma. The phosphate-coated voids could have two origins. Firstly, they could indicate igneous crystallisation at ~48 Ma was coeval with a hydrous fluid exsolving from the magma. However, these domains appear more likely to be post-magmatic, because of the way in which they traverse across the oscillatory zoning (Figs. 5, 6). Thus, it is more likely that these domains represent partial dissolution of the zircons by a hydrothermal fluid, before 45 Ma, when it is evident from the zircon petrography that these voids were being lost through patchy crystallisation of the zircons. Corrosion of zircons and partial replacement by other phases has been attributed to fluxing by alkaline hydrothermal fluids (rich in Na+Cl) as evidenced both in geological case studies of ophiolites and by experimentation (e.g., Rubatto and Hermann 2003; Ayers et al. 2012). The integration of zircon petrography and the U–Pb geochronology demonstrates recrystallisation of the corroded zircon in discrete events at ~45 and ~39 Ma, with the latter age being within analytical error of Ar–Ar hornblende and biotite ages acquired on noritic gabbro in the Bulfat complex (Aswad et al. 2016).

#### Origin of the Qaladeza trondhjemite

From its geochemical signature such as low TiO$_2$ and La for given silica content (Fig. 4C,D), the Qaladeza trondhjemite cannot be interpreted as plagiogranite formed as a late differentiate of MORB-like magma but instead indicates partial melting of a mafic source. This could have been triggered by incursion of meteoric water in the high heat flow extensional environment which spawned the Bulfat gabbro intrusions. Trondhjemites formed at great depth by melting of eclogitized mafic rocks within subducting oceanic crust form magmas with strong depletion of the HREE versus the middle and LREE, because of their equilibration with residual garnet (Martin 1986; Hoffmann et al. 2019). However, the lack of progressive depletion of HREE in the Qaladeza trondhjemites, as expressed by Dy/Yb$_{kr}$$\sim$ 1 (Fig. 4A; Table 1), indicates that they did not involve partial melting at high pressure with garnet fractionation. Instead, the overall concave-bowed REE pattern is suggestive of equilibration of the melt with either clinopyroxene or hornblende, which have complimentary convex-bowed REE patterns (e.g., Barker and Arth 1976;
### Table 2  Zircon U–Pb

| Spot | Site | U (ppm) | Th (ppm) | Th/U | 206Pb comm% | 238U/206Pb (meas) | 207Pb/206Pb (meas) | age 206Pb/238U (corr) |
|------|------|---------|----------|------|-------------|-------------------|-------------------|----------------------|
| 1.1  | e,rex, cur,v,p,fr | 76 | 36 | 0.473 | 0.89 | 165.4 ± 10.2 | 0.0549 ± 0.0106 | 38.51 ± 1.25 |
| 2.1  | m,h, > v,p | 280 | 50 | 0.179 | 0.37 | 133.0 ± 4.0 | 0.0504 ± 0.0049 | 48.12 ± 0.89 |
| 3.1  | m,h, > v,p | 457 | 96 | 0.210 | 0.24 | 134.4 ± 3.2 | 0.0492 ± 0.0038 | 47.68 ± 0.72 |
| 4.1  | m,h/rex, < v,p,fr | 102 | 84 | 0.825 | 2.0 | 159.8 ± 8.6 | 0.0651 ± 0.0102 | 39.42 ± 1.10 |
| 4.2  | m,h/rex, < v,p,fr | 97 | 80 | 0.826 | 0.67 | 161.5 ± 9.0 | 0.0529 ± 0.0094 | 39.53 ± 1.20 |
| 5.1  | m, sz/rex, < v,eq | 47 | 31 | 0.653 | 2.2 | 164.2 ± 12.3 | 0.0670 ± 0.0144 | 38.28 ± 1.52 |
| 6.1  | m,h/rex,cur, < v,p | 329 | 51 | 0.155 | 0.57 | 143.2 ± 4.1 | 0.0522 ± 0.0047 | 44.62 ± 0.78 |
| 7.1  | m,h/rex, < v,p | 687 | 161 | 0.234 | 0.18 | 141.9 ± 2.8 | 0.0485 ± 0.0031 | 45.18 ± 0.64 |
| 8.1  | m,h, eq | 1024 | 301 | 0.180 | 0.30 | 131.9 ± 4.0 | 0.0497 ± 0.0049 | 48.55 ± 0.92 |
| 9.1  | m,h, > v,p | 273 | 47 | 0.172 | 0.30 | 131.9 ± 4.0 | 0.0497 ± 0.0049 | 48.55 ± 0.92 |
| 10.1 | m,h/rex,cur, < v,p | 570 | 498 | 0.873 | 0.62 | 168.0 ± 4.0 | 0.0524 ± 0.0040 | 38.02 ± 0.61 |
| 11.1 | m,h/rex,cur, < v,fr | 115 | 91 | 0.788 | 1.36 | 162.9 ± 8.2 | 0.0592 ± 0.0091 | 38.92 ± 1.06 |
| 12.1 | m,h/rex,cur, < v,p | 302 | 47 | 0.157 | 0.24 | 140.2 ± 4.1 | 0.0492 ± 0.0047 | 45.70 ± 0.81 |
| 13.1 | m, rex, x,v,cur,p | 64 | 36 | 0.566 | 1.67 | 150.9 ± 9.8 | 0.0622 ± 0.0120 | 41.87 ± 1.41 |
| 14.1 | e, osc, < v,p | 906 | 161 | 0.178 | 0.12 | 134.0 ± 2.2 | 0.0480 ± 0.0026 | 47.86 ± 0.63 |
| 15.1 | e,h/rex,x,v,p | 99 | 80 | 0.808 | 0.76 | 159.4 ± 8.6 | 0.0538 ± 0.0092 | 40.00 ± 1.12 |
| 16.1 | m,h, < v,p | 675 | 122 | 0.180 | 0.31 | 133.7 ± 2.6 | 0.0499 ± 0.0031 | 47.88 ± 0.65 |

