CHROMITE ORE DEPOSITS WITHIN THE HELLENIDE OPHIOLITES: A KEY TO GENETIC PROCESSES AND POST-GENETIC EVOLUTION

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ABSTRACT

Chromite ore deposits hosted in the Hellenide ophiolites provide key insights into mantle processes, geodynamic evolution, and post-magmatic modification within the Mesozoic Neo-Tethyan realm. This study synthesizes geological, minero-chemical, and platinum-group elements (PGE) data from well-characterized chromitites hosted in the Pelagonian-Subpelagonian Zone (Vourinos, Pindos, Othrys, Evia), the Vardar Zone (Veria, Vavdos, Skyros), and the Serbo-Macedonian Massif (Gomati, Nea Roda). Chromite compositions are highly variable, reflected mainly by wide variations in Cr# and Mg#, due to both primary magmatic processes and secondary modifications. Principal Component Analysis (PCA) of major element data identifies three dominant controls on chromite variability. The first principal component (PC1) records Cr-Al and Mg-Fe^{2+} substitutions and captures the primary magmatic signal related to mantle depletion and melt composition. The second principal component (PC2) reflects subsolidus Mg-Fe^{2+} re-equilibration and the third principal component (PC3) records redox variations during metamorphic events.

Pelagonian-Subpelagonian chromitites display the widest compositional range, including both high-Cr, boninitic-like forearc chromitites and high-Al, transitional MOR-SSZ varieties, reflecting variable degrees of mantle depletion and melt-rock interaction. Vardar chromitites retain a primary supra-subduction zone (SSZ) affinity, but commonly record deformation and Fe-Mg re-equilibration and, locally, metasomatic PGE redistribution, particularly in high-strain zones. In contrast, chromitites of the Serbo-Macedonian Massif are strongly affected by amphibolite- to greenschist-facies metamorphism, resulting in systematic Fe^{3+} enrichment and partial to complete modification of primary magmatic signatures. This study demonstrates that PCA provides a robust quantitative framework for distinguishing between magmatic and secondary controls on chromite chemistry. The results highlight a progressive transition from magmatically dominated to metamorphically overprinted systems across the Hellenides, emphasizing the need to carefully consider post-magmatic processes when interpreting chromitite genesis in complex tectonic environments.

INTRODUCTION

Several types of metallic ore deposits can be hosted in the various lithologies of ophiolites and at different levels of the ophiolite layered sequence, such as sedimentary manganese and manganese crusts and nodules (Öztürk, 1997; Roy, 1992) and hydrothermal volcanic massive sulfide deposits. Among the various lithologies composing the ophiolitic sequences, podiform chromitites occurring within mantle peridotites and ultramafic cumulates are of particular importance, as they constitute major chromium resources.

The relevant socio-economic implications associated with the exploitation of such ores has resulted in numerous publications on their genesis and post-genetic evolution, where the reconstruction of the ophiolite geodynamic setting and geologic evolution is essential for developing predictive and exploration modelling. In turn, the study of mineralization, supported by the specific tools and concepts of the ore deposits framework, through a fruitful interdisciplinary exchange, can yield significant data, information and interpretations to unravel the petrologic and tectonic evolution of ophiolites. Chromite ore deposits can be useful in the study of the geodynamic setting of the ophiolite lithosphere and of its tectonic evolution. A great contribution derives, in this case, by the large use in the scientific literature of spinel as a petrogenetic indicator, thanks to its wide range of compositions due to ion exchanges in both the tetrahedral and octahedral sites of the crystals structure and that can record changes in the environment surrounding the crystals (Sack and Ghiorso, 1991). Podiform chromitites constitute key indicators of mantle processes (Leblanc and Ceuleneer, 1991) and supra-subduction zone (SSZ) geodynamics. Their occurrence is closely related to melt-rock interaction processes within depleted mantle tectonites, commonly involving boninitic or high-Mg melts in fore-arc environments (Sideridis et al., 2021). The geochemical characteristics of chromite, particularly Cr# and Mg#, together with platinum-group elements (PGE) distribution patterns, provide robust constraints on mantle source fertility, degree of partial melting, and parental melt evolution (Economou-Eliopoulos, 1996; Grammatikopoulos et al., 2011).

In this context, multivariate statistical approaches, such as Principal Component Analysis (PCA), represent a powerful tool to disentangle the relative contribution of different processes recorded in chromite chemistry. By reducing dataset dimensionality and identifying the main factors controlling variance, PCA can help recognize primary and alteration trends.

The present work aims to provide an overview of the most studied and best known chromite occurrences within the Hellenide ophiolites, focusing on their mineral chemistry and PGE geochemistry. The Hellenide ophiolites represent an ideal natural laboratory, due to i) the high number of ophiolite settings, of chromite occurrences and ore bodies in their ultramafic sections, ii) the long lasting and widely distributed mining of chromite ore bodies and iii) the focus of the scientific community research on these chromitites that has led to a high number of publications, implying that this area is one of the major grounds where the scientific community has had the opportunity to compare and test different models on chromite deposit genesis and evolution. By integrating classical geochemical approaches with multivariate statistical methods, this work aims to refine current models of chromitite genesis and contribute to a more quantitative understanding of their evolution within Tethyan ophiolites.

GEOLOGICAL SETTING AND OVERVIEWED CHROMITITES

The Hellenide ophiolites form a NNW-SSE-trending belt in the Balkan Peninsula and represent remnants of the Mesozoic Neo-Tethyan oceanic lithosphere that developed between the Apulian (Adria) and Pelagonian microcontinents (Dilek et al., 2008). The Hellenide orogenic system originated from Permo-Triassic rifting along the northern margin of Gondwana, which led to the opening of marginal oceanic basins. These basins were subsequently consumed by intra-oceanic subduction, followed by westward obduction of oceanic lithosphere during the Middle to Late Jurassic (Beccaluva et al., 1998; Dilek et al., 2008; Robertson and Dixon, 1984; Saccani and Tassinari, 2015).

The Hellenide belt is classically subdivided into five paleo-tectonic zones, from west to east (Beccaluva et al., 1998; Pe-Piper and Piper, 2002):

i. the Adria continental margin, dominated by shallow-water carbonate platform successions derived from the Adriatic-Apulian passive margin.
ii. the Jurassic Subpelagonian ophiolitic domain, represented by the Subpelagonian Zone, consisting of Jurassic ophiolites and associated deep-marine sedimentary sequences.
iii. the Pelagonian continental margin, characterized by a Palaeozoic basement unconformably overlain by Permo-Triassic clastic and volcanic successions, recording early rifting of the continental domain.
i. the Vardar ophiolitic domain, which represents the main oceanic suture between the Pelagonian microcontinent and the Rhodope massif and includes Jurassic ophiolites, remnants of Hercynian continental basement, deep-water sedimentary rocks, and calc-alkaline intrusives.
v. the Rhodope continental margin, composed predominantly of pre-Alpine continental basement units. The Serbo-Macedonian Massif, once part of the Rhodope Massif, was separated based on observation of different metamorphic grades.

Within this framework, the chromitites considered in this study are distributed across three main ophiolitic domains (Pelagonian-Subpelagonian, Vardar and Serbo-Macedonian massif, Fig. 1), reflecting distinct geodynamic settings and post-magmatic histories.

Geologically, these belts reflect the complex opening and closure of various Neotethyan oceanic basins and their subsequent obduction onto continental margins. In particular, we considered Vourinos, Pindos, Othrys and Northern Evia for the Pelagonian-Subpelagonian domain, Vavdos, Veria and Skyros for the Vardar domain, and Gomati and Nea Roda for the Serbo-Macedonian Massif (Fig. 1).

The Pelagonian and Subpelagonian zones ophiolites host the most economically significant chromite deposits in Greece. These ophiolites are remnants of the Mesohellenic oceanic slab, which was obducted westwards during the Middle-Late Jurassic. The major chromitite-hosting massif is Vourinos, in Grevena District, which contains the largest

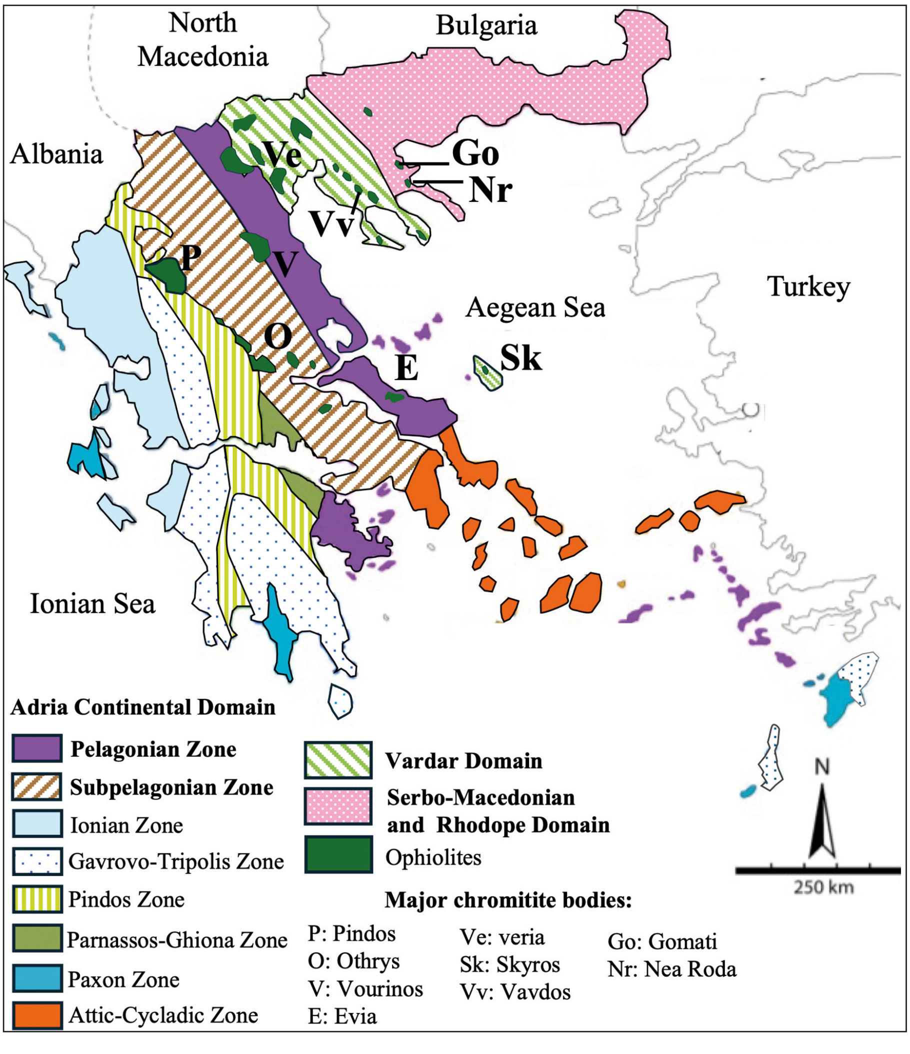

Fig. 1 - Schematic geological setting of Greece, divided into geotectonic domains. The main chromitite deposits associated with ophiolites are reported in the map. Modified after: (Bussolesi et al., (2025) and Zachariadis (2007).

and highest-quality reserves. The Xerolivado-Skoumtsa mine is world-renowned for its massive and schlieren-type metallurgical-grade (high-Cr) chromitites (Grieco et al., 2018; Rassios et al., 2020). Other key deposits include Aetoraches and Voidolakkos. These formed in a Supra-Subduction Zone (SSZ) environment. The Pindos and Othrys massifs also host economic chromitite deposits (Kapsiotis et al., 2018; Kapsiotis, 2013), as well as the ultramafic massifs of Northern Evia Island (Grieco et al., 2023).

