



Article Coexisting High-Al and High-Cr Chromitites in the Dingqing Ophiolite (SE Tibet): Inferences to Compositional Heterogeneity in the Tethyan Upper Mantle

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Abstract: The Dingqing ophiolite represents a significant allochthonous ophiolite nappe in the eastern segment of the Bangong-Nujiang suture zone in southeastern Tibet. The microanalytical data of associated podiform chromitites classify them into two distinct varieties: high-Al and high-Cr. The coexistence of both high-Cr and high-Al chromitites in the Dingqing ophiolite suggests a complex or multistage evolutionary history of the host rocks. New petrological and geochemical analyses are used herein to unravel the interrelationships between the chromitite ores and host rocks and assess the mechanism of formation. The Dingqing ophiolitic nappe is made up mainly of harzburgite, dunite, and less abundant pyroxenite and gabbro. Several small lens-shaped bodies of chromitite ore are mostly confined to the harzburgite rocks, with ore textures varying from massive to sparsely disseminated chromite. In addition to magnesiochromite, the orebodies contain minor amounts of olivine, amphibole, and serpentine. The textural relationships provide compelling evidence of plastic deformation and partial melting of the associated peridotites. Detailed examination of the Cr-spinel grains reveals a wide range of composition, spanning from high-Al (Cr# = 3.18–59.5) to high-Cr (Cr# 60.3-87.32). The abundances of the platinum-group element (PGE) in chromitites are significantly variable (93 to 274 ppb). Formation of the Dingqing peridotites most likely took place in a mid-ocean ridge (MOR) setting, and subsequent modifications by supra-subduction zone (SSZ) melts resulted in heterogenous or mixed geochemical characteristics of these rocks. Chemistry of the spinel-olivine-clinopyroxene assemblage demonstrates multiple stages of partial melting of the source mantle rocks, including an early phase of restricted partial melting ($\sim 20\% - 30\%$) and a later phase of extensive partial melting (>40%). The formation of the high-Al chromitite type was associated with the early phase (constrained melting), whereas extensive partial melting in the late stages likely led to the accumulation of high-Cr podiform chromitite bodies.

Keywords: Dingqing ophiolite; Bangong–Nujiang suture zone; high-Al chromitite; high-Cr chromitite; partial melting; multistage evolution

1. Introduction

Chromite deposits commonly occur as layered chromitites and podiform chromitites. The layered chromitite shares similarities with chromite in layered igneous complexes near the Moho and is typically associated with mafic–ultramafic intrusive complexes in the Precambrian stable continental platforms [1–3]. These deposits commonly occur in the



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). lower portions of layered mafic–ultramafic complexes, where ultrabasic rocks dominate. On the other hand, podiform chromitite deposits commonly form lens-shaped bodies within peridotite rocks. These deposits are typically classified into two main types: high-Al (Cr# = 20-60) and high-Cr (Cr# = 60-80) varieties [4]. The genesis of podiform chromitite deposits is commonly attributed to processes such as magmatic crystallization, melt-rock interaction, and partial melting of the mantle peridotite. Previous studies have proposed models, including the crystallization segregation model, the melt-rock reaction model, and the melting reconstruction model [5–7]. Among these models, the melt-rock reaction model has gained wide acceptance in the scientific community due to its ability to explain important geological features observed in the field. These features include the presence of thin dunite envelopes and the occurrence of harzburgite in layered or irregular veins [6–13].

Identification of ultra-high-pressure minerals such as diamond and moissanite within chromitite, coupled with the recognition of ancient recycled continental lithospheric mantle components, demonstrates the potential contribution of deep mantle processes, including mantle plume activity, to the formation of podiform chromite deposits [14–21]. These findings suggest that the origin of podiform chromite deposits may involve complex interactions between shallow oceanic lithospheric mantle and deeper mantle processes.

The specific tectonic environments associated with the formation of podiform chromite deposits have been distinguished based on the surrounding rock peridotite and the characteristics and origin of the interacting melt/fluid [15]. For instance, high-Cr chromitite is typically found in refractory harzburgite and is associated with boninitic magmas, indicating a tectonic environment related to subduction. In contrast, high-Al chromitite is commonly associated with relatively lherzolitic peridotite and tholeiitic magmas, suggesting a tectonic setting associated with mid-ocean ridges or back-arc basins [7,22].

