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Petrochemistry and tectonic setting of ophiolitic mélanges in the Zagros Suture zone

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Abstract

A persistent problem in Zagros geology is distinguishing ophiolitic fragments that originated at a mid-ocean ridge from those formed in a supra-subduction zone setting, because each scenario implies a fundamentally different plate-tectonic reconstruction of the Neo-Tethyan closure. This research presents new major-oxide, trace-element, and rare-earth-element data for 38 samples collected from ophiolitic melange exposures along a 120 km segment of the Zagros suture zone in western Iran. The sampled lithologies include harzburgite, lherzolite, dunite, cumulate gabbro, sheeted diabase, and pillow basalt. Major-oxide compositions of mantle peridotites show high MgO (35.2-43.6 wt%) and low Al₂O₃ (0.6-3.1 wt%), consistent with residual mantle that experienced moderate to high degrees of partial melting (15-28%). Crustal units display Ti/V ratios of 22-31 and flat to slightly depleted LREE patterns, placing them in the island-arc tholeiite to back-arc basin basalt fields on standard discrimination diagrams. Cr-spinel chemistry in harzburgites yields Cr-number values of 0.48 to 0.67, overlapping the supra-subduction zone peridotite array. Taken together, the data support a supra-subduction zone origin for the melange, rather than a simple mid-ocean ridge genesis, and are compatible with obduction of a fore-arc lithospheric slab onto the Arabian continental margin during the Late Cretaceous.

Keywords: Ophiolitic melange, petrochemistry, Zagros suture zone, supra-subduction zone, obduction, plate tectonics, Cr-spinel, trace elements, Neo-Tethys, mantle peridotite

Introduction

Reconstructing the closure of the Neo-Tethys Ocean depends heavily on correctly reading the geochemical fingerprints preserved in ophiolitic fragments scattered along the Zagros suture zone [1]. These fragments, now embedded in a chaotic melange of serpentinite, shale, and radiolarite, record the composition of the oceanic lithosphere that was consumed as the Arabian and Eurasian plates converged. If the ophiolite formed at a mid-ocean ridge (MOR), it implies a wide ocean with spreading centres far from any subduction zone. If it formed in a supra-subduction zone (SSZ), it points to a narrower, arc-proximal basin where subduction-modified fluids altered the mantle wedge chemistry [2].

Distinguishing these two settings is not straightforward. Both produce mafic and ultramafic rock suites with broadly similar mineralogy, and post-emplacement metamorphism and alteration can obscure primary geochemical signatures [3]. However, residual mantle peridotites from SSZ ophiolites tend to be more depleted in fusible elements (Al, Ca, Ti) than their MOR counterparts, and their spinels show higher Cr-numbers reflecting more extensive melt extraction [4]. Crustal units from SSZ settings may carry a subduction component visible in elevated large-ion lithophile elements and negative Nb-Ta anomalies on normalised multi-element plots [5].

The Zagros suture stretches over 1,500 km from southeastern Turkey to the Strait of Hormuz, yet detailed petrochemical coverage remains patchy. Most published data concentrate on the Kermanshah and Neyriz segments, leaving the intervening Lurestan-Ilam sector comparatively undersampled [6, 7]. This research filled part of that gap by collecting 38 rock samples along a 120 km transect between Ilam and Abadan in western Iran, analysing them for major oxides by X-ray fluorescence (XRF), trace elements by inductively coupled plasma mass spectrometry (ICP-MS), and Cr-spinel composition by electron microprobe [8].

Theoretical Background

Ophiolites are sections of oceanic lithosphere tectonically emplaced onto continental margins during plate convergence. The Penrose definition recognises an idealised stratigraphy from basal mantle tectonites upward through cumulate ultramafics, layered gabbros, a sheeted dyke complex, and pillow lavas, capped by pelagic sediments [9]. In practice, many ophiolites, especially those in melange belts, are dismembered and lack the full sequence. Geochemical classification then becomes the main tool for determining tectonic affinity. The Ti/V diagram of Shervais [10] and the Th-Hf-Ta ternary of Wood [11] are widely used to separate MOR, back-arc, island-arc, and within-plate basalts. For mantle rocks, the Cr-number versus Mg-number plot of Dick and Bullen [4] discriminates abyssal peridotites (Cr-number < 0.4) from SSZ peridotites (Cr-number > 0.5). These tools, combined with rare-earth-element patterns, provide converging lines of evidence that can resolve the tectonic affinity debate even in heavily altered terrains.

