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Pictorial Article

Late Cretaceous forearc ophiolites of Iran

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Ophiolites are on-land tracts of oceanic lithosphere and the tectonic setting that they form in is often controversial. Reconstruction of the Neotethyan Ocean from Permian rifting to final closure in Cenozoic time is largely based on the ophiolitic sutures, such as the Late Cretaceous Ophiolite Belt of Southwest Asia (LCOBSWA). The LCOBSWA stretches for 3000 km from Cyprus to Oman through Iran and is remarkably coherent, continuous, and contemporary but is only well known at its terminations: Cyprus (94–90 Ma) and Oman (95 Ma). The rest of the LCOBSWA, especially in the Zagros region of Iran, is more poorly known. The Zagros Fold-and-Thrust Belt formed as an accretionary prism and has grown in concert with the continuing subduction of Arabia beneath Iran, which began about 20 Ma. The Zagros Ophiolite Belt lies along the northeast flank of the Zagros Fold-and-Thrust Belt (Fig. 1a). Zagros ophiolites represent forearc lithosphere that formed during a Late Cretaceous episode of subduction initiation on the north side of the Neotethys (Shafaii Moghadam *et al.* 2010).

Zagros ophiolites can be subdivided into the 'Inner Zagros' and 'Outer Zagros' Ophiolitic Belts, separated by the Sanandaj–Sirjan metamorphic terrane, which we interpret as exhumed subducted materials (Fig. 1b). The Outer Zagros Ophiolitic Belt (OB) includes the Kermanshah, Neyriz and Esfandagheh ophiolites, from northwest to southeast, cropping out south of the Main Zagros Thrust Fault (Fig. 1a). The Inner Zagros Ophiolite Belt (IB) lies along the southwest margin of the Central Iranian Block, comprising the Nain, Dehshir, Shahr-e-Babak, and Baft ophiolites. These ophiolites are disrupted by faulting but generalized lithospheric columns can be reconstructed based on field observations (Fig. 2). Mantle sequences of IB and OB ophiolites are similar, comprising depleted harzburgites with diabasic–gabbroic dikes; melt impregnations, chromite pods, ultramafic cumulate sills (Fig. 3d), pegmatite gabbroic pockets/sills (Fig. 3b) and isotropic gabbro lenses. The crustal sequences of these ophiolites vary in thickness and lithology but are mostly similar (Fig. 2). Outer belt ophiolites are characterized by slices of sheeted dikes (Fig. 3e) associated with pillowed and massive lavas (Fig. 3f). Cenomanian to Campanian pelagic limestones are found as thin layers between the lavas or lie on top of ophiolite. Sheeted dikes and pillow lavas are common in IB (Fig. 3a,c). The typical IB (Fig. 2a) is overlain by pyroclastic rocks of Turonian to Maastrichtian age with basaltic to dacitic sills and rhyolitic dikes, demonstrating that the nascent Urumieh–Dokhtar Arc to the northeast developed slightly after ophiolite formation.

To reconstruct the tectonic setting of the Zagros ophiolites we use whole-rock and mineral geochemical indicators for peridotite and lavas. Most Zagros ophiolite peridotites are very depleted and have abundances of CaO and Al_2O_3 that plot in the forearc field (Fig. 4a) and have high Cr# (= Cr/Cr + Al) spinel compositions that also mostly plot in the forearc field (Fig. 4b).

Zagros ophiolitic lavas mostly have nearly flat to slightly light rare earth element (LREE)-depleted patterns. Extended trace element (spider) diagrams show typical supra-subduction geochemical signatures: enrichments in large ion lithophile and fluid mobile incompatible trace elements and depletions in high field strength elements (HFSE) (Fig. 4c). Some lavas have low REE and very low HFSE abundances, similar to boninites, generated by melting of highly depleted (harzburgitic) mantle. Nearly all of the Zagros ophiolite lavas fall into island-arc tholeiitic and boninite fields on a Ti–V diagram (Fig. 4d), similar to the depleted Lasail lavas (V_2 unit) of Oman.

