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Research Article

Reply to the comment on Zafar et al., 2020: "Petrogenesis, platinum-group element geochemistry and geodynamic evolution of Cretaceous Chilas gabbros, Kohistan island arc, NE Pakistan" by Hussain et al., 2021

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We welcome the comment by Hussain et al. (2021) on our paper published in Lithos "Petrogenesis, platinum-group element geochemistry and geodynamic evolution of the Cretaceous Chilas gabbros, Kohistan island arc, NE Pakistan, Lithos 372-373, 105691". The above authors raised several issues in our paper which they argue to contradict the previously proposed interpretations such as "(1) genesis of Chilas complex of the Kohistan arc through diapirism or rift-related magmatism and (2) the timing of the collision of the Indian continental plate with Kohistan island arc". The above authors argued that the formation of gabbroic rocks of the Chilas complex due to the northward subduction of the Indian plate beneath the Eurasian plate around 85 Ma as mature arc-type magmatism in the Neo-Tethys Ocean is contradictory and against the general consensus of the previously published papers by several authors (Burg et al., 2006; Jagoutz et al., 2006; Jagoutz et al., 2007; Jagoutz et al., 2009; Khan et al., 1993; Schaltegger et al., 2002) which have reported the existence of the thousands of km thick Kohistan-Ladakh Island Arc (KLA) system and the Neo-Tethys Ocean between the Indian and Eurasian plates. Hussain et al. (2021) also argued that the model proposed by Zafar et al. (2020) precludes the possibility for such subduction and direct collision in the northern territory of Pakistan. It is interesting that the above authors interpret the geochemical data presented by Zafar et al. (2020) in favor of a back-arc basin (BAB) origin for the Chilas complex gabbros. Based on the above postulations, Hussain et al. (2021) interpreted that geochemical signatures presented in Zafar et al. (2020) support the previously proposed back-arc basin origin and tectonic setting for the Chilas complex. Additionally, Hussain et al. (2021) suggested a thorough investigation and reappraisal of the data and interpretations of Zafar et al. (2020). Hussain et al. (2021) claimed that these new data and results are contrary to the previously proposed and generally accepted concepts for the genesis of the Chilas complex and the collision of the Kohistan arc with Indian and Eurasian plates. We are pleased to clarify and explain the arguments raised by Hussain et al. (2021). Moreover, we also suggest the above authors to reread the literature carefully before raising such questions, especially their comment "The irrefutable evidence for the existence of the thousands of km thick Kohistan-Ladakh Island Arc (KLA) system and the Neo-Tethys Ocean between the Indian and Eurasian plates preclude the possibility for such subduction and direct collision in

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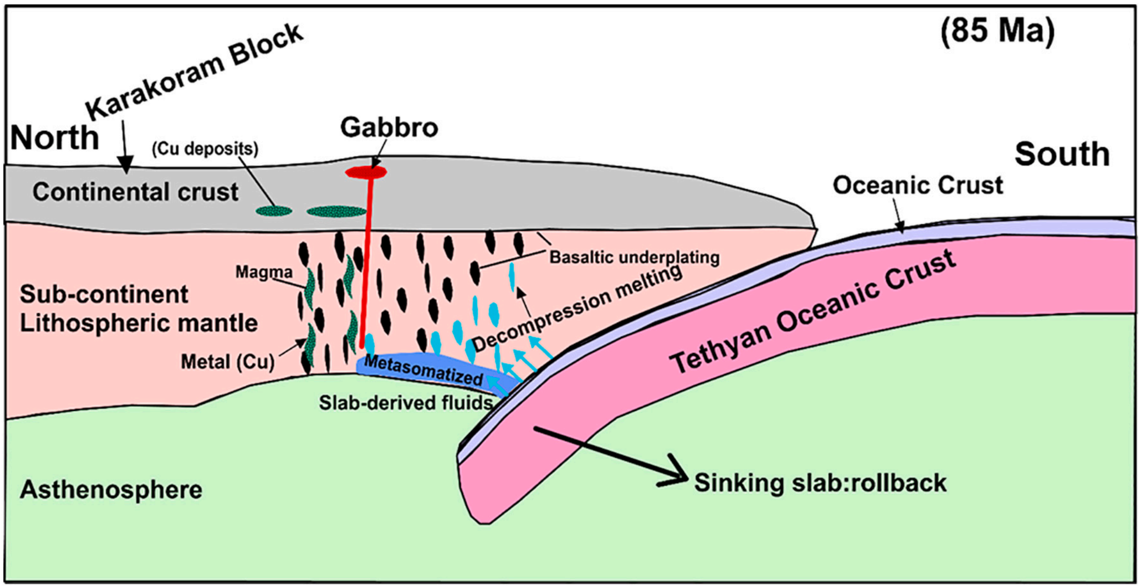