The Vardar (Axios) Zone represents the "innermost" ophiolite belt in Greece. The deposits here are often associated with highly depleted mantle peridotites and are significantly impacted by later metamorphic events. Major chromite deposits are Vavdos and Gerakini (Sideridis et al., 2021), in the Chalkidiki pensinsula, known mostly for their high-quality magnesite deposits but containing important podiform chromitites, and Veria-Vermion close to Veria city. Skyros chromitites, occurring in the Skyros island, are also tectonically and genetically correlated with the ophiolites of the Vardar Zone (Bussolesi et al., 2025).

The easternmost Greek deposits are located in the metamorphic basement of the Serbo-Macedonian Massif (SMM). These bodies are often considered "enigmatic" as they are heavily metamorphosed and their original tectonic setting is highly debated. They are small occurrences, locally mined in the past, and include the Gomati and Nea Roda deposits (Bussolesi et al., 2022b; Dixon and Dimitriadis, 1984; Sideridis et al., 2022).

GENESIS OF CHROMITITES

This review focuses on well-characterized podiform chromitite occurrences in the Hellenides whose geological context, chromite mineral chemistry and PGE data are sufficiently documented to allow a robust interpretation. The discussion therefore includes chromitites from the Pelagonian-Subpelagonian zone (e.g., Vourinos, Pindos, Othrys and Evia), the Vardar Zone (Veria, Vavdos and Skyros) and from the Serbo-Macedonian Massif (Gomati and Nea Roda). Other reported occurrences in Greece are not considered because they either do not represent primary ophiolitic mantle chromitites sensu stricto or lack the mineral-chemical constraints required for genetic evaluation. For this reason, chromite-bearing ultramafic bodies from the Vermion and Gerakini areas and minor localities in the Serbo-Macedonian Massif were not included in the review. The dataset used for this review is reported in the Supplementary Materials and summarized in Table 1.

Pelagonian-Subpelagonian Zone

Chromitites of the Pelagonian-Subpelagonian Zone are hosted by some of the best-preserved mantle sections of the Hellenides and represent classical examples of podiform chromitites formed in supra-subduction zone (SSZ) environments. The most extensively studied bodies occur in Vourinos, Pindos, Othrys, and northern Evia, where chromitites are typically enclosed within dunite envelopes cutting harzburgitic mantle tectonites.

Vourinos

The Vourinos ophiolite hosts one of the largest and best-studied podiform chromitite deposit in the Hellenides. Chromitite bodies occur as pods, schlieren, massive to semi-massive lenses and irregular ore zones enclosed within dunite envelopes hosted by a dominantly harzburgitic mantle tectonite (Savvidis and Hovorka, 1997). Individual ore bodies range from small, discontinuous schlieren to large, economically significant lenses, particularly in districts such as Xerolivado-Skoumtsa (Konstantopoulou and Economou-Eliopoulos, 1990). Detailed field and structural studies demonstrate that dunite bodies acted as the principal melt-transport pathways, while high-strain zones (fold noses, mylonitic bands, shear-related schlieren, and so-called "metalliferous zones") played a critical role in mechanically concentrating chromite into massive ores, superimposed on an initially magmatic chromite distribution (Grammatikopoulos et al., 2011; Rassios et al., 2020).

Chromitites in Vourinos display a wide compositional variability, both between and within individual ore bodies. Chromite compositions are generally characterized by high Cr# [Cr/(Cr+Al)], varying between 0.544 and 0.870, and variable Mg# [Mg/(Mg+Fe^{2+})], ranging from 0.361 to 0.824 (Fig. 2). This wide compositional range reflects both primary magmatic variability and variable degrees of subsolidus re-equilibration during cooling and deformation.

The Cr# ratio is commonly used as a proxy for the degree of mantle depletion and/or the affinity of the parental melts, with higher values indicating interaction with highly depleted mantle sources in supra-subduction zone (SSZ) settings (Arai, 1997; González-Jiménez et al., 2014). In Vourinos, the consistently high Cr# values link chromitite formation to focused melt flow in dunite channels within a depleted SSZ

Table 1 - Summary of the chromitite occurrences included in this study

Pelagonian-Subpelagonian	Vourinos	(Grieco et al., 2018; Rassios et al., 2020)
Pelagonian-Subpelagonian	Pindos	(Economou and Vacondios, 1995; Kapsiotis, 2013)
Pelagonian-Subpelagonian	Othrys	(Kapsiotis et al., 2018)
Pelagonian-Subpelagonian	Evia	(Grieco et al., 2023)
Vardar	Veria	(Tsoupas and Economou-Eliopoulos, 2021, 2008)
Vardar	Vavdos	(Sideridis et al., 2021; Pedrotti 2008, unpublished data)
Vardar	Skyros	(Bussolesi et al., 2025)
Serbo-Macedonian Massif	Nea Roda	(Bussolesi et al., 2022a, 2022b; Sideridis et al., 2022)
Serbo-Macedonian Massif	Gomati	(Bussolesi et al., 2022a, 2022b; Sideridis et al., 2022)

Chromitite occurrences are grouped by tectonic domain, with corresponding literature sources used for the compilation of the geochemical dataset. Full dataset is reported in the Supplementary Materials.

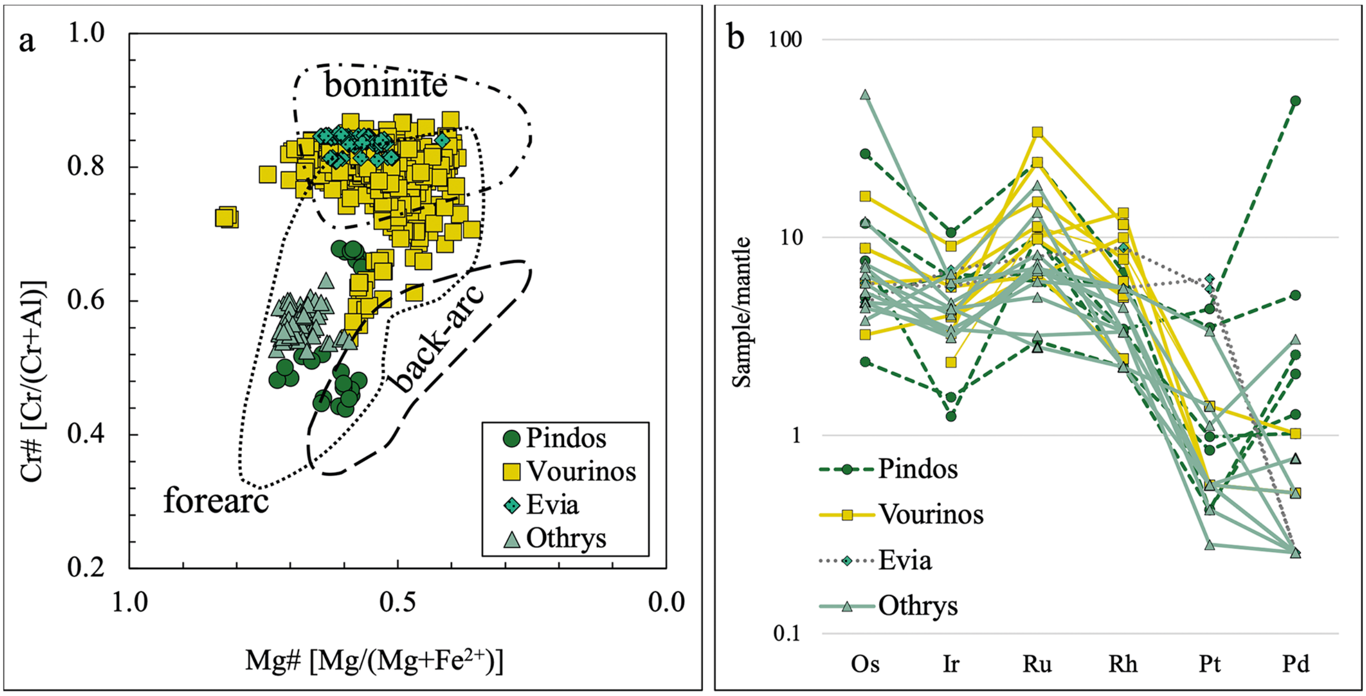

Fig. 2 - a) Cr# [Cr/(Cr+Al)] vs Mg# [Mg/(Mg+Fe^{2+})] plot of chromian spinel from Pelagonian-Subpelagonian chromitites, including Pindos (Economou and Vacondios, 1995; Kapsiotis, 2013), Vourinos (Grieco et al., 2018; Rassios et al., 2020), Evia (Grieco et al., 2023) and Othrys (Kapsiotis et al., 2018) with reference compositional fields for spinels crystallized from boninitic melts and from forearc settings (Barnes and Roeder, 2001) and back-arc settings (Khedr and Arai, 2016); b) Mantle normalized (McDonough and Sun, 1995) PGE patterns of Pindos (Economou and Vacondios, 1995; Kapsiotis, 2013), Vourinos (Economou-Eliopoulos, 1996; Grammatikopoulos et al., 2011), Evia and Othrys (Economou-Eliopoulos, 1996).

mantle wedge (Grammatikopoulos et al., 2011; Grieco et al., 2018; Rassios et al., 2020). Chromitite formation was controlled by melt-rock interaction processes, whereby high-Mg melts ascending through dunite conduits reacted with surrounding harzburgite, consumed orthopyroxene, and induced chromite saturation. Vourinos chromitites were formed in a supra-subduction zone, from boninitic-like parent melts, compatible with a subduction initiation or forearc geotectonic setting (Fig. 2a).

