

Research Article

Transitional High-Al to Intermediate-Cr Podiform Chromitites from Wadi Zikt (Khor Fakkan Block, United Arab Emirates): Evidence for Reactive Melt Percolation during Nascent Forearc Evolution

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Podiform chromitites at Wadi Zikt in the Khor Fakkan Block of the United Arab Emirates constitute a previously undescribed occurrence within the mantle section of the Semail ophiolite. We combine field relations, electron-probe microanalysis, in situ LA-ICP-MS mineral analyses and whole-rock Fe isotopes to evaluate their origin. Chromian-spinels show wide compositional variability (40.98–51.64 wt.% Cr₂O₃ and 17.14–26.13 wt.% Al₂O₃, with Cr# = 0.51–0.67 and Mg# = 0.53–0.72), classifying them as transitional high-Al to intermediate-Cr. Olivine is highly forsteritic (Fo_{91–95}), whereas clinopyroxene exhibits extreme magnesian numbers (Mg# up to 0.96); these highest Mg values may reflect subsolidus Mg–Fe exchange with the abundant coexisting spinel during post-magmatic cooling. Empirical modeling of spinel chemistry yields parental melt compositions (Al₂O₃ ~13–15 wt%) consistent with mid-ocean ridge basalt (MORB)-like forearc basalts. Trace element systematics indicate that interstitial clinopyroxene did not crystallize from the primary parental melt but rather formed as a product of late-stage reactive porous melt–rock interaction and mantle refertilization. Whole-rock Fe isotope compositions ($\delta^{56}\text{Fe} +0.056$ to $+0.064\text{‰}$) are compatible with interaction between basaltic melt and peridotitic mantle. The chemistry of chromian-spinel and associated silicates, along with the occurrence of chromitite pods within dunite envelopes suggest that Wadi Zikt chromitites crystallized in a nascent forearc setting during the onset of Neo-Tethyan subduction, driven by the reactive percolation of asthenospheric forearc basalt melts that were progressively modified by incipient slab-derived aqueous fluids.

1. INTRODUCTION

Podiform chromitites are chromian-spinel-rich cumulates that represent economically and petrologically significant chromium ore deposits hosted in the mantle and Moho transition zones (MTZ) of ophiolitic complexes. Their occurrence in dunite conduits links chromite accumulation to focused melt transport and reactive replacement of pyroxene-bearing peridotite (Zhou et al., 1994, 1996, 2014; Arai, 1997; Arai and Makoto Miura, 2016; Bo et al., 2023). Chromitite formation involves a complex interplay of crystal accumulation, magma mixing, and melt-rock reaction during various stages of mantle magmatism (González-Jiménez et al., 2014; Liu et al., 2025).

The conventional high-Al and high-Cr terminology is based chiefly on spinel Cr# [$\text{Cr}/(\text{Cr} + \text{Al})$, molar]. High-Al chromitites commonly have $\text{Cr\#} < 0.60$, whereas high-Cr chromitites commonly have $\text{Cr\#} > 0.60$ (Zhou and Bai, 1992). While many ophiolites host either distinct high-Al or high-Cr podiform chromitites, the transitional high-Al to intermediate-Cr suites provide unique petrogenetic insights into continuous, multi-stage magmatic histories during subduction initiation and forearc evolution. Few ophiolite complexes, including the Oman ophiolite (Rollinson and Adetunji, 2015), the Kempirsai ophiolite in Kazakhstan (Melcher et al., 1999), and the Lycian ophiolite in Turkey (Xu et al., 2020), contain both types, indicating complex and multi-stage magmatic histories during subduction initiation, arc evolution, and back-arc spreading. Importantly, the composition of Cr-spinels in ophiolitic chromitites and associated peridotites is highly sensitive to post-magmatic processes, including hydrothermal alteration, metamorphism, and subsolidus re-equilibration, necessitating careful selection of primary, unaltered grains for petrogenetic interpretation (Colás et al., 2014; Khedr et al., 2023; Zafar et al., 2025). Besides major elements, trace elements such as Ti, Ga, Ni, Mn, and V, incorporated into the Cr-spinel crystal lattice, provide additional constraints on mantle depletion, melt-rock reaction, redox conditions, and the physicochemical environment of chromitite formation (Colás et al., 2014; Tonboe et al. (2026)).

Water may influence ophiolitic chromitite genesis in several ways. Proposed mechanisms include fluid-melt immiscibility, direct hydrothermal precipitation, and enhanced Cr transport in hydrous silicate melts. A recent synthesis favors dissolved water in MORB-to-boninite-like melts as a potentially important control on Cr solubility, followed by chromite saturation as reaction with harzburgite increases melt silica activity (Rollinson, 2025). Nevertheless, the presence and source of water must be demonstrated for each occurrence; regional subduction-zone setting cannot substitute for local mineralogical or fluid-inclusion evidence.

Stable Fe isotopes offer an additional, whole-rock-scale tracer of the processes recorded by chromitite mineral chemistry. High-temperature Fe isotope fractionation is controlled primarily by iron oxidation state and bonding environments, such that partial melting and melt-rock reaction produce isotopically light residues and isotopically

heavy melts, and Fe^{3+} -rich phases preferentially incorporate heavy Fe isotopes (Williams et al. (2005); Dauphas et al., 2009; Dauphas et al., 2009, 2017; Sossi and O'Neill (2017)). Global reference reservoirs are well established: chondrites and bulk peridotitic mantle have near-zero $\delta^{56}\text{Fe}$ ($-0.005 \pm 0.008\text{‰}$ and $+0.025 \pm 0.025\text{‰}$, respectively; Craddock and Dauphas (2011); Weyer and Ionov (2007)), abyssal peridotites are near-chondritic (Teng et al., 2013), MORBs are systematically heavy ($+0.105 \pm 0.006\text{‰}$; Teng et al. (2013)), whereas boninites and many arc basalts, generated by high-degree and/or flux-assisted melting, retain chondritic to only slightly heavy compositions (Dauphas et al. (2009)). Whole-rock Fe isotope data for podiform chromitites therefore provide an independent test of the melt-rock reaction history inferred from spinel and silicate chemistry.

The Semail ophiolite formed at ca. 95 Ma and preserves a polyphase oceanic-to-supra-subduction-zone magmatic history (Goodenough et al., 2010, 2014; Rollinson and Adetunji, 2015). Most chromitite studies have focused on Oman, whereas occurrences in the UAE, including the Khor Fakkan Block, remain less well characterized. Early studies proposed that the UAE ophiolitic mantle formed initially at a mid-ocean ridge and was later modified by both MORB-type and supra-subduction zone (SSZ)-type melts migrating through it (e.g., Dare, 2007; Dare et al., 2009).

Podiform chromitites are typically enclosed in dunite conduits that focus melt flow and chromite crystallization (Rui et al., 2022; Bo et al., 2023). Their textures (massive, banded, and disseminated) reflect disequilibrium crystallization due to mixing of chemically distinct melts, varying degrees of partial melting, and reactive porous flow in the shallow mantle (Arai and Makoto Miura, 2016). Dunite-hosted chromitites, like those of Wadi Zikt (this study), provide crucial information on these melt-rock interaction processes (Arai, 1997).

In this study, Wadi Zikt chromitites (Khor Fakkan Block, UAE), a previously undocumented occurrence, present the first systematic mineral-chemical dataset from the locality. We integrate new electron microprobe and LA-ICP-MS analyses of chromian spinel, olivine, orthopyroxene (Opx), clinopyroxene (Cpx), and base-metal sulfides, together with the first whole-rock Fe isotope data for these chromitites, to constrain the parental melt, the conditions of chromite crystallization, and the tectonic setting. Our results reveal that Wadi Zikt chromitites formed from melts with a transitional MORB-boninite affinity in a nascent forearc spreading center during subduction initiation. This contribution presents the first systematic mineral-chemical dataset from the Wadi Zikt occurrence and refines the understanding of transitional high-Al chromitite genesis in the SSZ ophiolite setting, with broader implications for mantle wedge processes during the onset of subduction.

2. GEOLOGICAL SETTING

The UAE contains the northernmost segment of the Semail ophiolite (Figure 1a), which offer valuable insights into oceanic crust formation and emplacement processes (Pilia,