It is now evident that chromite formation may not be limited to a single tectonic environment [23,24]. Different types of chromitite can be formed through various tectonic processes and interactions. For example, high-Al chromitite can transform into high-Cr chromitite through melt-rock reactions during later stages of tectonic evolution [24]. Furthermore, high-Cr chromitite can be recycled within the mantle and reappear in mid-ocean ridge environments [15,25]. Recent findings also reveal the coexistence of multiple types of podiform chromitite within the same ophiolite body. Examples include the Mayarí-Cristal ultrabasic body in Cuba, the Mugla body in Türkiye, and the Purang and Dongbo bodies in Tibet [22,26–28]. These discoveries underscore the complexity of chromitite formation and emphasize the need to consider multiple tectonic processes and geological histories in the study of chromite deposits.

Rollinson [23] proposed that a basalt melt can crystallize into low Cr# "MORB end member chromite", which can undergo rock-melt reactions to form high Cr# chromite. The coexistence of high-Al and high-Cr chromite in the same massif suggests the involvement of multiple melts. To understand podiform chromitite formation, it is crucial to study the mineral composition changes in mantle peridotite and chromitite, consider structural control on ore bodies, and examine the presence of a dunite envelope.

The Bangong–Nujiang suture zone connects the Qiangtang and Lhasa blocks, forming a significant plate boundary in the Tibet Plateau. This zone underwent Mesozoic extension, subduction, and closure, leaving remnants of oceanic lithosphere that enable the understanding of the region's tectonic framework and evolutionary history [29–31]. Extending over 2000 km from west to east, the suture zone traverses Bangong Lake, Gaize, Dongqiao, and Anduo and turns southward towards the Nujiang River in Dingqing. It is divided into three sections: the western section (Bangong Lake to Gaize), the middle section (Anduo to Dongqiao), and the eastern section (Dingqing to Nujiang) based on its distribution [32,33]. The Mesozoic Bangong Lake–Nujiang Ocean underwent expansion, subduction, and closure, leaving remnants of the oceanic lithosphere. These remnants hold significant geological implications for understanding the tectonic framework and evolutionary history of the Tibet Plateau. The Bangong–Nujiang suture zone ophiolite has been extensively studied, but significant debates persist regarding the origin, age, and evolution model of the Bangong Nujiang Ocean [34–36]. Different views exist on the opening time and subduction direction of the ocean basin, with suggestions of Late PermianEarly Triassic opening and subduction either northward beneath the Qiangtang block, southward beneath the Lhasa block, or bidirectional subduction [34,37,38]. The Dingqing ophiolite, located in the eastern section of the suture zone, is the largest ophiolite in the area [39]. Previous studies propose a Late Triassic–Middle Jurassic formation age for the Dingqing ophiolite, with an emplacement age of ~197 Ma [40]. Petrochemical analyses suggest various tectonic environments, including subduction zones, mid-ocean ridges, and superimposed ocean island settings [41–43].

In this study, we used a range of analytical methods, including electron probe microanalysis (EPMA) and ICP-MS, to obtain a large data set of the mineralogical and petrochemical characteristics of the high-Cr and high-Al chromitites associated with the Dingqing ophiolite. By examining the trace elements and platinum-group elements (PGE) compositions, we aimed to gain insights into the formation processes, tectonic settings, and potential geodynamic events associated with the Dingqing ophiolite and chromitite. The results of this study contribute to a better understanding of the formation and evolution of the Dingqing ophiolite, as well as the broader geological implications within the Bangong–Nujiang suture zone.

2. Geological Setting

The Dingqing ophiolite in the southeastern bend of the Bangong Lake Nujiang is characterized by distinct units, including mantle peridotite, cumulate, gabbro, plagiogranite, and chromitite [41,42,44,45].

The Dingqing ophiolite occurs as a ~88 km-long, 2–8 km-wide E–W belt (Figure 1), with exposures covering an area > 400 km² (Figure 1). Harzburgite dominates the Dingqing ophiolite and constitutes 85%~90% of the eastern and western rock bodies. It displays a tectonic contact relationship with the adjacent strata on both sides. Within the southern boundary fault zone of the Dingqing ophiolite, harzburgite blocks are enclosed in listwanite (Figure 1). Several meters-long bodies of harzburgite are associated with dunite. The latter, which accounts for approximately 8% of the total area, is primarily yellowish-brown and extensively serpentinized. It forms thin shells, lenses, ribbons, and irregular blocks within the harzburgite. Dunite is the principal host rock for chromitite orebodies.

