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ORIGINAL ARTICLE

Geodynamic significance and genesis of chromitites from the Islahiye ophiolite (Gaziantep, SE Anatolia) as constrained by platinum group element (PGE) compositions and mineral chemistry characteristics

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Abstract

Chromitites associated with intensely altered dunites and harzburgites from fourteen different localities in the Islahiye ophiolites (SE Anatolia) is reported here for the first time. These chromitites were observed as lenticular and banded bodies with disseminated and massive textures and containing magnesiochromite grains with the following composition: $Cr_2O_3 = 58.91–59.74$ wt%, $Al_2O_3 = 10.85–11.20$ wt%, and $TiO_2 = 0.09–0.13$ wt%. The Mg# [Mg/ $(Mg + Fe^{2+})$] values of magnesiochromite from the Islahiye ophiolite range between 0.52 and 0.60 and their Cr# [Cr/ (Cr + Al)] values vary from 0.7802 to 0.7844. These contents vary with a constant pattern, coincident with the estimated parental liquids that have originated from the derivative of a single bulk of boninitic magma together with Al, Ti-poor, and Cr-rich initial contents. The chromitites are serpentinised in almost all parts of the study area, and harzburgite and dunite can be observed in different locations. Although the overall composition of platinum group elements (PGE) in most examined chromitites varies between 97 and 191 ppb, three chromitites from the Islahiye region present enrichments in overall PGE (up to 214 ppb). The mineralogical and geochemical features of chromitites from the Islahiye region exhibit a robust similarity to podiform chromitites in the mantle fragment of supra–subduction zone type ophiolitic bodies. The estimated parental magmas of the investigated chromites are consistent with the differentiation of arc-related melts and do not suggest an oceanic spreading centre tectonic environment. The Islahiye chromites are enriched in IPGE (Ir, Os, Ru), with the occasional presence of Ru and Ir and higher Os contents in chromite. Furthermore, we did not find any platinum group minerals (PGM) associated with the serpentine silicate sample matrix, which would have stated a secondary enrichment in PGEs. All chromitites in the investigated region have high Cr and low Ti values, are defined as magnesiochromite and were crystallised from a characteristic boninitic magma.

Keywords Chromite · Platinum group element · Platinum group mineral · Ophiolite · Mineral chemistry

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1 Introduction

In Anatolia, the Neo–Tethyan belt is broadly separated into two branches: the southern branch extends along the Anatolide–Tauride and Bitlis–Zagros suture zone, while the northern branch follows the İzmir–Ankara–Erzincan zone (Sengör and Yilmaz 1981; Çiftçi et al. 2019). (Fig. 1). Chromites have an important economic value; their value is even more important since they are often associated with enrichments in platinum group minerals (PGM). Platinum group elements (PGE; Os, Rh, Ir, Pt, Pd, and Ru) are highly sought after for their exceptional physicochemical properties (Uysal et al. 2005; Zhou et al. 2014; Su et al. 2021). Therefore the search for new deposits and the development of new extraction technologies are increasing. Although chromite occurrences in various parts of the world have been studied in detail, Anatolian chromites have received

