From subduction initiation to oceanic core complex formation: a tale of two ophiolites in the Kurdistan, NW Iran

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Abstract

The processes of subduction initiation and oceanic core complex (OCC) formation are essential to understanding plate tectonic evolution. The Kermanshah–Walash Ophiolitic Complex (KWOC) in Kurdistan, NW Iran, preserves a unique record of both mechanisms in spatially parallel but temporally distinct Late Cretaceous (Razab) and Eocene (Sarv-Abad) ophiolites. These ophiolites comprise peridotite, gabbroic bodies, a dike complex, and pillowed and massive basaltic lavas. Whole-rock geochemistry, U–Pb zircon geochronology, and field structures reveal distinct ages and tectonic settings for the two ophiolites. While radiolarian cherts constrain the Razab ophiolite to the Cretaceous, new U–Pb zircon (42–38 Ma) geochronology firmly places the formation of the Sarv-Abad oceanic core complex in the Eocene. The Cretaceous Razab unit contains high-Cr# spinel chromitite (0.77–0.82), forearc, and island arc tholeiitic (IAT) lavas, supporting formation during subduction initiation. In contrast, the Eocene Sarv-Abad unit features mylonitized gabbros, syn-extensional dikes, and contemporaneous D-MORB/E-MORB magmatism derived from heterogeneous mantle melting, diagnostic of an Oceanic Core Complex (OCC) in an extensional back-arc. Our results demonstrate that the KWOC was shaped by two distinct geodynamic mechanisms: subduction initiation in the Cretaceous and oceanic core complex formation in the Eocene. Despite ~50 Myr separation, both units were emplaced during the Miocene closure, suggesting how contrasting mechanisms may have shaped the KWOC. The OCC model also offers a potential resolution to prior ambiguities in the geodynamic evolution of Peri-Arabic ophiolites.

Keywords: Razab, Sarv-Abad, Forearc, Detachment faulting, Ocean core complex, Kermanshah-Walash ophiolitic belt

1. Introduction

Ophiolites offer unique opportunities to study the formation and evolution of plate boundaries in a range of geodynamic settings (e.g., Moores, 1982; Maruyama *et al.* 1996; Dilek and Furnes, 2011; 2014; Dilek and Yang, 2018; Furnes and Dilek, 2022). Geochemical and geochronological data have revealed that ophiolitic crust and lithospheric mantle is not only generated at mid-ocean ridges (MORs) far from subduction zones (Rollinson, 2017), but also during the initial stages of back arc/forearc formation in subduction zone settings (Miyashiro, 1973; Pearce *et al.* 1984; Dilek, 2003; Stern *et al.* 2012). Two parallel Late Cretaceous and Eocene-Oligocene ophiolitic and associated marine sedimentary sequences occur in the central parts of the Peri-Arabic ophiolitic system alongside the Zagros fold-thrust belt, a ~2000 km long orogenic belt that stretches from the East Anatolian Fault in southeastern Turkey and continues through northeastern Iraq–northwestern Iran (Ao *et al.* 2016; Agard *et al.* 2007; Whitechurch *et al.* 2013) to the Makran subduction zone in southern Iran (Sepidbar *et al.* 2020). They are characterized by scattered ophiolite fragments, each smaller than 150 km^2 with crustal ages ranging from ~90 to ~29 Ma and geochemical signatures indicating formation in the arc/back-arc in a nascent subduction zone (Whitechurch *et al.* 2013). Peri-Arabic ophiolites include the Khoy, Kermanshah (Harsin, Sahneh, Kamyaran) and Kurdistan (Razab, Sarv-Abad) of northwestern Iran, the Neyriz, Esfandagheh and Makran ophiolites to the southeast in Iran (Moghadam and Stern, 2014) and the Penjween and Mawat-Hasanbag ophiolites in Iraq (Aswad *et al.* 2011). To the northwest, Peri-Arabic ophiolites are exposed along the Iran–Iraq boundary between Kermanshah/Kurdistan (Iran) and Mawat-Hasanbag (Iraq), which together are known as the Kermanshah-Walash Ophiolitic Complex (KWOC) (Ghorbani *et al.* 2022).

The Kermanshah/Kurdistan region of northwestern Iran is a geologically dynamic area that preserves critical records of the tectonic evolution of the Tethyan realm during the Late Mesozoic to Cenozoic. The Kermanshah and Kurdistan ophiolites (Figure 1) belong to two different domains: (i) a section of Cretaceous oceanic sequences underplated beneath the Sanandaj–Sirjan Zone and (ii) a Cenozoic arc/backarc that formed upon Late Cretaceous oceanic crust (Ghorbani *et al.* 2022). Both the timing of ophiolite formation and the geochemical and temporal evolution of the Kermanshah and Kurdistan ophiolites are highly controversial. A plagiogranitic dyke in the Kermanshah ophiolite has a whole-rock K–Ar age of 86.3 ± 7.8 Ma (Delaloye and Desmons, 1980), whereas U–Pb zircon data from both rodingitized gabbro of the Harsin and Sahneh-Kamyaran (Kermanshah) ophiolite have plateau ages of 80 Ma and 38 Ma, respectively (Ao *et al.* 2016). However, only limited radiometric age constraints are available for the Cenozoic ophiolites of Kurdistan, with K–Ar ages of the Sarv Abad basaltic rocks ranging from 59 Ma to 29 Ma (Ghorbani *et al.* 2022). In addition, the geochemistry, petrogenesis, age and tectono-magmatic evolution of both the Cretaceous (Razab) and Eocene (Sarv-Abad) crustal sequences related to Kurdistan remain poorly known, and their investigation can provide new insight into the Mesozoic and Cenozoic evolution of this part of Kurdistan and adjacent regions. In addition, most crustal sequences have mixtures of mid-ocean ridge basalt-like (MORB-like) and somewhat arc-like lavas, where MORB-like lavas at the base are older than the arc-like lavas that lie above them (Ghorbani *et al.* 2022). Enriched mid-ocean ridge basalts (E-MORB) commonly erupt at mid-ocean ridge (MOR) systems and back-arc basins (BAB), but their relationship to “depleted” MORB (D-MORB) and the processes controlling their magmatic evolution at MORs and in BABs are not fully understood, therefore rising further general queries about magma generation in the mantle. Here, we report new high quality zircon U–Pb ages, structural field relations, and geochemical data of the Kurdistan ophiolite in order to more precisely constrain the time of formation of the Neo-Tethys oceanic floor and its subduction, to suggest a model for the geodynamic evolution of the Peri-Arabic ophiolitic system.

2. Geological Setting and Previous Work on Kermanshah-Walash ophiolitic complex (KWOC)

2.1. General geology of the KWOC

A wide variety of ultramafic to mafic rocks outcrop along the Peri-Arabic ophiolite belt, including the Kermanshah (Harsin, Sahneh, Kamyaran, Sarv-Abad), Kurdistan, Neyriz, and Esfandagheh ophiolites in Iran (Moghadam and Stern, 2014) and the Penjween, Mawat-Hasanbag ophiolites in Iraq (Aswad *et al.* 2011). The Cretaceous Kermanshah and Eocene-Oligocene Kurdistan ophiolites in the NW Iranian KWOC outcrop in a tectonic window within turbiditic phyllites of the Sanandaj-Sirjan zone (Figure 2A). Previous studies suggest a supra-subduction zone affinity for the mantle section of Mesozoic Kermanshah ophiolite

(Nouri *et al.* 2018). In the Kermanshah – and especially in the Sahneh-Kamyaran region (Ao *et al.* 2016) – Paleocene–Eocene turbidites and Eocene pillow lavas stratigraphically overlie Late Cretaceous peridotites. The Eocene pillow lavas differ from Late Cretaceous pillows by being intercalated with green shale and sandstone turbidites. Dyke swarms, including early basaltic and diabasic dykes and late dacitic rhyolitic to microdioritic dykes (usually <0.5 m, but locally >1 m wide), occur in the Kermanshah region and record Eocene U–Pb zircon ages (Moghadam and Stern, 2014). These dykes are interpreted to have formed during extension associated with intra-oceanic magmatism (Whitechurch *et al.* 2013). Whitechurch *et al.* (2013) suggested that the Eocene ophiolitic rocks (pillow lavas, gabbros and dykes) were emplaced into the Late Cretaceous Kermanshah ophiolite close to the ocean–continent transition.

The Kurdistan ophiolite forms one of the mantle and crustal outcrops (~150 km^2 areal extent) of the KWOC (Figure 1A, B). It contains the same Cretaceous (Razab) and Eocene (Sarv Abad) ophiolitic crustal sequences, separated by Sanandaj-Sirjan units, and range from tholeiite to calc-alkaline affinities, akin to depleted- and enriched-types mid-ocean ridge basalts (E-MORB) from Sahneh-Kamyaran (Ao *et al.* 2016). A geochronological study of Sarv-Abad lavas showed different ages of Paleocene–Eocene (59–52 Ma) and Oligocene (29 Ma) for the LREE-depleted and for LREE-enriched lava, respectively (Ghorbani et al. 2022). These authors considered the Sarv-Abad volcanic rocks as a Paleocene immature and Oligocene mature back-arc basin along the Eurasian continental margin that ultimately accreted to the Eurasian continent following Early Paleocene Ocean closure (Arvin and Robinson, 1994; Moghadam, 2009) and continental collision. In contrast, no detailed work has been performed on the geology and petrogenesis of the Cretaceous ophiolites, Eocene gabbros, or plagiogranites. Here, we study major and trace element variations in selected samples from both the Cretaceous and Eocene Kurdistan ophiolite occurrences within the KWOC, highlighting their ages by radiometric U–Pb dating and genesis from geochemistry, and elucidate their mechanisms and conditions of formation.