The chromitite is mainly distributed in the middle of coarse-grained olivine at the bulged and northward protruding part in the middle of the rock mass. The main ore bodies are inclined along the strike; although the continuity is good, most of them are characterized by expansion, contraction, branching and compounding. Most of the ore bodies within the Dingqing ophiolite are found as moderately north-dipping lenses, veins, or sills. The chromitite ores in the area can be classified into several types based on the relative content and arrangement of chromite and gangue minerals. These include massive, semi-massive, banded, and spotted varieties (Figure 2). Most of the high-Al chromitite is disseminated in the harzburgite host, whereas the high-Cr chromitite, generally 2–10 m long and 0.1–1 m thick, were observed next to a banded dunite outcrop. Microscopic observations suggest that the high-Cr chromitite overgrows or replaces the high-Al chromite grains. Relic chromite occurs as irregular, commonly amoeboid grains with highly variable grain sizes and shapes.

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Figure 1. (**A**) Simplified tectonic map of the Tibetan Plateau (after Xiong et al. [46]) showing various terranes separated by suture zones. The Yarlung–Zangbo suture zone represents the southernmost suture, separating the Lhasa block in the north from the Indian plate in the south. YZS—Yarlung Zangbo suture; suture zone includes six major ophiolite massifs: Luobusa, Xigaze, Saga, Dangqiong, Purang, and Dongbo. BNS—Bangong–Nujiang suture; suture zone includes the Dingqing, Amdo, Dongqiao, Dongco, Gaize, and Ritu ophiolite massifs. (**B**) Geological map of the Dingqing ophiolite and its surroundings: early and late.

Olivine within the dunite exhibits pervasive serpentine alteration, characterized by twisted bands, wavy extinction, and fragmented structures (Figure 2). Orthopyroxene commonly displays recrystallization (Figure 3), with particle sizes reaching up to 3 mm. Serpentine petrification is observed at the edges or fractures, indicating the presence of later alteration (Figure 3). Large particles of orthopyroxene often dissolve needle-like clinopyroxene. Clinopyroxene is primarily distributed as interstitial or internal exsolution or exists as inclusions in orthopyroxene. Additionally, small amounts of shaped chromium spinel are found in the cracks of clinopyroxene (Figure 3).

(g)



Figure 2. Field photographs showing the occurrence of chromitite in the Dingqing ophiolite. (a) Disseminated high-Al chromitite with dunite, (b) dunite vein with disseminated high-Cr chromitite, (c,d) Semi-massive disseminated high-Al chromitite as veins in dunite, (e,f) massive high-Cr chromitite intergrown with dunite, (g) serpentinization of harzburgite, and (h) pyroxenite in the harzburgite.

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Figure 3. (**a**–**c**) Backscattered electron (BSE) images of minerals in harzburgite. Harzburgite with fine-grained olivine (Ol) along the grain boundaries between coarse olivine, clinopyroxene (Cpx), and orthopyroxene (Opx), and (**d**) the border of chromian spinel had changed to magnetite. Cpx—clinopyroxene; Opx—orthopyroxene; Ol—olivine; Chr—chromite.

The dunite in the Dingqing ophiolite was partially or completely altered into serpentinite. Under the microscope, olivine particles appear fragmented, while fresh olivine exhibits island-like, semi-idiomorphic shapes with wavy extinction. The particle sizes of olivine range from 0.1 to 0.5 mm (Figure 3). Chromium spinel is distributed in randomized distribution, with the largest particles reaching a size of 1.2 mm. Magnetite mineralization is observed at the edges of the chromium spinel (Figure 3). No fresh clinopyroxene was identified within the dunite in the current rock core.

3. Methods

Fifty chromitite and peridotite samples were collected from three locations within the Dingqing ultramafic massif. Polished thin sections were prepared for fresh representative samples. The Cr-spinel and olivine analyses in the Dingqing chromitites were conducted using a JEOL JXA-8100 electron probe microanalyzer (EPMA) at the Institute of Geology, Chinese Academy of Geological Sciences. The analytical conditions were set at 15 kV accelerating voltage, 20 nA beam current, and 2 μ m spot diameter, with counting times of 20 s on peaks and 10 s on the background. Calibration was performed using natural and synthetic standard materials. The Fe³⁺ and Fe²⁺ concentrations in Cr-spinel were calculated based on an ideal spinel stoichiometry (A2 + B3 + 2O4) using the method of Droop [47]. Supplementary Tables S1–S4 present the results.