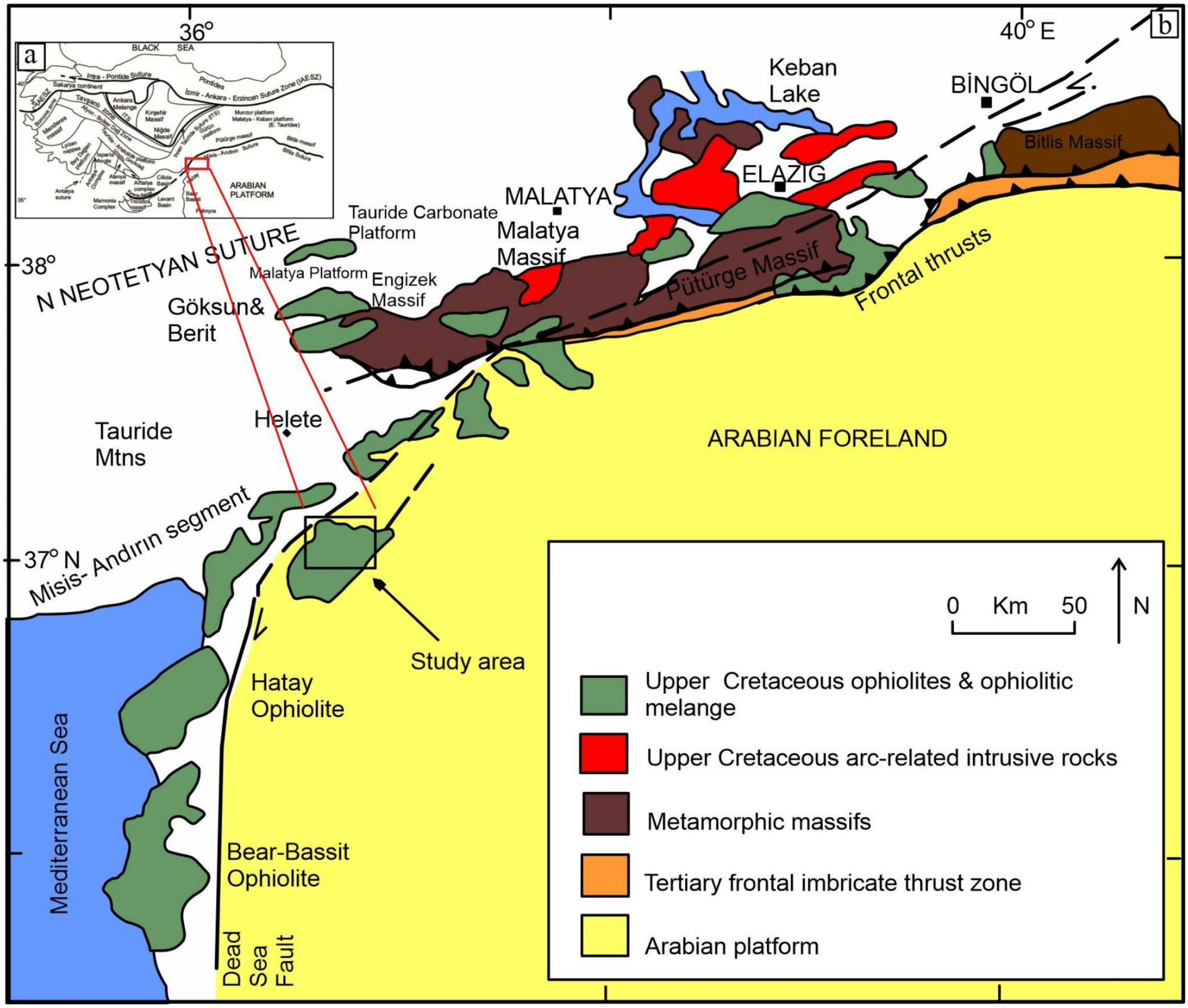

Fig. 1 (a) Outline geodynamic map of Anatolia (taken from Robertson and Ustaömer 2009) (b) Tectonic map of the SE Anatolia, presenting the study area (colorized and modified from Robertson et al. 2007)

insufficient research attention to date (Zhou et al. 2014; Su et al. 2021). Over the last three decades, ophiolitic chromitites have become crucial targets for the recovery of PGEs. The chromite compositions and PGE abundances of Turkish chromitites have been poorly reported (Engin et al. 1986; Uysal et al. 2005, 2007). Indeed, despite their economic importance, most Turkish chromitites have not been extensively studied concerning their compositions and PGE potential (Engin et al. 1986; Uysal et al. 2005, 2007). In fact, whilst being abundant, Anatolian chromitite mineralisations have not yet been studied enough, particularly concerning their mineral chemistry and whole-rock PGE characteristics. In this contribution, we present new petrological and geochemical investigations of Islahiye chromites to interpret the economic significance of PGEs. The aims were to examine the PGE concentrations of chromites from the Islahiye ophiolite (Gaziantep/SE Anatolia). Even though their obvious abundance, numerous Anatolia chromitite mineralization were not studied enough yet, particularly concerning their mineral chemistry and whole-rock PGE characteristics. One of the striking aims of this study has been to report a detailed examination of chromitite occurrences from the Islahiye (Gaziantep) region, SE Anatolia in terms of PGE inventory-mineralogy and chromite composition. To achieve this, we performed petrographic, mineralogical, and geochemical (mineral chemistry and PGE analyses) studies of rock and chromite samples obtained at Islahiye.

2 Geological setting

The ore bodies in the Islahiye region (SE Anatolia) consist mainly of podiform chromite occurrences in the tectonites of the ophiolitic bodies. As a result of observations performed in the field, a geological map was drawn according to structural, ore, and rock outcrops (Fig. 1). The southern region of Kahramanmaraş, located in eastern Anatolia, is interpreted in this research and has been actively deforming with a fault zone – a long-lasting triple junction (the triple junction of the Kahramanmaraş section, SE Anatolia) which evolved following the Alpine orogeny.