Fig. 1. Tectonic model indicating the tectonic evolution of 85 Ma Chilas gabbros from the Kohistan Arc.

the northern territory of Pakistan". We believe their claim refutable and illogical because it is unlikely that thousands of km thickness of arc system exist.

Below is our response to their specific comments.

1. Clarification on the tectonic model

Hussain et al. (2021) argued the tectonic model presented in Zafar et al. (2020) for the Chilas complex gabbros of the Kohistan arc due to its contradiction with the previously published tectonic models for the sequence of collisional events of the KIA with the Indian and Eurasian plates. Although, Hussain et al. (2021) had no serious issues with the data presented but they argued on the timing of collision of the KIA and subduction initiation of the Indian plate lithosphere presented in Zafar et al. (2020). Indeed, Zafar et al. (2020) reported in Section 6 "Geodynamic implications", the subduction initiation of the Indian plate beneath the Eurasian plate around 85 Ma that led to the activation of arc magmatism within the Neo-Tethys Ocean to form the Chilas gabbros in collisional or post-collisional settings. Moreover, Hussain et al. (2021) raised points regarding the magma source that formed the Chilas gabbros i.e., depleted mantle source for one and a metasomatized lithospheric mantle source for another dataset, indicating the oceanic crust (Tethys Ocean) subduction for the former set and the post-collision setting for the latter. The above authors favoured the previously published models that agreed with the timings of collision of the KIA with Eurasian plate around 102–75 Ma, and with Indian plate around 55–55 Ma (taking the advantage from the published literature, e.g., Burg, 2011; Bouilhol et al., 2013; Jagoutz et al., 2018). We agree with their pointing out that KLA was formed as an intra-oceanic arc well-before the Indian plate collision with it, hence their suggestion is well taken. However, it is well-known that Neo-Tethys oceanic crust existed between the Indian and Eurasian plates. We want to clarify, here, that by mentioning the formation of Chilas gabbros around 85 Ma in a subduction environment we meant for the part of the Tethys Oceanic crust that existed to the north of the Indian plate continental crust which subducted beneath the Eurasian plate and facilitated to the formation of KIA. We understand that the Indian plate continental crust subduction associated with the ultrahigh-pressure eclogite-facies, coesite-bearing, metamorphism (e.g., Kaneko et al., 2003; O'Brien et al., 2001; Rehman et al., 2011; Rehman et al., 2016 and references therein) took place around Eocene (ca. 50–46 Ma) and also evidenced from the northward drift of the Indian plate, based on paleomagnetic records (Klootwijk et al., 1992). The paleomagnetic data and UHP event are clear manifestations of subduction of the Neo-Tethys and leading-edge of the Indian plate lithosphere subduction prior to 55 Ma.