2.2. Geology of the Kurdistan ophiolite

Prior investigation of the Kurdistan ophiolite has defined four main units (Figure 2): (i) Sanandaj-Sirjan metamorphic rocks consisting of Cretaceous phyllite-slate interlayered with metamorphic limestone; (ii) collisional (thrust) zone units, including a metamorphic complex and related diabasic dykes, basic lava, sandstone, silt and Eocene flysch, which are located between the Sarv-Abad ophiolites and Bisotun-Avroman subzones (iii) both Razab (Late Cretaceous) and Sarv-Abad (Eocene-Oligocene) ophiolitic complexes, of which the latter includes mantle peridotites, lower crustal gabbros, upper crustal lava, plagiogranitic and basaltic dykes, and a pre-obduction sedimentary cover (Peters, 2000); and (iv) the Bisotun-Avroman zone, including thick and thin layered limestone, limestone-radiolarite, and radiolarite, interlayered by volcanic rock. This oceanic crustal sequence is unconformably overlain by post-obduction Oligocene-Miocene limestones.

In Kurdistan, the Sanandaj-Sirjan zone is a large pre-Permian Arabian-Iranian continental plate that rifted from Arabia during the Late Permian and thus represents a southern Andean-type continental margin of the Iranian block with abundant calc-alkaline magmatic rocks (Whitechurch *et al.* 2013). This zone consists of a sedimentary/metamorphic complex (Berberian and Berberian, 1981) containing Precambrian/Paleozoic continental basement that is unconformably covered by Permian-Triassic limestones and Jurassic low-grade metamorphic rocks (phyllites with interbedded metavolcanic rocks) that were intruded by Late Jurassic-Late Cretaceous calc-alkaline plutons. The metamorphic rocks are unconformably overlain by Barremian-Aptian limestones (Bisotun-Avroman Unite; zone iv) resembling those of the Central Iran block (Stöcklin, 1968). The Bisotun-Avroman Unit is composed of thick shallow water carbonates that range in age from Late Triassic to Late Cretaceous (Ricou *et al.* 1977; Braud, 1987). This unit is unconformably overlain by the shallow marine platform carbonates with basal conglomerates deposited between the Late Oligocene and Early Miocene, known as the Qom Formation (Agard *et al.* 2011). The Kurdistan ophiolitic units comprise imbricated dismembered fragments of mantle peridotites, gabbros, a dyke complex and pillow basalts, which generally occur as metamorphosed thrust slices within the collisional unit. The Kurdistan ophiolitic units can be divided based on age (Figure 1b): (i) Cretaceous components, which trend NW-SE along or parallel to the Zagros thrust or Sanandaj-Sirjan zones (Figure 2), and primarily consists of ophiolitic sequences located in the Razab region, northwestern part of the Sarv-Abad (younger ophiolite) (Figure 2), and (ii) young Eocene-Oligoene ophiolitic sequences exposed in the Sarv-Abad composed of serpentinized dunite, wehrlite and chromitite. These units are intruded by diabase and plagiogranite dykes, medium to coarse grained gabbros, pillow lavas and rodingitized gabbro.

2.3 Field observations and petrography

Cretaceous Razab ophiolite

The Cretaceous Razab ophiolite, occurring as elongated thrusted sheets, consists of highly to completely serpentinized slices of peridotite, cumulate isotropic gabbro, pillow lava and diabase and plagiogranite dykes and radiolarite (Figure 2). These lithologies are separated from the Eocene ophiolites by mylonitic and ultra-mylonitic units of the Sanandaj-Sirjan zone, and are unconformably overlain by limestones containing Upper Triassic Megalodons (Braud, 1987). The serpentinized peridotite is mylonitized and occurs in direct contact with the gabbro (Figure 3A-B). It primarily contains abundant olivine, orthopyroxene, Cr-spinel and magnetite, with serpentine, chlorite, talc, calcite and Fe-oxide as secondary phases. Some olivine grains are replaced by serpentine fibers, forming a mesh textures. Subhedral red chromian spinel occurs as disseminated grains. Most serpentinites show bastite and mesh textures after orthopyroxene and olivine, respectively, confirming their protoliths as being peridotite. All peridotites show some deformation textures, including foliations and kink structures. Large coarse- and fine-grained gabbroic intrusions show thrust fault contacts with serpentinized peridotite (Figure 3B) and are metamorphosed to greenschist and lower amphibolite facies.

Coarse- and fine-grained gabbros show granular (Figure 3F), microgranular, or interstitial (Figure 3G) textures, and contain plagioclase and pyroxene as major primary minerals, and epidote, albite, chlorite, and calcite as minor secondary phases. The pillow lavas (Figure 3C) are covered by Cretaceous radiolarite (Figure 3D) and highly altered and metamorphosed to greenschist facies; however, exposures in Razab village retain original pillow structures (Figure 3C). They show porphyritic and interstitial textures consisting of plagioclases and pyroxene as main minerals set in a fine-grained plagioclase, pyroxene and olivine groundmass. Plagioclase often has a skeletal texture (Figure 3H)

Eocene Sarv-Abad ophiolite

The Eocene ophiolitic complex located in the Sarv-Abad area is separated from Cretaceous ophiolite occurrences by mylonites belonging to the Sanandaj-Sirjan zone. The Sarv-Abad units consist of several thrust sheets composed of foliated serpentinized peridotite, gabbro, lava, and intercalated sediments of Paleocene to Middle Eocene age (Braud, 1987) which are intruded by mafic and felsic (plagiogranite) dykes (Figure 4A). Serpentinized peridotite contains abundant lenticular bodies, lenses and/or veins of serpentinized dunite (Figure 4B) that are oriented in a NW-facing direction. All peridotites show deformation textures, such as foliation and kinked structures, stretched and rotated porphyroclasts (~1–3 mm in size), set in a fine-grained matrix (crystals <0.5 mm in size). They contain olivine (up to 80 vol. %), orthopyroxene (up to 15 vol. %), augitic clinopyroxene (<5 vol. %), and spinel (ca. 1 vol. %) (Figure 4E).

Large gabbroic intrusions (Figure 4C) intrude the serpentinized peridotite and are overlain by pillow lava. Foliations within this unit are marked by aligned plagioclase and clinopyroxene/amphibole crystals. The main minerals include euhedral to foliated phenocrysts of plagioclase (~45 vol. %), (Figure 4F), pyroxene (~25 vol. %), which is mainly augite and diopside, olivine (~5 vol. %), amphibole and biotite (~5 vol. %) and quartz (<2 vol. %). Magnetite, apatite and ilmenite occur as accessory minerals (<3 vol. %). Clinopyroxene contains inclusions of magnetite, amphibole and biotite, and is uralitized and partly replaced by chlorite. Plagiogranites occur as fine- and coarse-grained layers in the gabbroic rocks and show sharp contacts with the surrounding gabbro (Figure 4C). The modal mineralogical compositions of the plagiogranites comprises sodic feldspar (~25 vol. %), quartz (35–55 vol. %), and plagioclase (40–60 vol. %) (Figure 4H), and biotite, hornblende and opaques as accessory minerals. Alteration of the plagiogranite formed secondary minerals such as epidote, kaolinite, chlorite, and sericite. Plagioclase crystals show polysynthetic zoning. Sodic feldspar crystals likely formed due to the influx of sodic aqueous solutions, albitizing primary Ca-rich plagioclase (Ahmadipour and Rostamizadeh, 2012).

Lavas form the main crustal exposures of the Sarv-Abad complex. Pillow structures (Figure 4D) occur at the highest stratigraphical level of the adjacent magmatic crustal sequence. The pillows range from 50 cm to 1.5 m in diameter, and display some vesicular textures. They typically have a centimeter-thick pale green, originally quenched crust and are overlain with fine hyaloclastites and breccias (Figure 4G). Marls and siliceous limestones interbedded with the lavas have Paleocene-Eocene paleontological ages (Braud, 1987). All these igneous rocks are surrounded by limestone and shale, which are attributed to flysch and turbidity currents of Cretaceous to Paleocene age. The pillow lavas preserve primary porphyritic and variably vesiculated textures and are dominated by plagioclase, clinopyroxene, and olivine (in order of abundances), with opaque and fine-grained titanite as accessory minerals. They are locally characterized by a secondary of minerals of zeolite, calcite, chlorite, albite, and locally epidote, indicating a low- to medium-grade hydrothermal alteration. Dykes are part of the contiguous magmatic crustal sequence and cut ultramafic sequences, both of which are deformed. The occurrences of plagiogranite dykes are generally limited to the uppermost part of the sequence. They also commonly crosscut ultramafic rocks and have well-developed chilled margins. Individual mafic dykes are generally ~0.8–1.5 m wide and can be crystal-rich, containing plagioclase (up to 50%, 0.1–3 cm) and to a lesser extent pyroxene and olivine (~0%–5%) phenocrysts and glomerocrysts.