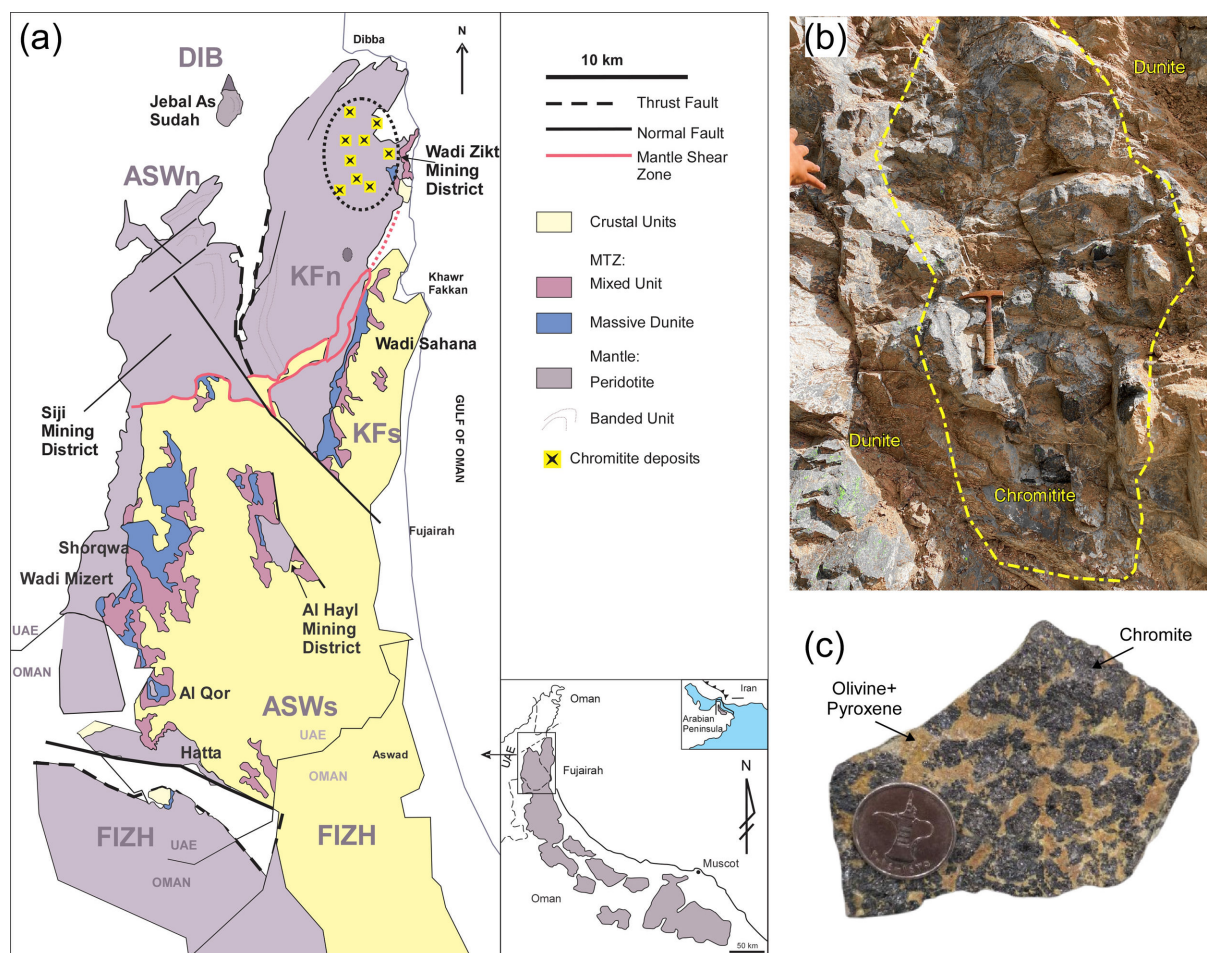


FIGURE 1: (a) Geological map of the Khor Fakkan and adjacent blocks, showing Wadi Zikt chromitite occurrences (modified from Dare, 2007). (b) Chromitite pod enclosed by a dunite envelope within serpentinized harzburgite. (c) Hand specimen with dark chromite aggregates in a strongly serpentinized olivine-rich matrix.

2025). These ophiolites, formed in a supra-subduction zone environment around 95 Ma ago, were rapidly obducted onto the eastern margin of Arabia (Rollinson and Adetunji, 2015). The UAE portion of the ophiolite is subdivided into three main blocks (from south to north): Fizh (mostly in Oman), Aswad, and Khor Fakkan. The Khor Fakkan Block measures $\sim 50 \times 35$ km (≈ 870 km²) and exposes a mantle–crust section that includes harzburgite, dunite, chromitite, layered and massive gabbros, sheeted dikes, and remnant lavas. Mantle peridotites (mainly harzburgite with minor dunite) form the lower sequence, transitioning upward through a MTZ of dunite to layered gabbro, then to a truncated crustal sequence (sheeted dikes and pillow basalts are largely eroded) (Sami et al., 2026). The Khor Fakkan and adjacent blocks are separated by major NE–SW faults (Wadi Ham Fault Zone, Hatta Zone) that were initially high-temperature shear zones active during oceanic spreading and later reactivated during ophiolite obduction (Goodenough et al., 2014). Obduction onto the Arabian margin (~ 95 –80 Ma) created a flexural foreland basin that preserved Late Cretaceous–Eocene sedimentary sequences along the ophiolite's western flank.

The Wadi Zikt area lies in the northernmost segment of the Semail (Oman–UAE) ophiolite, within the Khor Fakkan Block (Figure 1a), where only the mantle and MTZ lithologies crop out. The chromitite occurrences in the UAE ophiolite are generally smaller and less economically significant than those in Oman (Arai et al., 2004). The largest UAE chromitite bodies reach ~ 3 m in thickness and were mined briefly in the 1990s. Regionally, chromitite deposits in the UAE have been classified by structural position: (1) sub-Moho deposits (e.g., Al Hayl, Aswad South), (2) shallow crustal-level deposits (Siji, Aswad North), and (3) deeper mantle-level deposits (Wadi Zikt, Khor Fakkan North).

The chromitite bodies at Wadi Zikt are irregular, lenticular pods and networks within strongly serpentinized harzburgite, typically enveloped by dunite halos (Figure 1b). They range from a few centimeters to ~ 1 m in thickness and form anastomosing clusters rather than continuous seams. They preserve primary magmatic textures, including net-textured chromitite (anastomosing chromite-rich veins in an olivine matrix), chromite chain and schlieren textures, and nodular chromitite (rounded aggregates of chromite, typically < 5

mm across but reaching up to 2.5 cm) (Figures 1b–1c). The lack of significant foliation or stretching of chromite aggregates indicates minimal high-temperature solid-state deformation.

3. ANALYTICAL METHODS

3.1. Electron-Probe Microanalysis

Major and minor element compositions of chromian spinel, olivine, clinopyroxene, orthopyroxene, and sulfides were measured at the University of Vienna (Austria) using a CAMECA SXFive wavelength-dispersive electron microprobe. Analyzes were conducted at 15 kV accelerating voltage and 20 nA beam current with a focused beam of approximately 3–5 μm for silicates and spinels and a defocused beam of approximately 1–3 μm for sulfides. Natural and synthetic standards were utilized for calibration, with raw data corrected using the ZAF procedure. Typical detection limits were on the order of 0.01–0.02 wt% for most oxides. Only unaltered crystal cores were analyzed to avoid subsolidus modification effects (e.g., alteration rims on spinel) (Online Supplementary Table S1). Spinel Fe^{3+} was estimated stoichiometrically from total Fe reported as FeO^* , normalized to four oxygens and three cations following the general approach of Droop (1987). Calculated cation sums are close to the ideal value of 3 per formula unit, supporting the internal consistency of the estimates; however, minor uncertainties in absolute Fe^{3+} values may arise from subsolidus re-equilibration of spinel, and derived parameters ($f\text{O}_2$ estimates, $\text{Ga}/\text{Fe}^{3+}\#$ ratios) should therefore be treated with appropriate caution.

3.2. In-Situ LA-ICP-MS Analysis

Trace elements in chromite, olivine, and pyroxene were determined in situ by LA-ICP-MS at Wuhan SampleSolution Analytical Technology Co., Ltd., Wuhan, China, following the single-mineral analytical protocol of the laboratory. Laser ablation was performed using a GeolasPro laser ablation system equipped with a COMPexPro 102 ArF excimer laser operating at 193 nm and a MicroLas optical system, coupled to an Agilent 7900 ICP-MS. Helium was used as the carrier gas during ablation, and argon was used as the make-up gas; both gases were mixed via a T-connector before entering the ICP. A wire signal-smoothing device was installed in the laser ablation system to improve signal stability during analysis (Hu et al., 2015). Analyzes were carried out using spot diameters of 32, 44, or 60 μm and laser repetition rates of 5 or 6 Hz, selected according to grain size, mineral transparency, and signal intensity. Each time-resolved analysis consisted of approximately 20–30 s of background acquisition followed by 50 s of sample ablation. Trace-element concentrations were calibrated against the reference glasses BHVO-2G, BCR-2G, and BIR-1G using a multi-external-standard calibration strategy without applying an internal standard, following Liu et al. (2008). Offline data reduction was performed

using ICPMSDataCal (Liu et al., 2008), including selection and integration of background and analyte signals, correction for instrumental sensitivity drift, and quantitative calibration of trace-element concentrations. Analytical accuracy and reproducibility were monitored by repeated analyzes of the reference materials included in the analytical sequence. Element-specific limits of detection for chromite, olivine, and pyroxene are reported in Online Supplementary Table S2; values below detection limits were excluded from petrogenetic interpretation, particularly for low-abundance rare earth elements (REE) in olivine.

3.3. Whole-Rock Fe Isotope Analysis

Whole-rock Fe isotope compositions were determined on five representative chromitite samples (KFC1–KFC5; bulk chromitite powders comprising chromian spinel plus interstitial silicates, from the same sample suite characterized by EPMA and LA-ICP-MS) at Wuhan SampleSolution Analytical Technology Co., Ltd. (China). Approximately 50 mg of powder was dissolved in HF-HNO_3 in PTFE-lined steel vessels at 190 °C for 48 hours. The dried residues were repeatedly converted to nitrate and then to chloride form before dissolution in 8 M HCl containing 0.001% H_2O_2 . Iron was purified by anion-exchange chromatography using Bio-Rad AG-MP-1M resin following Liu et al. (2014). The supplied laboratory description reports Fe recovery >99% and procedural blanks <10 ng.

Isotope ratios were measured by MC-ICP-MS (Neoma, as specified in Online Supplementary Table S3) in high-resolution mode using wet-plasma introduction and Jet + X cones. Samples were analyzed at approximately 1.5 $\mu\text{g g}^{-1}$ Fe in 2% HNO_3 , and instrumental mass bias was corrected by standard-sample bracketing relative to IRMM-014. Values are reported as $\delta^i\text{Fe} = [({}^i\text{Fe}/{}^{54}\text{Fe})_{\text{sample}}/({}^i\text{Fe}/{}^{54}\text{Fe})_{\text{IRMM-014}} - 1] \times 1000$, where $i = 56$ or 57. Each sample mean represents three replicate measurements, and uncertainties are 2SD. BCR-2, BHVO-2, GSP-2, and JA-2 analyzed with the samples agree, within uncertainty, with the comparison values listed in Table S3.

4. RESULTS

4.1. Petrographic Features

Chromian spinel constitutes approximately 50–70 vol.% of the chromitites and occurs as subhedral to euhedral grains, mostly 3–10 mm and locally up to 1 cm. The spinel crystals are commonly fractured but retain fresh cores with only narrow rims of ferritchromite along some cracks, indicating minor low-temperature alteration. They occur as disseminated grains to semi-massive clusters within an olivine-rich matrix (Figure 2a). Olivine (forsterite-rich) is the dominant silicate in the chromitites and their dunite envelopes. In the hand sample, olivine forms a light-colored matrix surrounding dark chromite aggregates (Figure 1c). Texturally, most olivine is anhedral and interstitial between chromite grains, whereas rarer olivine inclusions

