ARTICLE IN PRESS
LITHOS-106055; No of Pages 3
Lithos xxx (xxxx) xxx
Contents lists available at ScienceDirect
Lithos
journal homepage: www.elsevier.com/locate/lithos

Research Article

Multi-stage magmatic activity in the Neotethyan ophiolite of Penjween: Reply on comments 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 Mohammad et al.

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1. Introduction

The research paper by Ismail et al. (2020) reported two types of granitoid intrusions within the Late Cretaceous Penjween Ophiolite Complex (POC) that have different genesis ages, but comparable exhumation ages, suggesting a multi-stage magmatic activity in a single Neotethyan ophiolite remnant. The first granitoid type (trondhjemite) of the Late Cretaceous age elucidated in relation to the formation of the POC. The second granitoid type (pegmatite granite) of the Eocene age interpreted as a product of melting process in association with the downgoing Neotethyan oceanic slab. These conclusions were based on new supporting data from whole-rock geochemistry results, petrography, zircon geochronology and thermochronology, and trace and rare earth elements concentrations in zircons.

2. Geologic background, field relationships and petrography

The geologic background, field relationships, and petrography of the granitoid rocks in the POC documented by Ismail et al. (2020) are inline with the reported observations and results in key literatures concerning the study area. For more clarification we highlight the following points: (1) the peridotites in the POC are mainly of two types that are geographically separate. The northern Boban Block part is mainly highly serpentinized harzburgite, whereas the southern Kerry-Kapla Block part is partially serpentinized harzburgite and Iherzolite (Bolton, 1956; Buday and Jassim, 1987). There is no evidence for meta-harzburgite as Mohammad et al. (2020) claim (Jassim and Goff, 2006); (2) the cross section in Fig. 1 of Mohammad et al. (2020) is not representative of the geology of Penjween area and is misleading. On the basis of previous researches (Jassim et al., 2006; Jassim and Buday, 2006a) and the published and updated geologic map of Sulaimaniyah quadrangle (Sissakian and Fouad, 2014), neither the Walash Group is exposed nor a thrust fault between the Cretaceous Balambo Formation and the Jurassic rocks is documented. Possibly, the thrust fault is between the Qulqula Formation and other Cretaceous rocks (Jassim and Buday, 2006b). The Cenozoic Red Bed Series is younger than the Cretaceous Qulqula Formation and has been deposited on top of the Qulqula Formation (Jassim et al., 2006; Karim et al., 2011), however Fig. 1 of Mohammad et al. (2020) shows opposite; (3) the size of the pegmatite granite is as mentioned in Ismail et al. (2020). The scale of Fig. 1 is adequate and can be independently and easily checked in Google Earth; (4) Mohammad et al. (2020) commented on only one intrusion, yet Ismail et al. (2020) reported seven granitoid intrusions in four locations (Table 1).

3. Geochemistry and origin of the Penjween granitoid intrusions

Sample selection for the whole-rock analysis was based on the petrographic study for the granitoid samples. Samples were prepared according to standard procedure for granite sample analysis, which includes splitting about 5 kg crushed sample in order to avoid selection bias. Triplot diagram of feldspars (O'Connor, 1965) was used to classify the Penjween granitoid intrusions into Group-I trondhjemite and Group-II pegmatite granite (Fig. 5B), which has supported our petrographic study. Two magmas of different genesis are responsible for the generation of Penjween granitoids as indicated by K_2O versus SiO_2 plot (Peccerillo and Taylor, 1976) (Fig. 5C). The tholeiitic granitoids of Group-I belong to mantle-derived group, whereas the calc alkaline and peraluminous granitoids of Group-II are crustal granitoids (Barbarin, 1990). The spider diagrams of the trace and rare earth element patterns (Fig. 6 A and B) support petrographic study and show evidence that the studied rocks are from two different granitoid bodies. The granitoids studied by Ismail et al. (2020) are clearly separated into two groups in all diagrams mentioned by Mohammad et al. (2020). Their assumptions on the origin and geochemistry of the granitoids have not been supported by any geochemical analysis and petrographic study.

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https://doi.org/10.1016/j.lithos.2021.106055

Please cite this article as: S.A. Ismail, R.I. Koshnaw, D.E. Barber, et al., Multi-stage magmatic activity in the Neotethyan ophiolite of Penjween: Reply on comments on "Generat..., Lithos, https://doi.org/10.1016/j.lithos.2021.106055

Table 1
Coordinate of granitoid intrusion samples within the Penjween ophiolite complex.