Concentrations of platinum-group elements (PGE) in five chromitite samples were analyzed using ICP-MS with a pre-concentration NiS fusion technique at the National Research Center of Geo-analysis (CAGS). The samples were prepared by mixing them with various substances, including sodium carbonate, sodium borate, borax, glass powder, Ni and Fe powder, and S. The limits of detection for Pt, Pd, Ir, Rh, Os, and Ru were 0.2 ppb, 0.2 ppb, 0.001 ppb, 0.001 ppb, 0.001 ppb, and 0.1 ppb, respectively. The analysis precision was better than 5% for Rh, Pd, and Ir and 10% for Os, Ru, and Pt [48,49]. The bulk-rock PGE compositions of chromitites and peridotites can be found in Supplementary Table S5.

4. Results

4.1. Mineral Chemistry

4.1.1. Olivine

A comprehensive electron microprobe (EMP) analysis was conducted on 54 olivine grains from 11 harzburgite and dunite samples. The EMP analysis results for representative samples are listed in Supplementary Table S1. In the dunite samples, the olivine Fo values range from 88.79 to 93.98, with an average value of 90.61. In contrast, the harzburgite samples display a narrow range of olivine Fo values, spanning from 90.15 to 93.45, with an average value of 91.83. The high Fo values are widely recognized as indications of high degrees of melting [50].

Furthermore, the NiO and MnO components of olivine hold significant implications for understanding the evolutionary processes of the mineral. Within the dunite samples, the NiO content of olivine ranges from 0.28 wt% to 0.42 wt%, with an average of 0.34 wt%, while the MnO content ranges from 0.08 wt% to 0.21 wt%, with an average of 0.14 wt%. In the harzburgite samples, the NiO content of olivine ranges from 0.26 wt% to 0.45 wt%, with an average of 0.39 wt%, and the MnO content ranges from 0.07 wt% to 0.16 wt%, with an average of 0.11 wt%. It is noteworthy that the NiO content in dunite and harzburgite exhibits similarities, and the Fo value displays a slight increase with the rise in NiO content. Conversely, the MnO content demonstrates significant variability, and a negative correlation is observed between the Fo value and MnO content (Figure 4).



Figure 4. (**a**,**b**) Olivine composition in the different lithologies of the Dingqing district. ABP—abyssal peridotite and FAP—fore-arc peridotite (after Pagé et al. [51]).

4.1.2. Pyroxene

Pyroxene is variably abundant in most of the investigated samples. Fresh orthopyroxene and clinopyroxene were exclusively observed in the harzburgite. Eighty orthopyroxene analyses were collected on 10 thin sections. The EPMA results for representative samples are presented in Supplementary Table S2. The composition of orthopyroxene shows variations in the En (enstatite) end-member content, ranging from 91.1 to 93.1, with an average value of 92.1.

The orthopyroxene composition in the harzburgite displays a notably low NiO content, ranging mainly from 0.03 wt% to 0.18 wt%, and a Cr_2O_3 content ranging from 0.27 wt% to 1.31 wt%. The Al_2O_3 content exhibits a relatively wide variation range in the harzburgite, ranging from 0.42 wt% to 2.82 wt%, with an average value of 1.63 wt%. The orthopyroxene composition in the dunite samples shows similar NiO, Cr_2O_3 , and Al_2O_3 contents, ranging from 0.056 wt% to 0.15 wt%, 0.52 wt% to 0.72 wt%, and 1.09 wt% to 1.39 wt%, respectively.

The Al_2O_3 content in orthopyroxene serves as an indicator of the degree of partial melting [52]. The low Al_2O_3 content and high Mg# characteristics suggest that the Dingqing mantle peridotite has experienced a significant degree of partial melting (Figure 5) [53].



Figure 5. (**a**,**b**) Orthopyroxene composition in the different lithologies of the Dingqing district. ABP—abyssal peridotite and FAP—fore-arc peridotite (after Pagé et al. [51]).

