GEOLOGICAL AND PETROLOGICAL INVESTIGATION OF THE WESTERN NORTH MAKRAN OPHIOLITES (SE IRAN): NEW CONSTRAINTS FOR THE LATE JURASSIC – CRETACEOUS TECTONO-MAGMATIC AND GEODYNAMIC EVOLUTION OF THE NEO-TETHYS OCEAN

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GEODYNAMIC SETTING OF THE MAKRAN ACCRETIONARY PRISM AND AIM OF THE THESIS

The Makran Accretionary Prism (SE of Iran) resulted from the Cretaceous to Present-day convergence between Arabia and the southern margin of the Eurasian plates, which was associated with the northward subduction of the Neo-Tethys below the Eurasia margin since the Early Cretaceous (McCall & Kidd, 1982; Barrier *et al.*, 2018; Burg, 2018). This prism has been subdivided in four tectono-stratigraphic domains, namely from north to south North Makran, Inner Makran, Outer Makran, and Coastal Makran (Dolati, 2010; Burg *et al.*, 2013). The North Makran domain (Figs. 1a, b) represents the innermost tectonic domain consisting of an imbricated stack of tectonic units that were juxtaposed during the pre-Eocene geodynamic history of the Makran Accretionary Prism (*e.g.*, McCall, 1985). In the studied area (Fig. 1a), these units include from top to bottom: the North Makran Ophiolites (including the Ganj Complex and the Band-e-Zeyarat ophiolite; McCall & Kidd, 1982); Bajgan-Durkan Complexes (fragments of continental crust and related sedimentary cover; McCall & Kidd, 1982; Hunziker *et al.*, 2015); the Sorkhband and Rudan slices of mantle ultramafic and lower crust sequences (Delavari *et al.*, 2016); the Coloured Mélange (Saccani *et al.*, 2018).