The examined rocks of the Islahiye region have been grouped into three units: ophiolite Nappes, Tertiary Cover Units, and the Autochthonous Arabian Platform (Figs. 1 and 2) (Yilmaz et al. 1993). The Autochthonous Arabian Platform contains Lower Cambrian to Upper Ordovician limestone, with alternating sandstone, quartzite, and shale at its base. These basement rocks are unconformably overlain by Upper Triassic-Lower Cretaceous dolomite and dolomitic limestone (Atan 1969; Bağcı 2013; Dubertret 1955; Yilmaz et al. 1984). The Arabian platform is tectonically overlain by a group of oceanic basin units such as ophiolitic units (Yilmaz et al. 1993) (Fig. 2). Like in the study area and its surroundings (Gölbaşi-Kahramanmaraş), the examined ophiolitic rocks have been extremely dismembered and consist of undifferentiated gabbroic rocks and mantle tectonites (Bağci 2013; Tanirli and Rizaoglu 2016; Nurlu et al. 2016). The highly serpentinised mantle tectonites occurring throughout the area are formed primarily by harzburgites and dunites, and exhibit foliation and lineation which reflect plastic deformation. The mantle tectonites are cut by pyroxenite dikes with thicknesses varying from 42 to 15 cm. The serpentinised peridotites and dunites in the region are incompatible with the Jurassic limestones and have a tectonic contact with upper Maastrichtian-aged limestone, shale, and sandstones (Yilmaz et al. 1993). The investigated area consists entirely of peridotites. However, tectonic movements are highly effective in this area, and the primary characteristics of peridotites (magmatic banding, lineation, foliation, etc.) cannot be observed, thus making it impossible to differentiate these rocks into different lithological units according to their chemical and mineralogical properties. The chromite occurrences are serpentinised in almost all parts of the study area and dunite and harzburgite – which can be observed in different locations – dominate the lithology of the Islahiye ophiolite in most of the investigated area (Fig. 2). These peridotites, which contain chromite formations in places, were serpentinised in almost every part of the study area and chromite formations could be observed at two different locations. The faults in the region produced semi-regular and irregular mineralisations. As a result of the observations made in the examined area, a geological map was drawn according to tectonic, ore, and rock outcrops. The presence of the dunite, harzburgite, mineralisations, and drill points are shown on the map (Fig. 2). The chromite ore mineralisations, which form the basis of the study, are located within the unit of the Lower Cretaceous 'ophiolite nap'. The ophiolite layer is located in the region with completely tectonic movements. The ore in the region comprises podiform chromite deposits in the tectonites of the ophiolite. Large and small NE–SW faults are apparent and the faults in the region were completely associated with the formation of mineralisations. The ophiolitic fragments in the research area consist of peridotites (dunite and harzburgite). Ophiolitic rocks of Late Cretaceous age mantle tectonites formed by serpentinised dunite, dunite, serpentinite, and serpentinised harzburgites are the most extensive rocks within the Islahiye ophiolite in the region.

3 Analytical methods

3.1 Electron microprobe analyses

Thin sections (about 30-micron thickness) for two samples were prepared by the Vancouver Thin Section Laboratory. Major element compositions of minerals and phase relationships were studied by electron microprobe at the Department of Earth and Atmospheric Sciences (EAS) at the University of Alberta. The operating conditions were 40 degrees take-off angle, accelerating voltage 20 kV, beam current 20 nA, and beam diameter < 1 micron (fully focused), except on the zeolite points that were run separately with a 10–micron diameter beam. The Kα X-ray lines of 13 elements were measured using the following diffraction crystals: PET (pentaerythritol) – P, K, Ca, Ti, V, Cr; TAP (thallium hydrogen phthalate) – Na, Mg, Al, Si; LIF (lithium fluoride) – Mn, Fe, Ni. Total count times of 30 s were used for both emission peaks and background positions for all elements except Na, for which 60 s were used. Interference corrections were applied to V for interference by Ti and Cr for interference by V and Mn for interference by Cr (Donovan et al. 1993). Intensity data were reduced according to Armstrong (1988) and the choice of mineral standards varied with the mineral analysed. Oxygen was calculated by stoichiometry and included in the data reduction. Representative data are shown in Table 1.