Hussain et al. (2021) argued the proposal of suturing time of the Indian plate presented by Zafar et al. (2020) and showed that the Indian plate (in their Fig. 1) was located close to Madagascar at ca. 80 Ma, therefore, considered its subduction beneath the Eurasian plate by that time unrealistic. We, somehow, agree with their pointing of the position of the Indian plate, far away from the KIA by the 80 Ma time, however, the proposed tectonic model indicating the Neo-Tethys Oceanic crust subduction beneath the KIA at ca. 85 Ma (our new and modified Fig. 1) makes a complete sense and does not contradict the well-agreed subduction models of the India-KIA-Eurasia plates.

2. Evidences on the support of geochemical interpretations about subduction-related magmatism

Hussain et al. (2021) also argued regarding the data presented in Zafar et al. (2020). Based on bulk-rock geochemistry, Hussain et al. (2021) postulated that the Chilas gabbros are generated with significant contamination involvement under rift-related environment and their petrogenetic interpretations endorse a back-arc tectonic setting for these rocks although the reasons for back-arc basin (BAB) or extensions are equivocal. However, geochemical modeling of this study attributes the genesis of gabbros in a classic subduction zone environment based on the following lines of credible evidence:

It is widely accepted that subduction-related gabbroic rocks display negative anomalies of Nb, Zr, and Ti in contrast to those originated under BAB or rift settings (e.g., Bhat et al., 2019; Manikyamba et al., 2020; Ugarkar, 2017, and references therein). For example, the mafic rocks including the Mariana BAB associated with back-arc settings do not represent obvious negative anomalies of Zr, Ti, and Nb (e.g., Gao et al., 2019). Subduction-related mafic bodies are also represented by a relative deficiency in terms of HFSEs with respect to LREEs and LILEs (Bhat et al., 2019; Manikyamba et al., 2020; Meng et al., 2019; Ugarkar, 2017, and references therein). The studied gabbros display pronounced negative anomalies of Nb, Zr, and Ti, and also corroborated by their LREEs, LILEs enrichment in contrast to HFSEs, confirming their affinity towards subduction environment rather than a transition from arc to spreading regime as argued by Hussain et al. (2021). The negative Ti, Nb, and Zr anomalies revealed by the Chilas gabbros were most likely produced as a result of a combination of slab dehydration, and lower arc