In summary, all rock units of the Inner and Outer Zagros Ophiolitic Belts, from harzburgitic mantle to lavas, are characterized by strong supra-subduction zone compositional features. The similarity of ages for igneous rocks and overlying

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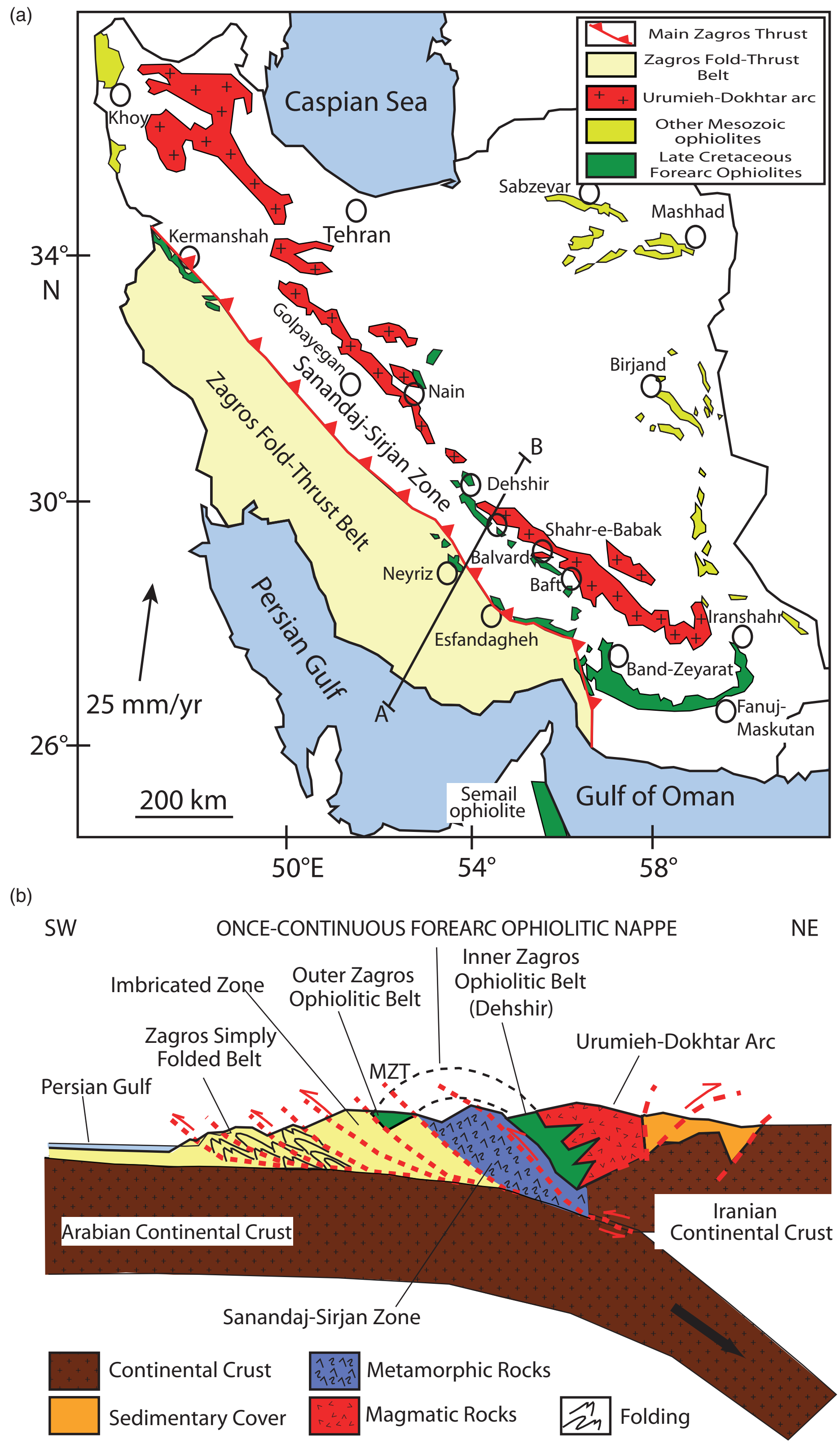
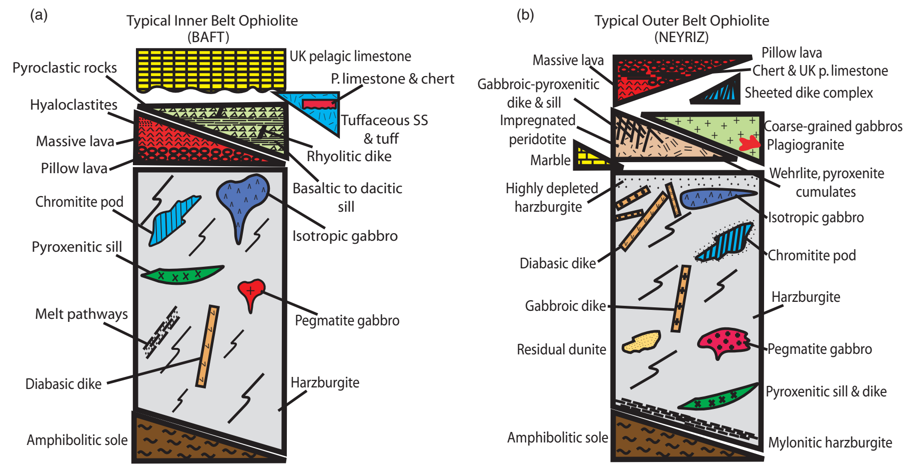