Locations	Sample name	Longitude	Latitude
One	Bb 8	35° 32′ 48″	45° 59′ 05″
	Bb 9		
Two	AA2	35° 32′ 49.6″	45° 59′ 06.5″
Three	Pnj6	35° 32′ 40.5″	45° 58′ 55.8″
	PnjBB2		
Four	Ai 10	35° 35′ 16.8″	45° 58′ 18.8″
	Ai 11		

4. Zircon data, age estimates and geodynamic evolution of the Arabia-Eurasia collision zone in the NW Zagros

The Th/U ratios in magmatic zircons commonly vary between 0.1 and 1, depending on the magma sources, chemistry, and formation temperature (Belousova et al., 2002; Castiñeiras et al., 2010). The Th/U ratios tend to decrease with decreasing zircon crystallization temperature (Castiñeiras et al., 2010) with several exceptions (Kirkland et al., 2015). Although both types of granitoid intrusions from the POC have Th/U ratios of <0.4, they are interpreted to have a magmatic origin. The low Th/U ratios in the studied zircons are due to low zircon formation temperatures (section 5.4). The average apparent Ti-in-zircon temperatures are 599.25 °C and 651.4 °C for pegmatitic granites and trondhjemites respectively. Additionally, there are several lines of evidence that support the magmatic and none metamorphic origin of the studied granitoids: (1) there are no petrographic indications for any metamorphism in the granitoid intrusion samples as indicated by thinsection studies. (2) Rare earth element chemistry of zircon has been used as a provenance indicator (Belousova et al., 2002; Hoskin and Ireland, 2000; Hoskin and Schaltegger, 2003). Zircons from both granitoids show positive Ce anomalies and negative Eu anomalies, and enrichments in heavy rare earth elements reflected in their steep MREE–HREE patterns (Fig. 7A, B), indicates that these zircons are igneous in origin based on Hoskin and Ireland (2000), Williams et al. (1996), Schaltegger et al. (1999), Rubatto (2002), Belousova et al. (2006), and Yusuke Sawaki et al. (2017). Most of the metamorphically grown zircons display consistent REE patterns with flat HREE patterns, unlike the trend of the studied granitoids (Chen et al., 2010); (3) The metamorphically grown zircons are distinguished from the magmatic zircons by their low $(Lu/Gd)_N$ values, which are commonly below 10 (Chen et al., 2010 and the references therein). Zircons from the Penjween granitoid intrusions have very high $(Lu/Gd)_N$ values of 89 for granite pegmatite and 71 for trondhjemite as displayed in Table 3 of Ismail et al. (2020); (4) The dotted lines in Ta versus Nb and Ta versus Yb/Sm discrimination diagrams of Sawaki et al. (2017) represent possible boundaries between zircons of M-type granites and the other types. The M-type granite refers to a granite that was probably generated by partial melting of subducted crust or overlying mantle (Whalen, 1985) and there is no reference for metamorphic origin;

The latest Oligocene-earliest Miocene exhumation ages of the granitiod intrusions are based on zircon (U-Th)/(He-Pb) double dating, which is a method that combines (U-Th)/He and U/Pb dating on a single-grain zircon (Reiners et al., 2005). During the Late Cretaceous ophiolite obduction, zircon from the Late Cretaceous granitoid intrusion has not been reset possibly because the entire ophiolite body has not been exhumed altogether, or parts of the body may not have been emplaced. A travers along the strike of the suture zone in Iraq and Iran shows that ophiolite bodies have been emplaced separately on rocks of different ages (Ali et al., 2012; Ali et al., 2014; Koshnaw et al., 2017). After the Late Cretaceous ophiolite obduction, segments of the ophiolite body might have been undergone burial and reheating due to over thrusting by younger thrust sheets and then exhumed due to out-of-sequence thrusting (Ali et al., 2014). The above-mentioned scenario is in accordance with the Late Cretaceous ophiolite obduction and explains exhumation after crystallization as mentioned by Ismail et al. (2020). Interpretation of the ~23 Ma zircon (U-Th)/He age as a direct result of the Late Cretaceous ophiolite obduction, as proposed by Mohammad et al. (2020), is erroneous. Exhumation age depends on the amount of the ^{4}H accumulation in the crystal lattice that results from the U, Th, and Sm decay, which can be transformed to the time since a rock sample cooled below the closure temperature (Farley, 2002; Reiners, 2005). Therefore, the ~23 Ma zircon (U-Th)/He age from Ismail et al. (2020) cannot be related to the early stage of the ophiolite obduction that took place during the Late Cretaceous.

In conclusion we confirm that the studied rocks and zircons by Ismail et al. (2020) are of magmatic origin with different crystallization ages (Late Cretaceous and middle Eocene), and have comparable exhumation ages (latest Oligocene-earliest Miocene), representing multiple magmatic and tectonic events.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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