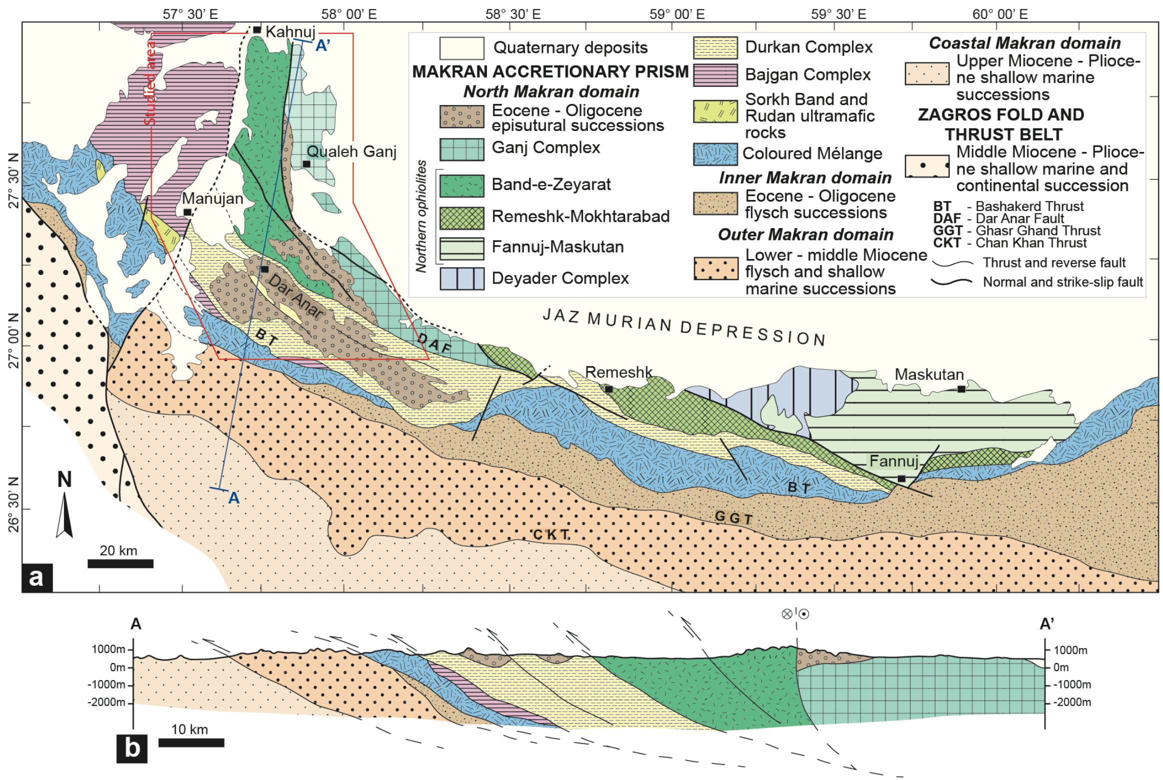

Fig. 1 - Simplified geological-structural map (a) and cross section (b) of the North Makran Domain showing the different tectonic units and the study area (modified from Burg, 2018; Samimi Namin, 1982, 1983).

The North Makran Ophiolites were interpreted as the remnants of the North Makran Ocean that is, a neo-Tethyan seaway that opened during the Late Jurassic separating the Lut-Afghan continental blocks (to the north) and a microcontinental block (to the south) that is believed to be represented by the Bajgan-Durkan Complexes (McCall & Kidd, 1982; Hunziker *et al.*, 2015; Monsef *et al.*, 2019). The geodynamic significance of this oceanic basin and its conjugate continental margins is still under debate due to the scarcity of data from the North Makran ophiolites. In fact, this basin has been interpreted as either an Early Cretaceous back-arc basin related to the northward subduction of the Neo-Tethys (McCall & Kidd, 1982) or a marginal basin opening during the Late Jurassic - Early Cretaceous at the southern margin of the Lut-Afghan blocks (Hunziker *et al.*, 2015; Burg, 2018). In both hypotheses, the Cretaceous-Eocene geodynamic evolution of the North Makran is thought to have been mainly controlled by the collision between the Bajgan-Durkan microcontinent and the southern Eurasia margin, occurred throughout the closure of the North Makran Ocean (McCall, 2002; Burg, 2018). In this framework, a detailed multidisciplinary study of the North Makran Ophiolite and the Bajgan-Durkan Complexes in the western North Makran is fundamental to provide new and robust constraints to understand the tectono-magmatic significance of the North Makran Ocean.

This work is focused on geological investigations and petrological-geochemical characterization of the magmatic rocks of four different tectonic units cropping out in the north-western North Makran domain, namely: the Band-e-Zeyarat ophiolite; the Ganj Complex; the Durkan Complex; the Bajgan Complex. In the extant interpretations, the Band-e-Zeyarat ophiolite and the Ganj Complex represent remnants of the North Makran Ocean, whereas the Durkan and Bajgan Complexes collectively represent remnants of the sedimentary cover and the continental basement, respectively, of the southern continental margin of this basin (McCall & Kidd, 1982). The aim of this work is to provide data for a better understanding of the geodynamic significance of the North Makran Ocean and its southern paleo-margin during the Cretaceous. Finally, these data have been used to discuss the role of the North Makran Ocean during the Late Cretaceous – pre-Eocene convergent tectonics of the Makran Accretionary Prism.

ANALYTICAL METHODS

A total of 183 samples of volcanic, subvolcanic, intrusive, and meta-magmatic rocks were sampled from the different units and analyzed for whole-rock major and selected trace elements composition by X-ray fluorescence (XRF) on pressed-powder pellets using an ARL Advant-XP automated X-ray spectrometer. In addition, trace elements, such as Rb, Sr, Y, Zr, Nb, Hf, Ta, Th, U, and the rare earth elements (REE) were determined by inductively coupled plasma-mass spectrometry (ICP-MS) using a Thermo Series X-I instrument. All whole-rock analyses were performed at the Department of Physics and Earth Sciences, Ferrara University.

Silicates were analyzed by electron microprobe using a Superprobe Jeol JXA 8200 (JEOL, Tokyo, Japan) at the Eugen F. Stumpfl Laboratory at the University of Leoben, Austria, using both ED and WD systems. For further details on analytical methods, see Barbero *et al.* (2020a, 2020b, 2021a, 2021b). As petrographic analyses revealed that most of the samples are affected by various degrees of low-grade ocean-floor hydrothermal alteration, the description of the geochemical features of the magmatic rocks is based on those elements considered virtually immobile during alteration processes (for further details see: Pearce, 1996; Barbero *et al*., 2020a, b). In brief, these elements include some incompatible elements (*e.g.*, Ti, P, Zr, Y, Nb, Ta, Hf, Th) and rare earth elements (REE).