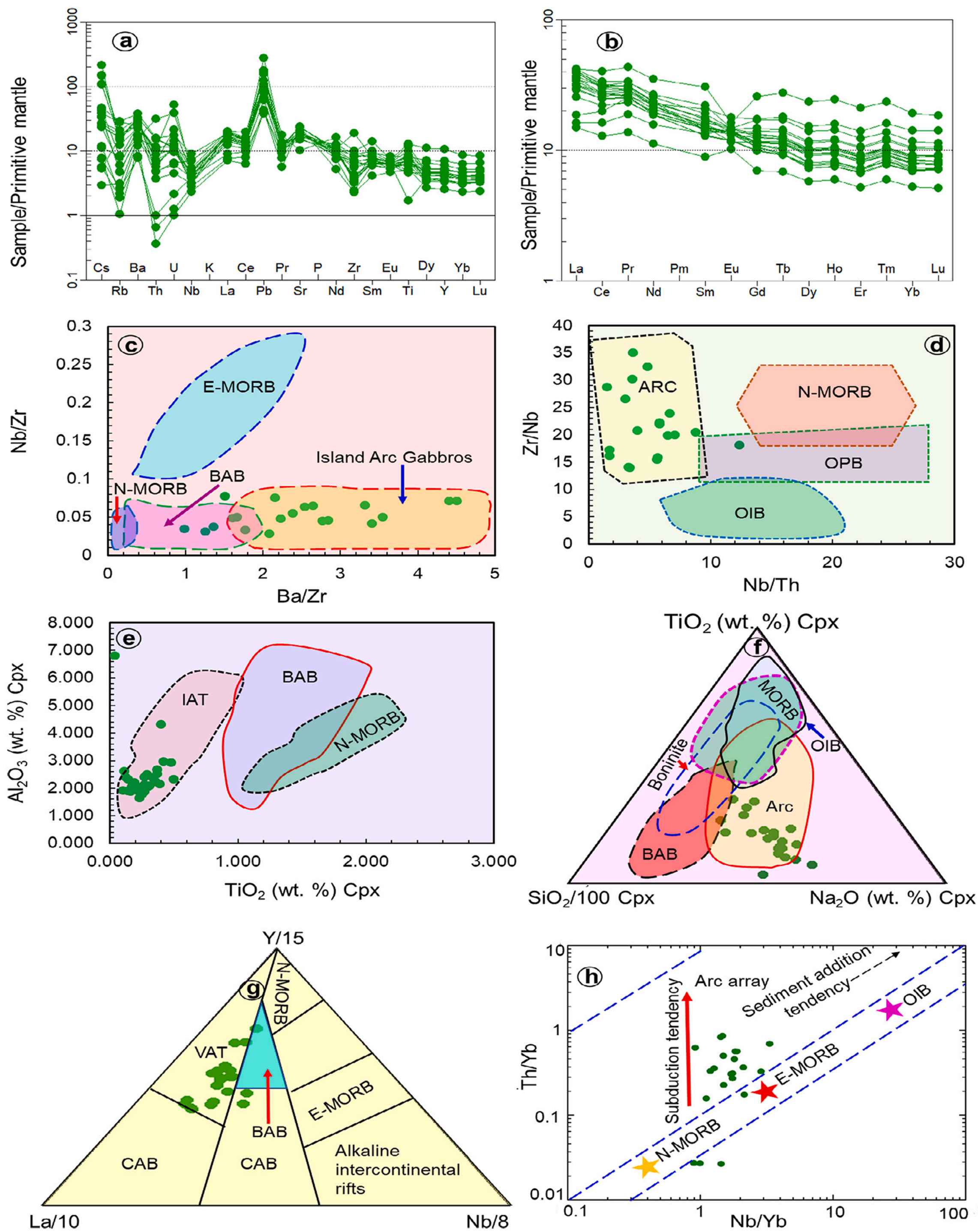

Fig. 2. (a-b) Primitive mantle-normalized trace element (Sun and McDonough, 1989) and chondrite-normalized REE patterns (Nakamura, 1974) of the Chilas gabbros; (c-d) Nb/Zr vs. Ba/Zr plot (Saccani et al., 2008) and Zr/Nb vs. Nb/Th (Condie, 2005) diagrams represent tectonic setting in arc environment; (e-f) Al_2O_3–TiO_2 plot of clinopyroxene (after Huot et al., 2002) and triangular plot TiO_2–Na_2O–SiO_2/100 (Beccaluva et al., 1989; Ovung et al., 2017) revealing the formation of gabbros in arc environment; (g) La–Y–Nb plot (Mogahed and Saad, 2020) also supporting tectonics of the Chilas gabbros in arc-related settings; (h) Th/Yb vs. Nb/Yb plot indicating subduction tendency within the samples of Chilas gabbros (Ali et al., 2013). Abbreviations: N-MORB = Normal Mid-Ocean Ridge Basalt; BAB = Back Arc Basin; OPB = Oceanic Plateau Basalts; OIB = Oceanic Island Basalts; IAT = Island Arc Tholeiite; *E*-MORB = Enriched Mid-Ocean Ridge Basalt; CAB = Calc-Alkaline Basalt; VAT = Volcanic Arc Tholeiite.

crust and slab fluid-hydrated sub-arc mantle wedge melting (Murphy, 2007; Pearce, 2008). This is caused by the fact that subduction is the most effective and common tool for producing negative anomalies of Nb Ti, and Zr (Murphy, 2007; Pearce, 2008). Primitive mantle-normalized and chondrite-normalized REE patterns of the studied subduction-related gabbros (Fig. 2a–b) are entirely different in contrast to mafic bodies of Mariana associated with the BAB environment (see Fig. 7c–d of Gao et al., 2019), thereby suggesting a consistent clue regarding the genesis of Chilas gabbros in subduction regime. There is a general consensus that a higher ratio of LILEs/HFSEs is a signal of subduction-related events (Brenan et al., 1994). This island arc signature is truly obvious with variable enrichment of LILEs followed by a nearly flat