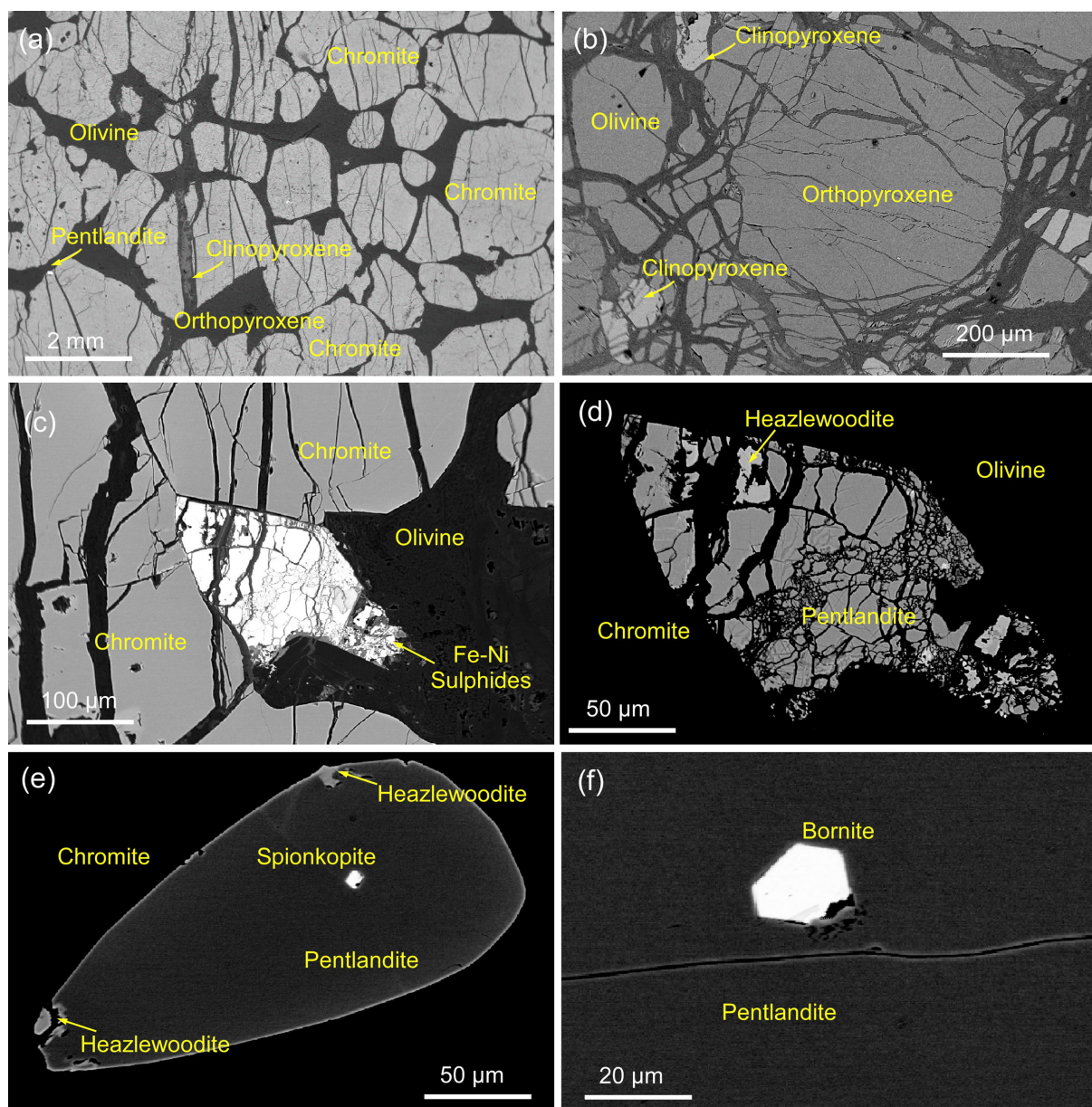


FIGURE 2: Back-scattered electron images of Wadi Zikt chromitites. (a) Chromian spinel with interstitial olivine, orthopyroxene, clinopyroxene, and minor pentlandite. (b) Olivine, clinopyroxene, and orthopyroxene as interstitial grains and inclusions within spinel; phase identities confirmed by EPMA. (c-f) Base-metal sulfides: (c, d) pentlandite and heazlewoodite at chromite-olivine contacts; (e) spionkopite enclosed in pentlandite; (f) bornite along microfractures.

enclosed in chromite are subhedral (Figures 2a and 2b). Grain cores of olivine in the chromitites are predominantly optically fresh, with no magnetite or serpentine inclusions preserved within the cores (Figures 2a and 2b). However, partial serpentinization is evident along grain margins and fractures and is visible at field scale as greenish alteration in the dunite host (Figures 1b and 1c).

Clinopyroxene and orthopyroxene occur as small anhedral grains in the matrix and occasionally as tiny euhedral inclusions within chromite (Figure 2b). These pyroxenes, along with interstitial olivine, occupy the residual space after chromite crystallization. The occurrence of euhedral clinopyroxene and orthopyroxene inclusions

enclosed within spinel is consistent with co-crystallization and early entrapment during chromite growth.

Base-metal sulfides in the Wadi Zikt chromitites occur as texturally significant minor phases, predominantly at chromite-silicate interfaces, within interstitial domains, and along transgranular fracture networks (Figures 2c–2f). Their distribution postdates crystallization of the primary spinel-silicate assemblage. Pentlandite is the dominant Fe–Ni sulfide, occurring as irregular blebs and fracture-bounded aggregates at chromite-olivine contacts (Figures 2c–2d). Heazlewoodite forms brighter BSE rims and fracture-controlled replacements around pentlandite, consistent with progressive desulfurization under low sulfur fugacity.

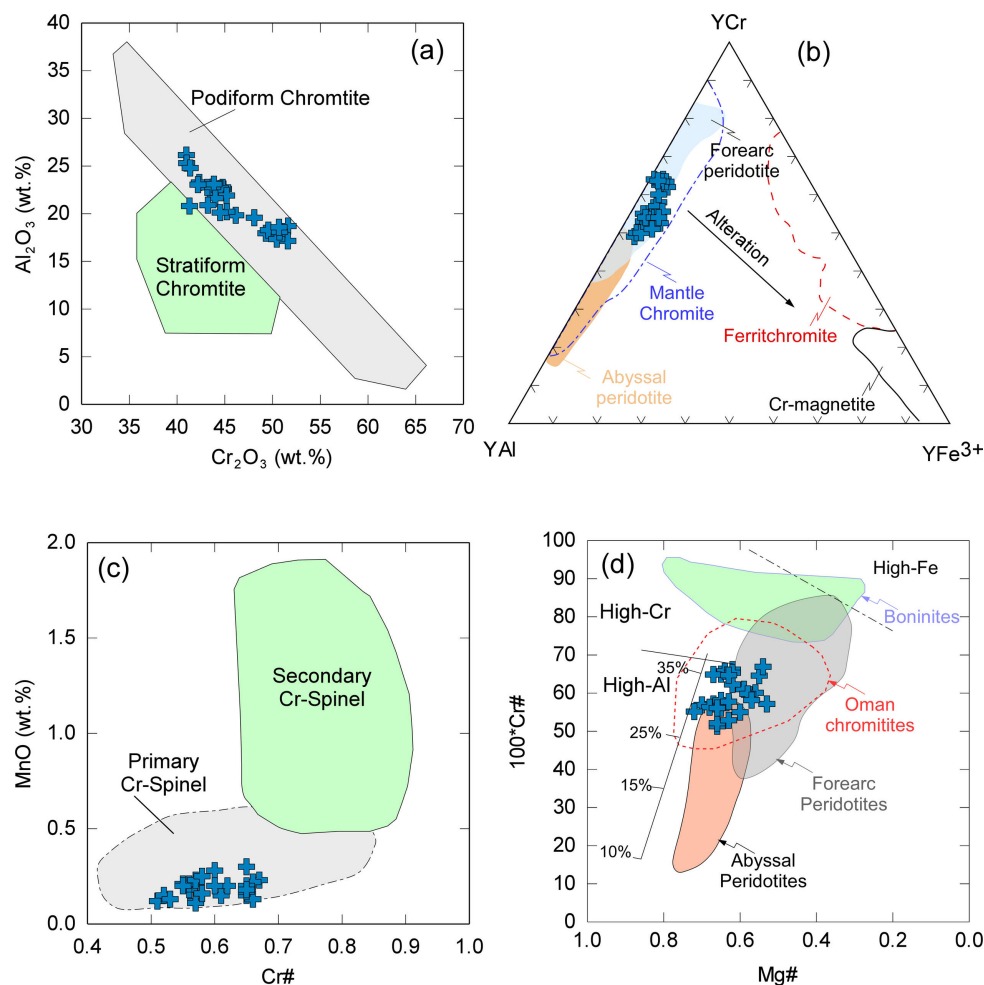


FIGURE 3: Major-element composition of Wadi Zikt chromian spinel. (a) Cr_2O_3 vs. Al_2O_3 . Compositional fields of podiform and stratiform chromitites are after Bonavia et al. (1993). (b) Ternary Cr–Al–Fe³⁺ (as Y-ratios); forearc and abyssal peridotite fields (Ishii et al., 1992) are shown for tectonic reference only and do not imply compositional equivalence between cumulus chromitite spinel and residual peridotite spinel. (c) Cr# vs. MnO. (d) Mg# vs. Cr#. The trend of partial melting degrees is after Hirose and Kawamoto (1995). Fields of chromian spinel in forearc peridotites (Parkinson and Pearce, 1998); boninites (Barnes and Roeder, 2001); abyssal peridotites (Dick and Bullen, 1984); Oman chromitites (Bo et al., 2023); and high Cr, high Al, and high Fe chromitites (Zhou and Bai, 1992) are shown for comparison.

Spionkopite ($\text{Cu}_{1.4}\text{S}$) is present as small high-contrast blebs enclosed in pentlandite, indicating late-stage Cu-sulfide re-equilibration (Figure 2e). Bornite is rare, occurring as minor inclusions within pentlandite along microfractures, reflecting limited late-stage Cu mobilization (Figure 2f).

4.2. Major-Element Mineral Chemistry

4.2.1. Chromian Spinel

Chromian spinels from Wadi Zikt chromitites show a transitional high-Al to intermediate-Cr composition (Cr# 0.51–0.67; Mg# 0.53–0.72), with variable Al_2O_3 (17.1–26.1 wt%) and Cr_2O_3 (41.0–51.6 wt%), and TiO_2 (0.08–0.76 wt%) (Table S1). On a Cr_2O_3 vs. Al_2O_3 plot (Figure 3a), the Wadi Zikt spinels span the compositional range of global podiform chromitites, straddling the boundary between high-Al and high-Cr fields.

Ternary Y–Cr–Al–Fe³⁺ ratios show YCr 0.49–0.67, YAl 0.33–0.47, and YFe³⁺ 0.00–0.08 (Table S1), plotting within the compositional space defined by forearc chromitite spinels (Figure 3b; Ishii et al., 1992). Note that these reference fields reflect different geological contexts (residual peridotites vs. chromite cumulates) and are used here for tectonic orientation rather than compositional equivalence. The spinels have very low MnO (0.11–0.30 wt%) and moderate Mg# (0.53–0.72), consistent with a primary magmatic origin rather than metamorphic re-equilibration (Khedr and Arai, 2017) (Figure 3c). Based on their Cr# (0.51–0.67), the Wadi Zikt spinels classify as transitional high-Al to intermediate-Cr chromitites (Cr# expressed as molar ratio Cr/(Cr+Al); corresponding to Cr# × 100 of 51–67), straddling the high-Al (Cr# < 0.60) and high-Cr (Cr# > 0.60) end-members defined by Zhou and Bai (1992).