3. Analytical Methods

Major-element contents of spinel from the Cretaceous Razab peridotites and chromitite were analyzed by a Cameca CAMEBAX electron microprobe (EMP) at the Padowa Earth Science Institute, Italy (Table 1). The accelerating voltage, beam current, and beam diameter for silicate and spinel analyses were ~15 kV, 20 nA, and 3 μm, respectively. The Cr-number (Cr#) and Mg-number (Mg#) of spinels are $Cr^{3+}/(Cr^{3+} + Al^{3+})$ and $Mg^{2+}/(Mg^{2+} + Fe^{2+})$ atomic ratios, respectively. All Fe in silicates was assumed to be ferrous (Fe^{2+}). These data were compiled and compared with major-element contents of silicate minerals and spinel from the Cenozoic Sarv-Abad ophiolitic sequences reported by Saccani *et al.* (2014).

Whole-rock (WR) major and trace element concentrations of Cretaceous Razab ophiolitic sequence units and Eocene diabase and plagiogranite dykes were analyzed via an ARL Advant-XP automated X-Ray Fluorescence (XRF) spectrometer hosted at the Department of Physics and Earth Sciences of the University of Ferrara, Italy. Data were analyzed with the Norris Scientific LADR software package using Al_2O_3 as an internal standard (Norris and Danyushevsky, 2018). Accuracy and precision were better than 2–5% for major elements and 5–10% for trace elements. Detection limits were 0.01 wt. % for major elements and 1–3 ppm for trace element concentrations, respectively. Analyses of Rb, Sr, Y, Nb, Hf, Ta, Th, U, and REE were carried out on a Thermo Series X inductively coupled plasma-mass spectrometer (ICPMS) hosted at the Department of Physics and Earth Sciences of the University of Ferrara, Italy. Precision and accuracy were better than 10% for all elements, well above the detection limits (see Casetta *et al.* 2020 and references therein). To demonstrate that our observed trends are representative for the whole ophiolite, WR compositions from this study are compared with a compilation of previously published and unpublished geochemical WR data for Kurdistan, categorized according to sample type, location, setting and field relations. These data were also compiled by major and trace element contents of Cenozoic peridotite, basalts and gabbro from the Sarv-Abad ophiolitic sequences reported by Saccani *et al.* (2014).

One gabbro and two plagiogranitic dykes from the young Sarv-Abad ophiolite were selected for high precision zircon U-Pb geochronology at the University of California. Single zircons were isolated from the rock material using Selfrag© and standard mineral separation techniques. To minimize the effect of Pb-loss, selected zircons were subjected to chemical abrasion to remove damaged parts of the crystal that likely experienced open-system behavior (Mattinson, 2005). Uranium-Pb isotopic compositions of individual zircons were determined by ID-TIMS using a ^{202}Pb-^{205}Pb–^{233}U–^{235}U mixed-spike and data reduction was carried out using UPb Redux (McLean *et al.* 2011). All dates were corrected for initial Th/U disequilibrium and the uncertainties on the tracer and blank compositions were propagated into the measurement uncertainty. The blank contribution was determined by monitoring ^{204}Pb and assuming that all common Pb (Pbc) was blank-derived.

4. Results

4.1 Geochemical compositions

Cretaceous Razab ophiolite

Several lithologies from the Razab ophiolitic sequence, including chromitite, gabbro and basalt, were analyzed for their mineral chemistry and whole-rock major and trace element contents. Spinel in the Razab chromitite show lower Al_2O_3 (7.4–11.5 wt. %) and TiO_2 (0.08–0.22 wt. %), higher FeO^{tot} (19.3–23.0 wt. %) and Cr_2O_3 (49.7–57.1 wt. %) contents, and similar MnO (<1.1 wt. %) contents to spinel from the young peridotites. This spinel has Mg# = 0.52–0.72 (mean value = 0.57) and Cr# = 0.77–0.82 (mean value = 0.79) (Table 1).

Based on their geochemical features, the lavas investigated in this study can be subdivided into two main groups (Table 2): i) basalt with high SiO_2 (47.9–54.2 wt. %) and MgO (6.6–9.9 wt. %), low Fe_2O_3 (8.5–9.6 wt. %), CaO (8.6–9.6 wt. %), and TiO_2 (1.0–1.2 wt. %), and moderate Al_2O_3 (13.4–14.6 wt. %); and ii) alkaline basalt with lower SiO_2 (45.7–46.6 wt. %) and MgO (3.8–4.0 wt. %) and higher Fe_2O_3 (11.3–12.6 wt. %) and CaO (10.5–12.3 wt. %), and TiO_2 (3.5–4.0 wt. %), and the same Al_2O_3 (13.4–14.6 wt. %) contents. On total Nb/Y vs. Zr/Ti (LeMaitre *et al.* 2002) and Co vs. Th (after Pearce, 1996) diagrams, all lavas fall in the ‘basalt’ and ‘alkaline basalt’ fields, and have island arc tholeiitic (IAT) or back-arc and calc-alkaline affinities, respectively (Figure 5A-B). Basalts with Ti/V ratios in the range 20–29 (average = 25) mainly show N-MORB-like signature (Shervais, 1982), and show a MORB and/or fore-arc affinity in TiO_2 vs. FeO/MgO (Figure 5C-D) and Yb vs. V diagrams (Lázaro *et al.* 2016). Their chondrite-normalized LREE contents show slight depletion and plot near the N-MORB field, with $(La/Yb)_N$ and $(Dy/Yb)_N$ having mean values of 0.86 and 1.1, respectively (Figure 5G). In PM-normalized multi-element diagrams (Sun and McDonough, 1989), the Razab basalts have slight negative Nb and Ti anomalies (Figure 6H). In contrast, the alkaline basalts show high Ti/V ratios of 71–81, which are similar to oceanic island basalt (OIB) Ti/V ratios of 50–100 (Shervais, 1982). Their chondrite-normalized pattern displays enrichment in LREE and plot near the OIB field, having $(La/Yb)_N$ and $(Dy/Yb)_N$ mean values of 9.62 and 1.9, respectively (Figure 5G).They are enriched and lack Nb and Ti negative anomalies (Figure 5H).

The gabbro samples from the Razab have SiO_2 = 50.1–50.3 wt. %, Al_2O_3 = 15.5–15.9 wt. %, CaO = 5.8–6.6 wt. %, FeO = 12.3–13.3 wt. %, and TiO_2 = 0.7–0.8 wt. %. The samples fall in the 'basalt' field, which is equivalent of gabbro on the Nb/Y vs. Zr/Ti (TAS) diagram (Winchester and Floyd, 1977) and Co vs. Th (Pearce, 1996), respectively (Figure 5A-B). The gabbros show Ti/V ratios with a range of 10–13 (average = 11), which resemble fore-arc signatures (Shervais, 1982). They also show affinity to mafic magma having signatures of fore-arc, as shown in the TiO_2 vs. FeO/MgO (Figure 5E) and Yb vs. V diagrams (Lázaro *et al.* 2016); however, two samples with high Al_2O_3 (>18 wt. %) are likely related to plagioclase accumulation. In the chondrite-normalized REE diagram (Sun and McDonough 1989), the gabbros display $(La/Yb)_N$ and $(Dy/Yb)_N$ mean values of 4.4 and 1.1, respectively. The Eu anomaly is slightly negative (average = 0.9). In PM-normalized trace elements diagram (Sun and McDonough 1989) (Figure 6I-J) gabbros show profiles similar to that of PM. They are characterized by depletion of LILEs (such as Th) and HFSEs (such as Ti, Zr, and Hf), with respect to clear positive anomalies of Nd and Eu (REEs).

Eocene Sarv-Abad ophiolite

Units of the Sarv-Abad ophiolitic sequences, including peridotite (dunite and wehrlite), gabbros and basalts (Saccani *et al.* 2014; Supplementary Table 1b) and diabase and plagiogranite dykes (this study) were evaluated for mineral chemistry and whole-rock major and trace elements.

Plagioclase in Sarv-Abad gabbroic intrusions has compositions of Ab = 38-45 mol. %, An = 55-60 mol. %, and Or = 0.4-0.6 mol. %. Spinel in the Sarv-Abad dunites show variable Al_2O_3

(12.5–19.7 wt. %) and FeO^{tot} (13.5–20.2 wt. %) with high Cr_2O_3 (40.3–44.5 wt. %) contents, but low MnO (<1.1 wt. %) and TiO_2 (0.98–4.24 wt. %) values (Saccani *et al.* 2014). Spinel shows Mg# of 0.49–0.66 (mean value = 0.54) and Cr# of 0.60–0.68 (mean value = 0.65) (Supplementary Table 1a; Saccani *et al.*2014). Spinel in the Sarv-Abad wehrlite has higher Al_2O_3 (20.1–29.2 wt. %), and lower Cr_2O_3 (32.4–42.7 wt. %) contents than those of the dunites. This spinel is characterized by narrow ranges in Mg# (0.60–0.69; average = 0.65) and Cr# (0.49–0.52; average = 0.51) (Supplementary Table 1a; Saccani *et al.* 2014). Spinel in wehrlite has higher Al (average = 0.82 a.p.f.u.) and lower Cr (average = 1.03 apfu) contents with respect to dunite, falling in the range of abyssal peridotite values, whereas those from dunite overlap ranges of abyssal and forearc peridotites.