THE GANJ COMPLEX

This Complex is represented by a > 2000 m-thick sequence consisting of a dyke-swarm showing transition to a volcano-sedimentary sequence with local interlayering of turbidite beds. This sequence grades-up to a Turonian-Coniacian turbidite sequence (based on calcareous nannofossil biostratigraphy). Volcanic rocks and dykes are represented mainly by intermediate and acidic rocks and minor basalts. They show a sub-alkaline nature, as exemplified by the low Nb/Y ratios (Fig. 2a), and a clear volcanic arc affinity (Fig. 2b). In detail, three different chemical groups have been distinguished according to trace and REE compositions. Group 1 and Group 2 show calc-alkaline and island arc tholeiites affinities, respectively (Fig. 2b). In contrast, Group 3 rocks show calc-alkaline nature with adakitic signature (high Sr/Y ratios, and HREE severely depleted). In contrast to previous interpretations, all these data clearly indicate that the Ganj Complex represents a Late Cretaceous volcanic arc, rather than the oceanic lithosphere of the North Makran Ocean. The geochemical affinity of the magmatic rocks indicates that the Ganj rocks derived from the partial melting of the sub-arc mantle wedge enriched by different types of chemical components released from the subducting slab (Fig. 3). The present-day structural position of the Ganj Complex suggests that this arc was built close or onto the southern continental margin of the Lut block (Fig. 3).

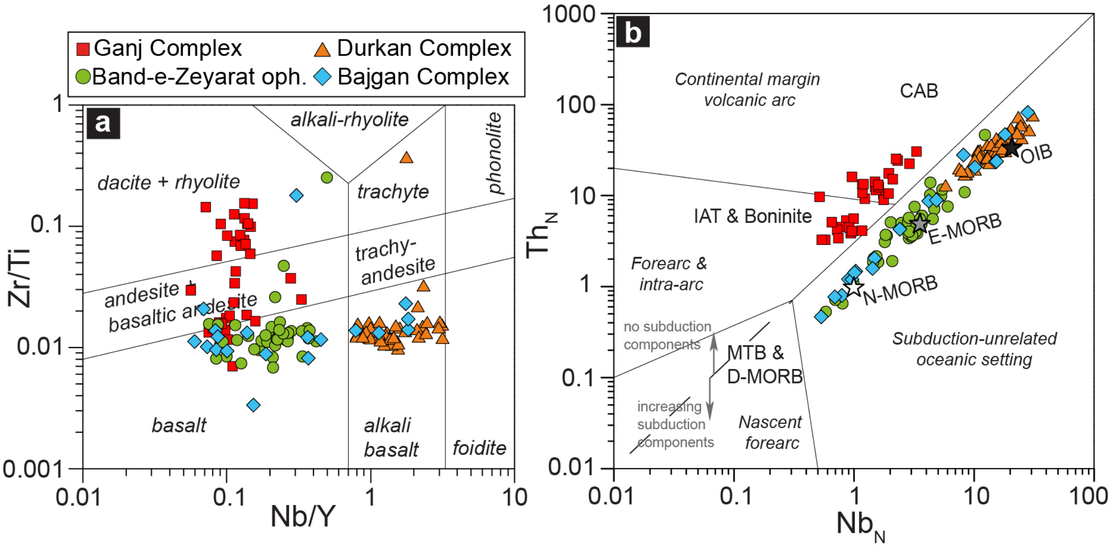

Fig. 2 - a) Nb/Y *vs*. Zr/Ti discrimination diagram modified by Pearce (1996) for the studied rocks from the different units; b) N-MORB normalized Th *vs.* Nb discrimination diagram of Saccani (2015) for the studied rocks from the different units. Abbreviations, MORB: mid-ocean ridge basalt, N-: normal type, E-: enriched type, D-: depleted type, IAT: island arc tholeiite, CAB: calc-alkaline basalt; OIB: oceanic island basalt; MTB: medium titanium basalt. Normalizing values, as well as the composition of typical N-MORB, E-MORB, and OIB (grey stars) are from Sun & McDonough (1989).