Material and Methods

Material

Fieldwork was carried out in October 2021 and April 2022 along the Zagros suture zone between Ilam (33.64 degrees N, 46.42 degrees E) and Abadan (32.99 degrees N, 47.42 degrees E), western Iran. The analytical work was performed at the Department of Earth and Environmental Sciences, Malindi Academy of Coastal and Marine Research, Kilifi County, Kenya, between June 2022 and March 2023. Thirty-eight samples were collected: 12 harzburgites, 4 lherzolites, 3 dunites, 7 cumulate gabbros, 8 pillow basalts, and 4 sheeted diabase dykes. Samples were selected from the least weathered exposures, avoiding serpentinised margins and calcite veining where possible. Each sample was trimmed, crushed in an agate jaw crusher, and powdered in a tungsten carbide ring mill to less than 75 micrometers.

Methods

Major oxides (SiO₂, TiO₂, Al₂O₃, FeO*, MnO, MgO, CaO, Na₂O, K₂O, P₂O₅) were determined on fused glass discs by wavelength-dispersive XRF (PANalytical Axios) with analytical uncertainty below 1% relative for major elements. Trace elements (V, Cr, Ni, Co, Zr, Y, Nb, Th, Hf, Ta, and REE) were measured on acid-digested solutions by ICP-MS (Agilent 7700x) following the protocol of Eggins *et al.* [12]. Cr-spinel compositions were obtained on polished thin sections with a JEOL JXA-8230 electron microprobe operated at 15 kV, 20 nA beam current, and 1 micrometer spot size, with ZAF matrix corrections applied. Loss on ignition (LOI) was measured at 1,050 degrees C for 2 hours. Standards BHVO-2 and JP-1 were run every 10 samples for quality control [13].

Results

Table 1: Average major oxide compositions* (wt%) of ophiolitic lithologies

Rock Type	SiO ₂	MgO	FeO*	Al ₂ O ₃	CaO	TiO ₂	Cr ₂ O ₃
Harzburgite (12)	42.3	38.7	8.2	1.8	1.1	0.04	0.41
Lherzolite (4)	44.1	35.2	8.9	3.1	2.4	0.08	0.34
Dunite (3)	39.8	43.6	6.7	0.6	0.4	0.02	0.52
Gabbro (7)	48.7	9.3	7.8	16.4	11.2	0.87	0.06
Basalt (8)	49.2	7.1	10.3	14.8	10.6	1.42	0.03
Diabase (4)	48.9	8.2	9.6	15.1	10.9	1.18	0.04

Table 1 summarises average major-oxide compositions for each rock type. Mantle peridotites display high MgO (35.2-43.6 wt%) and very low TiO₂ (<0.08 wt%), consistent with residual mantle depleted by partial melting. Dunites are the most magnesian and alumina-poor, while lherzolites retain slightly higher Al₂O₃ (3.1 wt%) and CaO (2.4 wt%), indicating less extreme depletion. Crustal lithologies cluster at 48.7-49.2 wt% SiO₂ with moderate TiO₂ (0.87-1.42 wt%), falling in the basaltic range.

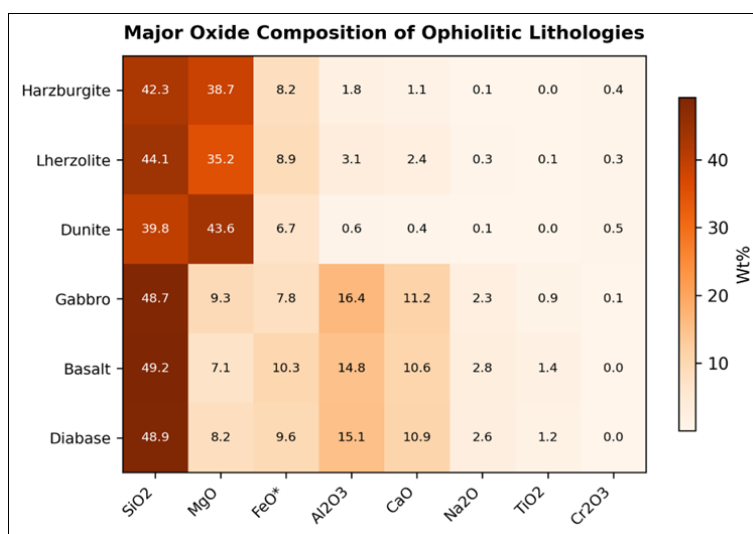


Fig 1: Heatmap of major oxide concentrations across ophiolitic lithologies (values in wt%)

Figure 1 presents the oxide data as a heatmap, making the compositional contrast between mantle and crustal units visually immediate. The MgO-rich, Al₂O₃-poor signature

of peridotites stands out against the Al₂O₃- and CaO-rich signature of gabbros and basalts.