Fig. 1 (a) Map showing the distribution of late Cretaceous Inner Zagros (IB) and Outer Zagros (OB) Ophiolitic Belt the location of the Urumieh–Dokhtar magmatic arc (Eocene–Quaternary), Zagros Fold–Thrust Belt and main Zagros thrust (MZT). (b) Schematic cross-section showing the relationships between the Outer and the Inner Zagros Ophiolitic Belts, the Zagros Thrust-Fold Belt, the Sanandaj-Sirjan Zone, and the Urumieh-Dokhtar Magmatic Arc.



Inner Belt Ophiolites

Ophiolite	Overlying pelagic sediments age	Crust thickness (km)
Nain	*Coniacian to Maastrichtian*	*1-2*
Dehshir	*Turonian to Maastrichtian*	*0.5-1*
Shahr-e-Babak	*Turonian-Coniacian to Maastrichtian*	*1-2*
Baft	*Cenomanian?-Turonian to Maastrichtian*	*2-3*

Outer Belt Ophiolites

Ophiolite	Overlying pelagic sediments age	Crust thickness (km)
Neyriz	*Cenomanian-Turonian to early Santonian*	*1-2*
Kermanshah	*Turonian to Campanian*	*2-3*
Haji-Abad	*late Cretaceous, study in progres*	*2-3*

Fig. 2 Simplified psuedostratigraphic lithospheric columns displaying generalized lithological successions in typical (a) inner (Baft), and (b) outer (Neyriz) belt ophiolites. The age of the overlying pelagic sediments and crust thickness of each ophiolite from IB and OB are presented for comparison.