Olivine from Sarv-Abad dunites and wehrlite has a similar composition, having low MnO (0.1–0.2 wt. %) and Cr_2O_3 (<0.1 wt. %) contents. Their Fo = 88–91 mol. % and NiO = up to 0.4 wt. % (Supplementary Table 1a; Saccani *et al.* 2014) resembles residual mantle olivine (e.g. Arai, 1994; Khedr *et al.* 2014; Khedr and Arai, 2013) that formed at the intersection of abyssal and forearc peridotites (Pagé *et al.* 2008).

The Sarv-Abad peridotite samples show loss of ignition (LOI) values in the range 7.3–12.4 wt. %, signifying moderate to high degrees of serpentinization (Supplementary Table 1b; Saccani *et al.* 2014). They have low SiO_2 (40.6–45.4 wt. %), Al_2O_3 (0.7–1.9 wt. %), CaO (0.2–0.6 wt. %) and TiO_2 (0.02–0.13 wt. %) contents. Their CaO/Al_2O_3 (0.12–0.4) and Mg# (0.89–0.91) ratios, and Cr (1313–2393 ppm) and Ni (2102–2263 ppm) contents are close to PM values (CaO/Al_2O_3 = 0.8, Mg# = 0.88, Cr = 3240 ppm; Hart and Zindler, 1986; McDonough and Sun, 1995; Workman and Hart, 2005), showing a peridotite with refractory character ($Al_2O_3/SiO_2 < 0.05$ and MgO/SiO_2 = 0.98–1.1). In a chondrite-normalized diagram (Sun and McDonough 1989) (Figure 6A), the Sarv-Abad peridotites show LREE to HREE sub-chondritic flat profiles, with $(La/Yb)_N$ and $(Dy/Yb)_N$ values of 0.07–1.07 and 0.007–1.03, respectively. The Eu anomaly ($Eu/Eu^* = [Eu_N/(Sm_N \times Gd_N)^{1/2}]$) and the Ce anomaly ($Ce/Ce^* = [Ce_N/(Ce_N \times Nd_N)^{1/2}]$) are negligible (mean values 0.99 and 1.02, respectively). In a PM-normalized multi-element diagram (Sun and McDonough, 1989) (Figure 6B), the peridotites show slightly depleted profiles with a minor enrichment of HFSEs (e.g. Zr, and Ti). The Sarv-Abad peridotites are similar to abyssal peridotites (Figure 6), and have compositional similarity to those from the South-Sandwich arc-basin system (SSABS) (Pearce *et al.* 2000).

The major element compositions of the whole-rock lava are basaltic (Figure 5A), with variable MgO = 5.8–11.7 wt. % (Mg# = 0.43–0.61) contents and very little evidence of hydrous alteration (L.O.I. = 1.1–3.0 wt. %) (Supplementary Table 1b; Saccani *et al.* 2014). They are characterized by SiO_2 = 48.3–52.5 wt. %, with moderate Al_2O_3 (13.9–17.8 wt. %), FeO (6.4–11.7 wt. %), CaO (8.6–11.9 wt. %) and TiO_2 (1.03–1.76 wt. %). On Nb/Y vs. Zr/Ti (Winchester and Floyd, 1977) and Co vs. Th (After Pearce, 1996) diagrams, all basalts fall in the 'basalt' field, except for one sample that shows a tholeiitic island arc signature. They show moderate Cr (73–317 ppm), Ni (57–161 ppm), and V (178–332 ppm). The basalts contain TiO_2 = 0.8–2.5 wt. % and have Ti/V values of 25–45 (average = 35), which are E-MORB-like signatures (Shervais, 1982). They also show affinity to mafic lava having a signatures between MORB and back-arc in the TiO_2 and Al_2O_3 versus MgO (Figure 5C-D) and TiO_2 vs. FeO_t/MgO diagrams (Lázaro *et al.* 2016). These diagrams indicate that most of the studied samples fall within or very close to the field of back-arc and MORB basalts (Figure 5E).

Magmatic major element fractionation trends can be affected disrupted by crystal accumulation and hydrothermal alteration. The following geochemical characterization thus focuses on immobile or little-mobile trace elements (TiO_2, Zr, Y, Nb, V, Yb and REEs) that largely remain unaffected by alteration and low-grade metamorphism (e.g., Seyfried *et al.* 1988; Gillis and Thompson, 1993; MacLean and Barrett, 1993; Hofman and Wilson, 2007; Furnes *et al.* 2012). Following the definitions from Gale *et al.* (2013), most lavas have MORB-like to back-arc-like TiO_2, Zr, Y, and Nb contents (Nb/Y < 0.8, "low-Nb") and variable REE compositions that range from D-MORB ($La_N/Sm_N < 0.8$; McDonough & Sun, 1995) to E-MORB ($La_N/Sm_N > 1$). They also show affinity to mafic lava having a signatures between MORB and back-arc in the V vs. Yb (Figure 5F) diagram (Lázaro *et al.* 2016). Most compositions overlap (La_N/Yb_N = 0.82–1.9), although one mafic sample is slightly more enriched (La_N/Yb_N = 7.06), indicating two geochemical types: LREE-depleted and LREE-enriched (Figure 5G). Those with slightly depleted LREE lie near to the N-MORB field, whereas slightly enriched LREE samples plot near the E-MORB field. The rocks with slightly depleted LREE contents have $(La/Yb)_N$ and $(Dy/Yb)_N$ mean values of 0.8–1.9 and 1.1–1.2, respectively, with lack an Eu anomaly (average = 1.0). In contrast LREE-enriched samples have $(La/Yb)_N$ and $(Dy/Yb)_N$ average values of 7.06 and 1.2, respectively (Figure 5G). In PM-normalized multi-element diagrams (Sun and McDonough, 1989), both types of Sarv-Abad basalts show enriched patterns, without Nb and Ti negative anomalies (Figure

5H). They show affinities of normal and enriched-type mid-ocean ridge basalts (N-MORB and E-MORB) respectively (Sun and McDonough, 1989).

Gabbro samples have SiO_2 = 48.5–51.4 wt. %, Al_2O_3 = 12.9–19.5 wt. %, CaO = 10.9–13.6 wt. %, FeO = 3.8–7.5 wt. %, TiO_2 = 0.2–0.7 wt. %, Cr = 99–705 ppm, Ni = 83–463 ppm, and V = 35–205 ppm (Supplementary Table 1b; Saccani *et al.* 2014). All fall in the field of ‘basalt and basaltic andesite’, which lie within trachyandesite and calc-alkaline series on the Nb/Y vs. Zr/Ti diagram (Winchester and Floyd, 1977) and Co vs. Th (after Pearce, 1996) (Figure 5A-B). They show heterogenous LILE (e.g., Sr: 65–413 ppm) and HFSE (e.g., Nb: 2–13.8 ppm, Y: 2–24 ppm, and Zr: 16–81 ppm) contents, with signatures between MORB and back-arc basin (BABB) in the TiO_2 and Al_2O_3 versus MgO (Figure 5C-D). In addition, some gabbros have TiO_2, Zr, Y and Nb contents (Nb/Y: < 0.8; “low-Nb) and REE compositions ($La_N/Sm_N < 1$; La_N/Yb_N = 0.8–1.2; McDonough & Sun, 1995) resembling D-MORB (definitions from Gale *et al.*, 2013; Figure 5A-D). In contrast, some have more enriched features with Y and Nb contents (Nb/Y = 1.6–6.93; “high-Nb”) and REE compositions resembling E-MORB ($La_N/Sm_N > 1$; $La_N/Yb_N = 1.7$, with lack a Eu anomaly (mean value of ~1.0; McDonough & Sun, 1995). The chondrite-normalized REE pattern is rather flat in the MREE–HREE plots (at about 10–13 × C1) and is relatively LREE enriched ($La_N/Sm_N > 1$).

The major and trace element whole-rock compositions of the diabase and plagiogranite dykes are reported in Table 2. Mafic dykes have SiO_2 = 41.7–53.8 wt. %, Al_2O_3 = 14.0–18.3 wt. %, FeO = 9.3–13.2 wt. %, CaO = 4.6–12.4 wt. %, and TiO_2 = 0.6–2.3 wt. % and show variable LOI contents (2.4–8.6 wt. %; Table 2). They overlap within MORB and back-arc basin basalt (BABB) compositional spaces and resemble differentiation trends seen in the Semail ophiolite (Figure 5C-F). Samples with TiO_2 = 0.6–2.3 wt. % and Ti/V ratios of 14–60 (average = 38) mainly show E-MORB-like signature (Shervais, 1982). All of the diabase dykes have MORB-like Y and Nb contents (Nb/Y < 0.8, “low-Nb”), but have REE compositions that are comparable with E-MORB ($La_N/Sm_N > 1.5$; Table 2). They are slightly more enriched (La_N/Yb_N = 1.9–8.2, average = 4.4, $n = 4$) than the lava (La_N/Yb_N = 0.85–1.9, with one analysis of 7.1), average 1.4, $n = 5$.

The Sarv-Abad plagiogranite dykes have higher SiO_2 contents (62.8–7 wt. %) than the diabase dykes (Table 2), and are enriched in Na_2O (5.4–9.6 wt. %) and depleted in K_2O (0.1–0.2 wt. %) (Table 2), which are characteristic of plagiogranites (Coleman and Peterman,

1975) worldwide. Total REE contents of the plagiogranite vary from 90 to 220 ppm, which are generally higher than those of diabase dykes (62.0–117 ppm). They are relatively enriched in LREE (Figure 5I), with $(La/Yb)_N$ ratios of 2.2–8.3 and negative Eu anomalies (0.3–0.6; except for one samples with positive value of 1.17) (Figure 5G). Most of the plagiogranites are depleted in HFSE (Nb, Ti and P) and enriched in LILE (Rb and K) (Figure 5H).