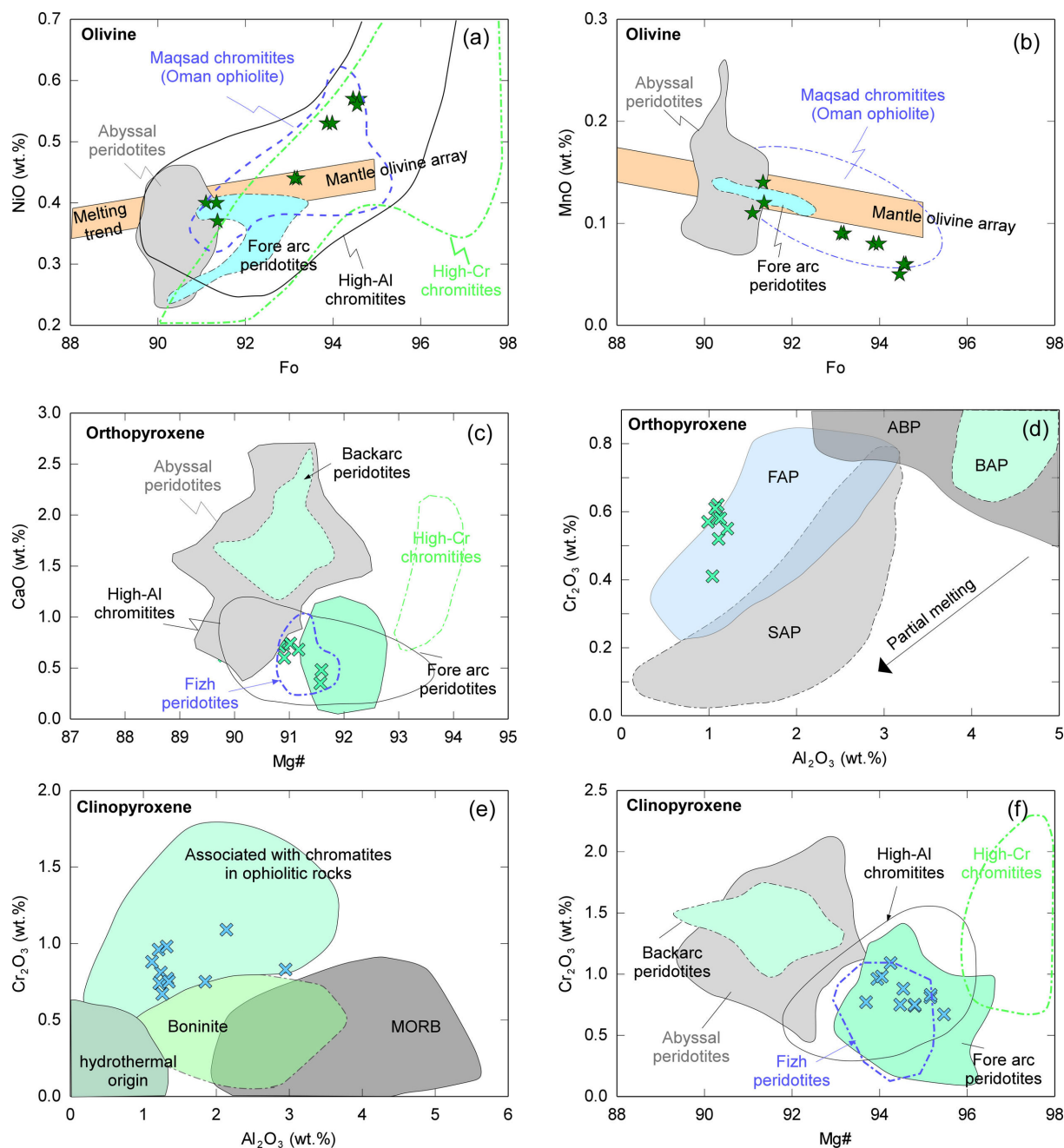


FIGURE 4: Mineral chemistry of olivine, orthopyroxene, and clinopyroxene in Wadi Zikt chromitites. (a) Fo vs. NiO and (b) Fo vs. MnO for olivine (Fo_{91–95}); the highest Fo values may partly reflect subsolidus Mg–Fe exchange with coexisting spinel. (c) Orthopyroxene Mg# vs. CaO binary diagrams. (d) Al₂O₃ vs. Cr₂O₃ binary diagram after Pagé et al. (2008). Fields of Forearc (FAP), backarc (BAP), and abyssal (ABP) are from Lian et al. (2018); Fizz peridotites (Bo et al., 2023), and subarc peridotite (SAP) (Parkinson et al., 2003) are shown for comparison. (e–f) Clinopyroxene Cr₂O₃ vs. Al₂O₃ and Mg#. Boninites, mid-ocean ridge basalts (MORB), and hydrothermal clinopyroxene fields are after Su et al. (2020) and references therein. Fields of abyssal, back-arc, and forearc peridotites are from Lian et al. (2018); Maqсад chromitites of Oman ophiolite are from Rollinson (2019); high-Al chromitite (Su et al., 2019; Rui et al., 2022; Bo et al., 2023); high-Cr chromitite (Lian et al., 2018; Su et al., 2019; Zhang et al., 2020) are used for comparison.

(Figure 3d). Compositionally, they are most similar to chromitites from the Fizz and Maqсад massifs of the Oman ophiolite (Bo et al., 2023).

4.2.2. Olivine

Olivine in the Wadi Zikt chromitites is highly magnesian, with forsterite content (Fo_{91–95}; Table S1). These values are within the range reported for olivine in high-Al podiform

chromitites globally (Su et al., 2019; Rui et al., 2022) and are comparable to those in the Maqsad chromitites of Oman (Rollinson, 2019). NiO ranges from 0.37 to 0.57 wt% and MnO from 0.05 to 0.14 wt% (Table S1). A subset of analyzes shows slightly elevated Ni and depleted Mn relative to typical mantle olivine values (Figures 4a and 4b). These compositional deviations may reflect minor interaction with Ni-bearing sulfides or subsolidus re-equilibration with coexisting chromite (Pagé and Barnes, 2009; Su et al., 2019); the positive NiO–Fo and negative MnO–Fo covariation (Figures 4a and 4b) is consistent with this interpretation, though the chemical controls on these trends are discussed in Section 5.2.

4.2.3. Orthopyroxene

Orthopyroxenes are less abundant than olivine, but where present are enstatite (En_{89–92}) in composition, with Mg# ranging from 0.90 to 0.92. Major oxide compositions are Al₂O₃ (0.99, 1.21 wt%), Cr₂O₃ (0.41–0.62 wt%), CaO (0.35–0.74 wt%), TiO₂ (0.006–0.012 wt%), and MnO (0.15–0.18 wt%) (Table S1; Figures 4c–4d). These compositions are broadly comparable to Opx reported from high-Al chromitite assemblages (Su et al., 2019) and fall within the compositional space of forearc and depleted back-arc peridotites shown for tectonic reference in Figures 4c–4d (Lian et al., 2018; Bo et al., 2023). The very low TiO₂ and moderate Cr₂O₃ in the Wadi Zikt Opx are consistent with crystallization in a depleted, low-Ti melt environment.

4.2.4. Clinopyroxene

Clinopyroxene in the Wadi Zikt chromitites is diopsidic (Wo_{47–50}En_{48–52}Fs_{0–3}) with Mg# ranging from 0.94 to 0.96 (Table S1). Major oxides include Al₂O₃ 1.12–2.95 wt%, Cr₂O₃ 0.67–1.09 wt%, CaO 23.43–24.29 wt%, and TiO₂ 0.04–0.09 wt%. Na₂O is low, ranging from 0.17 to 0.30 wt%. The Cpx compositions plot within reference fields for ophiolitic chromitite-associated pyroxenes and are distinct from Cpx in typical MORB or arc lavas, which carry higher Na and Ti contents (Su et al., 2020; Figure 4e). Their Cr₂O₃ and Mg# values overlap those of Cpx from high-Al chromitites reported in the literature (Khedr and Arai, 2017; Rui et al., 2022; Figure 4f).

4.2.5. Base-metal sulfides

Representative EMPA compositions of base-metal sulfides are provided in Table S1. Pentlandite contains Fe (32.0–36.1 wt%), Ni (29.8–32.7 wt%), S (33.1–33.6 wt%), and Co (~1.0–1.2 wt%), consistent with ideal (Fe,Ni)₉S₈ and comparable to sulfides associated with supra-subduction zone chromitites (Bussolesi et al., 2022). Heazlewoodite is characterized by very high Ni (71.40–72.20 wt%), S (26.54–26.93 wt%), and Fe <1 wt%, consistent with Ni₃S₂. Spionkopite (Cu_{1.4}S) contains Cu (70.24–71.29 wt%), S (25.37–26.27 wt%), and low Ni (~2.03 wt%), occurring as small inclusions within pentlandite, indicating late-stage

Cu redistribution. Bornite (Cu₅FeS₄) contains Cu (62.74–62.91 wt%), Fe (10.43–10.63 wt%), and S (~26.03 wt%), occurring as rare inclusions along microfractures, reflecting limited late-stage Cu mobilization.

4.3. In Situ Trace Element Geochemistry

Transitional high-Al chromitites such as those at Wadi Zikt typically have spinels enriched in Ti, V, Ga, and Zn relative to spinels from abyssal chromitites. In the Wadi Zikt spinels, Ti ranges from 1319 to 2390 ppm, V from 692 to 1052 ppm, Mn from 906 to 1768 ppm, Co from 189 to 290 ppm, Ni from 582 to 1660 ppm, Zn from 262 to 614 ppm, Ga from 14.7 to 38.8 ppm, and Sc from 3.8 to 5.8 ppm (Table S2). Trace element and selected major oxide concentrations of Wadi Zikt Cr-spinels, normalized to MORB-chromite values of Pagé and Barnes (2009), are compared with global chromitite types in Figure 5a. The Wadi Zikt spinels show relative enrichment in Ti, Co, Mn, and Fe and depletion in Al, Ga, and Ni, compared to MORB-chromite spinel (Figure 5a). The normalized patterns broadly overlap with those of high-Al chromitites (González-Jiménez et al., 2014; Zhou et al., 2014) and show partial similarity to podiform chromitites from the Thetford Mines Ophiolite (Pagé and Barnes, 2009) in Ti, Al₂O₃, Ga, and Ni (Figure 5a). Because Ga in spinel is thought to be minimally affected by subsolidus re-equilibration (Economou-Eliopoulos et al., 2019), Ga was used as an index element to assess the coherence of other elements. Plots of Sc, Mn, Co, V, and Ni vs. Ga (Online Supplementary Figure S1) show generally positive trends, suggesting broadly coherent behavior of these elements. Following Tonboe et al. (2026), Sc, Ga, V, Ni, and Mn versus Cr# (Online Supplementary Figure S2) place the Wadi Zikt spinels on the global mantle-chromitite depletion array at the transitional high-Al/high-Cr boundary. Ga and Ni decrease and Mn and Sc increase with Cr#, consistent with a moderately depleted source, while elevated Ti records melt–rock reaction. V (692, 1052 ppm) reflects both depletion and oxygen fugacity rather than redox alone.