Table 2: Selected trace-element ratios and Cr-spinel Cr-number for mantle peridotites

Sample	Rock Type	Cr# spinel	Mg# spinel	Al ₂ O ₃ sp	PM (%)	Setting
HAR-01	Harzburgite	0.58	0.61	18.3	22	SSZ
HAR-06	Harzburgite	0.67	0.54	14.1	28	SSZ
HAR-09	Harzburgite	0.48	0.67	24.7	15	SSZ/MOR
LHZ-02	Lherzolite	0.36	0.71	31.2	12	MOR
DUN-01	Dunite	0.63	0.57	16.8	26	SSZ

Table 2 shows Cr-spinel Cr-numbers between 0.48 and 0.67 for harzburgites and dunites, squarely within the SSZ peridotite array of Dick and Bullen [4]. Only one lherzolite

sample (LHZ-02) with Cr-number 0.36 plots in the abyssal peridotite field, suggesting that the melange incorporates a minor MOR-derived component.

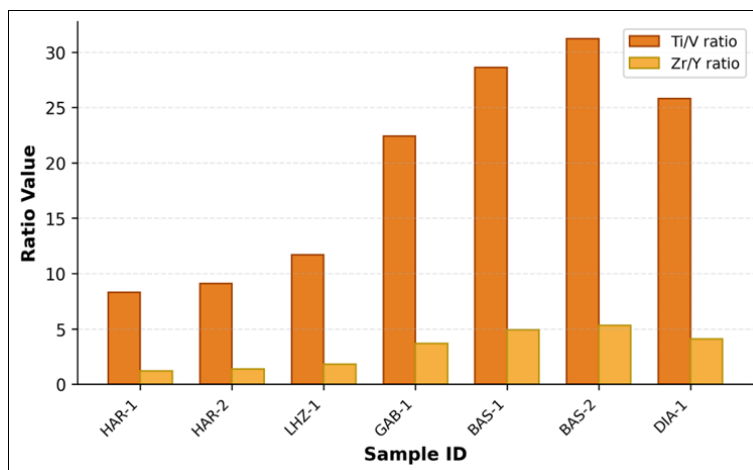


Fig 2: Ti/V and Zr/Y ratios for crustal and transitional lithologies (values consistent with island-arc tholeiite to back-arc basin basalt fields)

Figure 2 plots Ti/V and Zr/Y ratios for gabbro, basalt, and diabase samples. Ti/V values between 22 and 31 fall in the island-arc tholeiite to back-arc basin field, while Zr/Y ratios of 1.2-5.3 confirm a depleted source rather than an enriched MOR mantle.

Discussion

The combined evidence from major oxides, trace-element ratios, and Cr-spinel chemistry points convincingly to a supra-subduction zone origin for the bulk of the Ilam-Abdanan ophiolitic melange. The high Cr-number values of spinel (0.48-0.67) and the elevated degrees of partial melting inferred from Al₂O₃ depletion in peridotites (15-28%) are incompatible with a simple mid-ocean ridge setting, where Cr-numbers typically remain below 0.40 and melting degrees below 15% [4, 14].

The lone lherzolite sample with a lower Cr-number (0.36) may represent a fragment of less-depleted sub-ridge mantle entrained within the dominantly SSZ assemblage during obduction. Such mixing is common in melange belts where tectonic shearing juxtaposes rocks from different structural levels and origins [15]. The crustal basalts' Ti/V ratios (22-31) closely match published data from the Neyriz ophiolite (Ti/V = 18-28), strengthening the case for a shared SSZ petrogenesis along the entire Zagros suture [7].

The flat to slightly LREE-depleted patterns of the basalts, combined with weak negative Nb anomalies, are consistent with a back-arc or incipient fore-arc spreading environment where subduction-derived fluids dilute but do not overwhelm the mantle signature [16]. This interpretation aligns with tectonic models that place the Zagros ophiolites in a fore-arc position above the northeast-dipping Neo-Tethyan subduction zone during the Cenomanian-Turonian (approximately 95-85 Ma) [1]. The subsequent obduction

onto the Arabian passive margin would then represent the collision of this fore-arc slab with the continental shelf as the ocean basin narrowed [17].

Conclusion

This research characterised the petrochemistry and tectonic affinity of ophiolitic melange exposures along a 120 km segment of the Zagros suture zone between Ilam and Abdanan, western Iran. Major-oxide and Cr-spinel data from mantle peridotites indicate moderate to high degrees of partial melting (15-28%) and Cr-numbers (0.48-0.67) consistent with a supra-subduction zone origin. Crustal units show Ti/V ratios of 22-31 and weakly depleted LREE patterns that place them in the island-arc tholeiite to back-arc basin basalt fields. A single lherzolite sample with a lower Cr-number (0.36) may record the incorporation of less-depleted mid-ocean ridge mantle into the predominantly SSZ assemblage. Collectively, the findings support obduction of a fore-arc lithospheric slab during the Late Cretaceous closure of the Neo-Tethys. Extending this geochemical transect northwestward toward Kermanshah and southeastward toward Neyriz would test whether the SSZ signature persists uniformly along the suture or gives way to MOR affinities in certain segments.

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