Spot: x,y = grain followed by analysis number
Site and habit: e = edge; m = middle, p = prism, eq = equant, fr = fragment
CL imagery: osc = oscillatory zoning, sz = sector zoning, h = homogeneous, rex = recrystallized
CL imagery continued: > v = numerous voids, < v = few or no voids, xv = no voids, cur = curved domain boundaries
Isotopic ratios and ages: meas = measured, corr = corrected for common Pb
Analytical errors: all are reported at 1σ level

---

**Fig. 7 (A)**  $^{238}\text{U}/^{206}\text{Pb} - ^{207}\text{Pb}/^{206}\text{Pb}$ concordia diagram (uncorrected for small amount of common Pb – see Table 2). Inset shows relationship between zircon age and Th/U ratio. 
**(B)** Frequency distribution and histogram for the zircon ages, corrected for common Pb
Norman et al. 2005). Equilibration with clinopyroxene and/or hornblende without garnet is indicative of a lower pressure melting regime (e.g., Wyllie 1977). The strong positive Eu anomaly is indicative of local plagioclase accumulation/over-presentation in the coarse-grained sample.

The Qaladeza trondhjemite with its strong enrichment of the LREE over the HREE and its low K2O/Na2O and low CaO differs from ‘plagiogranites’ considered to have formed solely by hydrous anatexis of mafic rocks, such as the Jebbel Fayyad and Wadi Rajmi Oman ‘plagiogranites’ (Fig. 4A; Rollinson 2009). On the other hand, the LREE enrichment and the low K2O/Na2O character of the Qaladeza trondhjemite have more in common with the Oman Hamaliya ‘plagiogranites’. Rollinson (2009) proposed such compositions contain both crust and mantle components and that they formed through a mixing or contamination process during, or immediately following, the emplacement of the Oman ophiolite. Therefore, we propose that the Qaladeza trondhjemites have a hybrid origin, where melts formed by low pressure hydrous anatexis of mafic rocks and some evolved crustal materials, or that melts derived solely from a mafic source were contaminated upon their emplacement.