3.2 PGE analyses

Samples (rock and chromites) were collected from Islahiye ophiolitic units for petrographic and chemical analyses

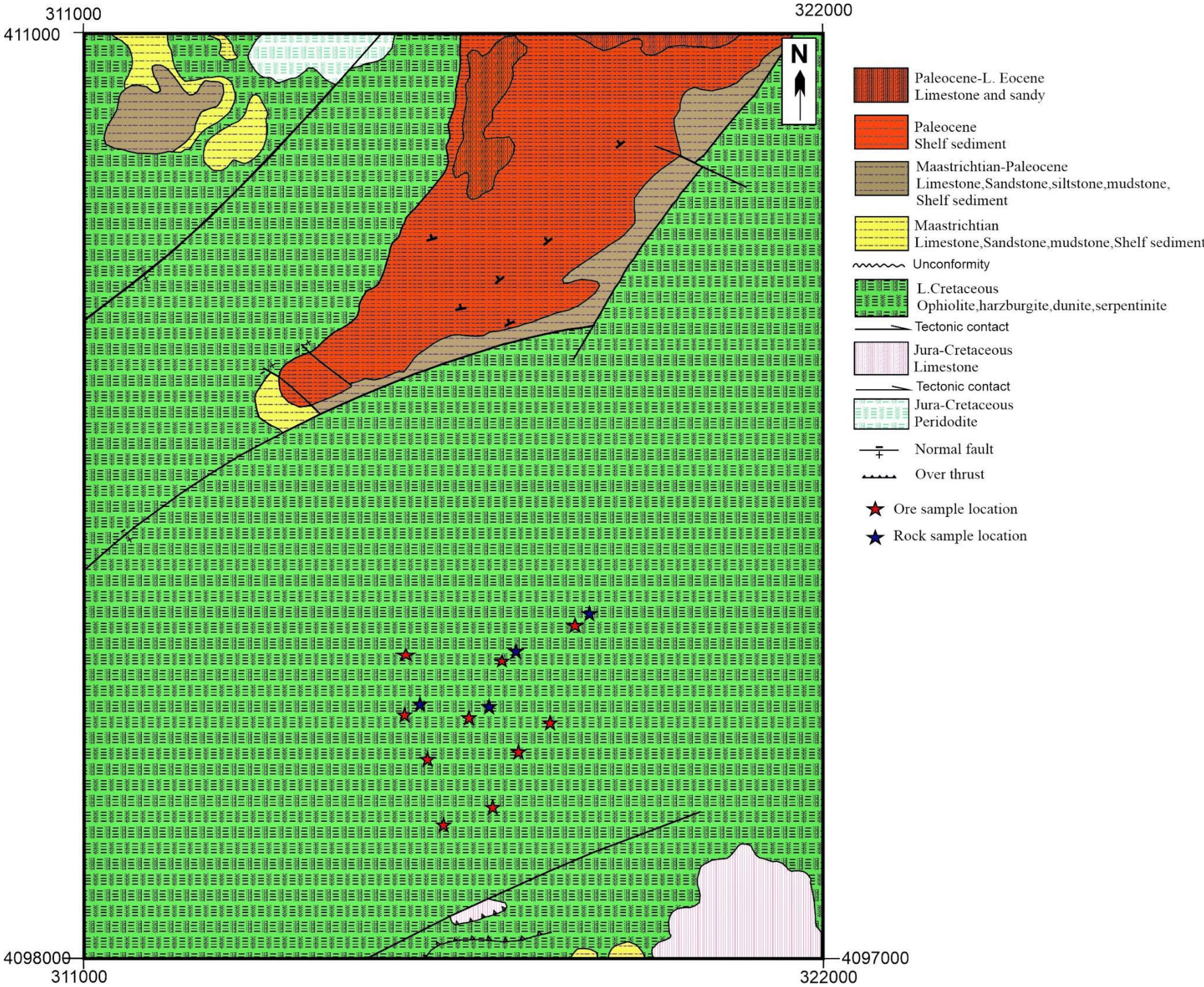

Fig. 2 Geological and drilling map of ophiolitic rocks (revised from MTA 2015)

(field observation and drilling). During the field investigations, the GPS (Global Positioning System) was used to take the coordinates of the sampling points. The major element concentrations of the whole–rock samples were determined by Inductively Coupled Plasma–Emission Spectrometry (ICPES) at ACME Analytical Laboratory, Vancouver (Canada) with a precision better than ± 5 %. 14 samples were prepared from massive, nodular, scattered, and ribboned chromite ore collected from underground and outcrops of the study area. 4 rock samples were analysed to know the chemical composition and 8 chromite ore samples were analysed for platinum group elements (PGEs) at ACME Analytical Laboratories Ltd., Vancouver, Canada.