Platinum-group elements (PGE) systematics in Vourinos chromitites are dominated by the IPGE (Os-Ir-Ru), whereas PPGE (Rh-Pt-Pd) contents are very low. PGEs are hosted primarily by magmatic platinum-group minerals, dominated by laurite and subordinate Os-Ir alloys, which occur as inclusions within fresh chromite grains (Grammatikopoulos et al., 2011; Savvidis and Hovorka, 1997). Overall PGE abundances are generally low to moderate, consistent with typical ophiolitic chromitites, and no pervasive secondary PGE enrichment is recorded. The strong IPGE enrichment (Fig. 2b) and dominance of laurite-bearing assemblages indicate chromite crystallization under low sulfur fugacity conditions, prior to sulfide saturation of the parental melts. This PGE signature is consistent with early chromite precipitation from high-Mg, boninitic melts in SSZ environments, where IPGE behave compatibly and are efficiently sequestered into chromite-hosted PGM during the earliest stages of melt evolution (Grammatikopoulos et al., 2011). Structural studies further demonstrate that ductile deformation and subsequent brittle reworking enhanced the mechanical concentration of chromite and locally redistributed PGM without substantially modifying the primary magmatic PGE signature, preserving a clear genetic link between chromitite formation and SSZ melt-rock interaction processes (Rassios et al., 2020).

Pindos

Chromitites of the Pindos ophiolite occur as small- to medium-sized podiform bodies, schlieren and irregular lenses enclosed within dunite envelopes hosted by a dominantly harzburgitic mantle sequence. Individual chromitite bodies are typically discontinuous and laterally limited, lacking the large, laterally persistent ore zones characteristic of Vourinos, but showing clear spatial association with dunite channels that cut the mantle tectonite (Economou and Vacondios, 1995). Field observations indicate that dunite bodies represent focused melt-transport pathways, along which chromite saturation and accumulation occurred during melt-rock interaction processes in the upper mantle (Economou and Vacondios, 1995; Kapsiotis, 2013).

Pindos chromitites display a markedly bimodal chromite composition. The first group consists of high-Cr chromitites, with chromite Cr# in the range 0.64 - 0.69, whereas the second group comprises high-Al chromitites, characterized by chromite Cr# values <0.50 (Fig. 2a).

This bimodality results in a broader compositional spectrum than that observed in Vourinos, where chromitites are dominantly high-Cr. In Pindos, both high-Cr and high-Al chromitites coexist within the same mantle sequence, reflecting significant variability in melt composition and chromite saturation conditions (Kapsiotis et al., 2009; Kapsiotis, 2013). The coexistence of high-Cr and high-Al chromitites in Pindos is interpreted as the result of chromite crystallization from melts of variable composition, ranging from hydrous boninitic to MORB- or island-arc tholeiitic (IAT)-like (Kapsiotis, 2013). High-Cr chromitites (e.g. Milia and related occurrences) are interpreted to have crystallized from high-Mg, hydrous boninitic melts interacting with a depleted mantle source in a forearc geotectonic setting. In contrast, high-Al chromitites are attributed to chromite saturation from less depleted, more evolved melts, likely generated in back-arc or transitional SSZ environments, where lower degrees of partial melting and reduced melt-rock interaction limited Cr enrichment (Economou and Vacondios, 1995; Kapsiotis, 2013). This genetic diversity reflects the complex tectono-magmatic evolution of the Pindos mantle, which records both forearc and back-arc signatures (Fig. 2a).

Platinum-group elements signatures in Pindos chromitites vary systematically with chromite type. High-Cr chromitites are generally low in total PGE contents and dominated by IPGE (Os-Ir-Ru) (Fig. 2b), hosted mainly by laurite and subordinate Ru-Os-Ir alloys. In contrast, high-Al chromitites, particularly those from the Korydallos area, exhibit significant PPGE enrichment and host abundant Pt-Pd-bearing alloys and sulfides. PGE concentrations in these Al-rich chromitites are locally elevated relative to the Cr-rich counterparts, indicating more efficient late-stage PGE concentration (Economou and Vacondios, 1995; Kapsiotis et al., 2009; Kapsiotis, 2013). The contrasting PGE signatures of Pindos chromitites provide important constraints on melt evolution and chromitite genesis. IPGE-dominated patterns in high-Cr chromitites reflect early chromite crystallization from primitive, sulfur-undersaturated boninitic melts, where compatible IPGE were preferentially incorporated into chromite-hosted PGM (Kapsiotis et al., 2009). Conversely, the strong PPGE enrichment in Al-rich chromitites is attributed to progressive melt differentiation and localized sulfur saturation, which promoted late-stage concentration of incompatible PPGE (Pt-Pd) in evolved melts (Kapsiotis, 2013). These features support a model in which Pindos chromitites record multiple chromite-forming events from compositionally distinct melts within a back-arc to SSZ geodynamic framework, rather than a single, uniform chromitite-forming process.

Othrys

Chromitites of the Othrys ophiolite occur as small to medium-sized podiform bodies, schlieren and irregular lenses enclosed within dunite envelopes hosted by a harzburgitic mantle section. Compared to the world-class deposits of Vourinos, Othrys chromitite bodies are generally smaller, less laterally continuous, and lack large chromitite-rich areas like the 13-km-long "metalliferous zone" at Vourinos (Garuti et al., 1999; Kapsiotis et al., 2018; Tsikouras et al., 2016). These ores are characteristically of high-Al (refractory) grade and are hosted within a mantle section dominated by harzburgite and lherzolite (Kapsiotis et al., 2018; Zaccarini et al., 2024). Although they initially formed via focused melt flow within dunite channels through melt-rock interaction and mixing, the original magmatic textures have often been overprinted by intense deformation (Kapsiotis et al., 2018). This suggests that mechanical concentration within high-strain zones was a significant factor in shaping the final state of these ores, recording a complex history of magmatism at the junction of a transform fault and an infant subduction zone.

Othrys chromitites are characterized by intermediate Cr# values, generally higher than those of Pindos but lower than those of Vourinos, defining a distinct compositional field among Pelagonian-Subpelagonian chromitites (Fig. 2a). The intermediate Cr# and Mg# are systematically lower than those of typical high-Cr SSZ chromitites, reflecting differences in melt composition and mantle source characteristics (Kapsiotis et al., 2018).

The intermediate Cr# values indicate crystallization from melts derived from a less depleted mantle source and/or lower degrees of partial melting compared to the strongly depleted boninitic-like melts responsible for Vourinos chromitites (Garuti et al., 1999). This chemical signature implies reduced melt-rock interaction within dunite channels and more limited orthopyroxene consumption, resulting in lower chromite saturation efficiency (Garuti et al., 1999; Kapsiotis et al., 2018). Consequently, Othrys chromitites are interpreted to have formed in a transitional geodynamic setting between mid-ocean ridge (MOR) and supra-subduction zone (SSZ) environments, likely reflecting incipient SSZ or fore-arc conditions.

Platinum-group elements systematics in Othrys chromitites are characterized by moderate total PGE contents and assemblages dominated by IPGE-bearing phases (Garuti et al., 1999; Tsikouras et al., 2016; Zaccarini et al., 2024). The most common platinum-group minerals are Os-rich laurite-erlichmanite and Ru-Os-Ir sulfides, typically occurring as inclusions within chromite. PPGE-bearing phases are scarce or absent. Overall PGE abundances are lower than those observed in high-Cr SSZ chromitites and do not indicate significant secondary enrichment (Tsikouras et al., 2016). The dominance of Os-rich laurite-erlichmanite and Ru-Os-Ir sulfides suggests chromite crystallization under relatively higher sulfur fugacity and more oxidized conditions compared to boninitic systems, where sulfide saturation is delayed (Garuti et al., 1999). These PGE signatures indicate that chromite precipitation occurred from moderately evolved, hydrous melts in which IPGE (Os-Ir-Ru) were still compatible but less efficiently concentrated than in highly depleted SSZ settings. Together with the intermediate Cr# values, the PGE data support a model in which Othrys chromitites formed from compositionally transitional melts, recording a mantle regime that bridges MOR-like and SSZ environments, in contrast to the strongly depleted fore-arc systems typified by Vourinos (Zaccarini et al., 2024).

Evia

Chromitites of northern Evia Island occur as podiform bodies, irregular lenses and schlieren enclosed within dunite envelopes hosted by a harzburgitic mantle section. Chromitite bodies are typically small to medium-sized and are systematically associated with dunite channels that cut the mantle tectonite, indicating focused melt transport as a primary control on chromite saturation (Gartzos et al., 1990; Grieco et al., 2023). Field and structural observations highlight the importance of dunite conduits as preferential pathways for melt focusing, like at Vourinos, although chromitite bodies in Evia are generally less extensive and lack large, laterally continuous metalliferous zones. Post-magmatic reactivation of these dunite channels by fluid circulation is locally documented, linking chromitite distribution to both magmatic and later fluid-assisted processes (Grieco et al., 2023).

Evia chromitites are dominated by high-Cr compositions and moderate to high Mg# values (Fig. 2a). The relatively restricted range of Cr# values indicate a consistently depleted mantle source, whereas the spread in Mg# reflects variable degrees of subsolidus Fe-Mg re-equilibration during cooling and limited post-magmatic modification.

The high Cr# values of Evia chromitites indicate crystallization from highly depleted, high-Mg melts generated by extensive partial melting of a mantle wedge source (Gartzos et al., 1990; Grieco et al., 2023), consistent with a supra-subduction zone (SSZ) affinity, specifically a forearc geotectonic setting (Grammatikopoulos et al., 2011). Chromitite formation is interpreted to have occurred during focused melt-rock interaction within dunite channels, where ascending boninitic to boninite-like melts reacted with harzburgite, consumed orthopyroxene, and induced chromite saturation in the upper mantle (Cocomazzi et al., 2020; Economou-Eliopoulos, 1996; Grieco et al., 2023; Spiegelman and Kelemen, 2003). Compared to the Othrys ophiolite, Evia chromitites record more efficient chromite saturation and stronger mantle depletion, reflecting a more mature SSZ forearc setting (Fig. 2).

Platinum-group elements systematics in northern Evia chromitites are characterized by enrichment in IPGE (Fig. 2b) and very low PPGE contents. Platinum-group minerals are dominated by laurite and Ru-Os-Ir alloys, typically preserved as magmatic inclusions within fresh chromite grains. Overall PGE abundances are moderate and comparable to those of other high-Cr SSZ chromitites, with no evidence for secondary PGE enrichment (Economou-Eliopoulos, 1996). The dominance of IPGE-rich PGE patterns and the prevalence of laurite-bearing assemblages indicate chromite crystallization under low sulfur fugacity conditions, prior to sulfide saturation of the parental melts. These features are consistent with early chromite precipitation from primitive, boninitic melts in a strongly depleted SSZ mantle environment, where IPGE behave compatibly and are efficiently incorporated into chromite-hosted PGM. Subsequent fluid circulation along reactivated dunite channels locally modified the host peridotites but did not significantly overprint the primary magmatic PGE signature of the chromitites. Overall, the Mg#-Cr# and PGE systematics of northern Evia chromitites reflect formation in a mature forearc SSZ setting, contrasting with the more transitional, lower-Cr# chromitites of Othrys.