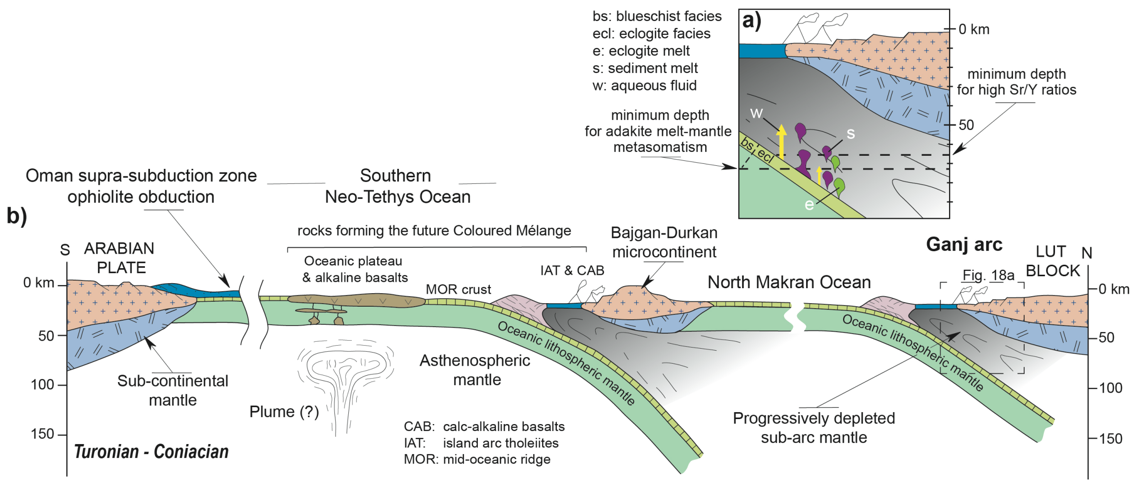

Fig. 3 - a) 2D tectono-magmatic model for the formation of the volcanic and subvolcanic rocks in the Ganj volcanic arc setting; b) Tectonic reconstruction along N-S profile of the Makran-Oman system in the Turonian-Coniacian time.

THE BAND-E-ZEYARAT OPHIOLITE

The Band-e-Zeyarat ophiolites include, from bottom to top: 1) a rather thick (~5 km) intrusive complex consisting of layered gabbros and minor ultramafic cumulitic rocks (in the lower part) that gradually pass upward to isotropic gabbros; 2) a sheeted dyke complex (~1.5-2 km-thick); 3) a volcanic sequence up to ~2-3 km-thick. In addition, a mainly carbonatic, pelagic sedimentary cover stratigraphically overlays the volcanic sequence. Sheeted dykes and volcanic rocks are mainly represented by sub-alkaline basalts and minor andesites and rhyolites (Fig. 2a) showing either normal-type (N) or enriched-type (E) mid-ocean ridge basalt affinities (MORB) (Fig. 2b). The compositions of rock-forming minerals (olivine, plagioclase, and clinopyroxene) also indicate a general MORB-type affinity for both gabbros and basalts. Petrogenetic modelling based on REE, Th, Nb, and TiO_2 contents points out for partial melting of different types of sub-oceanic mantle sources, which melted at different conditions in terms of source composition, partial melting degrees, and melting depths. In detail, the Band-e-Zeyarat N-MORBs formed from partial melting of a depleted sub-oceanic mantle peridotite in the spinel-facies (Type-I in Fig. 4). By contrast, Band-e-Zeyarat E-MORBs formed from partial melting of a depleted sub-oceanic mantle peridotite that was metasomatized by OIB-type (plume-type) components (Type-II in Fig. 4). The significant contribution of partial melting in the garnet-facies shown by the E-MORB rocks suggest interaction of rising OIB-mantle patches with depleted sub-oceanic mantle. The geochemical and petrogenetic data suggest that the Band-e-Zeyarat ophiolite represents a chemical composite upper oceanic crust, which records an Early Cretaceous plume–ridge interaction in the Makran Neo-Tethys (Fig. 4).