Tectonic significance of the Qaladeza trondhjemite

The Qaladeza trondhjemite was emplaced at ~48 Ma, but later there were superimposed tectonothermal events witnessed at the outcrop scale by weak deformation of some trondhjemites (Fig. 2B) and in thin section by the internal distortion of large feldspars (Fig. 3B) and alignment of biotite into a foliation. This also gave rise to variable recrystallisation of the original igneous zircons, probably connected with the tectonic recrystallisation observed in the thin sections of these rocks. It is noted that the zircon U–Pb recrystallisation age of 38.74 ± 0.74 Ma is indistinguishable from the Ar–Ar amphibole ages of 39.23 ± 0.21 and 38.87 ± 0.24 Ma acquired from the host Bulfat gabbros (Aswad et al. 2016). Therefore, we contend that the evidence for late Eocene zircon recrystallisation relates to a tectonothermal event in which Ar–Ar amphibole and biotite ages in the host gabbros were reset.

Geochronological data of zircon in trondhjemite from the Bulfat Igneous Complex, combined with available geochronological data (U–Pb, Ar–Ar) for various igneous rocks along the collision zone with the Iranian plate, reveal that the rocks at the studied locality reside in an early Eocene magmatic protoarc (Agard et al. 2011; Ali et al. 2019; Azizi and Tsuboi 2020). These intra-oceanic rocks were subsequently affected by the ~39 Ma tectonothermal event that is attributed to collision of the Arabian plate with the Iranian plate (Mohammad et al. 2014, 2020; Mohammad and Cornell 2017; Azizi et al. 2019).

Conclusions

(1) Early Eocene trondhjemite dykes in the Bulfat Igneous Complex formed by hydrous partial melting of ophiolitic mafic rocks at ~48 Ma, probably in a Neotethyan intraoceanic setting. (2) A tectonic event at ~39 Ma caused partial recrystallization of the magmatic zircons and reset Ar–Ar amphibole and biotite ages in the host gabbros. This tectonic event is attributed to the onset of collision between the Arabian plate and Eurasia in Kurdistan.

Acknowledgements Tom McMahon (UOW) is thanked for undertaking the CL imaging of the zircons. Shane Paxton (ANU) is thanked for undertaking the zircon separation. Access to the CL-imaging facilities at the UOW Electron Microscopy Unit is acknowledged.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions Funding for analytical work was from the GeoQuest Research Centre, University of Wollongong (Australia). Field work/sample collection was supported by the University of Kirkuk (Iraq).