Fresh clinopyroxene is less abundant in harzburgite. Forty-two clinopyroxene analyses were collected on five samples, and the analysis results for representative samples are listed

in Supplementary Table S3. The En (diopside) end-member content varies from 49.50 to 52.7, with diopside being the predominant composition. The clinopyroxene in harzburgite is characterized by high CaO content (21.66 wt% to 25.68 wt%), low Al₂O₃ content (0.26 wt% to 2.55 wt%), and high Mg# (93.60 to 96.11). The Mg#–Al₂O₃ composition evolution diagram (Figure 6) demonstrates a negative correlation between Al₂O₃ and Mg# in harzburgite, indicating its position along the melting trend.



Figure 6. (**a**–**c**) Clinopyroxene composition in the harzburgite of the Dingqing district. ABP—abyssal peridotite and FAP—fore-arc peridotite (after Pagé et al. [51]).

4.1.3. Chromian Spinel

Chromian spinel is abundant in dunite and harzburgite samples, although its content is typically unevenly distributed and generally constitutes less than 5% of the rock. The outer parts of the spinel grains often exhibit magnetic characteristics. The chemical composition of 150 chromian spinel grains from different lithologies was analyzed, and representative results are given in Supplementary Table S4.

The Cr# values of chromian spinel range from 45.3 to 85.2 in dunite, while in harzburgite, they vary from 40.1 to 75.1, with an average value of 57.3. The Cr# variation range is similar between dunite and harzburgite, with most falling within the forearc mantle peridotite range. The Cr# values of chromian spinel exhibit a negative correlation with Mg#, similar to the characteristics observed in forearc peridotites, where Cr# values decrease with increasing Mg# values [53]. Data of the chromite-bearing dunite falls in the forearc peridotites (Figure 7).



Figure 7. (a) Cr# [Cr/(Cr + Al) \times 100] vs. Mg# [Mg/(Mg + Fe²⁺) \times 100] plot of Cr-spinel from the Dingqing chromitites. Fields for spinel in equilibrium with N-MORBs and boninites are from Dick

and Bullen [51]. (b) TiO₂ vs. Al₂O₃ (wt%) plot of Cr-spinel from the Dingqing chromitites. Compositional fields are from Kamenetsky et al. [54]. Abbreviations: BSV—boninite series volcanics, IAT—island arc tholeiites, OIB—ocean islands basalts, MORB—mid-ocean ridge basalts, LIP—large igneous province (basalts).

In the TiO₂ vs. Al₂O₃ diagram (Figure 7), the data of dunite and harzburgite exhibit similarities with SSZ (supra-subduction zone) and MORB (mid-ocean ridge basalt) peridotite. In high-Cr chromitite, the Cr₂O₃ compositions range from 49.0 wt% to 64.9 wt%, with an average of 59, and Al₂O₃ compositions range from 6.1 wt% to 21.6 wt%, with an average of 11.3. The MgO content remains relatively constant, ranging from 10.2 wt% to 15.9 wt%, with an average of 14.0, resulting in Mg# values between 50 and 77 and Cr# values between 60.3 and 87.32 (Supplementary Table S4). Forty analyses of magnesiochromite in high-Al chromitite reveal Cr₂O₃ contents ranging from 21.79 wt% to 64.31 wt%, with an average of 47.02 (Supplementary Table S4), indicating that the high-Al chromitite is similar to the MORB spinel (Figure 7).

4.2. Platinum Group Element (PGE) Composition

To determine the PGE concentrations, whole-rock analyses were conducted on 33 samples that were characterized by scattered PGE minerals in thin sections. The chromitites consistently display high and relatively uniform total PGE contents, ranging from 93 to 275 ppb (Supplementary Table S5).

Relative to the chondrite values, the Dingqing chromitites have IPGE contents similar for both chromitite types (high-Al and high-Cr), while the PPGE values are lower and display a rightward dipping trend [55]. The high-Cr and high-Al chromitites exhibit enrichment in Ir and Rh compared to other elements and display negatively sloping chondrite-normalized PGE patterns, consistent with typical high-Cr and high-Al chromitites found elsewhere (Figure 8) [56].

In terms of PGE ratios, the high-Cr chromitites and high-Al chromitites have average Pd/Ir ratios of 0.09 and 0.12, respectively, and Pt/Pd ratios of 3.9 and 2.4, respectively (Supplementary Table S5). In contrast, the dunite samples exhibit an average Pd/Ir ratio of 4.2 and a Pt/Pd ratio of 1.6, while the harzburgite samples show an average Pd/Ir ratio of 1.6 and a Pt/Pd ratio of 3.2. The Pd/Ir ratio correlates negatively with the Pt/Pd ratio, with most values lower than the original mantle values, although a few samples exhibit higher ratios.



