Received: 11 June 2020 | Revised: 7 July 2020 | Accepted: 17 July 2020

DOI: 10.1111/ter.12489

REPLY TO COMMENT

Terra Nova WILEY

Reply to comment on "Jurassic igneous rocks of the central Sanandaj–Sirjan zone (Iran) mark a propagating continental rift, not a magmatic arc (Azizi and Stern, Terra Nova, 31(5), 415–423, 2019)"

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We thank Elahi-Janatmakan, Maghdour-Mashhour, and Shabani (in press) for their interest in our (Azizi & Stern, 2019) reinterpretation of Jurassic igneous rocks of the central Sanandaj–Sirjan zone (SaSZ) of Iran. In a nutshell, Elahi-Janatmakan et al. (in press) embrace the orthodox interpretation that these rocks represent a continental arc and reject our new interpretation that these formed in a rift. Their criticism provides a good opportunity for us to further explain our arguments and to address the problem that lies at the root of their concern: the misinterpretation of trace element data as being reliable indicators of the tectonic setting in which melts are generated. We completely agree with their closing comments: "This study may also be regarded as a wake-up call for our research community. We should be aware that extreme caution should be exercised in the interpretations of the geochemical diagrams for distinguishing between subduction-contamination basalts and plume-derived basalts that are contaminated with continental crust or subcontinental lithosphere." We agree whole-heartedly that any interpretations should also be based on lines of evidence beyond plotting a few trace elements on diagrams. Our study is built on such a firm foundation; their criticism and embrace of the orthodox interpretation of SaSZ as a continental arc is based entirely on trace element and isotopic data. In rebuttal to the criticism of Elahi-Janatmakan et al. (in press), we make the following five points which support our model and refute the continental arc model.

1. Time–space relationships of the igneous rocks are inconsistent with a magmatic arc interpretation. Magmatism in the central SaSZ migrated NW systematically from 177 to 144 Ma. Modern U-Pb zircon ages on plutonic rocks show this irrefutably. Such migration of magmatism is seen for within plate magmatism, not convergent margin magmatism. Yes, there are arc segments that are not active, for example the magmatic gap between the Northern and Central Volcanic Belts in the Andes, but we know of no modern convergent margin magmatic arc where the locus of igneous activity systematically migrates in one direction. Such migration is seen for mantle hotspots, like the Columbia River-Snake River Plain-Yellowstone hotspot track in the NW USA, and may also be expected to occur near the tip of propagating continental rifts and backarc basins. This is the key observation that motivated our reinterpretation. We are very surprised that Elahi-Janatmakan et al. (in press) do not acknowledge this key observation, much less address it.
2. After all other possible explanations are considered, only a NW-propagating continental rift can explain the systematic migration of Jurassic igneous activity in the central SaSZ. Presence of Cadomian (~550 Ma) crust like that to the north indicates SaSZ formed on the margin of Iran, not out in Tethys to the south. Central SaSZ magmas cannot have formed in a backarc basin, as Elahi-Janatmakan et al. (in press) suggest, unless the ~300 km wide arc and forearc that are required by this interpretation to have existed south of the SaSZ were completely removed. There is no evidence that these key tectonic elements ever existed. If magmatic migration did not occur in a propagating backarc basin, it must represent the track of a mantle plume or a propagating continental rift. Jurassic Iran was welded to Eurasia and moved with it. Because magmatism migrated NW more rapidly than a

large continent like Jurassic Eurasia is likely to have moved (17–20 mm/year vs. perhaps a few mm/year), we excluded the fixed mantle plume possibility. With elimination of the backarc basin and the mantle plume hypotheses, only the interpretation of a propagating continental rift remains. Interpretation of a propagating continental rift must be closer to the truth than explanations of continental arc, backarc basin or mantle plume.

3. Trace element and isotopic compositions of central SaSZ igneous rocks reflect complex processes of mantle source heterogeneity, fractionation, and interaction with continental crust and sediments. Because of this complexity, using trace elements and tectonic discrimination diagrams to infer the tectonic setting in which these melts formed is fraught with uncertainty. We can say that felsic rocks provide more information about crustal contamination, whereas mafic rocks reveal more about mantle source heterogeneity, although even though many mafic magmas experienced significant interaction with crust and sedimentary rocks. Because continental crust and sediments have trace element concentrations similar to arcs (e.g. Nb-Ta depletions and Th enrichment), felsic igneous rocks that form in any tectonic environment and assimilate significant continental crust and sediments will tend to look like convergent margin igneous rocks (Förster, Tischendorf, & Trumbull, 1997). We think it unwise to only use trace elements and tectonic discrimination diagrams to infer the tectonic setting of such rocks. In contrast, mafic igneous rocks have experienced less interaction with crust and sediments. Application of trace elements and tectonic discrimination diagrams to infer the tectonic setting provide more reliable results than do felsic rocks.