Vardar Zone

The Vardar Zone represents a major suture zone characterized by tectonic mélanges, intense deformation, and multistage fluid-rock interaction. Chromitites in this domain display greater heterogeneity and stronger post-magmatic modification than those of the Pelagonian-Subpelagonian Zone.

Veria

Chromitites of the Veria ophiolite occur as podiform bodies, brecciated lenses, schlieren and irregular ore zones hosted within dunite bodies enclosed in a harzburgitic mantle sequence. In contrast to Pelagonian-Subpelagonian chromitites, Veria ores are strongly associated with high-strain zones, including shear zones, fold-related structures and brecciated domains, which exert a primary control on ore geometry and internal textures. Chromitite bodies are commonly fragmented, tectonized and locally remobilized, reflecting intense ductile to brittle deformation during emplacement within the Vardar Zone lithosphere (Tsoupas and Economou-Eliopoulos, 2021, 2008).

Veria chromitites are dominated by high-Cr compositions and high Mg# values, defining a compositional field distinct from Pelagonian-Subpelagonian chromitites and overlapping other Vardar Zone occurrences (Fig. 3a) and plotting in the compositional field of forearc type chromitites from other Greek ophiolites such as Vourinos.

Chromite compositions in the Veria ophiolite exhibit significant intra-grain and intra-sample variability, which is systematically associated with deformation-related textures, brecciation, and the circulation of metasomatic fluids along high-strain shear zones. This has resulted in a notable

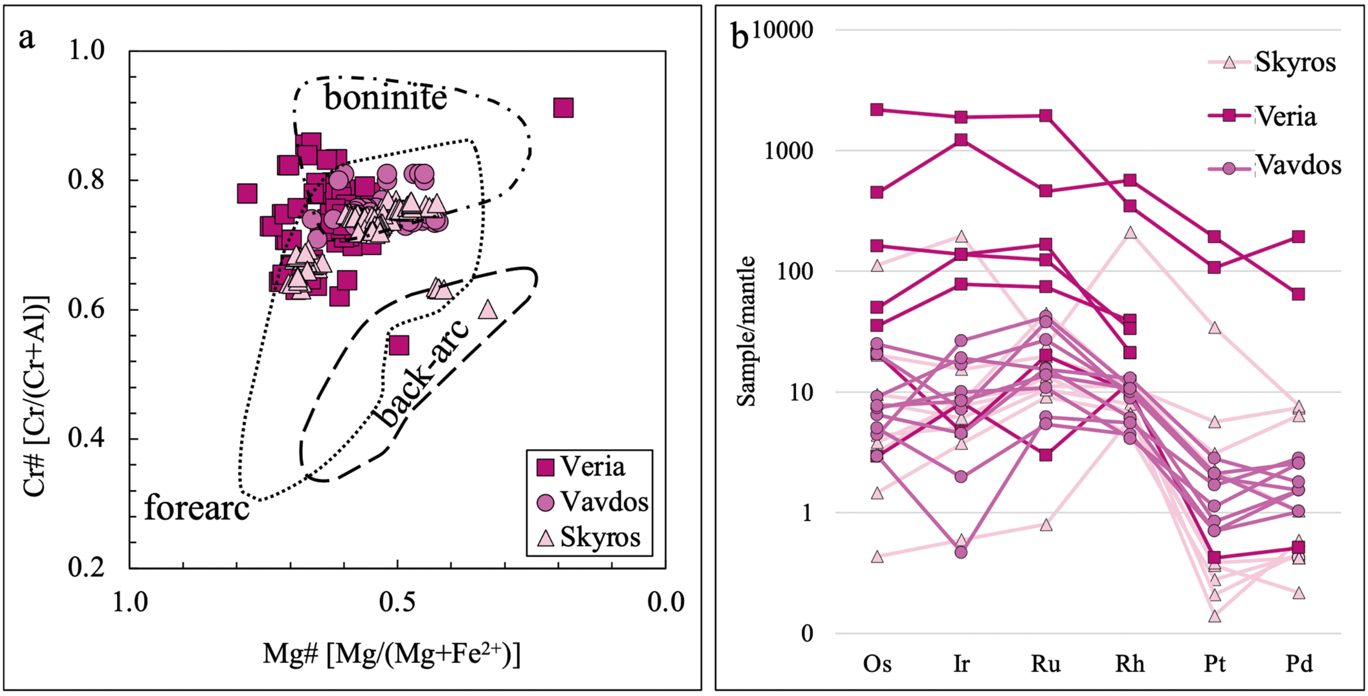

Fig. 3 - a) Cr# [Cr/(Cr+Al)] vs Mg# [Mg/(Mg+Fe^{2+})] plot of chromian spinel from Vardar chromitites, including Veria (Tsoupas and Economou-Eliopoulos, 2021, 2008), Vavdos (Sideridis et al., 2021) and Skyros (Bussolesi et al., 2025) with reference compositional fields for spinels crystallized from boninitic melts and from forearc settings (Barnes and Roeder, 2001) and back-arc settings (Khedr and Arai, 2016); b) Mantle normalized (McDonough and Sun, 1995)(McDonough and Sun, 1995) PGE patterns of Veria (Economou-Eliopoulos, 1996; Tsoupas and Economou-Eliopoulos, 2008), Vavdos (Economou-Eliopoulos, 1996; Sideridis et al., 2021) and Skyros (Bussolesi et al., 2025; Economou-Eliopoulos, 1996) chromitites.

decoupling between high Cr# values and low, scattered Mg# values. Such chemical heterogeneity reflects extensive post-magmatic modification, characterized by the transformation of primary grains into ferrian-chromite. These alteration processes are superimposed on an originally high-Cr chromitite protolith that formed from boninitic parental melts within a supra-subduction zone environment before being tectonically fragmented during the overthrusting of the Vardar Zone (Tsoupas and Economou-Eliopoulos, 2021, 2008).

The preservation of high Cr# values indicates that Veria chromitites initially crystallized from highly depleted, boninitic melts in a supra-subduction zone (SSZ) mantle wedge (Tsoupas and Economou-Eliopoulos, 2008). Cr# is largely insensitive to subsolidus modification and therefore retains information on mantle depletion and primary melt composition (Bussolesi et al., 2019; Rassios et al., 2020). In contrast, Mg# was variably modified during subsolidus re-equilibration, as deformation and fluid-assisted processes promoted Fe-Mg exchange between chromite and surrounding silicates (Grieco et al., 2018) during tectonic emplacement and cooling within the Vardar Zone lithosphere. The preservation of high Cr# values thus indicate an SSZ, boninitic affinity for the parental melts, whereas the scattered Mg# values record subsolidus re-equilibration during tectonic emplacement and cooling within the Vardar Zone lithosphere.

Veria chromitites are distinguished by high IPGE contents (Fig. 3b), locally reaching tens of ppm (Tsoupas and Economou-Eliopoulos, 2008). The platinum-group minerals are dominated by coarse Ru-Os-Ir alloys, typically occurring within brecciated chromitite domains spatially associated with Cr-garnet-bearing assemblages and shear zones. Primary IPGE-bearing phases, such as laurite, are commonly overprinted or replaced by secondary alloys and oxide/hydroxide phases, indicating extensive post-magmatic redistribution. Although the primary chromitite protolith formed from depleted, boninitic SSZ melts (Gartzos et al., 1990), the extreme IPGE enrichment in Veria is largely secondary in origin (Tsoupas and Economou-Eliopoulos, 2021, 2008). Progressive deformation and metasomatism during fluid-rock interaction promoted PGE remobilization and localized enrichment along high-strain zones. Increasing oxygen fug acity during fluid ingress led to the destabilization of sulfides and the formation of secondary alloys, decoupling PGE distributions from primary magmatic chemistry (Economou-Eliopoulos, 1996). As a result, Veria represents a composite record of primary SSZ formation overprinted by a prolonged tectono-metasomatic evolution, sharply contrasting with the more magmatically preserved chromitites of the Subpelagonian Zone.

Vavdos

Chromitites of the Vavdos ophiolite occur as podiform lenses and small, discontinuous bodies enclosed within dunite channels hosted by a highly depleted harzburgitic mantle section. Chromitite bodies are heavily fractured and brecciated, with cataclastic and pull-apart textures as distinctive features (Sideridis et al., 2021). Their close spatial association with dunite conduits highlights focused melt transport as the primary control on chromite saturation and accumulation, with only a minor influence from deformation-related mechanical remobilization.

Vavdos chromitites display predominantly high-Cr compositions, with Cr# values ranging between 0.710 and 0.810, coupled with low to moderate Mg# values (0.424-0.660) (Fig. 3a).

In contrast to Veria, chromite compositions show limited intra-grain and intra-sample variability, indicating restricted post-magmatic chemical variability. The relatively low but coherent Mg# values reflect efficient subsolidus Fe-Mg equilibration between chromite and olivine during cooling, rather than metasomatic overprinting (Sideridis et al., 2021).

The consistently high Cr# values indicate that Vavdos chromitites crystallized from highly depleted, high-Mg boninitic melts derived from extensive partial melting of a supra-subduction zone (SSZ) mantle wedge, in a forearc setting. Chromitite formation occurred during focused melt-rock interaction within dunite channels, where ascending melts reacted with harzburgite, consumed orthopyroxene and induced chromite saturation. The relatively low Mg# values do not reflect a less depleted mantle source but record subsolidus re-equilibration under high olivine/chromite ratios typical of dunite conduits, a process widely documented in ophiolitic chromitites worldwide (Bussolesi et al., 2019; Sideridis et al., 2021).

Platinum-group elements systematics in Vavdos chromitites are dominated by IPGE-enriched patterns (Fig. 3b), with laurite as the principal platinum-group mineral. Laurite occurs as magmatic inclusions within fresh chromite and is locally associated with minor Os-Ir alloys. PPGE contents are very low, and secondary PGM assemblages are scarce or absent, indicating limited post-magmatic PGE redistribution. The dominance of IPGE-rich PGE patterns and the preservation of laurite-bearing assemblages indicate high-temperature chromite crystallization (1200 °C) under relatively low sulfur fugacity and reducing conditions, prior to sulfide saturation of the parental melts (Economou-Eliopoulos, 1996; Sideridis et al., 2021). These features are consistent with early chromite precipitation from primitive, boninitic melts in a forearc SSZ environment. The coupled behavior of Cr# and Mg#, together with the absence of significant secondary PGM formation, demonstrates that melt-rock interaction within focused dunite conduits was the dominant process controlling chromitite formation in Vavdos. Subsequent deformation, metasomatism and redox-driven re-equilibration, so prominent in Veria, played only a subordinate role, allowing preservation of clear primary magmatic relationships between chromite and olivine chemistry.