4.2 Geochronology

Cretaceous (Razab) ophiolites

Samples from Razab contain some poorly preserved radiolarians and abundant sponge spicules. These spicules are Mesozoic, and probably Jurassic–Cretaceous in age (not Triassic), although a precise stratigraphic age cannot be obtained from them as sponges typically show very slow evolutionary changes (Supplementary Appendix 1; Supplementary Figure 1)

Cenozoic (Sarv-Abad) ophiolites

U–Pb dating was performed on zircons from one gabbro and two plagiogranite dykes from the Sarv-Abad ophiolite (Table 3). Zircons from gabbro sample Q-41 are euhedral prismatic crystals of 100–250 µm in length with aspect ratios of 2:1–3:1. They are typical magmatic zircons with clear oscillatory zoning and high Th/U ratios (0.99–1.07). The $^{206}Pb/^{238}U$ apparent ages of three points range from 37.4 Ma to 38.98 Ma, with a weighted average of 38.4 ± 1.3 Ma (MSWD = 0.2) (Figure 7A). Zircons from two plagiogranitic dykes (Q-122 and Q-81) are euhedral prismatic crystals of 100–300 µm in length with aspect ratios of 1:1–3:1. The zircons are magmatic with clear oscillatory zoning and high Th/U ratios (1.0–1.3 and 0.5-1.4, respectively). The $^{206}Pb/^{238}U$ apparent ages of six analyses from Q-81 range from 38.1 Ma to 50.69 Ma, with a weighted average value of 41.2 ± 1.0 Ma (MSWD = 0.02) and six analyses from Q-122 range from 37.8 Ma to 43.9 Ma, with a weighted average value of 42.1 ± 1.1 Ma (MSWD = 0.001) (Figure 7B-C).

5. Discussion

The Kurdistan ophiolite complexes comprise the Eocene Sarv-Abad and Cretaceous Razab ophiolites. Both sequences contain mantle and crustal components, including peridotites, gabbros, and diabase sheeted dykes and extrusive sequences including pillow lava, and mafic and felsic (plagiogranite) dykes. The geochemical and geochronological results obtained in this work for the Kurdistan ultramafic-mafic rocks and felsic dykes provide context to understand the chemical and temporal evolution of the Kurdistan ophiolite complexes, and the relationship between D-MORB and E-MORB on Sarv-Abad and present-day MORs. Although, the existences of E-MORB and D-MORB rocks have been inferred as temporal variations in parental melt components (e.g., Batiza and Niu, 1992), the simultaneous occurrence of distinct magma plumbing systems (e.g., Perfit *et al*. 1994), and temporal variations in magma volumes that affect the productivity of contemporaneously D- and E-MORB magmas (e.g., Waters *et al*. 2011) can be also deduced. A revised geochronological and tectonic model for Kurdistan ophiolites has also been proposed.

5.1. Chemical Evolution of Kurdistan ophiolites

Petrogenesis of Kurdistan ultramafic melts

The whole-rock compositions of peridotites from the Cretaceous Razab and Eocene Sarv-Abad ophiolite complexes, along with their mineral assemblages (Spl + Ol + Px) and chemistry, records the nature and evolution of the Kurdistan ultramafic rocks. The Cr-spinel from the Razab chromitite has high Cr# (0.76–0.82, average = 0.79) and Mg# (0.53–0.72, average = 0.57), which resemble those found in forearc environments (Mg# = 0.45–0.65; Cr# = 0.40–0.80; Parkinson and Pearce, 1998), and shows some similarity with those that form in SSZ settings (e.g. Ishii *et al*. 1992; Khedr and Arai, 2017). The affinity with SSZ environments was also suggested by Nouri *et al*. (2018) for the mantle section of Mesozoic ophiolites from the Kurdistan and Makran peridotite (Sepidbar *et al*. 2020) and South-Sandwich arc-basin system peridotites (Pearce *et al*. 2000).

The Cr-spinel in Sarv-Abad peridotites has a high Cr# (0.58–0.69, average = 0.64) and Mg# (0.48–0.65, average = 0.57), signifying its origin from a depleted mantle source region. Based on Mg#, Cr# and Al–Cr–Fe^{3+} values, spinel analyses show affinities to forearc (Mg# = 0.45-0.65; Cr# = 0.40–0.80; Parkinson and Pearce, 1998) and abyssal peridotites (Mg# = 0.45–0.85; Cr# = 0.10–0.60; Warren, 2016). The Fo (88–91 mol. %) and NiO (0.22–0.56 wt. %) contents of olivine from the Sarv-Abad peridotites resembles residual mantle olivine (Fo = 89–92 mol. %; NiO = 0.20–0.55 wt. %; (after Pagé *et al*. 2008). The Cr# of spinel and Fo content of olivine in Sarv-Abad peridotites corresponds with the olivine–spinel mantle array ($Fo_{olivine}$ = 88–94; OSMA; Arai, 1994), abyssal peridotites ($Cr\#_{Spinel}$ = 0.10–0.60; $Fo_{olivine}$ = 0.90–0.92; After Arai, 1994) and SSZ peridotites ($Cr\#_{Spinel}$ = 0.30–0.85; $Fo_{olivine}$ = 0.90–0.93; Pearce *et al*. 2000). The studies samples are therefore similar to peridotite from Izu-Bonin-Mariana fore-arc peridotites (Pearce *et al*. 2000), and we interpret that the Sarv-Abad peridotites are moderately depleted and originated in a SSZ setting. Relationships between spinel Cr# and olivine Fo content (not shown) show that the Sarv-Abad peridotite represents a mantle residuum that formed after 20–30 vol. %, melt extraction from a pristine fertile MORB mantle (FMM; e.g., Khedr and Arai, 2017). The geochemical characteristics of the Sarv-Abad peridotite, such as MgO (38.1–42.8 wt. %), CaO (0.22–02.56 wt. %), and Al_2O_3 (0.75–1.86 wt. %) contents (Supplementary Table 1b), are typical of depleted mantle (MgO = 38.73 wt. %; CaO = 0.7–2.8 wt. %, and Al_2O_3 = 0.7–3.0 wt. %; Pearce *et al.* 1992), signifying that these ultramafic units experienced partial melting and extraction of melts (Lian *et al.* 2019). Elevated MgO/SiO_2 ratios (average = 1.04) and depleted Al_2O_3/SiO_2 ratios (average = 0.03) (Supplementary Table 1b) in Sarv-Abad peridotite samples compared to PM (MgO/SiO_2 = 0.8; Al_2O_3/SiO_2 = 0.1; after McDonough and Sun, 1995; Workman and Hart, 2005) and DMM (MgO/SiO_2 = 0.84.; Al_2O_3/SiO_2 = 0.10; after McDonough and Sun, 1995) also specify that the Sarv-Abad peridotites are mantle residues that formed following moderate to high degrees of melt extraction (Barnes *et al.* 2014; Lian *et al.* 2019).

Petrogenesis of Kurdistan mafic melts

The Razab mafic suite contains gabbro that is crosscut by diabase dikes, and overlain by pillow lavas. A minimum Cretaceous age for basaltic lavas eruption and emplacement can be inferred from the age of radiolarite that covers the pillow lavas. The primary contact between the gabbros and the upper pillow lava and the presence of cross-cutting diabase dikes require a relatively older age for the gabbros, which must have solidified prior to basaltic eruption and diabase emplacement. Basalts display two (Figure 6I-J) REE- and trace-element patterns that are (i) distributed between depleted MORB mantle (DMM) and N-MORB fields, compatible with low-Ti IAT from SSZ (Saccani *et al.* 2018) and falling in the forearc basalt (FAB, Reagan *et al.* 2010) field of conventional classification diagrams, and (ii) those distributed in the OIB field. Gabbro records enriched REE and trace-patterns comparable to E-MORB and high-Ti N-MORB melts from SSZ environments (Saccani *et al.* 2018). The consistent Nb, Th, and Ti depletion in gabbro and some DMM and the N-MOR mafic rocks again supports magma genesis in a SSZ environment (e.g. Khedr and Arai, 2017;

Rossetti *et al.* 2017). While some basalts have an N-MORB character, and gabbros from Razab have E-MORB affinity, some of the studied lavas have OIB-like alkaline signatures (Ghazi *et al.* 2004), which can be interpreted as distinctive of the evolution of Early Cretaceous arc-basin system or lower partial melting of mantle source. The N-MORB and OIB basalts from Razab plot in the MORB-OIB array, while E-MORB, calc-alkaline gabbros plot above the MORB-OIB array towards the composition of lower continental crust (Supplementary Figure 2A; LC; after Pearce, 2008), which implies selective Th addition from subducted sediments and/or from assimilation of continental crust components. In summary, the Razab mafic magmatic rocks (especially N-MORB basalts and gabbros) are characterized by an IAT and calc-alkaline signature (Figure 5B; Hastie *et al.* 2007) respectively, subduction-related ophiolite (Th/Yb vs Nb/Yb diagram in Supplementary Figure 2A; after Dilek and Furnes, 2011), and a main forearc affinity (FAB in Th vs Gd/Lu diagram; modified after Deschamps *et al.* 2013) (Supplementary Figure 2B).