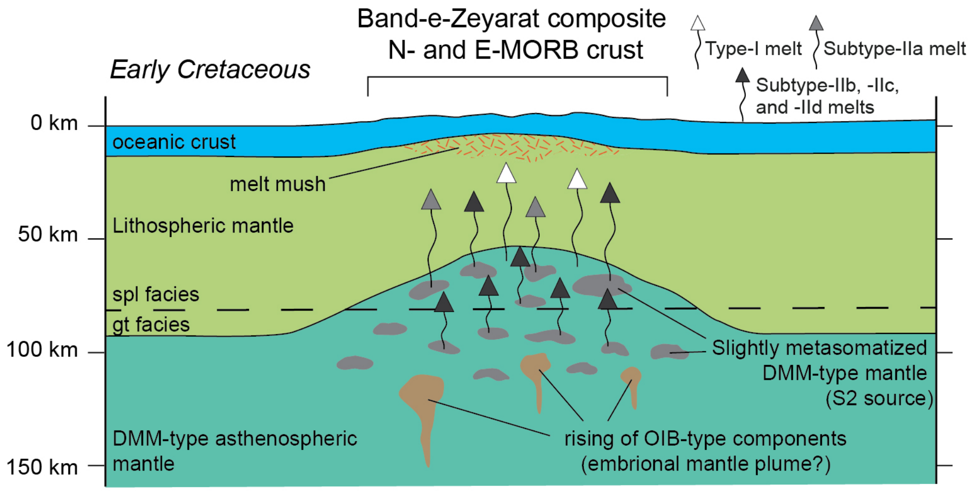

Fig. 4 - 2D conceptual cartoon showing the petrogenetic processes responsible for the formation of the N- and E-MORB composite crust of the Band-e-Zeyarat ophiolites in a mid-oceanic ridge tectono-magmatic setting. Abbreviations: N-MORB: normal mid-oceanic ridge basalt; E-MORB: enriched mid-oceanic ridge basalt; OIB: oceanic island basalt; DMM: depleted MORB mantle.

THE DURKAN COMPLEX

This complex consists of distinct tectonic slices showing both non-metamorphic and very low-grade metamorphic deformed successions. Stratigraphic and biostratigraphic data allow to recognize three types of successions. Type-I is composed by a Coniacian - early Campanian pelagic succession with intercalation of pillow lavas and minor volcaniclastic rocks. Type-II succession includes a volcanic sequence passing to a volcano-sedimentary sequence with Cenomanian pelagic limestones, followed by a hemipelagic sequence. This succession is characterized by abundant mass-transport deposits. Type-III succession includes volcanic and volcano-sedimentary sequences, which are stratigraphically covered by a Cenomanian platform succession. These stratigraphic successions can be reconciled to those found at different depths of a seamount setting, recording coeval volcanic activity and sedimentation. The volcanic and metavolcanic rocks are largely basaltic in composition and show relatively high Nb/Y ratios (Fig. 2a). Based on whole rock chemistry and clinopyroxene chemistry, basaltic rocks consist of transitional basalts showing plume-type mid-oceanic ridge basalts (P-MORB) composition (Group 1) and alkaline basalts showing OIB composition (Groups 2a and 2b) (Fig. 2b). The chemical composition of clinopyroxenes from the different rock groups is strictly depending on the whole rock composition of their hosting rocks. In particular, TiO_2, Al_2O_3, and Na_2O contents in minerals increase from transitional to alkaline basalts. Trace element and REE petrogenetic models show that the Durkan basaltic rocks were generated from partial melting of a depleted sub-oceanic mantle source that was metasomatized by OIB-type chemical components in a within-plate oceanic setting. The chemical differences between the Groups of basalts are related to different combinations of partial melting degree, depths of melting, and various extents of metasomatic enrichment. These new data indicate that the different volcano-sedimentary successions of the Durkan Complex represent remnants of seamounts of different ages formed during both shallow-water shield stage (Fig. 5a - Cenomanian) and deep-water stage (Fig. 5b - Coniacian-Campanian). These findings strongly suggest that a mantle plume existed in the Makran sector of the Neo-Tethys during the Late Cretaceous and that it played a major role in influencing the volcanic activity and sedimentation (Fig. 5).