3a. Central SaSZ felsic igneous rocks show strong crustal input, making trace elements unreliable indicators of tectonic setting. Most granitic rocks in the central SaSZ are S-type or mixed I-S type, showing a large contribution from sediments. Many are rich in garnet and aluminosilicates and are peraluminous (figure 3c in Azizi & Stern, 2019). Many plutons are surrounded by broad zones of high temperature metamorphic rocks and some are associated with migmatite. Radiogenic isotopes also reveal strong input of partial melts of crust and sediments. Initial $^{87}Sr/^{86}Sr$ for these rocks is high and variable (0.710–0.715 or greater). The $\varepsilon_{Nd(t)}$ of central SaSZ granites is as low as −6, again supporting significant crust and/or sediment inputs.

3b. Mafic igneous rocks better preserve information about their mantle sources, although some of these are also contaminated by crust and sediments. As shown in Azizi and Stern (figure 6), mafic rocks are generally more mantle-like (lower initial $^{87}Sr/^{86}Sr$, higher $\varepsilon_{Nd(t)}$) than felsic rocks (higher initial $^{87}Sr/^{86}Sr$, lower $\varepsilon_{Nd(t)}$). This is exactly what is expected when mantle-derived mafic magmas melt older crust—such as ~550 Ma crust of Iran—and derived sediments and undergo coupled assimilation-fractional crystallization to produce felsic melts (DePaolo, 1981). Mafic igneous rocks show mixed intra-plate (OIB) and or arc affinities (Azizi & Stern, 2019; figure 3b). We agree with Elahi-Janatmakan et al. (in press) that central SaSZ mafic rocks represent partial melts of subcontinental lithospheric mantle. We also agree that trace elements do not clearly point to a single tectonic setting, scattering between arc, backarc and OIB fields on tectonic discrimination diagrams. We disagree with Elahi-Janatmakan et al. (in press) that the scatter shown on the Th/Nb versus Nb/Yb diagram "…clearly reflects the influence of subduction components…" Yes, sediment involvement is indicated but this could reflect upper plate contamination, not subduction inputs. We disagree with Elahi-Janatmakan et al. (in press) that about the significance of no clear curvilinear trends on this diagram; such scatter is to be expected in nature and does not preclude a role for crustal contamination. Finally, we note that mafic igneous rocks do not show the deep, negative Nb, Ta and Ti anomalies on spider diagrams that are diagnostic of convergent margin mafic magmas, although there are some minor trace element similarities to arc magmas such as positive LILE and Pb anomalies. The weak convergent margin trace element signature in central SaSZ mafic rocks probably reflects two inputs: (1) modest contamination by continental crust and sediments and (2) fossil metasomatism of mantle beneath the SaSZ associated with formation of Cadomian (~550 Ma) crust of Iran at a convergent plate margin (Shafaii Moghadam et al., 2020).

4. There is independent evidence for Jurassic rifting in the SaSZ: (a) great thicknesses of Jurassic marble, metachert and metabasalt with pillow structures in the Ghalaylan and Panjeh area (figure 3 in Azizi et al., in press) and figure 4 in Azizi et al., 2018). (b) Development of syn-sediment extensional structures (Stefano et al., 2018) and (c) development of a rift basin in the Jaz-Murian area in the S-SaSZ (Hunziker et al., 2015). Further efforts by sedimentologists and structural geologists are needed to reconstruct the evolution of the SaSZ Jurassic—Early Cretaceous basin which can constrain is subsidence and tectonic history.

5. There is no arc-like mineralization associated with central SaSZ, for example porphyry copper or orogenic gold deposits. The lack of arc-like mineralization in the central SaSZ igneous province is consistent with our rifting model but is very difficult to explain for those who prefer to interpret Jurassic SaSZ igneous activity as having occurred at a convergent plate margin, like Elahi-Janatmakan et al. (in press).

We believe that our model represents a turning point for geologic studies of Iran. It is built on integrating field observations with geochronologic and geochemical results. It explains strong evidence that mantle-derived mafic magmas interacted with older crust and sedimentary rocks to generate felsic magmas. Our effort is not only useful for understanding the SaSZ but it also shows that the most useful geodynamic models should not be based on a single igneous body or a handful of trace elements or any single data set; instead, we should assemble and consider all of the evidence for the larger system in the effort to accurately understand it. Our model challenges all of us, but especially Iranian geoscientists, to rethink old ideas for the SaSZ and other geologic problems. If we want to understand the fascinating and complex geologic evolution of Iran, we have to read this "book of rocks" thoughtfully and discuss it thoroughly. We thank Elahi-Janatmakan et al. (in press) for advancing this discussion.

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How to cite this article: Azizi H, Stern RJ. Reply to comment on “Jurassic igneous rocks of the central Sanandaj–Sirjan zone (Iran) mark a propagating continental rift, not a magmatic arc (Azizi and Stern, Terra Nova, 31(5), 415–423, 2019)”. *Terra Nova*. 2020;32:473–475. https://doi.org/10.1111/ter.12489