Declarations

Competing interests There authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Agard P, Omrani J, Jolivet L, Whitechurch H, Vrielynck B, Spakman W, Monié P, Meyer B, Wortel R (2011) Zagros orogeny: a subduction-dominated process. Geol Mag 148:692–725
Ali SA, Buckman S, Aswad KJ, Jones BG, Ismail SA, Nutman AP (2012) 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. Lithosphere 4:395–410
Ali SA, Buckman S, Aswad KJ, Jones BG, Ismail SA, Nutman AP (2013) The tectonic evolution of a Neo-Tethyan (Eocene-Oligocene) island-arc (Walash and Naopurdan Groups) in the Kurdistan region of the NE Iraqi Zagros suture zone. Island Arc 22:104–125
Ali SA, Nutman AP, Aswad KJ, Jones BG (2019) Overview of the tectonic evolution of the Iraqi Zagros thrust zone: sixty million years of Neotethyan subduction. J Geodyn 129:162–177
Aswad KJ (1999) Arc-continent collision in Northeastern Iraq as evidenced by Mawat and Penjein ophiolite complexes. Rafidain Journal of Sciences 10:51–61
Aswad KJ, Pasdadi MAA (1984) Thermal metamorphism of impure carbonate xenoliths in the gabbroic rock of Bulfat Complex NE Iraq. Journal of the Geological Society of Iraq 17:208–235
Aswad KJ, Aziz NRH, Koyi HA (2011) Cr-spinel compositions in serpentinites and their implications for the petrotectonic history of the Zagros Suture Zone. Kurdistan, Geological Magazine 148:802–818
Aswad KJ, Al-Shereffy RM, Ali SA (2013) Pre-collisional intrusive magmatism in the Bulfat Complex, Wadi Rashid, Qala Deza, NE Iraq: geochemical and mineralogical constraints and implications for tectonic evolution of granitoid-gabbro suites, Iraqi National Journal of Earth Sciences, Vol. 13, pp. 103–137
Aswad KJ, Ali SA, Al Shereffy RA, Nutman AP, Buckman S, Jones BG, Jourdan F (2016) 40Ar/39Ar hornblende and biotite geochronology of the Bulfat Igneous Complex, Zagros Suture Zone, NE Iraq: New insights on complexities of Paleogene arc magmatism during closure of the Neotethys Ocean. Lithos 266–267:406–413
Azizi H, Hadad S, Stern RJ, Asharani Y (2019) Age. geochemistry, and emplacement of the ~40-Ma Baneh granite–aplite complex in a transpressional tectonic regime Zagros Suture Zone, Northwest Iran. International Geology Review 61:195–223
Azizi H, Tsuboi M (2020) The Van microplate: A new microcontinent of the Zagros Suture. Krystalnikum 16:87–108
Koepe J, Feig ST, Snow J, Freise M (2004) Petrogenesis of oceanic plagiogranites by partial melting of gabbros: an experimental study. Contrib Miner Petrol 146:414–432
Koepe J, Berndt J, Feig ST, Holtz F (2007) The formation of SiO2-rich melts within the deep oceanic crust by hydrous partial melting of gabbros. Contrib Miner Petrol 153:67–84
Ludwig K (2003) Isoplot. Publication, Berkeley Geochronology Center, p 1
Martin H (1986) Effects of steeper Archean geothermal gradient on geochemistry of subduction zone magmas. Geology 14:753–756
Mohammad YO, Cornell DH, Qaradaghji JH, Mohammad FO (2014) Geochemistry and Ar–Ar muscovite ages of the Daraban Leucogranite, Mawat Ophiolite, northeastern Iraq: implications for Arabia-Eurasia continental collision. J Asian Earth Sci 86:151–165
Mohammad YO, Cornell DH (2017) U–Pb zircon geochronology of the Daraban leucogranite, Mawat ophiolite, Northeastern Iraq: a record of the subduction to collision history for the Arabia–Eurasia plates, Island Arc, Vol. 26, p.12188
Mohammad YO, Ali SA, Aziz NR, Yara JO, Abdulla KL (2021) Comment on “Generation and exhumation of granitoid intrusions in the Penjween ophiolite complex, NW Zagros of the Kurdistan region of Iraq: Implications for the geodynamic evolution of the Arabia–Eurasia collision zone” by Ismail et al., 2020, V. 376–377, 105714, Lithos, 390(391), 105915
Norman M, Garcia MO, Pietruszka AJ (2005) Trace-element distribution coefficients for pyroxenes, plagioclase, and olivine in evolved tholeiites from the 1955 eruption of Kiluea Volcano, Hawaiï, and Petrogenesis of Differentiated Rift-Zonelavas, American Mineralogist 90:888–899
Norris K, Chappell BW (1977) X-ray fluorescence spectrography. Zussman J. (Ed.), Physical Methods in Determinative Mineralogy, Academic Press, pp. 161–214
O’Nions RK, Pankhurst RJ (1974) Rare earth element distribution in oceanic plagiogranites by partial melting of gabbros. Contrib Miner Petrol 158:67–84
Rollinson H (2009) New models for the genesis of plagiogranites in the Oman ophiolite. Lithos 112:603–614