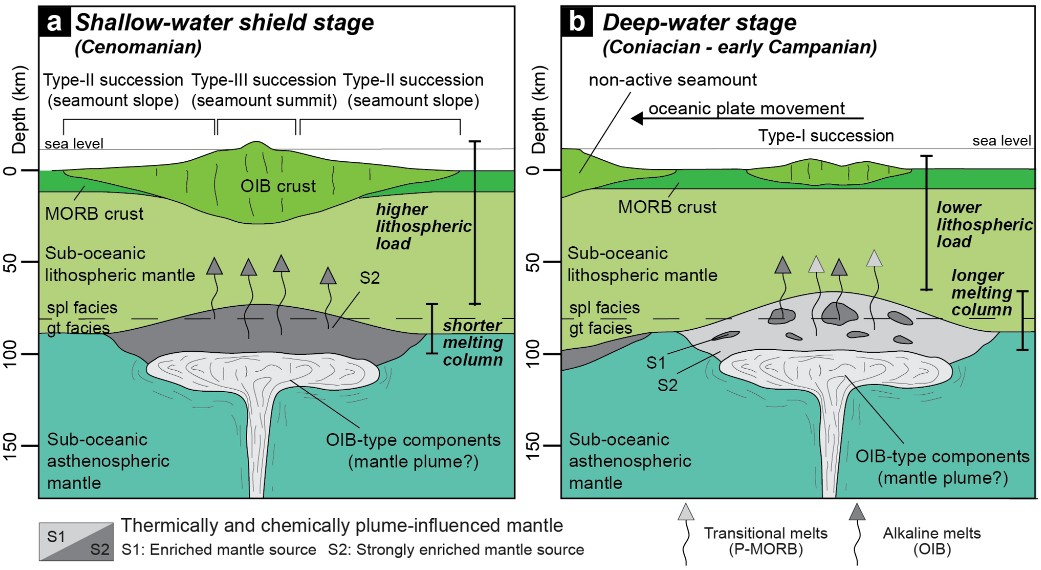

Fig. 5 - 2D conceptual cartoon showing the petrogenetic processes operating during the shallow-water (a) and deep-water (b) stages of growth of the Durkan seamounts. The depositional positions of the different types of successions are also shown. Abbreviations, MORB: mid-oceanic ridge basalt; OIB: ocean island basalt; S1 and S2: enriched mantle sources derived from different degrees of enrichment by an OIB-type chemical component of a sub-oceanic slightly depleted lherzolite residual after small volume of MORB melt extraction; spl: spinel; gt: garnet.

THE BAJGAN COMPLEX

The Bajgan Complex is composed by tectonic slices bordered by mylonitic shear zones. These slices show a wide range of metamorphic rocks including meta-serpentinites, meta-intrusive rocks, meta-volcanic rocks and meta-sedimentary rocks. The meta-intrusive rocks mainly derived from different protoliths, ranging from gabbros to melagabbros, and anorthosite, whereas meta-volcanic rocks likely derived from basalts and basaltic andesites. The meta-sedimentary rocks include meta-volcanoclastites, quarzites, micaschists, paragneisses, calcschists and impure marbles. This type of tectono-stratigraphic architecture is comparable with a MOR-type original ophiolitic succession. The geochemistry of the meta-intrusive and meta-volcanic rocks show both sub-alkaline and alkaline natures (Fig. 2a) and they range from N-MORB to E-MORB and OIB (Fig. 2b). Trace element and REE petrogenetic study indicates that the N-MORB derived from partial melting of a sub-oceanic mantle source with a DMM composition (Workman & Hart, 2005), whereas E-MORB and OIB rocks derived from partial melting of a DMM-type mantle source modified by OIB-chemical components and an enriched OIB-type mantle source, respectively. Zircons dating (data kindly provided by A. Langone, CNR Pavia) on different meta-intrusive rocks points out for a Late Jurassic - Early Cretaceous ages for the protoliths proving that the Bajgan Complex do not represent a Palaeozoic continental basement as previously thought (*e.g.*, McCall, 1985). As a consequence, this new multidisciplinary study suggests that the Bajgan Complex represents an assemblage of different meta-ophiolitic tectonic slices, which were formed during the Late Jurassic to the Early Cretaceous in a MOR tectono-magmatic setting most likely influenced by mantle plume activity.