Olivine has low rare earth element concentrations (Σ REEs = 0.22–0.61 ppm), with chondrite-normalized patterns of LREE enrichment relative to HREE (La_N/Yb_N = 1.20–3.74, La_N/Tb_N = 4.60–18.40; Figure 5b, Table S2). Olivine has high Ni content (4566, 6091 ppm), subordinate Co (38, 60.3 ppm), and Cr (7.5, 22 ppm). Clinopyroxene has higher REE concentrations than olivine (Σ REE = 1.5–3.1 ppm; Table S2). Chondrite-normalized REE patterns are spoon-shaped, with HREE enrichment relative to MREE and LREE (Lu_N/Gd_N = 0.32–1.68; Lu_N/La_N = 59–304) (Figure 5c).

4.4. Whole-Rock Fe Isotope Compositions

Whole-rock Fe isotope compositions of five representative Wadi Zikt chromitites (KFC1–KFC5) are presented in Table S3 and Figure 6. The samples display a narrow range of $\delta^{56}\text{Fe}$ from $+0.056 \pm 0.024\text{‰}$ to $+0.064 \pm 0.023\text{‰}$ (2SD), with a corresponding $\delta^{57}\text{Fe}$ range of $+0.092 \pm 0.047\text{‰}$ to $+0.118 \pm 0.038\text{‰}$ and a mean $\delta^{56}\text{Fe}$ of $+0.060 \pm 0.007\text{‰}$

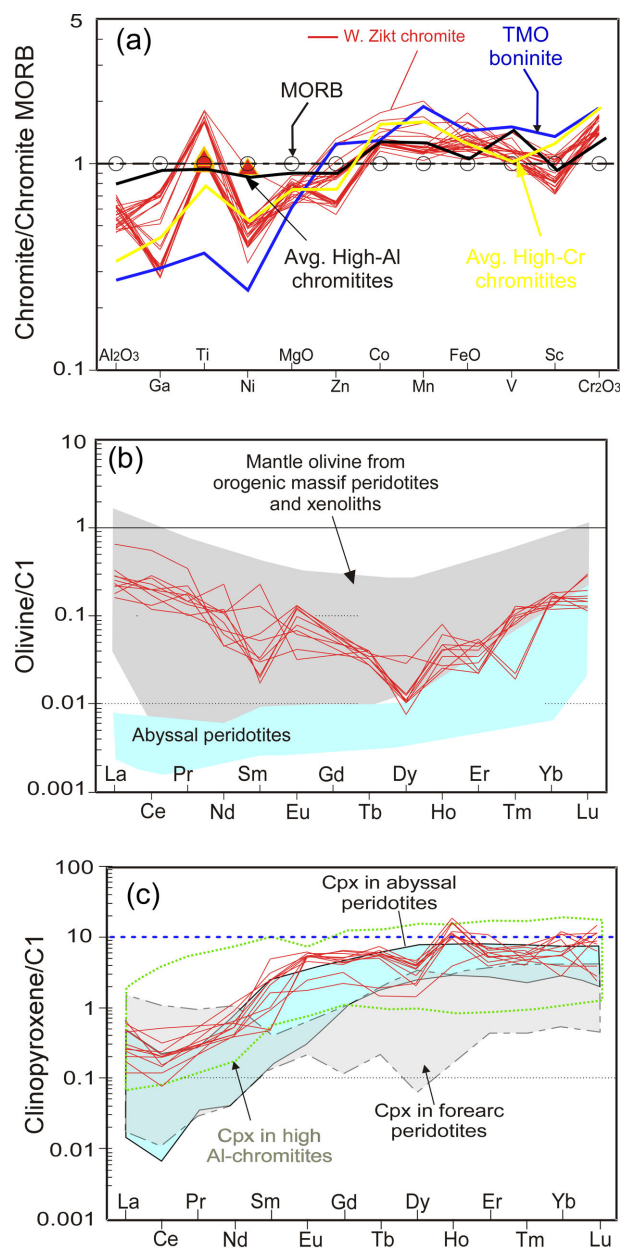


FIGURE 5: (a) Multi-element pattern normalized to the composition of chromite from the MORB analyzed (Pagé and Barnes, 2009). Cr-spinels from MORB and boninite chromitites (Pagé and Barnes, 2009), high-Al chromitites (González-Jiménez et al., 2014; Rui et al., 2022), high-Cr chromitites (Zhou et al., 2014; Su et al., 2019). (b) Chondrite (CI)-normalized REEs patterns of olivine and clinopyroxene. The CI normalized values are from McDonough and Sun (1995). Fields of olivine from orogenic massif peridotites and xenoliths (Grégoire et al., 2000), olivine in Gakkal Ridge peridotites (D'Errico et al., 2015), Cpxs in abyssal and forearc peridotites (Uysal et al., 2012), and Cpxs in high-Al chromitites (Khedr and Arai, 2017; Rui et al., 2022).

(2SD, $n = 5$). All five samples form a tight cluster between $+0.056\text{‰}$ and $+0.064\text{‰}$. All five chromitites are resolvable heavier than chondrites ($-0.005 \pm 0.008\text{‰}$; Craddock and Dauphas (2011)) and abyssal peridotites (Craddock

et al. 2013) and plot at or slightly above the upper bound of the fertile mantle peridotite field ($+0.025 \pm 0.025\text{‰}$; Weyer and Ionov (2007)). Relative to mean MORB glasses ($+0.105 \pm 0.006\text{‰}$; Teng et al. (2013)), all five samples are resolvable lighter than MORB and remain below its uncertainty envelope (Figure 6a). All analyzes plot on the terrestrial mass-dependent fractionation line in $\delta^{57}\text{Fe}$ – $\delta^{56}\text{Fe}$ space (Figure 6b), confirming the fidelity of the data. The dataset as a whole thus occupies an intermediate position between the peridotitic mantle and MORB–peridotite mixing array.

5. DISCUSSION

5.1. Composition and Origin of Parental Melts

Chromian spinel chemistry provides a robust proxy for the composition of the melt from which chromitite crystallized (Pagé and Barnes, 2009; Zhou et al., 2014; Gamal El Dien et al., 2019; Rui et al., 2022). Empirically, high-Cr podiform chromitites ($\text{Cr\#} > 0.60$) are linked to boninitic melts, whereas high-Al types ($\text{Cr\#} < 0.60$) typically crystallize from less refractory, MORB-like tholeiitic melts (Khedr and Arai, 2017). The Wadi Zikt transitional high-Al to intermediate-Cr chromitites span $\text{Cr\#}$ 0.51–0.67, with a subset exceeding the 0.60 threshold, indicating a parental melt with a hybrid MORB–boninite character (Table S1).

In discrimination diagrams plotting $\text{Mg\#}$ vs. $\text{Cr\#}$ (Figure 7a; Borisova et al. (2012)), the data span both MORB and boninite reference fields. Some compositions cluster near the Maqсад chromitites of Oman, which formed from MORB-like melts (Bo et al., 2023), while others extend toward boninitic fields, confirming a transitional magma affinity. Spinel Ti and V contents are elevated relative to MORB chromite and intermediate relative to boninite-related chromitites (Figure 5a), consistent with this transitional affinity; the petrogenetic significance of these variations is addressed below.

Quantitative parental melt compositions were estimated from spinel chemistry using the empirical expressions:

$$\text{Al}_2\text{O}_3 (\text{spinel}) = 0.035 \times (\text{Al}_2\text{O}_3)^{2.42} (\text{melt}) \quad (\text{Maurel and Maurel, 1982})$$

$$\text{TiO}_2 (\text{melt}) = 1.0963 \times \text{TiO}_2^{(0.7863)} (\text{spinel}) \quad (\text{Rollinson, 2008})$$

$$\ln(\text{FeO/MgO})_{(\text{spinel})} = 0.47 - 1.07 \text{YAl}_{(\text{spinel})} + 0.64 \text{YFe}^{3+}_{(\text{spinel})} + \ln(\text{FeO/MgO})_{(\text{melt})} \quad (\text{Maurel and Maurel, 1982})$$

The calculated parental melt compositions yield $\text{Al}_2\text{O}_3 = 12.93$ – 15.39 wt%, $\text{TiO}_2 = 0.16$ – 0.98 wt%, and $\text{FeO/MgO} = 0.92$ – 1.81 (Table S1), all within the range of SSZ ophiolitic chromitites (Khedr and Arai, 2017). The calculated Al_2O_3 values overlap the compositional ranges of Archean boninites (8.78, 14.1 wt%; Manikyamba et al., 2005) and N-MORB (15.19 wt%; Wilson, 1989) and fall within the field of IBM forearc basalts (14.13, 17.4 wt%; Reagan et al., 2010; Figure 7b). The calculated TiO_2 range similarly bridges boninite (0.24, 0.52 wt%) and MORB (0.6, 2.9 wt%)