Skyros

The tectonic affiliation of the Skyros ophiolitic units has long been debated, with earlier studies variably assigning them to the Pelagonian-Subpelagonian domain or to the Vardar suture zone. This ambiguity reflects the strongly tectonized nature of Skyros, where ophiolitic slices are imbricated above Pelagonian carbonate successions (Boundi et al., 2024; Karkalis et al., 2017). Recent structural and geochemical constraints indicate that the chromitite-bearing ultramafic bodies belong to sub-ophiolitic mélanges of the Vardar Domain (Bussolesi et al., 2025), rather than to an in situ Pelagonian mantle section (Economou-Eliopoulos, 1996). In particular, chromite chemistry and PGE signatures closely resemble those of undisputed Vardar Zone ophiolites (e.g. Veria, Vavdos), supporting a Vardar affinity. On this basis, Skyros chromitites are here considered part of the Vardar tectonic domain.

Chromitite occurrences are typically small, discontinuous pods, schlieren and disseminated lenses enclosed within highly deformed dunite and harzburgite, reflecting intense tectonic imbrication and disruption rather than a coherent mantle section (Bussolesi et al., 2025).

Chromite compositions from Skyros define two distinct compositional fields (Fig. 3a). The first group is characterized by high Cr# and relatively low Mg#, overlapping the compositional field of typical Vardar Zone chromitites such as Veria and Vavdos. The second group displays lower Cr# coupled with higher Mg# values, approaching the field of more transitional or less depleted chromitites.

The coexistence of two chromite populations reflects the heterogeneous nature of the Skyros ophiolitic fragments and indicates chromite crystallization from compositionally distinct melts (Bussolesi et al., 2025). The high-Cr#, low-Mg# chromites are consistent with formation from depleted, SSZ-related melts similar to those forming Vardar Zone chromitites (Fig. 3). In contrast, the lower-Cr#, higher-Mg# chromites likely record either interaction with more fertile mantle domains or crystallization from less depleted, more evolved melts, followed by variable degrees of subsolidus re-equilibration during tectonic mixing within the sub-ophiolitic mélange (Bussolesi et al., 2025).

Available PGE data indicate generally low to moderate total PGE contents, with assemblages dominated by IPGE-bearing phases. Platinum-group minerals are mainly represented by laurite and Ru-Os-Ir sulfides and alloys, typically occurring as inclusions within chromite. No evidence for large-scale secondary PGE enrichment has been reported (Economou-Eliopoulos, 1996), but the double-peak of Os and Ru (Fig. 3b) may be interpreted as a clue of PGE remobilization during serpentinization (Bussolesi et al., 2025; Grieco et al., 2020). The dominance of IPGE-rich PGE patterns supports early chromite crystallization under relatively low sulfur fugacity conditions from primitive melts, consistent with an SSZ affinity for, at least, part of the Skyros chromitites. The chemical heterogeneity recorded by both chromite compositions and PGE systematics is best explained by tectonic juxtaposition of chromitites formed in different mantle domains and/or under different melt regimes within the Vardar sub-ophiolitic mélange, rather than by evolution of a single, coherent Pelagonian mantle section.

Serbo-Macedonian Massif

Chromitites of the Serbo-Macedonian Massif occur within metamorphosed ultramafic complexes, where greenschist- to amphibolite-facies overprinting complicates the interpretation of primary magmatic features.

Nea Roda

At Nea Roda, chromitite mineralization occurs as small, discontinuous banded to nodular lenses hosted within dunite bodies enclosed in harzburgite, forming part of ultramafic lenses tectonically emplaced within the Serbo-Macedonian Massif. The ultramafic rocks crop out as isolated slivers and boudins interleaved with high-grade gneisses and amphibolites, and do not preserve a coherent ophiolitic mantle-crust stratigraphy. Chromitite bodies are typically centimeter- to decimeter-scale and occur as disseminated, banded or nodular concentrations, reflecting a fragmented and tectonized setting rather than primary podiform chromitite formation (Bussolesi et al., 2022a, 2022b).

Chromite compositions from Nea Roda define two distinct populations (Fig. 4a). The first population is characterized by low Mg# values (<0.5) coupled with moderate Cr#, whereas the second population displays higher Mg# values (0.5-0.7) at comparable Cr# ranges. The low-Mg# chromites correspond to compositions reported by Bussolesi et al. (2022a) of disseminated chromitite, indicating extensive metamorphic modifications. The second population corresponds to massive chromitites with high Mg#, comparable to other chromitites formed from a boninitic parental melt, generated by relatively high degrees of partial melting (Fig. 4) (Bussolesi et al., 2022b).

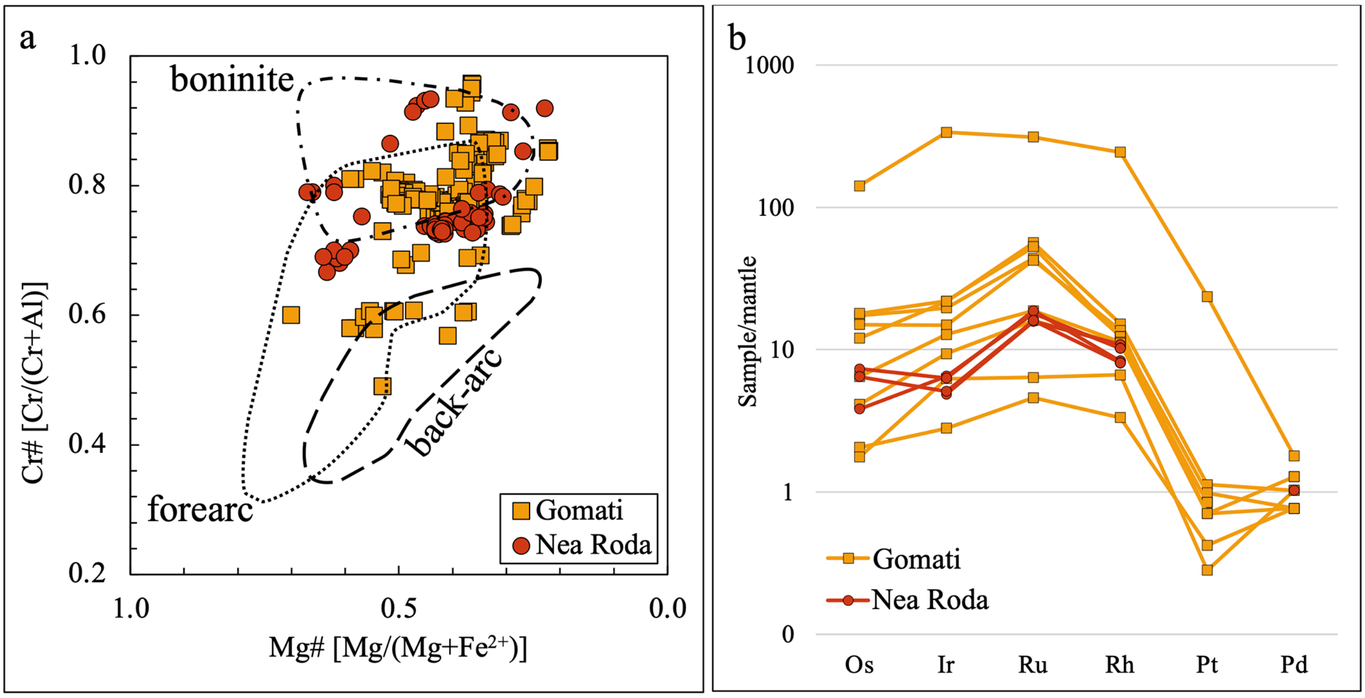

Fig. 4 - Cr# [Cr/(Cr+Al)] vs Mg# [Mg/(Mg+Fe^{2+})] plot of chromian spinel from Serbo-Macedonian chromitites, including Nea Roda (Bussolesi et al., 2022a, 2022b) and Gomati (Bussolesi et al., 2022b; Sideridis et al., 2022) with reference compositional fields for spinels crystallized from boninitic melts and from forearc settings (Barnes and Roeder, 2001) and back-arc settings (Khedr and Arai, 2016); b) Mantle normalized (McDonough and Sun, 1995) PGE patterns of Nea Roda (Bussolesi et al., 2022b) and Gomati (Bussolesi et al., 2022b; Economou-Eliopoulos, 1996) chromitites.

Although chromitites at Nea Roda are spatially associated with dunite channels, both textural and mineral-chemical evidence indicate that primary magmatic signatures have been largely obliterated. Textural studies highlight that the original magmatic features were modified by high-grade amphibolite-facies metamorphism, likely related to a Permo-Triassic event reaching temperatures of 550-656 °C (Bussolesi et al., 2022a). Olivine-spinel geothermometry and diffusion modelling further demonstrate that Nea Roda chromitites underwent complete subsolidus re-equilibration during an amphibolite-facies metamorphic event, preventing preservation of primary Mg# gradients and original chromite compositions (Bussolesi et al., 2022a).

Platinum-group elements contents in Nea Roda chromitites are consistently low, and no significant PGE enrichment comparable to other ophiolitic chromitites has been documented. Discrete platinum-group minerals are rare or absent, and PGEs are inferred to be dispersed within chromite or silicate phases rather than concentrated in magmatic PGM assemblages (Bussolesi et al., 2022b).

Gomati

Chromitites at Gomati occur as small podiform to irregular lenses, schlieren and disseminated concentrations hosted within dunite bodies enclosed in harzburgite, forming part of ultramafic lenses tectonically emplaced within the Serbo-Macedonian Massif. The ultramafic rocks are discontinuous and occur as tectonic slices interleaved with high-grade gneisses and amphibolites, lacking a continuous ophiolitic mantle stratigraphy. Chromitite bodies are typically meter- to decimeter-scale and spatially associated with dunite channels, indicating a magmatic control on chromite concentration that was later modified by deformation and metamorphism (Bussolesi et al., 2022b, 2020; Sideridis et al., 2022).

Chromite compositions from Gomati are characterized by moderate to high Cr# values and intermediate Mg# values, overlapping the compositional range of SSZ-related chromitites but showing systematic Fe enrichment compared to well-preserved ophiolitic examples (Fig. 4a).