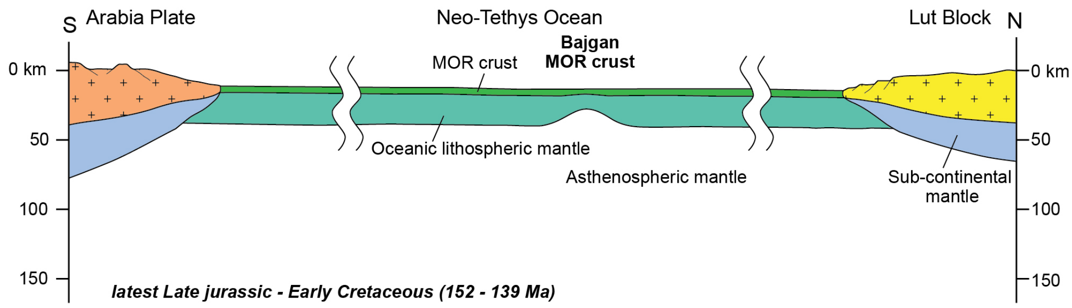

Fig. 6 - 2D tectono-magmatic and geodynamic reconstruction for the Makran sector of the Neo-Tethys realm during Late Jurassic - Early Cretaceous.

TECTONO-MAGMATIC IMPLICATIONS AND CONCLUSION

Up to now, the geodynamic reconstruction for the North Makran Ocean proposed that this basin opened in consequence of an Early - Late Jurassic rift of the southern part of the Central Iran, causing the detachment of a microcontinental block (McCall, 2002; Hunziker *et al*., 2015). The new data presented in this work indicate that this geodynamic model and the existence of a microcontinent must be critically revaluated.

During the Late Jurassic - Early Cretaceous a mid-oceanic ridge (MOR) was active as testified by the tectono-magmatic evolution recorded by the Bajgan Complex. In fact, the Bajgan Complex metaophiolites likely corresponds to fragments of the Neo-Tethys Ocean, which was separating the Eurasian and the Arabian continental margin (Barrier *et al.*, 2018).

During the Cretaceous, there is a general agreement about the inception of convergent kinematics in the Neo-Tethys ocean (Barrier *et al.*, 2018). In the Makran sector of the Neo-Tethys realm, a north dipping intra-oceanic subduction nucleated, identifying thus two distinct branches of the Neo-Tethys, namely the southern Neo-Tethys Ocean and the North Makran Ocean. The North Makran Ocean was characterized at this time by an active mid-oceanic ridge that was influenced by the embryonal activity of a mantle plume as testified by the tectono-magmatic evolution recorded by both the Band-e-Zeyarat ophiolites and the Cretaceous meta-ophiolite in the Bajgan Complex.

The Late Cretaceous tectono-magmatic and geodynamic evolution of the North Makran Ocean is dominated by the contemporaneous closure of this ocean and diffuse mantle plume activity. In fact, the Late Cretaceous Ganj Complex represents a volcanic arc formed close to the Eurasian margin in response to the northward subduction of the North Makran oceanic lithosphere. By contrast, the Durkan Complex testifies for the existence in the North Makran Ocean of a seamount chain formed by alkaline magmatism related to a Late Cretaceous mantle plume.

The present-day structural setting of the North Makran domain mainly resulted from multiple pre-Eocene deformative stages, which involved the deformation of the different units at different depth in an accretionary prism and was likely controlled by the interaction between topographic reliefs (*e.g.*, arc and seamounts) and the frontal part of the accretionary prism.

The Makran Accretionary Prism represents an important sector of the Alpine-Himalayan belts, as it links the Turkish and Zagros belts (to the West) to the Pakistani-Himalayan belts (to the East) through a still active subduction system. This Thesis provides robust constraints for a new geodynamic model for the Late Jurassic - Cretaceous evolution of the Makran area, which may have important implications for the regional-scale tectonic evolution of the entire Alpine-Himalayan belt.

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