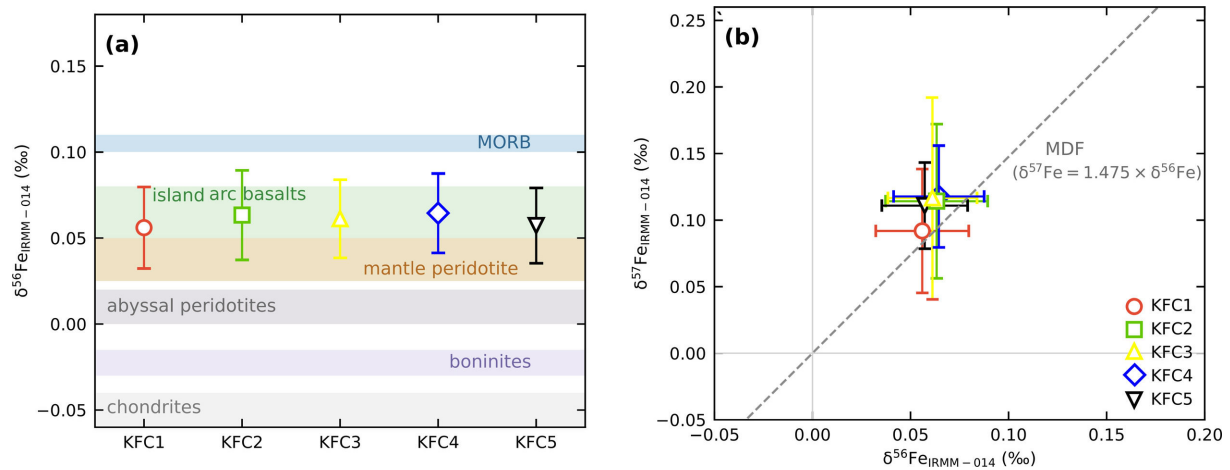


FIGURE 6: Whole-rock Fe isotope compositions of Wadi Zikt chromitites. (a) $\delta^{56}\text{Fe}$ values of individual samples (error bars are 2SD of $n = 3$ replicate measurements) compared with the compositional ranges of chondrites (Craddock and Dauphas (2011)), abyssal peridotites (Craddock et al. (2013)), fertile mantle peridotite (Weyer and Ionov (2007)), boninites and island-arc basalts (IAB) (Dauphas et al. (2009)), and MORB (Teng et al. (2013)); reference ranges are shown schematically. (b) $\delta^{57}\text{Fe}$ vs. $\delta^{56}\text{Fe}$ showing that all analyzes plot on the terrestrial mass-dependent fractionation (MDF) line ($\delta^{57}\text{Fe} \approx 1.475 \times \delta^{56}\text{Fe}$). All values are relative to IRMM-014.

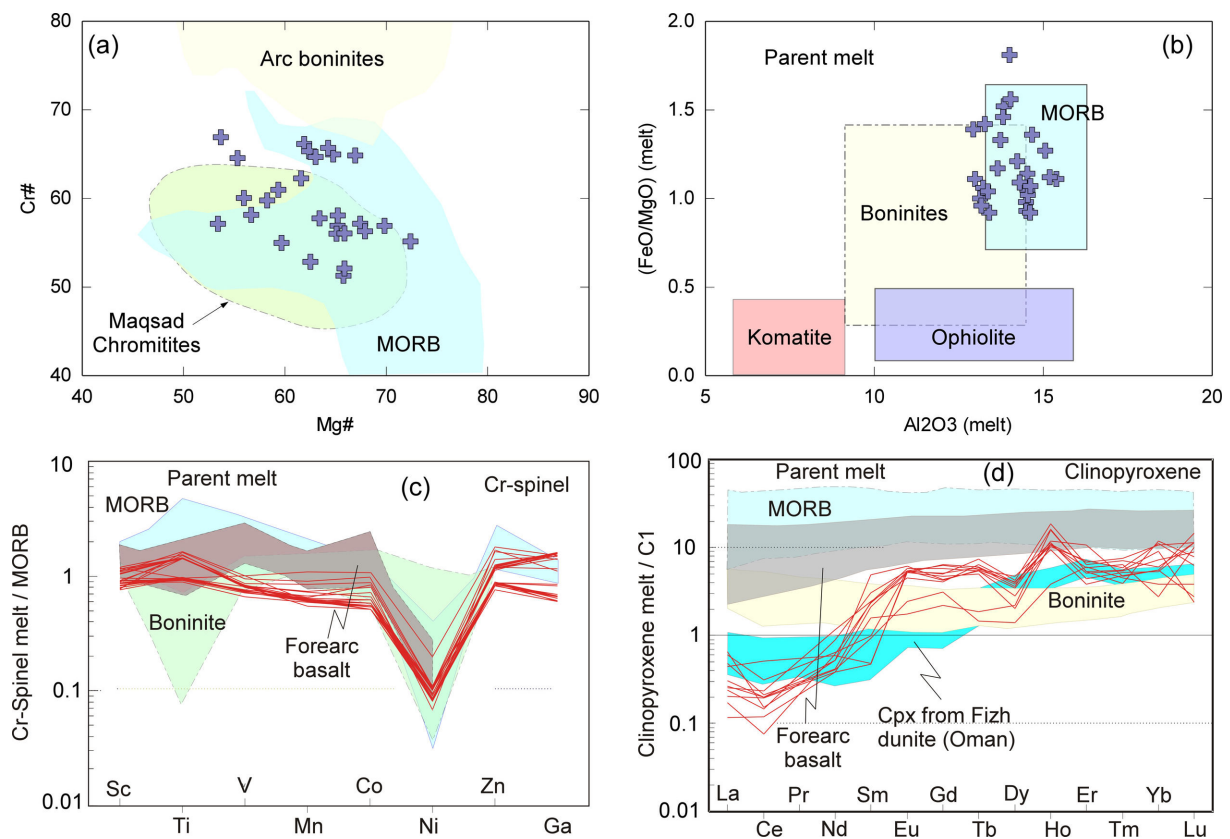


FIGURE 7: Chemical features of Cr-spinels in Wadi Zikt chromitites and their implications. (a) Variation diagrams of Mg# vs. Cr# of Cr-spinels (Borisova et al., 2012 and references therein). Field of Maqсад chromitites in Oman ophiolite (Bo et al., 2023). (b) Calculated parental-melt compositions in terms of $(\text{FeO}/\text{MgO})_{\text{melt}}$ vs. $(\text{Al}_2\text{O}_3)_{\text{melt}}$ on the basis of the Cr-spinel composition of chromitites; tectonic discrimination fields are from Barnes and Roeder (2001). (c) Multi-element pattern showing the calculated trace element compositions of the parental magmas of Wadi Zikt chromitites normalized to MORB chromite (Pagé and Barnes, 2009). Cr-spinel/melt partition coefficients are from White (2013). Fields of MORB (Jenner and O'Neill, 2012), forearc basalt (Shervais et al., 2019), and boninite (Li et al., 2013) are shown for comparison. (d) CI-normalized REE patterns for calculated melts in equilibrium with Cpx from Wadi Zikt chromitites. Normalized CI values are from McDonough and Sun (1995); Cpx/melt partition coefficients are from Hart and Dunn (1993) and Johnson (1998). Fields of IBM boninites and forearc basalt are after Reagan et al. (2010), Li et al. (2013), and Shervais et al. (2019); the MORB is after Jenner and O'Neill (2012); Fizz dunites of Oman are after Bo et al. (2023).

values and overlaps the transitional FAB-to-boninite lava spectrum (Reagan et al., 2010).

MORB-chromite-normalized trace element patterns of the calculated parental melt (using spinel/melt partition coefficients of White (2013) (Figure 7c) show nearly flat profiles from Sc to Co, with a distinct positive Ti anomaly. This pattern is more consistent with forearc basalt (FAB) melts than with MORB or IBM boninites (Figure 7c), supporting an FAB-type parental melt in which TiO_2 has not yet been suppressed by extreme mantle depletion.

Chondrite-normalized REE patterns for melts in equilibrium with Wadi Zikt clinopyroxene (calculated using partition coefficients of Hart and Dunn, 1993; Johnson, 1998) show HREE-enriched, spoon-shaped profiles comparable to IBM forearc basalts and clinopyroxene from Fizz dunites (Bo et al., 2023; Figure 7d). However, the Wadi Zikt Cpxs are interpreted not as direct crystallization products of the primary chromitite-forming melt, but as phases generated during a later stage of reactive melt percolation (see Section 5.2). Their very high Mg# (0.94, 0.96) may partly reflect subsolidus Mg-Fe re-equilibration and should not be used in isolation to constrain the primary melt temperature or depletion degree. The Cpx-derived melt calculation therefore reflects the composition of the late reactive melt rather than the original parental melt; the convergence of both the spinel-derived and Cpx-derived estimates on a FAB-like composition (Figures 7c–7d) indicates that this FAB character was maintained throughout the percolation history.

Vanadium concentrations in the Wadi Zikt spinels (692, 1052 ppm) are elevated relative to high-Cr chromitites from Thetford Mines (417, 585 ppm; Pagé and Barnes, 2009). V partitioning in spinel is sensitive to $f\text{O}_2$, melt composition, and crystal-chemical effects simultaneously, and elevated V cannot in isolation be interpreted as evidence for lower oxygen fugacity. Rather, the difference in V between high-Al and high-Cr chromitites likely reflects the greater slab-fluid involvement and hence higher oxidation state associated with the more arc-like high-Cr end-member (Liu et al., 2024).

Based on the combined spinel and clinopyroxene evidence presented above, the parental melts responsible for Wadi Zikt chromitite formation are interpreted as forearc basalt-type melts, generated by decompression melting of upwelling subforearc asthenospheric mantle during early subduction initiation (Reagan et al., 2010; Ishizuka et al., 2011). These melts were progressively modified by the influx of incipient slab-derived aqueous fluids, driving composition toward greater depletion and boninitic affinity. Water plays a fundamental role in this transition: hydrous conditions promote elevated degrees of partial mantle melting, enhance Cr solubility in the melt prior to saturation, and are widely considered a prerequisite for chromitite formation in forearc settings (Edwards et al., 2000; Su et al., 2020; Rollinson, 2025). The Wadi Zikt transitional high-Al to intermediate-Cr chromitites therefore capture a specific stage in the FAB-to-boninite magmatic continuum that characterizes subduction initiation sequences, preserving

the geochemical imprint of both MORB-like and nascent arc processes in a single chromitite occurrence.

5.2. Genesis of Wadi Zikt Podiform Chromitites

Chromite saturation cannot be achieved by simple cooling or differentiation of typical MORB (~460 ppm Cr) or boninite (~1200 ppm Cr) melts (Allen et al., 1989); a chemical trigger is required. For podiform chromitites, reactive melt–rock interaction is the dominant mechanism (Zhou et al., 2014; Arai and Makoto Miura, 2016). The Cr budget of the Wadi Zikt chromitites is interpreted as sourced from both the infiltrating melt and the host peridotite, liberated during dissolution of Cr-bearing orthopyroxene and clinopyroxene.