Rubatto D, Hermann J (2003) Zircon formation during fluid circulation in eclogites (Monviso, Western Alps): Implications for Zr and Hf budget in subduction zones. Geochim Cosmochim Acta 67:2173–2187
shervais JW (1982) Ti-V plots and the petrogenesis of modern and ancient oceanic ridge magmas: implications for the origin of oceanic plagiogranites. Contrib Miner Petrol 158:155–170
Broomby JG (2009) Rare earth element-SiO2 systematics in mid-ocean ridge magmas: implications for the origin of oceanic plagiogranite. Contrib Miner Petrol 158:67–84
Buda GY (1993) Igneous petrology of the Bulfat Area (North-East Iraq). Geological Magazine, Brno, 341 pp
Buda T (1980) Stratigraphy and Palaeogeography: The Regional Geology of Iraq 1, GEOSURV, Baghdad
Compston W, Williams IS, Meyer C (1984) U-Pb geochronology of zircons from lunar breccia 73217 using a sensitive high mass resolution ion microprobe, Journal of Geophysical Research, Vol. 89, Supplements, B525, B534
Hoffmann JE, Zhang C, Moyen J-F, Nagel TJ (2019) The formation of tonalites-trondhjemite-granodiorites in early continental crust: In: Van Kranendonk MJ, Bennett VC and Hoffmann JE (editors) Earth’s Oldest Rocks (second edition), Elsevier, pp. 113–168
Jassim SZ, Suk M, Waldhaeusla J, Suk M (1982) Evolution of magmatic activity in Iraqi Zagros complexes. Krystalnikum 67:98–108
Koepe J, Feig ST, Snow J, Freise M (2004) Petrogenesis of oceanic plagiogranites by partial melting of gabbros: an experimental study. Contrib Miner Petrol 146:414–432
Koepe J, Berndt J, Feig ST, Holtz F (2007) The formation of SiO2-rich melts within the deep oceanic crust by hydrous partial melting of gabbros. Contrib Miner Petrol 153:67–84
Ludwig K (2003) Isoplot. Publication, Berkeley Geochronology Center, p 1
Martin H (1986) Effects of steeper Archean geothermal gradient on geochemistry of subduction zone magmas. Geology 14:753–756
Mohammad YO, Cornell DH, Qaradaghji JH, Mohammad FO (2014) Geochemistry and Ar–Ar muscovite ages of the Daraban Leucogranite, Mawat Ophiolite, northeastern Iraq: implications for Arabia-Eurasia continental collision. J Asian Earth Sci 86:151–165
Mohammad YO, Cornell DH (2017) U–Pb zircon geochronology of the Daraban leucogranite, Mawat ophiolite, Northeastern Iraq: a record of the subduction to collision history for the Arabia–Eurasia plates, Island Arc, Vol. 26, p.12188
Mohammad YO, Ali SA, Aziz NR, Yara JO, Abdulla KL (2021) Comment on “Generation and exhumation of granitoid intrusions in the Penjween ophiolite complex, NW Zagros of the Kurdistan region of Iraq: Implications for the geodynamic evolution of the Arabia–Eurasia collision zone” by Ismail et al., 2020, V. 376–377, 105714, Lithos, 390(391), 105915
Norman M, Garcia MO, Pietruszka AJ (2005) Trace-element distribution coefficients for pyroxenes, plagioclase, and olivine in evolved tholeiites from the 1955 eruption of Kiluea Volcano, Hawaiï, and Petrogenesis of Differentiated Rift-Zone lavas, American Mineralogist 90:888–899
Norris K, Chappell BW (1977) X-ray fluorescence spectrography. Zussman J. (Ed.), Physical Methods in Determinative Mineralogy, Academic Press, pp. 161–214
O’Nions RK, Pankhurst RJ (1974) Rare earth element distribution in oceanic plagiogranites by partial melting of gabbros. Contrib Miner Petrol 158:67–84
Rollinson H (2009) New models for the genesis of plagiogranites in the Oman ophiolite. Lithos 112:603–614
Rubatto D, Hermann J (2003) Zircon formation during fluid circulation in eclogites (Monviso, Western Alps): Implications for Zr and Hf budget in subduction zones. Geochim Cosmochim Acta 67:2173–2187
Shervais JW (1982) Ti-V plots and the petrogenesis of modern and ophiolitic lavas. Earth Planet Sci Lett 22:328–338
Rollinson H (2009) New models for the genesis of plagiogranites in the Oman ophiolite. Lithos 112:603–614
Rubatto D, Hermann J (2003) Zircon formation during fluid circulation in eclogites (Monviso, Western Alps): Implications for Zr and Hf budget in subduction zones. Geochim Cosmochim Acta 67:2173–2187
Shervais JW (1982) Ti-V plots and the petrogenesis of modern and ophiolitic lavas. Earth Planet Sci Lett 59:101–118
Williams IS (1998) U-Th-Pb geochronology by ion microprobe. In: Applications of microanalytical techniques to understanding mineralizing processes. In: McKibben, M.A., Shanks III, W.C.P., Ridley, W.L., (Eds.), Soc. Econ. Geol. Short Course vol. 7
Wyllie PJ (1977) Crustal anatexis: An experimental review. Tectonophysics 43:41–71