The Sarv-Abad mafic suite also contains basalt, gabbro, diabase, and felsic dykes. Our data also show that the different gabbro, lava, and dyke groupings on Sarv-Abad have variable ranges in trace elements concentrations that overlap with the MORB array (from N-MORB to E-MORB) and extending to more enriched LREE compositions in the younger mafic dykes (Figs. 5). The minor variations in MgO, Cr, and Ni contents between lava and gabbro, along with the restricted thickness of the gabbroic lower crust, argues against a secondary role for magmatic fractionation in forming the trace element variations. Alternatively, the enriched trace element compositions could have formed by a combination of low degrees of partial melting and an increased influence/contamination by an enriched mantle source. To discriminate between the importance of degree of melting and mantle source, we tested covariations between Nb/Y and Zr/Y, which have been studied in detail in Icelandic lavas (Fitton *et al.* 1997). This covariation has global importance and can be used to recognize enriched mantle sources in MORB and OIBs. Low pressure fractional crystallization has no significant effect on these ratios for MgO > 5 wt. % and various degrees of melting causes covariance along linear arrays parallel to the Iceland array (Figure 8A). Any vertical changes from the array, stated as additional values from the reference pattern of the lower bound of the Iceland array, can be inferred from source heterogeneity (Fitton *et al.* 1997). This modeling suggests that the studied units formed from a diverse range of melt compositions, including Nb-depleted to Nd-enriched melts. This geochemical overlap proposes that the magmatic processes that generated the lava, gabbro and dyke are closely intertwined, in agreement with a transitional magmatic system where the range of melt compositions becomes more enriched over time (Figure 8B). However, despite the irregular differences within each defined subgroup, the mafic dykes are somewhat more LREE enriched (Figure 5E) and Nb/Y- enriched than the other components (Figure 8B), a phenomenon in Sarv-Abad that may be expected since they are younger than the lavas (59–52 Ma; Ghorbani *et al.* 2022).

Figure 8 shows that the Sarv-Abad gabbro, lava and mafic dykes are derived from a source with heterogeneous Nb concentrations. Additionally, the results propose that the more Nb-enriched rock that can be generated by low degrees of partial melting of the enriched component may also contributed to the formation from E-MORB sources. This agrees with previous works, which show that the Sarv-Abad melts are geochemically variable (Ghorbani *et al.* 2022; Ao, 2016). It has been suggested that melting in the spinel, spinel-garnet transitional, or garnet stability fields would generate low Dy/Yb ratios (<1.5), moderate Dy/Yb ratios (1.5–3), and high Dy/Yb (>2.4) ratios, respectively (e.g., McKenzie and O'Nions, 1991). The measured Dy/Yb ratio of all basalt, gabbro and mafic rocks in Sarv-Abad is less than 2, which suggests that all mafic rocks formed in the spinel-garnet transitional stability field. These rocks with N- and E-MORB characteristics thus partly correspond with suites of the Masirah ophiolite (Oman), as suggested by Jansen *et al.* (2024).

The plagiogranitic dykes are characterized by elevated Zr/Hf ratios (36.0–48.5) that are close to those of typical MORB (33–40) (Büchl *et al.* 2002), but markedly more than those of average granite (25) (Münker *et al.* 2003), implying a mantle-derived source. Plagiogranites may originate from fractionation of basaltic magmas (Pedersen and Malpas, 1984; Jiang *et al.* 2008) or via partial melting of metasomatized gabbros, basalts, or amphibolites (Pedersen and Malpas, 1984). Research shows that plagiogranitic melt compositions resulting from fractional crystallization of basaltic magmas differs distinctly from those formed by partial melting of gabbros and amphibolites (Kopek *et al.* 2004), particularly for TiO_2, SiO_2, and K_2O contents. The former model suggests that plagiogranites are extremely fractionated melts generated by the fractionation of parental MORB melt (Coleman and Peterman, 1975), while the latter model suggests that plagiogranitic melts formed during partial melting of metasomatized gabbros, caused by the deep infiltration of hydrothermal fluids into oceanic crust along detachment faults (France *et al.* 2010). The Sarv-Abad plagiogranites have a compositional variation that shows similarities with melts produced by partial melting of metasomatized gabbroic and amphibolitic rocks from the lower oceanic crust (Supplementary Figure 3).

5.2. Temporal Evolution of Kurdistan Ophiolites

New U–Pb zircon ages presented here propose a formation age of 38 Ma for gabbros and 41 Ma for plagiogranite dykes from Sarv-Abad (Table 3), which correspond with the ages of Sahneh-Kamyaran gabbro from Kermanshah ophiolite obtained by Ao *et al.* (2016). Previous geochronological studies suggest two episodes of oceanic crust formation within the KWOC: (1) Late Cretaceous ophiolitic units in the Harsin and Sahneh (Kermanshah), Sarv-Abad and Razab (Kurdistan), Hassanbang, Mawat, Rayat, Qalender and (ii) Paleocene-Middle Eocene to Oligocene ophiolitic units in Sarv-Abad, Sahneh, Kamyaran, Walash and Naupordan. The zircon age of 79.3 ± 0.9 Ma reported by Ao *et al.* (2016) is the best estimate of the crystallization age of the gabbro in the Harsin ophiolite, and these authors also reported DMM and N-MORB signatures for this gabbro. In contrast, ages of 39–37 Ma have been reported for the Sahneh and Kamyaran gabbros, which are characterized with flat REE patterns and positive Eu anomalies, marked positive Sr anomaly and weak negative anomalies for Nb and Zr. These characteristics resemble those of gabbroic rocks from the Atlantis Massif, a well-known example of an oceanic core complex exposed by detachment faulting (Boschi *et al.* 2006) in an extensional setting. Recently, Allahyari *et al.* (2010) also reported both E-MORB and N-MORB signatures for the gabbros in the Sahneh areas. The Eocene gabbros (~38 Ma) in the Sarv-Abad region also show similar geochemical signatures (i.e. REE patterns) and ages to the Sahneh-Harsin gabbro, although show no Eu anomalies and are more enriched in Nb. They are compatible with moderate- to high-Ti N-MORB (Saccani *et al.* 2018), and plot in the field of extensional (back-/fore-arc) basins (Reagan *et al.* 2010).

The Eocene basalts and mafic dykes of Sahneh and Kamyaran show either OIB to E-MORB or calc-alkaline signatures (Whitechurch *et al.* 2013). However, the rocks reported here and basalts reported by Gorbani *et al.* (2022) suggest two types of lavas with different REE patterns: those weakly depleted in LREE and those with relatively flat REE patterns ($(La/Yb)_N$ values of 0.77–1.24), and weakly LREE-enriched rocks ($(La/Yb)_N$ average = 1.7) that lack an Eu anomaly. Ghorbani *et al.* (2022) indicated that these subgroups show different K-Ar extrusion ages, being Paleocene–Eocene (59–50 Ma) and Oligocene (29 Ma), respectively. The basalts of this study show depleted to slightly enriched REE patterns with $(La/Yb)_N$ values between 0.8 and 1.8. These values agree with the features reported by Gorbani *et al.* (2022), and they have no negative Nb or Ti anomalies, indicative of minimal, or any role of a subducted-modified mantle source; however, one basaltic sample is characterized by high-Ti, tholeiitic to slight calc-alkaline affinity, more like those of immature back-arc basins. Consequently, we propose that the Eocene Sarv-Abad basalts were derived from a depleted mantle source situated below an extensional basin above a subduction zone that was weakly metasomatised by fluid from dehydrating crustal materials undergoing prograde metamorphism during subduction (e.g., Palin and White, 2016).

The Oligocene lavas (29 Ma) (Ghorbani *et al.* 2022) and one undated basaltic sample (this study) (Whitechurch *et al.* 2013) show intermediate tholeiitic to calc-alkaline affinity, and are moderately fractionated and characterized by somewhat enriched LREE patterns, signifying lower partial melting degrees in their source region and/or more enrichment in incompatible elements. It has been proposed that Ba/Nb, Th/Nb and Ba/Th ratios can be used as tracers for evaluating contributions by total, deep and shallow subduction, respectively (Pearce and Stern, 2006). Geochemical mapping of subduction input proxies of the Sarv-Abad mafic rocks are characterized by higher Ba/Nb (average = 8.3), Th/Nb (average = 0.08), Ba/Th (average = 94) ratios relative to average values of these ratios for N-MORB (Ba/Nb = 2.70; Th/Nb = 0.052; Ba/Th = 52.50), respectively (Sun and McDonough, 1989), emphasizing the minor role of slab-derived fluid component(s) in the genesis of Sarv-Abad Paleocene-Eocene extensional basin basalts. The Oligocene basaltic rocks from Sarv-Abad, which are reported by Ghorbani *et al.* (2022), are characterized with higher Ba/Th (average = 59–202) and Ba/Nb (average = 4–31) ratios compared to Paleocene-Eocene basalts and N-MORB. These authors suggested that the Sarv-Abad Oligocene basalts formed in a more mature back-arc basin.

5.3. Associations between D-MORB and E-MORB in Sarv-Abad and present-day MORs

This study highlights the difficulty in labelling magmatic systems or mid-ocean ridge/extensional segments as entirely N-MORB, D-MORB, E-MORB, or OIB, and reveals that the compositional evolution of a ridge segment may be complex or change with time. Significantly, the crustal suites defining the Razab and Sarv-Abad ophiolites show that D-

MORB and E-MORB and OIB melts can originate from the same melting column and form basalt, gabbro and crosscutting dykes during accretion of oceanic crust As mentioned above, the changes in melt compositions of the studied basalt and gabbro were derived from variable degrees of partial melting at moderate depth (garnet-spinel-field) of a heterogeneous source and were conserved during melt transference and crustal processing.