The enclosure of Wadi Zikt chromitite pods within dunite halos hosted in depleted harzburgite (Figure 1b) provides direct petrographic evidence for reactive melt percolation. The dunite envelopes formed through the reaction: $\text{Opx} + \text{Cpx} + \text{melt}_{\text{unsaturated}} \rightarrow \text{Ol}_{\text{solid}} + \text{SiO}_2\text{-rich melt}$ (Zhou et al., 1994, 2014) in which pyroxene dissolves into the migrating melt, olivine precipitates, and SiO_2 is added to the melt. Because this dissolution–precipitation reaction continuously modifies the composition of the infiltrating melt, the melt was compositionally distinct from, and not in chemical equilibrium with, the surrounding harzburgite, an inherently open-system process (Arai, 1997; Suhr et al., 1998; Pagé and Barnes, 2009). The contemporaneous formation of chromitite and its enclosing dunite, documented globally (Zhou et al., 2014; Rui et al., 2022; Bo et al., 2023), is accordingly interpreted as a coupled product of this single reactive percolation event. The addition of SiO_2 to the melt reduces Cr solubility, driving the melt progressively toward chromite oversaturation and triggering spinel precipitation within the developing dunite channel (Zhou et al., 1994).

The highly magnesian compositions of coexisting olivine and Cpx (Mg# up to 0.95–0.96) are consistent with crystallization from, or re-equilibration with, a highly depleted percolating melt; however, both phases may have been further enriched in Mg by subsolidus Mg-Fe exchange with spinel (Zhou et al., 1996; Pagé and Barnes, 2009). Subsolidus Mg-Fe exchange between olivine and chromite is well established, with the direction and magnitude of re-equilibration controlled by the modal olivine-to-chromite ratio; the high chromite modal abundance at Wadi Zikt (~50–70 vol.%) would have promoted more pronounced Mg enrichment in olivine (Su et al., 2019).

Clinopyroxene trace-element systematics independently record the percolation history. The elevated LREE contents of the Wadi Zikt Cpxs relative to depleted MORB mantle, and in particular, the selective La enrichment visible in CI-normalized REE patterns (Figure 5c), are characteristic of fertilization by a small fraction of percolating melt reacting with previously depleted peridotite (Kelemen et al., 1992; Sano and Kimura, 2007; Seyler et al., 2007). These features confirm that the Cpxs are not primary residual mantle phases but crystallized during the reactive porous-

flow event, providing a chemical record of the infiltrating melt's evolving composition.

Slab-derived aqueous fluids are inferred to have progressively amplified the reactive percolation process during early subduction initiation. These fluids raised the fO_2 of the system, promoted hydrous melting of the mantle wedge, and are widely regarded as essential for chromitite formation in forearc environments (Edwards et al., 2000; Su et al., 2020; Rollinson, 2025). The elevated fO_2 values ($\Delta \log fO_2 = 0.45\text{--}1.72$ above FMQ; Table S1) are consistent with progressive incorporation of slab-derived oxidizing components into the source, a feature shared with chromitites from other nascent forearc settings (Zhang et al., 2020; Bo et al., 2023).

In summary, the Wadi Zikt transitional high-Al to intermediate-Cr chromitites formed through open-system reactive percolation of a MORB-like forearc basalt melt through depleted harzburgite, with Cr supplied from both the melt and the peridotite, SiO_2 addition driving chromite saturation, and incipient slab-derived fluids sustaining the hydrous, oxidized conditions required for crystallization.

5.3. Fe Isotope Constraints on Chromitite Petrogenesis

The whole-rock Fe isotope compositions of the Wadi Zikt chromitites provide an independent, bulk-rock-scale test of the petrogenetic model developed above from mineral chemistry. Three first-order observations are relevant. First, the position of the data between the peridotitic mantle and MORB reservoirs (Figure 6a) is the pattern expected for a chromite-forming assemblage that inherited its Fe from a MORB-like melt undergoing reaction with depleted mantle. Basaltic melts are systematically enriched in heavy Fe isotopes relative to their peridotitic sources ($\delta^{56}Fe \approx +0.105 \pm 0.006\text{‰}$ for MORB vs. $+0.025 \pm 0.025\text{‰}$ for fertile peridotite; Weyer and Ionov (2007); Teng et al. (2013)), whereas melt-depleted harzburgites extend to chondritic and lighter values (Williams et al. (2005); Weyer and Ionov (2007)). During pervasive reactive percolation, dissolution of orthopyroxene and olivine from the isotopically light refractory host and precipitation of chromite and secondary silicates from the hybridized melt should displace the bulk composition of the crystallizing assemblage away from the pure-melt value toward the mantle array. The intermediate $\delta^{56}Fe$ of the Wadi Zikt chromitites ($+0.056$ to $+0.064\text{‰}$), with all five samples lighter than the mean MORB, is consistent with this hybridization. The tight clustering of the dataset suggests broadly comparable melt-rock reaction conditions and effective rock/melt ratios among the analyzed chromitite samples. In this respect, the Fe isotope data record, at the whole-rock scale, the same interaction between a MORB-like melt and refractory mantle that is inferred from the transitional spinel chemistry and from the reacted character of the interstitial silicates.

Second, the moderately heavy compositions remain well below the values expected for assemblages whose Fe budget

is dominated by ferric-iron-rich oxides, because heavy Fe isotopes are preferentially incorporated into Fe^{3+} -bearing phases such as magnetite (Williams et al. (2005); Sossi and O'Neill (2017); Dauphas et al. (2017)). The absence of anomalously heavy whole-rock values is therefore consistent with the low calculated Fe^{3+} contents of the Wadi Zikt spinels (Table S1) and with the interpretation that the elevated olivine-spinel oxybarometry values record subsolidus closure rather than a strongly oxidized magmatic crystallization environment. Because the analyzed powders are bulk chromitite (chromian spinel plus interstitial olivine and pyroxene), and inter-mineral Fe isotope fractionation at magmatic temperatures is small (Sossi and O'Neill, 2017), these whole-rock values are regarded as robust first-order estimates of the Fe isotope composition of the chromite-forming assemblage.

Third, the narrow range and mass-dependent behavior of the data argue against significant open-system disturbance of the Fe budget after chromitite formation. Fe mobility in serpentinizing and subduction-zone fluids can fractionate Fe isotopes substantially in altered ultramafic systems (Debret et al. (2016)); the coherence of the Wadi Zikt values, together with the petrographic freshness of the analyzed assemblages, indicates that such effects were minor. It should be noted that the $\delta^{56}Fe$ values slightly heavier than typical boninites, which retain chondritic to only mildly heavy compositions owing to high-degree flux-assisted melting (Dauphas et al. (2009)), are consistent with the parental melt being a MORB-like forearc basalt rather than a boninite *sensu stricto*, in agreement with the spinel-melt calculations (Section 5.1). Given the modest sample set ($n = 5$), these inferences are necessarily first-order; nevertheless, the Fe isotope data are fully consistent with, and add whole-rock-scale support to, chromitite formation by reactive percolation of a hydrous MORB-like melt through depleted harzburgite during subduction initiation.

5.4. Geotectonic Implications

The tectonic environment of Wadi Zikt chromitite formation is assessed through the integrated chemistry of Cr-spinel and associated silicate minerals, with particular reference to estimates of partial melting degree, fO_2 , and comparison with global tectonic reference datasets. The Wadi Zikt Cr-spinel compositions (Cr# 0.51–0.67; TiO_2 0.08–0.76 wt%; Al_2O_3 17.1–26.1 wt%; Mg# 0.53–0.72) occupy a transitional compositional field between MOR and SSZ environments (Figure 8a–b; Zhang et al., 2020; Bo et al., 2023). Cr#-based partial melting estimates (Arai, 1994; Figure 8c) indicate ~25–35% melt extraction, consistent with a highly depleted forearc mantle source. High olivine Fo values (up to Fo₉₅; Figure 8c) plot in the forearc peridotite field, though the highest Fo values are partly attributed to subsolidus re-equilibrium and should not be used as a standalone primary melting proxy. Oxygen fugacity estimates from olivine-spinel equilibria (Ballhaus et al., 1991) yield $\Delta \log fO_2 = 0.45\text{--}1.72$ above FMQ (Table S1; Figure 8d), overlapping the forearc and arc peridotite fields. These elevated fO_2 values are consistent