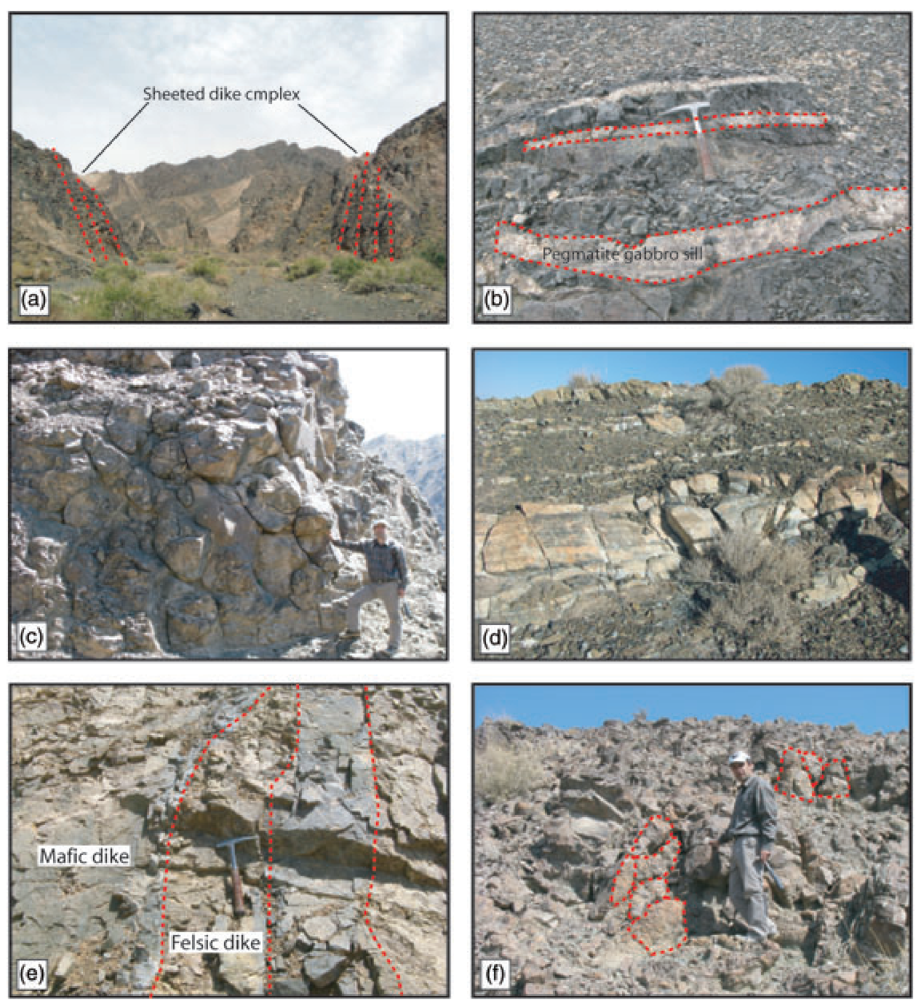


Fig. 3 Field photographs of inner and outer belt ophiolite components. (a) Sheeted dike complex in the Nain ophiolite (inner belt, IB). (b) Pegmatite gabbro sill within depleted harzburgite from the Nain ophiolite (IB). (c) Pillow lava sequence from the Baft ophiolite (IB). (d) Ultramafic–mafic cumulate sills within the mantle sequence from the Neyriz ophiolite (outer belt, OB). (e) Contact between dikes in sheeted dike complex from the Kermanshah ophiolite (OB). (f) Outcrop of pillow lavas in the Haji–Abad ophiolite (OB). Author (Hadi Shafaii) for scale.