Textural and mineralogical evidence indicate that Gomati chromitites originated through chromite saturation from melts focused in dunite channels, consistent with typical ophiolitic mantle processes. Unlike the coherent ophiolitic suites of the Pelagonian-Subpelagonian or Vardar zones, these occurrences consist of dismembered ultramafic fragments interlayered with high-grade gneisses and amphibolites of the Serbo-Macedonian Massif (Bussolesi et al., 2022b). The complex exhibits a bimodal compositional character, where Al-rich varieties and Cr-rich ores outcrop in close proximity (Bussolesi et al., 2022b; Sideridis et al., 2022). The Al-rich chromitites possess low Cr# (0.48-0.67) and high PGE contents (locally up to 3516 ppb), a combination ascribed to crystallization above the Moho (Bussolesi et al., 2022b). Conversely, high-Cr chromitites have high Cr# (0.72-0.96) and lower PGE abundances, indicating an origin from boninitic magmas in a mature supra-subduction zone (SSZ) setting (Bussolesi et al., 2022b; Sideridis et al., 2022). PGE normalized patterns (Fig. 4b) show a Ru peak and lower Os, a sign that post-magmatic alterations did not remobilize PGEs (Grieco et al., 2020). Subsequent amphibolite-facies metamorphism (reaching 450-700 °C) caused partial re-equilibration of chromite and the replacement of primary silicates by chromian clinochlore, serpentine, and uvarovitic garnets, yet primary magmatic signatures like Cr# and IPGE patterns were largely preserved (Sideridis et al., 2022). This metamorphic event was later overprinted by greenschist-facies alteration (<400 °C), during which metasomatic fluids rich in As, Sb, Pb, and Cu, potentially derived from nearby porphyry systems, precipitated an uncommon suite of arsenides and antimonides (Bussolesi et al., 2020).

DISCUSSION

The comparison of chromite compositions across the Pelagonian-Subpelagonian zones, the Vardar Zone, and the Serbo-Macedonian Massif (Fig. 5a) reveals systematic chemical differences that reflect both primary magmatic processes and variable degrees of post-magmatic re-equilibration.

In the Mg# vs Cr# biplot, chromitites from the Pelagonian-Subpelagonian domain define two principal populations: a high-Cr# group, typical of fore-arc SSZ chromitites (e.g., Vourinos, northern Evia), and a lower-Cr# group, reflecting crystallization from less depleted or transitional melts (e.g., Pindos, Othrys) (Fig. 5b). This bimodality likely records variable degrees of mantle depletion and melt-rock interaction within evolving supra-subduction settings, ranging from boninitic to more MORB- or IAT-like melt regimes.

In contrast, chromitites from the Vardar Zone cluster between these two Pelagonian-Subpelagonian populations in terms of Cr# (Fig. 5c), suggesting derivation from moderately depleted mantle sources or melts that experienced less extreme depletion than typical fore-arc systems. However, their Mg# variability, particularly the decoupling observed at Veria, reflects significant post-magmatic modification, including deformation-assisted Fe-Mg exchange and redox-driven re-equilibration. Thus, although Vardar chromitites retain SSZ affinities based on Cr#, their present compositions partly reflect tectono-metamorphic overprinting during emplacement along the suture zone.

Chromitites from the Serbo-Macedonian Massif are distinguished by systematically lower Mg# values relative to the other two domains (Fig. 5d). This feature does not necessarily indicate derivation from less primitive melts but instead reflects extensive subsolidus Fe-Mg re-equilibration and amphibolite-facies metamorphism affecting ultramafic lenses tectonically incorporated into continental basement. In these occurrences (e.g., Nea Roda), chromite compositions have been strongly modified by oxidation and Fe enrichment, leading to partial or complete obliteration of primary magmatic signatures.

Principal Component Analysis

Principal Component Analysis (PCA) was applied to chromite major elements composition (Cr_2O_3, Al_2O_3, Fe_2O_3, FeO and MgO) to investigate the main controls on compositional variability and to distinguish between geochemical processes occurring in the inter-tectonic zone and intra-tectonic zone. A multivariate analysis is a key step to disentangle the relative contributions of primary magmatic processes and secondary modifications. Unlike conventional discrimination diagrams which primarily reflect binary compositional relationships, PCA allows the identification of independent geochemical vectors, and evaluates their relative importance across different tectonic domains. The dataset comprises 1217 total analyses, with 681 analyses from the Pelagonian-Subpelagonian zone, 273 analyses from the Vardar zone and

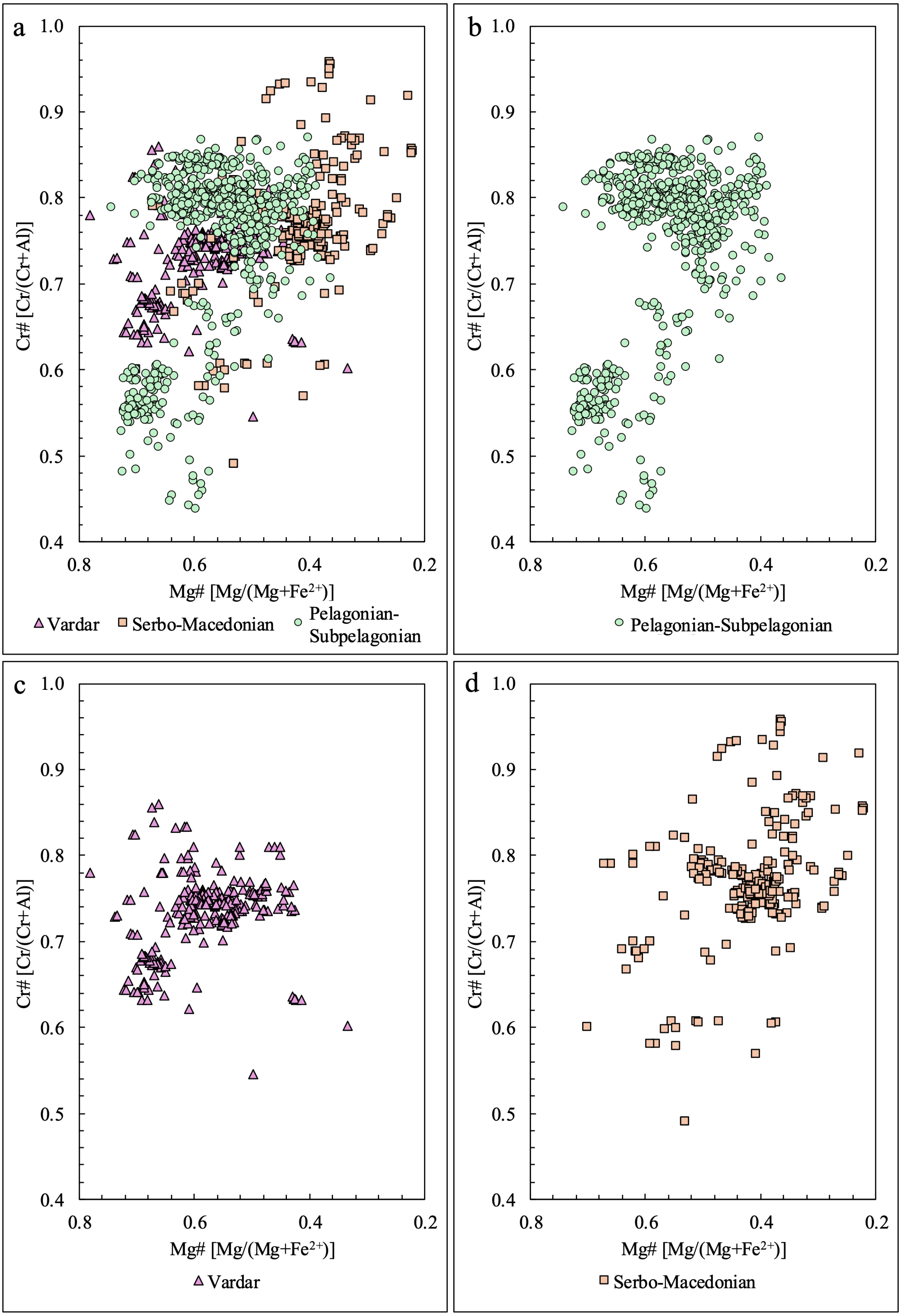

Fig. 5 - Cr# [Cr/(Cr+Al)] vs Mg# [Mg/(Mg+Fe^{2+})] charts of chromian spinel; a) Complete dataset; b) Pelagonian-Subpelagonian zone c) Vardar Zone and d) Serbo-Macedonian Massif.

263 analyses from the Serbo-Macedonian Massif. The dataset is reported in the Supplementary Materials and it consists of a compilation of published and unpublished data, summarized in Table 1. Prior to the analysis, data were standardized (mean centered and scaled to unit variance) to avoid scale-dependent bias, and a covariance matrix was calculated. Calculation of the Eigenvectors and Eigenvalues was performed using Python.

Global PCA: dominant controls on chromite chemistry

The global PCA (Table 2, Fig. 6) reveals that the first principal component (PC1), explaining 51.8% of the total variance, reflects the coupled substitution between Cr-Al and Mg-Fe^{2+}. This component captures the primary magmatic signal, consistent with progressive melt-rock interaction and increasing degrees of mantle depletion, which promote Cr enrichment and Al depletion in chromite. The second principal component (PC2), accounting for 29.6% of the variance is dominated by high positive loadings of FeO and Fe_2O_3 suggesting that post-magmatic alterations exert a control on chromite chemistry. This component defines a secondary, independent geochemical axis, which reflects redox variations during crystallization, and/or post-magmatic Fe redistribution during metamorphism. Chromite chemistry cannot be described by a single magmatic trend but is always the result of the superimposition of at least two independent processes. The third principal component (PC3), accounting for 17.25% of the total variance, provides additional constraints on post-magmatic processes, mainly regarding Fe2O3 variability, and therefore reflecting redox modifications in chromite composition.

When projected into PCA space, chromitites from different tectonic domains define distinct fields, reflecting the interplay between magmatic processes and post-genetic modification.

The Pelagonian-Subpelagonian chromitites display the widest dispersion along PC1 (Fig. 6a), indicating that their variability is primarily controlled by differences in melt composition and degree of mantle depletion. This large spread reflects the coexistence of highly depleted boninitic systems and more transitional MOR-SSZ melts within the same geotectonic domain. The spread along PC2 and PC3 is limited (Fig. 6a, d), suggesting a secondary geochemical trend reflecting a local overprint of the primary magmatic signal.