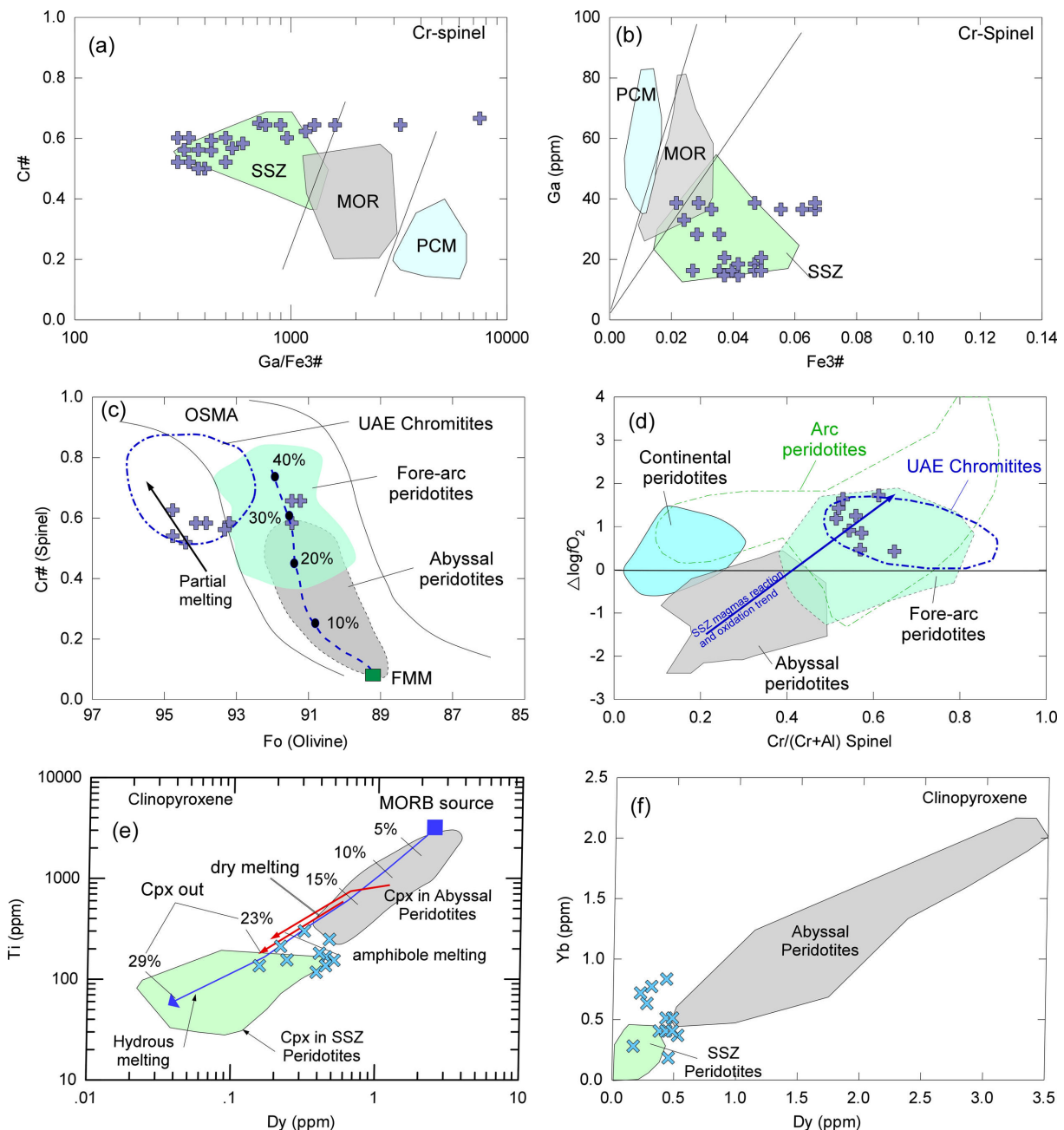


FIGURE 8: (a, b) Ga/Fe₃# vs. Cr# and Fe₃# vs. Ga tectonic setting discrimination diagrams of Cr-spinels after Dare et al. (2009). (c) Olivine Fo (forsterite) vs. spinel Cr# showing partial melting% and tectonic settings. Fields of chromian spinel in abyssal peridotites (Arai, 1994), forearc peridotites (Parkinson and Pearce, 1998), and UAE chromitites (Dare, 2007) are used for comparison. (d) Oxygen fugacity ($\Delta\log f_{O_2}$) versus spinel Cr# based on fayalite-magnetite-quartz (FMQ) buffer (Ballhaus et al., 1991). Fields of arc peridotites (Rolland et al., 2002), abyssal peridotites (Dick and Bullen, 1984), and forearc peridotites (Parkinson and Pearce, 1998) are shown for comparison. The continental peridotite field and the blue arrow show the trend for residual peridotites interacting with supra-subduction zone (SSZ) melts after Parkinson and Pearce (1998). (e, f) Dy vs. Ti and Dy vs. Yb of Cpxs. Dry melting is residual clinopyroxene compositions during dry melting (incremental batch melting at 0.1% increments) of a MORB source; amphibole melting is melting of a MORB-depleted source in the presence of amphibole, and hydrous melting is melting in the presence of fluids (Bizimis et al., 2000). The fields of primary Cpx from IBM forearc peridotites (Parkinson and Pearce, 1998; Murata et al., 2009) and Cpx from abyssal peridotites (Johnson and Dick, 1992).

with oxidized, slab-fluid-influenced conditions and support formation in a nascent forearc environment, though they carry inherent uncertainty from the stoichiometric Fe³⁺ calculation used and should be regarded as indicative rather than precise. Together, the partial melting degree

and f_{O_2} data argue against a “true” MOR setting and favor a hydrous, nascent forearc mantle environment (Edwards et al., 2000; Rollinson, 2025).

Independent tectonic evidence is provided by Cpx trace element systematics. On the Dy–Ti and Dy–Yb diagrams

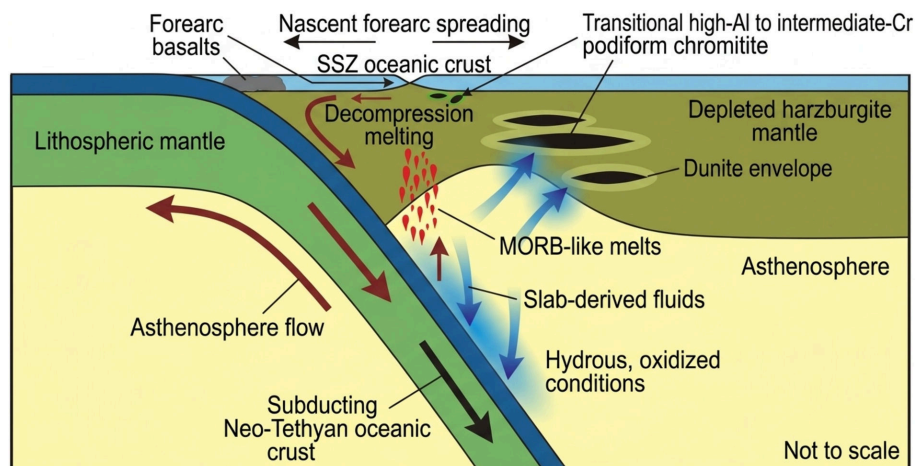


FIGURE 9: Schematic model depicting the formation of Wadi Zikt chromitites of the UAE ophiolites in a nascent forearc setting.

of Bizimis et al. (2000), the Wadi Zikt Cpxs plot is in the transitional SSZ–abyssal field, indicating ~20–25% melt extraction under hydrous conditions (Figures 8e and 8f) and a nascent forearc setting. This estimate is consistent with, though somewhat lower than, the ~25–35% inferred from spinel Cr#, reflecting the multi-stage percolation history recorded in the Cpx. The Cpx REE patterns (Figure 5c) overlap those of abyssal peridotites and high-Al chromitites worldwide (Uysal et al., 2012; Khedr and Arai, 2017; Rui et al., 2022; Bo et al., 2023). Olivine (Fo_{91–95}; NiO 0.37–0.57 wt%; MnO 0.05–0.14 wt%) and Opx (Mg# 0.90–0.92; Al₂O₃ 0.99–1.21 wt%; Cr₂O₃ 0.41–0.62 wt%) compositions are broadly comparable to those from high-Al chromitite assemblages and forearc peridotite reference datasets (Lian et al., 2018; Bo et al., 2023; Figures 4 and 5).

Collectively, the spinel and silicate mineral evidence supports the formation of the Wadi Zikt transitional high-Al to intermediate-Cr chromitites in a nascent forearc (supra-subduction zone) setting during the onset of Neo-Tethyan subduction (Reagan et al., 2010; Ishizuka et al., 2011) (Figure 9). The parental melts represent the forearc basalt stage of the subduction initiation sequence, progressing from MORB-like tholeiite toward boninitic affinity with increasing slab-fluid flux. This places the Wadi Zikt chromitites within the same subduction initiation framework established for the broader Semail ophiolite (Bo et al., 2023; Rollinson, 2025) and confirms the significance of transitional chromitites as recorders of the earliest stages of the FAB-to-boninite magmatic continuum.

6. CONCLUSIONS

The Wadi Zikt chromitites (Khor Fakkan Block, UAE) provide the first systematic mineral-chemical dataset from this previously undescribed occurrence and document how transitional high-Al to intermediate-Cr podiform chromitites form during subduction initiation. They occur within the mantle section of the Semail ophiolite, where chromitite pods are hosted by harzburgite and surrounded by dunite envelopes, and exhibit magmatic textures, disseminated

to semi-massive chromite with cumulus chromian spinel grains, alongside olivine, clinopyroxene, orthopyroxene, and minor Ni–Fe sulfides.

Chromian spinels classify as transitional high-Al to intermediate-Cr chromitites, reflecting a hybrid MORB–boninite magma affinity. Olivine (Fo_{91–95}) shows NiO and MnO contents consistent with a primary igneous origin, with the highest Fo values partly reflecting subsolidus Mg–Fe exchange with spinel. Clinopyroxene and orthopyroxene compositions are consistent with crystallization in a depleted forearc-type melt environment, noting that the Cpx is interpreted as a product of late reactive melt percolation rather than direct primary crystallization from the parental melt. Base-metal sulfides (pentlandite–heazlewoodite ± bornite) record low sulfur fugacity and late-stage Cu mobilization, features typical of mantle-hosted chromitites.

Integrated major and trace element data indicate the chromitites crystallized from a MORB-like forearc basalt melt with incipient arc signatures. MORB–chromite-normalized spinel patterns, enriched in Ti and V, and Cpx-derived equilibrium melt REE patterns are consistent with forearc basalt parental magmas. Oxygen fugacity is estimated from olivine–spinel pairs, consistent with slab fluid involvement during subduction initiation.

We interpret Wadi Zikt transitional high-Al to intermediate-Cr chromitites to have formed in a nascent forearc spreading center at the onset of Neo-Tethyan subduction. Upwelling asthenosphere generated MORB-like forearc basalt melts, which, upon reactive percolation through refractory harzburgite, dissolved pyroxenes, formed dunite, and became supersaturated in Cr, precipitating chromite. Progressive fluxing by incipient slab-derived aqueous fluids sustained the hydrous, oxidized conditions necessary for chromitite formation. Thus, transitional high-Al chromitites in the UAE ophiolite record the earliest transition from oceanic spreading to subduction initiation regimes.

Chromitite formation was driven by reactive melt percolation in open-system disequilibrium with the host peridotite: dissolution of Opx and Cpx supplied SiO₂ to the melt, reducing Cr solubility and triggering localized

chromite saturation within growing dunite channels. The interstitial Cpx records refertilization of the peridotite by this percolating melt, as evidenced by selective LREE enrichment in its REE patterns. This melt–rock interaction scenario coherently explains the net and nodular chromite textures, the dunite envelopes, the late-crystallizing Cpx, and the covariation of spinel and olivine chemistry, reaffirming that podiform chromitites are products of focused, disequilibrium melt flux through depleted mantle.

The Wadi Zikt transitional high-Al to intermediate-Cr chromitites record the forearc basalt stage of this process, bridging MORB-like and boninitic geochemical signatures in a single occurrence. Transitional high-Al chromitite occurrences, even with MORB-like traits, should be interpreted in the context of nascent subduction zones. This study underlines the value of chromitite mineral chemistry as a tectonic proxy for ophiolite genesis and highlights that both high-Al and high-Cr chromitites must be considered together to reconstruct the full magmatic history of a forearc system.

Editor Disclosure Statement

Note: Hamed Gamaleldien holds the position of Associate Editor for *Lithosphere* and has not peer reviewed or made any editorial decisions for this paper.

Data Availability

All data supporting the conclusions of this study are included in the article and its Supplementary Materials. Additional datasets generated and analyzed during the current study are available from the corresponding authors upon reasonable request.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary Materials Available

The Supplementary Materials include complete electron microprobe (EPMA) and LA-ICP-MS analytical data for chromian spinel, olivine, clinopyroxene, orthopyroxene, and base-metal sulfides, along with calculated parental melt compositions and oxygen fugacity estimates. These datasets underpin the mineral chemistry interpretations, petrogenetic modeling, and tectonic conclusions presented in the manuscript.

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