Figure 8. Chondrite-C1-normalized (Naldrett and Duke [57]) PGE patterns for Dingqing chromitite and comparison with (**a**) high-Cr and (**b**) high-Al hosted in the ophiolitic mantle elsewhere (data sources: [56,58,59]).

5. Discussion

5.1. Partial Melting Characteristics

The presence of H_2O in mantle regions controls the extent and mechanism of partial melting in several ways, including lowering the solid-phase line of peridotite, decreasing the proportion of olivine and clinopyroxene in the melt, and inconsistent melting of orthopyroxene [60–62]. Partial melting of peridotite in the Dingqing ophiolite exhibits distinct characteristics. Based on the observed clinopyroxene depletion, formation of harzburgite was related to ~20% partial melting and dunite by 50–60% partial melting (Figure 9) [63–65].



Figure 9. (a) Clinopyroxene composition of Al_2O_3 vs. Cr# of chromian spinel, (b) Clinopyroxene composition of Al_2O_3 vs. TiO₂, (c) Olivine Fo contents vs. Cr# of chromian spinel, and (d) chromian spinel composition of Cr# versus TiO₂ in the Dingqing peridotites. These plots are based on the work of Pearce et al. [66] and data of the Luobusa peridotites and chromitites by Xiong et al. [67] and Xu et al. [68].

In the Dingqing massif, the distribution of dunite veins within the peridotite and the presence of pyroxene veins indicate melt-rock interactions and peridotite reactions [67,69]. The REEs distribution in the Dingqing peridotite resembles mantle peridotites, but with slightly higher heavy rare earth element (HREE) contents, likely as a reflection of parental HREE-rich melts [70]. Petrographic observations, including plastic deformation of porphyritic

orthopyroxene in harzburgite and the presence of un-deformed olivine within orthopyroxene porphyrites, provide evidence of partial melting in the Dingqing massif [71,72].

The mineral chemistry of the Dingqing peridotite, including orthopyroxene and clinopyroxene, shows trends consistent with partial melting, with changes in major element compositions (Al₂O₃, Mg#, CaO, Cr₂O₃) [69]. The high NiO content in olivine and the presence of spinels within orthopyroxene or olivine suggest melt-rock reactions and crystallization processes [6,73–76]. Similar microstructures and mineral chemistries have been reported in mantle peridotites from the Mid-Atlantic Ridge, indicating the crystallization of clinopyroxene and chromium spinel due to melt penetration or reaction with orthopyroxene [77,78].

The mineral chemistry and PGE content of the investigated Dingqing chromitites suggest a polygenetic origin, with different magma inputs and heterogeneous distribution of PGE in the mantle [79,80]. However, the absence of a clear correlation between Pd/Ir and Pt/Pt* further supports the notion of distinct parental melts and multiple stages of melting in the formation of chromitites in the Dingqing mining district (Figure 10).



Figure 10. Pd/Ir vs. Pt/Pt* diagram for the Dingqing chromitites and peridotite. The average composition of the asthenosphere, as well as fractionation and partial melting trends, are from Garuti et al. [81]. The platinum (Pt) anomaly is calculated as follows: Pt/Pt* = (Pt/8.3)/[(Rh/l.6) × (Pd/4.4)]1/2.

5.2. Genesis of the Dingqing Chromitite

The genesis of Dingqing chromitite can be understood by examining its geochemical and mineralogical characteristics. The Dingqing high-Al and high-Cr chromitites show similarities in terms of structure and mineral assemblage. However, there are significant differences in the chemical composition of chromium spinels between the two types. The high-Al chromitite from the Sartohay and Hegenshan regions has higher TiO₂ content (0.18% to 0.28%), while the high-Cr chromitites, including Dingqing chromitite, show lower TiO₂ contents (up to 0.53%) [7].