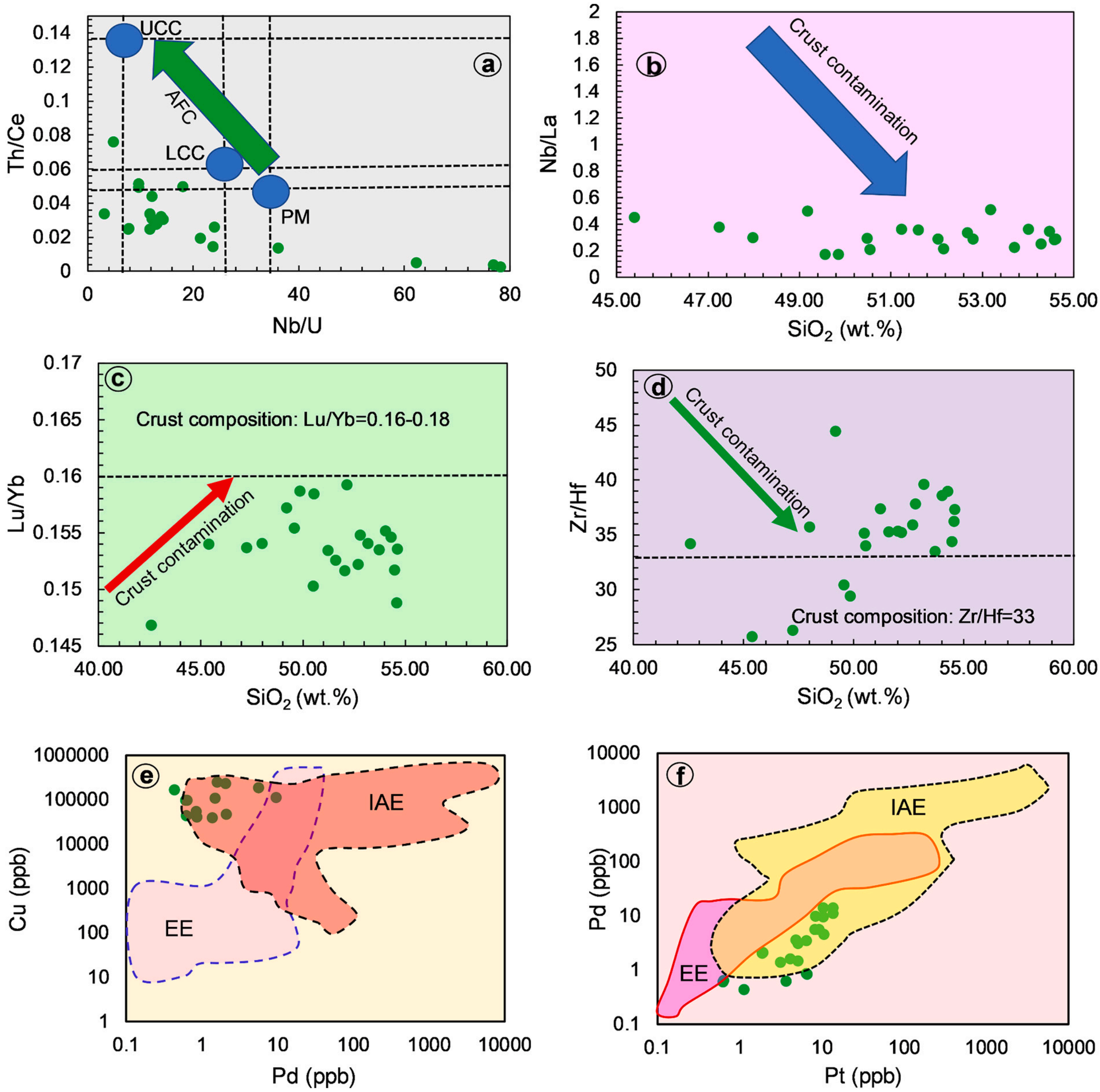

Fig. 3. (a-d) Crustal contamination discriminative plots indicating minimal contamination in the studied gabbros. Note: (a) UCC: upper continental crust from (Gao et al., 1998), PM: primitive mantle from (Sun and McDonough, 1989); LCC: lower continental crust (Rudnick and Gao, 2003); (c, d) Crust compositions are from Rudnick and Gao (2003); (e-f) Plots of Pt, Pd and Cu displaying higher Pt and Pd contents and genesis of Chilas samples in island arc environment (IAE) instead of the extensional environment (EE) (fields after Wang et al., 2020).

pattern (Fig. 2a–b). The fairly flat patterns of Chilas gabbros are also promising to their subduction-related origin. Some scholars have argued that the transitional nature of gabbroic rocks between IAB and MORB is suggestive of their generation in suprasubduction extensional regimes, that is, back-arc basin (e.g., Pearce et al., 1995). In contrast, gabbroic rocks of the Chilas complex do not indicate any transitional signatures between IAB and MORB (Fig. 2) therefore, discarding their generation in the back-arc basin. Relatively low contents of Ti, Ni, Co, and the range of Fe_2O_3 (7–15 wt%) (see Tables 1–2 of Zafar et al., 2020) suggest consistent facts in favor of their subduction-related origin (Manikyamba et al., 2020).

Although, as pointed out by Li et al. (2015), the use of discrimination diagrams in geological settings is tricky and not simple, sample selection and internal heterogeneity cause the data to plot in different fields in the commonly used discriminatory diagrams. We assume this can be the case with data used by Hussain et al. (2021) and that of ours. However, if the majority of diagrams show consistent results, the interpretations are considered authentic and geologically meaningful. We plot the data on several other binary geochemical diagrams that provide reliable and solid clues for the Chilas gabbroic rocks to depart