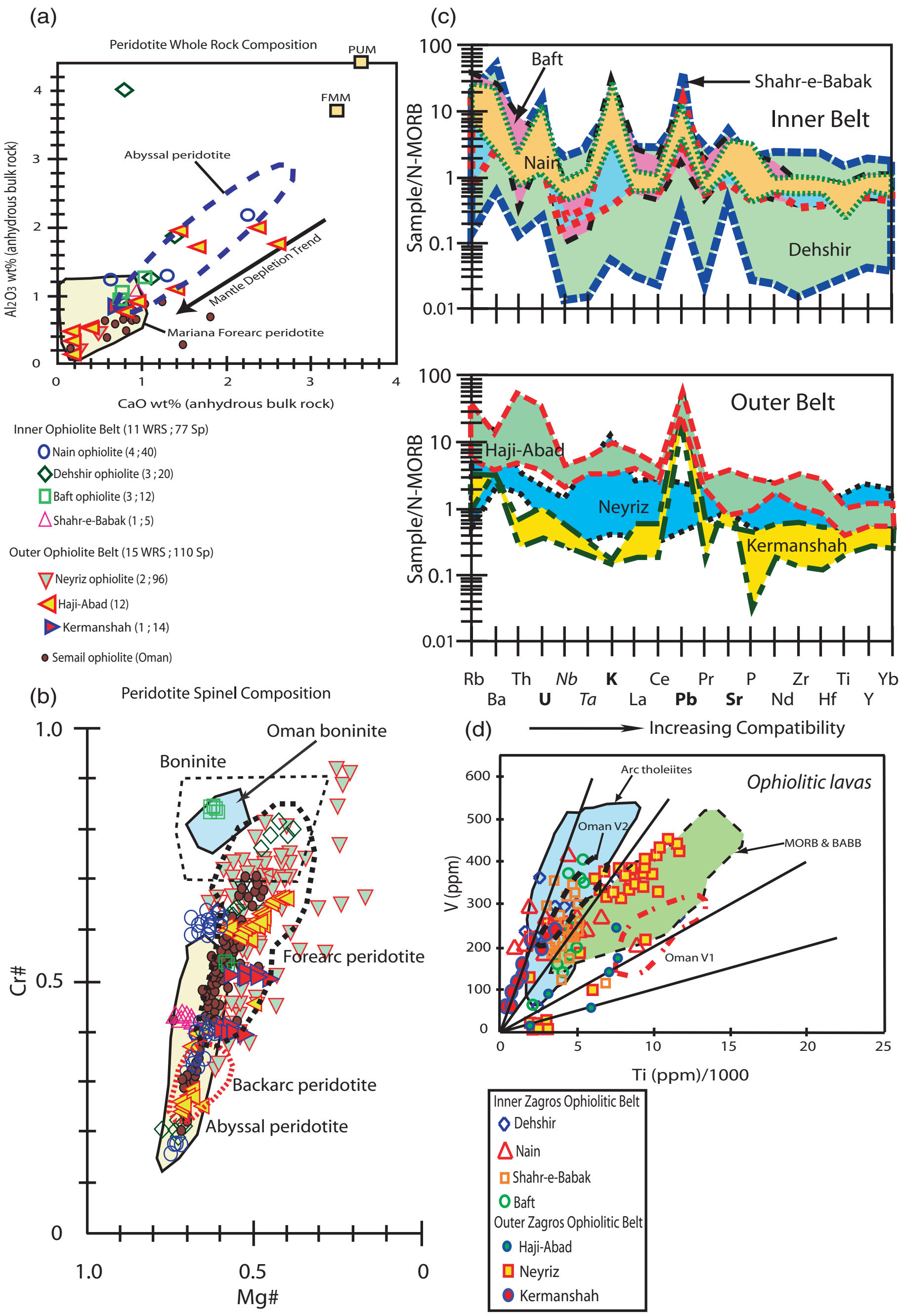


Fig. 4 (a) Al_2O_3 *vs* CaO diagram (volatile free, normalized to 100% total) for Zagros forearc ophiolitic peridotites. The composition of primary upper mantle (PUM) and fertile mid-oceanic ridge basalt (MORB) mantle (FMM) are also shown for comparison. WRS, whole rocks; Sp, spinel. (b) Cr# (=Cr/Cr + Al) *vs* Mg# (=Mg/Mg + Fe) diagram (modified after Dick & Bullen 1984) for spinels in Zagros forearc harzburgites. (c) N-MORB normalized multi-elements patterns for inner belt and outer belt Zagros ophiolitic lavas. *Nb*, *Ta* are immobile critical elements for supra-subduction ophiolites; **K**, **U**, **Pb**, **Sr** are mobile elements. (d) Ti *vs* V diagram (after Shervais 1982) for inner belt (IB) and outer belt (OB) mafic rocks. Most IB mafic rocks occupy island arc tholeiites (IAT) and boninite (Ti/V < 10) fields, whereas more OB mafic rocks fall into the MORB/back-arc basin (BABB) field. Fields for the V_1 (lower, Geotimes unit) and V_2 (upper, Lasail unit) lavas of the Oman ophiolite are also shown for comparison. Data for Dehshir ophiolite come from Shafaii Moghadam *et al.* (2010).

sediments, and of geochemical compositions for both IB and OB Zagros ophiolites, along with similarity to other LCOBSWA ophiolites (in Cyprus, Syria, Turkey and Oman), and along with the location of IB and OB between the slightly younger Urumieh–Dokhtar magmatic arc and the Zagros accretionary prism, suggest that the entire ophiolite belt formed as an approximately 3000-km-long tract of forearc oceanic lithosphere fringing southern Eurasia during a subduction initiation event.

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