Based on the spinel composition, the Yilashan chromitite in Dingqing likely crystallized from melts with high Al₂O₃ content (11.67% to 13.49%) and FeO/MgO ratios of 0.92 to 1.12, comparable to boninitic melts in a subduction arc setting (Figure 11). The high Cr# values (>60) observed in the chromitite suggest a supra-subduction zone (SSZ) setting, with mid-ocean ridge basalt (MORB)-like melts generated by moderate degrees of melting and

boninitic melts resulting from extensive hydrous melting. The presence of both high-Al and high-Cr chromitite types within the same massif is relatively rare and has been reported in a few other ophiolites, such as the Mayarí-Cristal ultramafic rock in Cuba and the Bulqiza rock mass in Albania [46,80].



Figure 11. (a) Al₂O₃ (wt%) melt vs. FeO/MgO melt, calculated based on the chemical composition of Dingqing chromitites, (b) Al₂O₃ contents of the melt in equilibrium with the Dingqing chromitites. The figure incorporates tectonic discrimination fields from Barnes and Roeder [82], and the equations are derived from Rollinson [24]. The typical chromite composition for MORB and Arc is sourced from Garuti et al. [83], and the chromite-melt inclusion data for MORB* and arc* lavas are from Kamenetsky et al. [54].

The differences in mineralogical and geochemical characteristics between the two chromitite types in Dingqing can be attributed to the specific processes and conditions of chromite formation. Comparisons with other podiform chromitite deposits worldwide reveal similarities and differences with Dingqing chromitites. The high-Al chromitite in Dingqing shares mineral chemical characteristics with the Cr-spinel in Xinjiang Sartohai chromite, while the high-Cr chromitite shows similarity with Luobusa chromitite (Figure 12). The distribution of platinum-group elements (PGEs) in the Dingqing mantle peridotite and chromitite follows a similar pattern to Luobusa chromitite and Sartohay chromite, with enrichment of Os and Ir and strong deficiency of Pt and Pd.

These observations suggest that the formation of Dingqing chromitite involved different melting processes and parent rock characteristics. The high-Cr chromitite likely formed through the reaction of boninite melt with peridotites in the subduction zone, transitioning from MORB to SSZ environments. The tectonic evolution of ophiolites in the Bangong–Nujiang region, which includes Dingqing, also supports the transition from MORB to SSZ settings.



Figure 12. Different spinel in the chromitite of the world (modified from González-Jiménez et al. [84]).

6. Conclusions

The high-Al and high-Cr chromitite in Dingqing share similar structural and mineralogical features, but they differ significantly in terms of chromium spinel chemistry. The high-Al chromitite is characterized by lower TiO_2 contents, while the high-Cr chromitite shows relatively higher TiO_2 contents. The composition of the Yilashan chromitite suggests that it crystallized from melts with high Al_2O_3 content and FeO/MgO ratios comparable to boninitic melts in a subduction arc setting. The high Cr# values observed in the chromitite indicate a supra-subduction zone (SSZ) setting, with the presence of both mid-ocean ridge basalt (MORB)-like melts and boninitic melts resulting from varying degrees of melting.

The occurrence of both high-Al and high-Cr chromitite types within the same massif, although rare, has been reported in a few other ophiolites worldwide. The similarities in mineralogical characteristics between the Dingqing chromitite and chromitite from other regions, such as Xinjiang Sartohai chromite and Luobusa chromitite, further support the special massif of Dingqing chromitite. The distribution of PGEs in the Dingqing mantle peridotite and chromitite exhibits a pattern similar to Luobusa chromitite and Sartohay chromite, with enrichment of Os and Ir and a deficiency of Pt and Pd. This pattern can be attributed to the nature of the parent rock and the different melting mechanisms of PGEs in the magma.

The formation of Dingqing chromitite was likely a result of repeated partial melting in the source region. The transition from MORB to SSZ settings, as supported by tectonic evolution in the Bangong–Nujiang region, was most likely responsible for upgrading of the ore and deposition of massive high-Cr chromitite ores.

Supplementary Materials: The following supporting information can be downloaded at: https: //www.mdpi.com/article/10.3390/min13091234/s1. Supplementary Table S1. Representative microprobe analyses of olivine of the Dingqing ophiolite; Supplementary Table S2. Representative microprobe analyses of orthopyroxene of the Dingqing ophiolite; Supplementary Table S3. Representative microprobe analyses of clinopyroxene of the Dingqing ophiolite; Supplementary Table S4. Representative microprobe analyses of chromian spinel of the Dingqing ophiolite; Supplementary Table S5. PGE compositions of whole-rock samples of chromitites in Dingqing massif.

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