The Vardar Zone chromitites plot in an intermediate position along PC1, forming a comparatively tighter cluster. This distribution suggests more homogeneous mantle sources or more uniform magmatic conditions relative to the Pelagonian-Subpelagonian domain (Fig. 6b, e). The spread along PC2 indicates that subsolidus re-equilibration affected Mg-Fe^{2+} distribution to some extent (especially in Vavdos). The spread along PC3 is minimal, mainly concerning Vavdos, indicating limited influence of redox or metamorphic modifications. This pattern reflects a system where primary SSZ signatures are partially overprinted by tectono-metamorphic processes.

The Serbo-Macedonian Massif chromitites are displaced toward higher Fe contents and show a stronger influence of PC2, which is associated with FeO and Fe_2O_3 loadings. Their position in the PCA space suggests that, in addition to primary magmatic controls, secondary processes such as redox

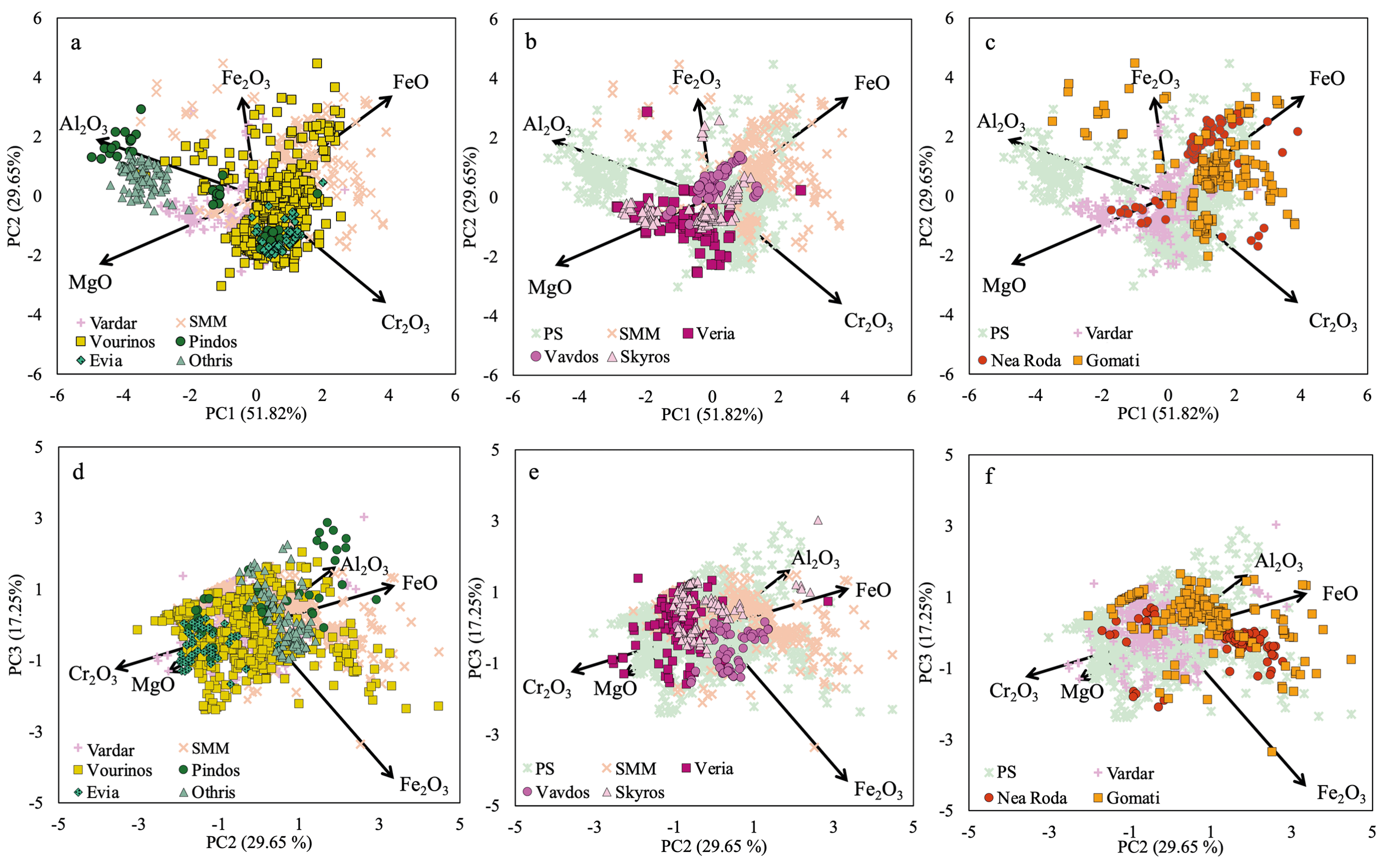

Fig. 6 - Principal Component Analysis (PCA) biplots of chromite major elements compositions. The upper panels show PC1 vs PC2 biplots of chromitites from a) Pelagonian-Subpelagonian Zone, b) Vardar Zone and c) Serbo-Macedonian Massif; the lower panels show PC2 vs PC3 biplots of chromitites from d) Pelagonian-Subpelagonian Zone, e) Vardar Zone and f) Serbo-Macedonian Massif.

Table 2 - Principal Component Analysis results for chromite major elements compositions (standardized data) for the whole dataset

Loadings	PC1	PC2	PC3
Al_2O_3	-0.88	0.35	0.30
Cr_2O_3	0.71	-0.66	-0.23
Fe_2O_3	-0.08	0.61	-0.79
MgO	-0.86	-0.42	-0.24
FeO	0.75	0.62	0.20
	PC1	PC2	PC3
Eigenvalue	2.59	1.48	0.86
Variance explained %	51.82	29.65	17.25
Cumulative variance %	51.82	81.48	98.73

Table 3 - Principal Component Analysis results (for chromite major elements compositions (standardized data) for Pelagonian-Subpelagonian Zone, Vardar Zone and Serbo-Macedonian Massif.

Pelagonian-Subpelagonian loadings	PC1	PC2	PC3
Al_2O_3	-0.89	0.30	-0.34
Cr_2O_3	0.80	-0.54	0.24
Fe_2O_3	-0.18	0.54	0.82
MgO	-0.89	-0.37	0.23
FeO	0.72	0.65	-0.19
Eigenvalue	2.77	1.23	0.94
Variance explained %	55.40	24.53	18.80
Cumulative variance %	55.40	79.93	98.73
Vardar loadings	PC1	PC2	PC3
Al_2O_3	0.76	-0.58	0.21
Cr_2O_3	-0.47	0.86	-0.01
Fe_2O_3	0.19	-0.11	-0.97
MgO	0.89	0.45	-0.04
FeO	-0.79	-0.59	-0.08
Eigenvalue	2.24	1.64	1.00
Variance explained %	44.73	32.78	20.02
Cumulative variance %	44.73	77.51	97.53
Serbo-Macedonian Massif loadings	PC1	PC2	PC3
Al_2O_3	0.91	-0.26	-0.30
Cr_2O_3	-0.72	0.66	0.19
Fe_2O_3	0.23	-0.77	0.59
MgO	0.80	0.54	0.18
FeO	-0.60	-0.75	-0.21
Eigenvalue	2.40	1.95	0.56
Variance explained %	48.04	39.09	11.13
Cumulative variance %	48.04	87.13	98.26

variations and metamorphic re-equilibration have played a more significant role in modifying chromite composition in this domain (Fig. 6c, f).

Internal PCA: contrasting geochemical regimes

PCA performed separately for each tectonic domain (Fig. 7; Table 3) further refines these observations. In the Pelagonian-Subpelagonian domain (Fig. 7a, b) variability is dominated by PC1. With regards to internal variability, there are essentially two groups. The first group, composed of Othrys chromitites and part of Pindos chromitites is clustered on the negative side of PC1, whereas the other group (Vourinos, Evia and Pindos) is more widespread along the PC2 axis. The spread along the PC1 axis is related to different degrees of partial melting, from MORB-like (Othrys and partially Pindos) to SSZ (Vourinos, Pindos, Evia). The spread along PC2 reflects limited Fe-Mg subsolidus re-equilibration.

In the Vardar Zone, chromitites variability is controlled by both Mg-Fe^{2+} exchange and Cr-Al substitution (Fig. 7c). Fe_2O_3 shows negligible contribution to PC1 and PC2 but has strong negative loadings on PC3. Chromitites from Vavdos are the only ones showing spread along the PC3 axis, indicating localized metasomatic overprinting and redox modifications.

The Serbo-Macedonian Massif (Fig. 7e, f) displays a different behaviour. PC1 is dominated by strong positive loadings of Al_2O_3 and MgO and negative loadings of Cr_2O_3 and FeO, defining the principal Cr-Al-Mg-Fe^{2+} substitution vector that reflects primary melt composition and mantle depletion. However, unlike the Vardar domain, PC2 (39.1% of the variance) shows strong coupling between FeO and Fe_2O_3 indicating that iron redistribution exerts a major influence on chromite chemistry in this domain. The substantial involvement of Fe_2O_3 in PC2 suggests that redox-controlled processes and post-magmatic re-equilibration have significantly contributed to the internal dispersion of the SMM chromitites.

PCA summary

Overall, PCA provides a quantitative framework for distinguishing between primary and secondary controls on chromite chemistry across the Hellenides. The results demonstrate that PC1 systematically records magmatic differentiation, controlled by mantle depletion and melt

composition across all domains. PC2 and, locally, PC3 capture secondary processes, including Mg-Fe^{2+} subsolidus re-equilibration, redox changes and metamorphism. This indicates that while magmatic differentiation is the primary driver of mineral chemistry variability, at least for the Pelagonian-Subpelagonian and Vardar Zones, the importance of secondary processes in all geotectonic domains is also critical. This must be taken into account when using spinel mineral chemistry as a proxy for chromitite genesis and parent melt composition.

Geological implications

The chromitites from the Pelagonian-Subpelagonian zone (Vourinos, Pindos, Othrys, Evia), the Vardar Zone (Veria, Vavdos, Skyros), and the Serbo-Macedonian Massif (Nea Roda, Gomati) display systematic differences in geodynamic affinity, melt composition, structural control, and post-magmatic overprint (Table 4). Pelagonian-Subpelagonian chromitites are predominantly SSZ-related and largely derived from boninitic melts, with Vourinos and Evia representing mature forearc systems characterized by high Cr# and relatively limited secondary redistribution. Pindos records a more complex evolution, preserving both high-Cr (boninitic, forearc) and high-Al (MORB/back-arc) populations, reflecting variable melt compositions within an evolving SSZ setting. Othrys shows a transitional MOR-SSZ affinity with intermediate Cr# and moderate IPGE enrichment, indicating lower degrees of mantle depletion and reduced melt-rock interaction efficiency.