To test whether the compositional evolution observed at Sarv-Abad may be applicable to other MORs worldwide, we examined the compositional variation of MORB within ridge slices using the compilation of Gale *et al.* (2013). Figure 9 displays the La_N/Sm_N and Nb/Y compositions of several MORB slices that are situated more than 500 km away from a hotspot. Most MORB slices range in composition from D-MORB to E-MORB, showing that the variability preserved in Sarv-Abad also occurs along some modern MORs. Furthermore, Nb-enriched compositions (Nb/Y > 0.8, heavy brown symbols; Figure 9) are present at some MORB slices. Studies on modern MORBs show that trace element variation derived from mantle source regions decreases with increasing magma supply and increasing magmatic fractionation (Rubin and Sinton, 2007). In widely spaced magmatic ridge settings, a broader diversity of melt compositions tends to be retained owing to the limited extent of magma mixing. Importantly, the coexistence of D-MORB and E-MORB within a single ridge segment is significantly more frequent at slower-spreading ridges (<~40 mm/yr; 10 out of 37 segments, ~27%) than at faster-spreading ridges (>~60 mm/yr; 1 out of 10 segments, ~10%; Figure 8), which are characterized by higher magmatic activity. The Sarv-Abad mantle source maintained a well-constrained system that yielded basalts with depleted and enriched compositions, and Nb-depleted and -enriched basalts that formed in plume-unrelated oceanic system (e.g., Hirano *et al.* 2006). These basalts additionally seem to have a higher potential to preserve their compositions throughout subduction processes, as exemplified by the accretion of trace element enriched seamounts in Costa Rica (Buchs *et al.* 2011) and Anglesey, UK (Saito *et al.* 2015), along with the extensive occurrence of alkali basalts in the Tethyan realm (e.g., the Haybi volcanics beneath the Semail Ophiolite nappe in the northern Oman; Searle *et al.* 1980). Although there are differences in tectonic setting, some of these rocks seem to have similarity in terms of formation by low degrees of melting of an enriched mantle source (e.g., Fitton, 2007). Our work shows that such rocks do not essentially need a deep mantle source and can, alternatively, be generated from the same heterogeneous mantle that underlies the extensional slow spreading ridge.

5.4. Tectonic evolution model for Kurdistan ophiolites

The Iranian plate rifted from the Arabian plate as a micro-continental fragment in response to the Neo-Tethys oceanic lithosphere opening during the Late Triassic (Moghadam *et al.* 2015; Agard *et al.* 2005; Agard *et al.* 2011) (Figure 10A). It was followed by subduction initiation of Neo-Tethys beneath the Iranian plate during Late Jurassic-Early Cretaceous (Ghasemi and Talbot, 2006; Moghadam and Stern, 2021), leading to formation of low-to medium-pressure metamorphism along with magmatic activity across the Iranian plate. We suggest that interoceanic subduction initiation plays a critical role in the formation of Late-Cretaceous KWOC ophiolites, including those in the Kurdistan ophiolite. The process involves the onset of subduction in a previously passive or extensional tectonic setting (Figure 10B). Therefore, during the Late Cretaceous, the Neo-Tethys Ocean was undergoing closure due to convergence between the Arabian and the Iranian plates. Subduction initiation often occurs at the zones of weakness such as detachment faults in the lithosphere, leading to the initiation of a fore/island arc setting magmatism (Figure 10B). High-temperature/low-pressure conditions in the forearc and island arc environments leads to upwelling and decompression melting, resulting in the layered structure of ophiolites (peridotites, gabbro, dike complexes, and pillow lavas) (Figure 10B). Following their formation, these ophiolites were emplaced onto the continental margin during continued plate convergence, marking the transition from oceanic to continental tectonic environments (Figure 10C). This model is confirmed by SSZ signatures of Kurdistan ophiolite igneous rocks, particularly for mantle peridotite (Nouri *et al.* 2018), and by the existences of early MORB-like lavas in some of these ophiolites, which are succeeded by more arc-like lavas (Whattam and Stern 2011).

Mineral compositions show that chromitite from Razab ophiolite formed within a forearc peridotites. This confirms the existence of an extensional/forearc environment for Mesozoic peridotites during forearc spreading associated with subduction initiation. This requires a depleted SSZ mantle origin for these chromitites, given the high degrees of partial melting in SSZ settings. Similar geochemical signatures in peridotite caused by comparable degrees of melting in the response of comprehensive extension that accompanied subduction initiation were reported by Moghadam and Stern (2021). These are the mantle expressions of subduction initiation, as documented in several well-known ophiolite volcanic sections by Whattam and Stern (2011), whereby subduction initiation is manifested by early expressions of tholeiitic basalts in the forearc. Upwelling of asthenospheric (OIB-like) mantle beneath the forearc region during the early stages of subduction initiation first resulted in decompression melting in the FAB (Reagan *et al.* 2010). Such melts crystallized spinel with compositions like those of chromities and the OIB-like basalts in Kurdistan. These FAB melts were also followed by generation of arc-like melts as slab-derived fluids intruded in the zone of melt generation in the mantle wedge as the sinking slab descended further. These later arc-like melts formed Mesozoic tholeiitic basalts and calc-alkaline gabbro of Kurdistan (Figure 10C).

The magmatic rocks exposed on Sarv-Abad ophiolite took place at 59 Ma (Ghorbani *et al.* 2022), extended to Eocene (41–36 Ma; this study) and the latest magmatic activity occurred in the Oligocene (~29 Ma, Ghorbani *et al.* 2022). U–Pb dating of gabbros and plagiogranites (~42-38 Ma; this study) (Figure 7) and basaltic rocks (59–29 Ma; Ghorbani *et al.* 2022) indicates that the crustal section of Sarv-Abad is part of the Cenozoic magmatic slices of Kurdistan ophiolite. In this case, the transition from Late Cretaceous to Cenozoic ophiolite is attributed to post-obduction tectonic processes and subsequent deformation. Following the obduction of Late Cretaceous ophiolites during the closure of the Neo-Tethys Ocean, the region experienced continued plate convergence throughout the Cenozoic. These processes led to the reworking and emplacement of ophiolitic materials during the Alpine orogeny, resulting in the modification of Cretaceous ophiolites and their incorporation into younger Cenozoic tectonic settings.

Consanguineous mafic rocks of Sarv-Abad ophiolite display contemporaneous D-MORB and E-MORB compositions, while recording a broad evolution to E-MORB and additional enriched components derived from lower degree melting of an enriched mantle source in the younger units (Oligocene basalts; Ghorbani *et al.* 2022). The gabbros are cut by extensional micro-cracks, which could not have been the source of the regional metamorphic imprint (Saccani *et al.* 2014). In addition, the characteristic features in the Sarv-Abad area comprise extremely deformed, mylonitized gabbro that rest on serpentinized harzburgite and are cut by mafic and felsic dykes (Figure 1A). Alongside these microcracks, other characteristic fabrics in the rocks of the Sarv-Abad area normal faults that transect the serpentinites, and ribbon texture of serpentine in a gabbro, which are extensional structures that outline the foliation in oceanic core complexes (OCC). Additionally, the gabbros and mafic dykes in the Sarv-Abad area have a N-MORB geochemical signature (Figure 5C-F), similar to the Atlantis Massif, a well-known example of an OCC exposed by detachment faulting (Blackman *et al.* 2006). Thus, comparison of the Sarv-Abad ophiolite with the structure and life cycle of modern, in situ OCCs enables us to propose a new scenario to explain the observed heterogeneity of the Sarv-Abad ophiolite. Here, we tested two different mechanisms that may clarify the observed evolution of Sarv-Abad magmatic unit. The first mechanism is one where the occurrence of trace element-enriched melts as well as the progressive increase in trace element enrichment through time is referred to as the effect of magmatism related to hotspot (e.g., Meyer *et al.* 1996). Although hotspots characteristically cause trace element enrichment in OIB, and E-MORB in regions of hotspot-ridge interaction, their REE patterns are typically HREE depleted due to melting in the garnet stability field. The lack of this HREE depletion in Sarv-Abad is inconsistent with deep melting (Figure 5g). Furthermore, the absence of the seamount lavas in the Sarv-Abad argues against a hotspot origin or influence since hotspots tend to be places of enhanced melting. The second scenario is that they can be produced from the same heterogeneous source that generated the melts and show a likeness with basalts from the Masirah Island. Formation of Masirah Island records ridge magmatism ending and a change in plate motions that occurred in the Indian Ocean about ~135–130 Ma, which contributed to the termination of seafloor spreading at the Masirah paleoridge.

In this scenario, the first stage involved intrusion of basaltic rocks into the upper mantle (ca. 52 Ma), which affected the rheology of the upper mantle, weakening it by the spread of fracture networks and hydrothermal circulation. The second stage was characterized by lithosphere-scale detachment faulting developed within the serpentinized front of the upper mantle (ca. 38 Ma). Extension induced by slab rollback was a critical factor for initiation of the detachment faulting (Figure 10D). Continued extensional deformation was accompanied by extensive low-grade facies metamorphism and hydrothermal metasomatism. The third stage was characterized by syn-extensional magmatism associated with the development of the detachment fault. Invasion of mafic dykes into the upper part of the Sarv-Abad suggests that the active detachment fault was the main magma conduit during this stage. The detachment faulting evolved to its last stage following exhumation of the extensive syn-extensional serpentinite breccias that were emplaced in the sheared serpentinite. Thus, we suggest that the life cycle of Sarv-Abad ophiolite denotes a combination of tectonic and magmatic processes.