from the BAB or rift settings and largely reveal affinity towards subduction signatures/arc magmatism (Fig. 2c–d). Apart from the whole-rock data, the chemical composition of clinopyroxene also plots on binary and triangular representation supports an association of Chilas gabbros in arc-related affinity (data from Bilqees et al., 2016; Takahashi et al., 2007; Khan, 1989; Fig. 2e–f). The same geochemical signatures are also noticeable in data presented by Zafar et al. (2020) (triangular plot shown in Fig. 2g). Likewise, the geochemical fingerprints in Fig. 2h also favor subduction-related signatures. In addition, contamination during the magmatic evolution of Chilas rocks indicates an insignificant character as evidenced in Fig. 3a–d. The Lu/Yb ratios are 0.14–0.15 and Zr/Hf ratios are 25–44, which are dissimilar to the crustal Lu/Yb value of 0.16–0.18 and

Zr/Hf value of 33, indicating insignificant contamination (Fig. 3c–d). In nutshell, the geochemical signatures do not favor the formation in rift or back-arc spreading but support their genesis in subduction-related magmatism with insignificant contamination.

3. Clues from platinum group elements (PGEs) geochemistry

Hussain et al. (2021) argued that the rifting in BAB has led to changes in the Sr-Nd-Hf isotopic composition. Based on old isotopic data, they claim that the Chilas gabbros show Sr-Nd-Hf isotopic compositions that exclude any contribution of the subduction-related magmatism in their genesis. Interestingly, these authors suggest that the geochemical and petrological information do not support the genesis of the Chilas gabbros in subduction-related magmatism but favor their generation in back-arc spreading. However, we want to clarify here that the new PGEs data and its geochemical modeling supports new insights towards the origin of Chilas gabbros in a typical subduction-related tectonic regime and island arc environment based on the following consistent facts:

The Pd contents (0.43–13.87 ppb) and Pd/Ir ratios (0.76–40.04, exceptions of two samples) are relatively high compared to the values of Pt (0.63–13.75 ppb) and Pt/Pd (0.76–7.89) in the majority of the samples (see Table 3 of Zafar et al., 2020 for PGEs data). These signatures suggest the participation of PGEs from the slab-dehydrated fluids and point out hydrous melting of depleted mantle wedge under high-fluid pressure and temperatures in subduction regimes reflecting association with subduction episodes (Saha et al., 2018). The relative and noticeable enrichment of PPGE over IPGE in some enriched samples (typical enrichments of Pd comparative to Pt) of the Chilas gabbros advocates multi-stage petrogenetic processes attested by the involvement of fluids, and mantle metasomatism during the subduction process (Saha et al., 2018). The higher Pd contents in the Chilas samples corroborate subduction influx into the mantle source of the Chilas gabbros (Saha et al., 2018). The Pd/Pt ratios (0.12–1.31) are considerably higher compared to the average Pd/Pt ratios of the mantle (0.57), thereby verifying to PGEs depletion in the parental magma. The most promising cause of PGE depletions in the Chilas gabbros can be attributed to PGE-depleted mantle source during the subduction process (Song et al., 2016). The Cu/Pd ratios of Chilas rocks (11–3161) in combination with the distinction of Pd (0.43 ppb–13.87 ppb) over Pt (0.63 ppb–13.75 ppb) can be endorsed to the influx of subduction-derived fluids into the mantle wedge and generation of magma under S-undersaturated circumstances of subduction regime. The S-undersaturation with fairly low contents of Ti in Chilas gabbros points out the generation of its parental magma at a shallow level of the subduction events (Saha et al., 2015). Considering these signatures of PGEs, we can conclude that the petrogenesis of the PGEs-bearing Chilas gabbros reflects their association with subduction episodes rather than extensional or back-arc events. None of the previous studies have looked into the PGEs role for the Chilas gabbros, hence, their interpretations were based on mainly major and trace element concentrations or ratios. As we know, major and trace elements may yield unrealistic results that affect the interpretations due to alteration and secondary geochemical signatures, therefore, the interpreted immobile REEs and PGEs of this study serve as strong tools to provide meaningful information.

It is widely accepted that the mafic rocks are usually developed under different tectonic environments, for example, Island arc, Intra-continent, Mid-ocean ridge, Ocean island, and Back-arc basin. Hence, geochemical modeling based on PGEs systematics such as Pt and Pd along with chalcophile Cu is necessary to distinguish the tectonic regimes in which the gabbroic rocks form. Here we plot our data of PGEs and Cu on the most recent tectonic discrimination schemes (Wang et al., 2020) with the aim to further testify tectonic signatures of the Chilas gabbros. The Pd vs. Cu plotting enhances our justification for the arc affinity (Fig. 3e). Likewise, in Pd vs. Pt tectonic discrimination plot (Fig. 3f), the Chilas gabbros fall in the domain of island arc environment supporting for the arc or subduction-related magmatism rather than the rift-related or extensional setting. In addition, recent studies suggested that the samples from the island arc environment indicate higher Pt and Pd contents in contrast to those from the extensional environments (e.g., Wang et al., 2020). Similarly, plotted samples of the studied gabbros express relatively higher Pt and Pd contents (Fig. 3e–f), suggesting their generation in the island arc regime.

In summary, clues based on regional and global tectonics coupled with mineral chemistry data, whole-rock trace, and PGEs data do not support the tectonic and petrogenetic interpretations proposed by previous researches and Hussain et al. (2021). Therefore, we do not need to agree with the past publications including that of Hussain et al. (2021), because, new data provide new insights so that we can better understand the tectonic settings that were not understood before.

Declaration of Competing Interest

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

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