In contrast, chromitites of the Vardar Zone retain a primary SSZ-boninitic signature but are strongly influenced by deformation and fluid-assisted metasomatism. Veria exemplifies extreme post-magmatic modification, with intense shear-zone localization, ferritchromite formation, and secondary IPGE enrichment. Vavdos preserves a clearer primary magmatic signal with limited chemical overprint, whereas Skyros records tectonic mixing of distinct chromitite populations within a sub-ophiolitic mélange.

The Serbo-Macedonian chromitites differ markedly, being hosted in metamorphosed ultramafic slivers and affected by amphibolite- to greenschist-facies overprint. Nea Roda shows complete subsolidus re-equilibration and obliteration of primary features, while Gomati preserves partial SSZ affinity but exhibits bimodal Cr# populations and metasomatic overprint linked to late fluid circulation. Overall, the main discriminating factors among the studied areas are: (i) degree of mantle depletion (Cr#), (ii) melt affinity (boninitic vs MOR/IAT), (iii) structural control (dunite-channel vs shear-zone dominated), and (iv) intensity of post-magmatic deformation and metamorphic re-equilibration.

Overall, the Hellenide ophiolitic belt, despite its relative limited spatial extent, records a remarkable variability in chromite-forming processes. The combined geological, mineral-chemical and multivariate analysis highlights three main controls on chromite composition: i) primary magmatic differentiation related to melt composition and degree of mantle depletion, ii) Mg-Fe^{2+} subsolidus re-equilibration during cooling and deformation and iii) redox-controlled processes leading to Fe^{3+} enrichment (e.g., serpentinization) and late-stage modifications. This systematic variation defines a regional trend from dominantly magmatic to progressively overprinted chromitite compositions from west (Pelagonian-Subpelagonian Zone) to east (Serbo-Macedonian Massif). In this context, Hellenide chromitites provide a natural laboratory where primary mantle processes and secondary modifications can be evaluated together, offering a more comprehensive framework for interpreting chromitite genesis in complex orogenic settings.

Limitations and uncertainties

This study is based on a compilation of published and unpublished datasets, which introduces some inherent limitations that should be considered when interpreting the results. First, the analytical data were obtained using different laboratories, potentially leading to minor inter-laboratory variability. Although data standardization and the use of major oxides mitigate these effects, some degree of analytical bias cannot be completely excluded. Where possible, chromite data were used in their raw form, and Fe^{2+} and Fe^{3+} were recalculated using a consistent approach, in order to minimize potential bias related to Fe partitioning. Finally, the use of compiled datasets may introduce sampling bias, as some ophiolites are more extensively studied than others, resulting in uneven data distribution across tectonic domains. This may influence statistical outputs, including PCA variance structure and clustering patterns.

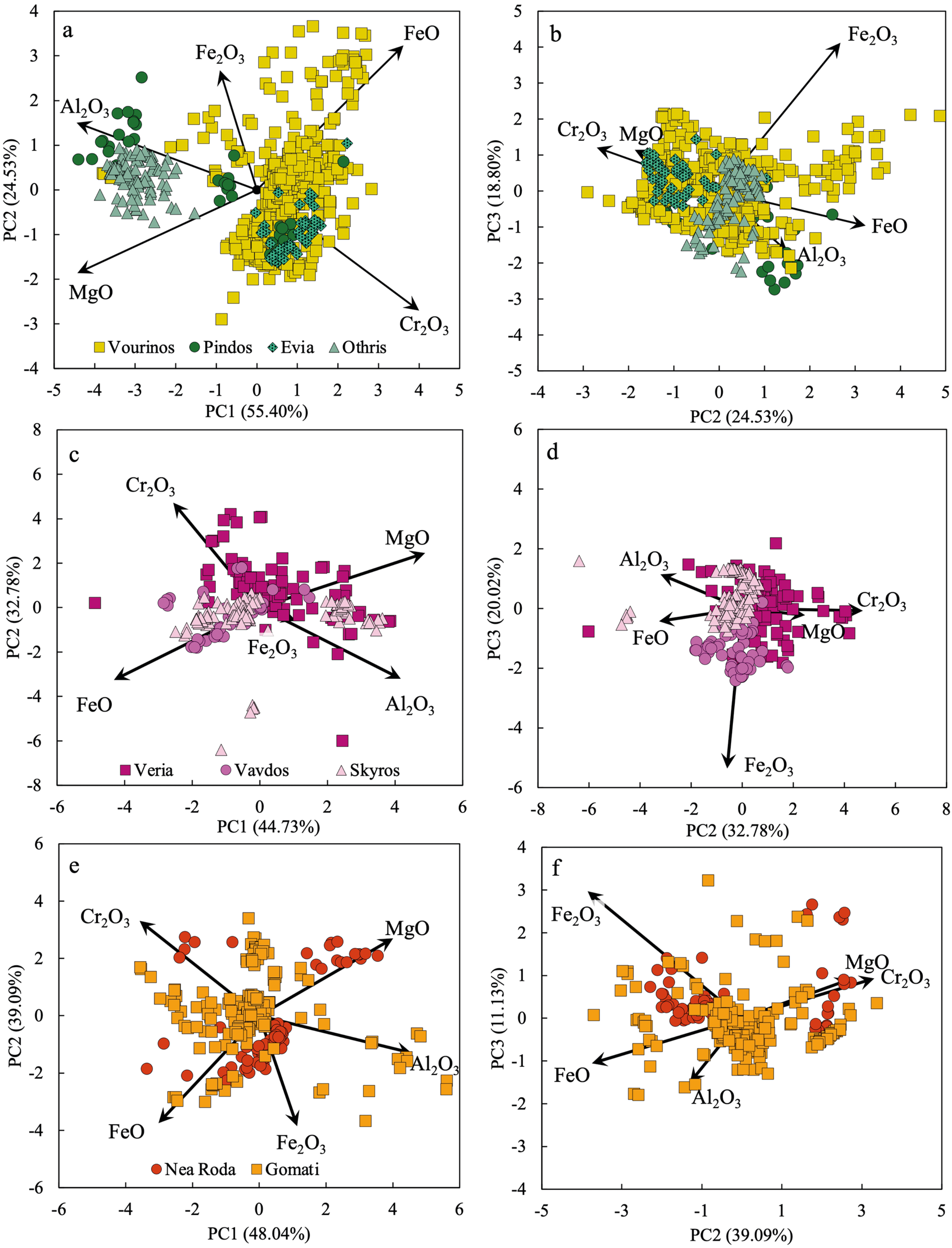

Fig. 7. Principal Component Analysis (PCA) biplots of chromite major elements compositions performed separetly for each tectonic domain. Pelagonian-Subpelagonian Zone: a) PC1 vs PC2; b) PC2 vs PC3. Vardar Zone: c) PC1 vs PC2; d) PC2 vs PC3. Serbo-Macedonian Massif: e) PC1 vs PC2; f) PC2 vs PC3.

Table 4 - Comparative features of the considered chromitites in terms of geodynamic setting, parent melt affinity, chromite mineral chemistry, structural control on ore geometry and post-magmatic modifications

Domain	Geodynamic setting	Melt affinity	Cr#	Mg#	Structural control & deformation	Post-magmatic alteration
PS - Vourinos	SSZ - forearc	Boninitic	Predominantly high-Cr	Variable (subsolidus Fe–Mg exchange)	Dunite channels; Ductile to brittle reworking	Subsolidus re-equilibration
PS - Pindos	Transitional SSZ (forearc + back-arc)	Boninitic to MORB/IAT-like	Bimodal: high-Cr + high-Al	Variable (subsolidus Fe–Mg exchange)	Dunite channels as melt pathways	/
PS - Othrys	Transitional MOR–SSZ (incipient SSZ / forearc)	Moderately evolved, less depleted	Intermediate Cr#	High Mg#	Dunite channels; Deformation overprints magmatic textures	Subsolidus re-equilibration
PS - Evia	SSZ - forearc	Boninitic	Predominantly high-Cr	Moderate to high Mg#	Dunite channels as melt pathways	Limited post-magmatic modification
Vardar - Veria	SSZ - forearc	Boninitic	Predominantly high-Cr	Variable (subsolidus Fe–Mg exchange)	High-strain zones (shear, fold-related structures)	Extensive metasomatism; Ferrian chromite
Vardar - Vavdos	SSZ - forearc	Boninitic	Predominantly high-Cr	Moderate to low Mg#	Dunite channels; Cataclastic and pull-apart textures	Subsolidus re-equilibration
Vardar - Skyros	SSZ - forearc	Depleted SSZ-melts + more evolved melts	Bimodal: high-Cr + high-Al	Variable (subsolidus re-equilibration)	Small pods in highly deformed dunite; Strong tectonization	/
SMM - Nea Roda	SSZ - forearc	Boninitic	Moderate to high-Cr	Variable (high to low due to metamorphism)	Discontinuous lenses in tectonic boudins; Strong tectonic fragmentation	Subsolidus re-equilibration
SMM - Gomati	SSZ - forearc	Boninitic to MORB/IAT	Bimodal: high-Cr + high-Al	Intermediate Mg#; systematic Fe enrichment	Small lenses in dunite; Dismembered ultramafic fragments	Amphibolite-facies re-equilibration + greenschist alteration

PS: Pelagonian-Subpelagonian domain; SMM: Serbo-Macedonian Massif.

Despite these limitations, the consistency of the observed geochemical trends across independent datasets and tectonic domains supports the robustness of the interpretations. The PCA results should therefore be considered as a framework to identify dominant processes and relative differences, rather than as a strict quantitative classification.

CONCLUSIONS

The combined geochemical and statistical evidence supports a model in which the Hellenide chromitites formed predominantly in a supra-subduction environment, under variable conditions of melt evolution and mantle interaction. High Cr# values, coupled with IPGE enrichments indicate derivation from highly depleted mantle sources interacting with boninite-like melts. The variability observed within and between ophiolite complexes reflects differences in degree of mantle depletion, melt flux and composition and extent of melt-rock interaction.

However, the PCA results demonstrate that these primary signals are variably preserved depending on the tectonic and metamorphic history of each domain. In particular, the progressive increase in the importance of PC2 and PC3 from Pelagonian-Subpelagonian to Serbo-Macedonian domains reflects a transition from magmatic control to metamorphic overprint. This study highlights the importance of integrating multivariate statistical approaches with classical petrological and geochemical tools. PCA not only confirms established genetic models for chromitite formation but also quantifies the relative preservation of primary signatures, providing provides a robust framework for comparing chromitites across different tectonic settings. The results emphasize that: i) chromite composition alone is not always a reliable proxy for melt composition ii) tectono-metamorphic processes can significantly modify primary geochemical signals; iii) quantitative approaches such as PCA are essential for distinguishing between primary and secondary controls.

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ONLINE SUPPLEMENTARY MATERIAL

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