Our new model provides an explanation for other ophiolites in KWOC, specifically, many ophiolites with similar emplacement ages (ca. 79–38 Ma). Most KWOC have large ultramafic massifs crosscut by various mafic dykes (Ao *et al.* 2016, Whitechurch *et al.* 2013).

Dick *et al.* (2008) described similar off-axis magmatism along the OCC and suggest that it is a common phenomenon. We suggest that the Kurdistan ophiolite formed at the OCCs within the extensional basin, whereas the large ultramafic massifs in the Sarv-Abad (this study) and Sahneh-Kamyaran (Kermanshah) ophiolites were crosscut by mafic dykes. Consequently, we suggest that the Sarv-Abad is part of an OCC, which was generated by large late Eocene oceanic detachment faulting in the extensional basin. Detachment faults probably occurred in the initial stages of oceanic opening, which was probably produced by continental rifting. Detachment faults also could contribute to an absence of a driving force for slab rollback-subduction. On the other hand, even by considering subduction processes at this time, it would have been weak and short-lived. During the Eocene, the Kurdistan ophiolite might still have been forming, and our favored interpretation is that the original mechanism was also probably caused by detachment faulting in the Late Eocene. The shear sense of the foliation in the gabbro is also clear in the outcrop, which is a typical feature in the Kamyaran area, suggesting that it is different from that of a metamorphic sole that forms when an ophiolite is obducted.

7. Conclusions

1. U–Pb dating of zircons shows that magmatism on Sarv-Abad occurred during the Eocene, as previously reported. Two crosscutting intrusions yielded ages of ~42–38 Ma, overlapping with the proposed Eocene emplacement age of the Kermanshah-Walash ophiolites. In contrast, the radiolarites from Razab ophiolite contain radiolarians and a large amount of sponge spicule that are Cretaceous in age.

2. The geochemical characteristics of mafic igneous rocks from Razab Cretaceous ophiolite suggest a petrogenetic evolution from early-stage low-Ti IAT-like basalts to later-stage high-Ti E-MORB-like gabbro progressively less-affected by subduction-derived components and also containing OIB-like basalts. The Sarv-Abad igneous crust was generated by contemporaneous D-MORB and E-MORB magmatism formed by melting a heterogeneous mantle, whereas later stages reveal an increasing contribution of low-degree spinel-garnet stability field melting of the enriched component in the source. The substantial similarity in trace element compositions of the mafic dykes and lava units suggests that they formed during a transitional magmatic event where the main phase of crustal was accreted.

3. Trace element compositions of gabbro and lava from Razab ophiolite indicate formation from tholeiitic melts generated during early proto-forearc/island arc spreading during subduction initiation, while those of the gabbro, lava and dykes from Sarv-Abad ophiolite may have been formed via low degree partial melting of the same heterogeneous source that generated the axial melts of extensional spreading center.

4. The Kurdistan ophiolite components experienced ductile and brittle deformation along extensional detachment faults that occurred in Sarv-Abad as well as Kamyaran. Consequently, we suggest the Sarv-Abad-Sahneh-Kamyaran part of the Kermanshah ophiolite was possibly an oceanic core complex that was generated by large oceanic detachment faults at ca. 40–38 Ma.

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Figure Captions:

Figure 1. (A) Regional map of the Middle East, including the NW Zagros belt in the Iran-Iraq border of (modified from Koshnaw *et al.* 2017); (B) Basic map showing the spreading of the Kermanshah-Walash ophiolitic complex with highlighting on the Sarv-Abad ophiolite (After Ali *et al.* 2013).

Figure 2. Geological map of the Sarv-Abad ophiolite.

Figure 3. A-field photo from the Cretaceous Razab ophiolite (Razab village). B-Serpentinite thrust onto gabbro. C-Serpentinite. D-Pillow lava basalt. E-radiolarite. Thin section photography from the Cretaceous ophiolite; F-Pegmatoid gabbro; G-Microgabbro. H-Skeletal plagioclase in pillow lava basalt.

Figure 4. A-field photo from Eocene Sarv-Abad ophiolite; B- peridotite; C-plagiogranite in isotropic gabbro; D- Pillow lava basalt. Thin section photography from the Eocene ophiolite E- dunite; F-Pegmatoid gabbro; G-Basalt and H- Plagiogranite.

Figure 5 Whole-rock geochemistry of mafic rocks and felsic dyke from the Razab and Sarv-Abad ophiolite complex. **(**A) Nb/Y vs. Zr/Ti plot (after Pearce (1996)); (B) Th vs Co diagram (Hastie *et al.* 2007). Rock type: B, basalt; BA/A, basaltic andesites/andesites; CA, calc-alkaline series; D/R, dacite/rhyolite; H–K, high-K series; IAT, island arc tholeiitic. Petrological group and references: BABB, back-arc basalts (Pearce *et al.* 2005; Buchs *et al.* 2013); FAB, forearc basalts (Ishizuka *et al.* 2011; Reagan *et al.* 2010); Tholeiite-OIB, ocean island basalts (Buchs *et al.* 2013); *E*-MORB, enriched mid-ocean ridge basalts (after Jenner and O'Neill, 2012); 85% probability contour of Island Arc Tholeiite composition (after Hastie *et al.* 2007); (C-D) Differentiation trends for the Sarv-Abad lava, gabbro and mafic dykes compared to MORB, BABB and the subduction setting Semail ophiolite. Most Sarv-

Abad rocks follow the MORB trends for TiO_2 vs. MgO and Al_2O_3 vs. MgO. MORB and BABB data from Gale *et al.* (2013); (E) Chemical variation for the TiO_2 vs. FeOt/MgO and (F) V vs. Yb diagrams (Lazaro *et al.* 2016). (G) Chondrite-normalized rare earth element (REE) diagrams (Sun and McDonough, 1989) and (H) primitive mantle-normalized multi-element diagrams (Sun and McDonough, 1989) for the Sarv-Abad crustal sequences, respectively.

Figure 6. (A) Chondrite-normalized rare earth element (REE) and (B) primitive mantle-normalized diagrams (Sun and McDonough 1989) for Sarv-Abad peridotites. Data for OIB, N-MORB, and E-MORB are after Sun and McDonough (1989, abyssal peridotites are after Niu and Batiza (1997) and Lian *et al.* (2019), and South Sandwich forearc peridotites are after Pearce *et al.* (2000).

Figure 7. Zircon U–Pb Concordia diagrams show the $^{206}Pb/^{238}U$ ages of the analyzed zircons with 2 sigma errors for samples Q-41 (A), Q-81 (B), and Q-122 (C).

Figure 8. (A) The range of Nb/Y vs. ages in the Sarv-Abad dykes and lava-gabbro. Ranges for present-day N-MORB (all MORB > 500 km from a plume-fed hotspot), D-MORB (all MORB with $La/Sm_N < 0.8$) and E-MORB (all MORB with $La/Sm_N > 0.15$) come from Gale *et al.* (2013). (B) Nb/Y vs. Zr/Y trace element diagram (excluding data with MgO < 5 wt. %) after Fitton *et al.* (1997), showing the effects of source enrichment vs. degree of melting.

Figure 9. Sarv-Abad lava and dykes La_N/Sm_N compositions (left) compared to present-day MORB variations within individual MOR spreading segments (Gale *et al.* 2013) showing that the wide compositional variability in Masirah is mirrored in certain parts of the slower spread mid-ocean ridge system. MORB data are filtered to exclude segments within 500 km from a plume-fed hotspot as well as segments that have fewer than 10 samples with La/Sm analyses. Data are normalized to primitive mantle (McDonough & Sun, 1995) and colored by Nb/Y content, with star symbols indicating Nb-enriched compositions (Nb/Y > 0.8). CIR = Central Indian Ridge, GR = Galapagos Ridge, SEIR = Southeast Indian Ridge, SWIR = Southwest Indian Ridge.

Figure 10. Schematic model for tectono-magmatic evolution and genesis of two parallel Late Mesozoic and Cenozoic ophiolites of NW Iran. Bi-Av: Bisotun-Avroman; Cre-vol: Cretaceous volcanic rocks; J-Plu.: Jurassic plutonic rocks; Cre-Oph.: Cretaceous ophiolite; J-Cre Arc: Jurassic-Cretaceous Arc; E-Oph.: Eocene ophiolite.

A- Iranian plate rifted as a micro-continental fragment from the Arabian plate, in response to the Neo-Tethys oceanic lithosphere opening during the late Triassic.

B-due to convergence forces, intraoceanic subduction initiated through the Zagros suture zone, leading to formation of mafic rocks with MORB and supra-subduction affinity

C- in the Early Cenozoic, during continued conversion forces, Cretaceous ophiolites obducted on Arabian plate and roll back of Neo-Tethys has occurred and extensional tectonic setting has occurred leading to formation of detachment faulting and replacement of Cenozoic magmatic rocks related to young ophiolite.

D-in continuous with closure of Neo-Tethys all two ophiolitic rock close to each other are emplaced onto the continent.