4 Results

4.1 Petrographic description of the host rocks and chromitites

Petrographical study by polarising microscope covers investigations of ca. 115 thin sections to provide the basis for further mineralogical and petrological analyses. The macroscopic and microscopic features of the studied rocks from the Islahiye region were defined in detail prior to geochemical and PGE analyses.Harzburgites The harzburgites, less clastic and less fragmented than the dunites, are distinguished by colour changes; dunites, on the other hand, present monochrome tones such as pistachio green and dark blue. The harzburgites are mainly related to dunites and their average pyroxene contents increase with proximity to

Table 1 The average composition (wt%) and cation proportions of magnesiochromite grains from Hamidiye/Islahiye chromitites. Cr# = Cr/(Cr+Al), Mg# = Mg/(Mg+Fe^{2+})

Sample	NY-1	NY-2	NY-3	NY-4	NY-5	NY-6	NY-7	NY-8	NY-9	NY-10	NY-11	NY-12	NY-13	NY-14
TiO_2	0.1	0.09	0.11	0.1	0.1	0.11	0.11	0.12	0.12	0.11	0.09	0.12	0.13	0.1
ZnO	0.06	0.05	0.06	0.06	0.03	0.06	0	0.07	0	0	0	0	0.06	0.05
Al_2O_3	11.06	10.9	10.85	11.05	11.19	11.11	11.04	11.05	11.18	11.2	11.06	11.15	11.02	11.02
Cr_2O_3	59.36	58.91	58.89	59.5	59.22	59.42	59.5	59.54	59.23	59.43	59.43	59.74	58.93	59.23
FeO	15.37	16.7	17	15.09	15.67	15.31	15.45	15.28	16.81	15.36	15.05	15.06	16.56	15.48
NiO	0.13	0.11	0.13	0.12	0.08	0.11	0.14	0.1	0.09	0.13	0.12	0.1	0.09	0.15
MnO	0.18	0.2	0.2	0.17	0.18	0.16	0.17	0.17	0.21	0.16	0.14	0.18	0.19	0.17
MgO	13.06	11.75	11.77	12.77	12.42	12.77	12.44	12.78	11.12	12.71	13	12.65	11.85	12.67
Total	99.34	98.7	99.01	98.87	98.91	99.05	98.88	99.12	98.78	99.15	98.93	99.03	98.84	98.88
Ti	0.005	0.004	0.005	0.005	0.005	0.006	0.005	0.006	0.006	0.006	0.005	0.006	0.006	0.005
Zn	0.003	0.003	0.003	0.003	0.001	0.003	0	0.004	0	0	0	0	0.003	0.003
Al	0.844	0.844	0.839	0.849	0.86	0.851	0.85	0.847	0.869	0.858	0.847	0.856	0.852	0.847
Cr	3,038	3,062	3,053	3,065	3,054	3,055	3,072	3.06	3,088	3,053	3,054	3,075	3,056	3,053
Fe^{+2}	0.832	0.918	0.932	0.823	0.855	0.832	0.844	0.831	0.927	0.835	0.818	0.82	0.908	0.844
Ni	0.007	0.006	0.007	0.006	0.004	0.006	0.007	0.005	0.005	0.007	0.007	0.005	0.005	0.008
Mn	0.01	0.011	0.011	0.009	0.01	0.009	0.009	0.01	0.011	0.009	0.008	0.01	0.01	0.009
Mg	1.26	1,152	1.15	1.24	1,208	1,238	1,211	1,239	1,093	1,231	1.26	1,227	1,158	1,232
O	7,945	7,957	7,951	7,962	7,961	7,959	7,966	7,959	7,984	7,961	7,954	7,971	7.96	7,955
Cations	5,999	6	6	6	5,997	6	5,998	6,002	5,999	5,999	5,999	5,999	5,998	6,001
Cr#	0.782586	0.783922	0.78443	0.783086	0.780276	0.78213	0.783274	0.78321	0.780389	0.780619	0.782876	0.782244	0.781986	0.782821
Mg#	0.602294	0.556522	0.552354	0.601066	0.585555	0.598068	0.589294	0.598551	0.541089	0.595837	0.606352	0.599414	0.560503	0.593449

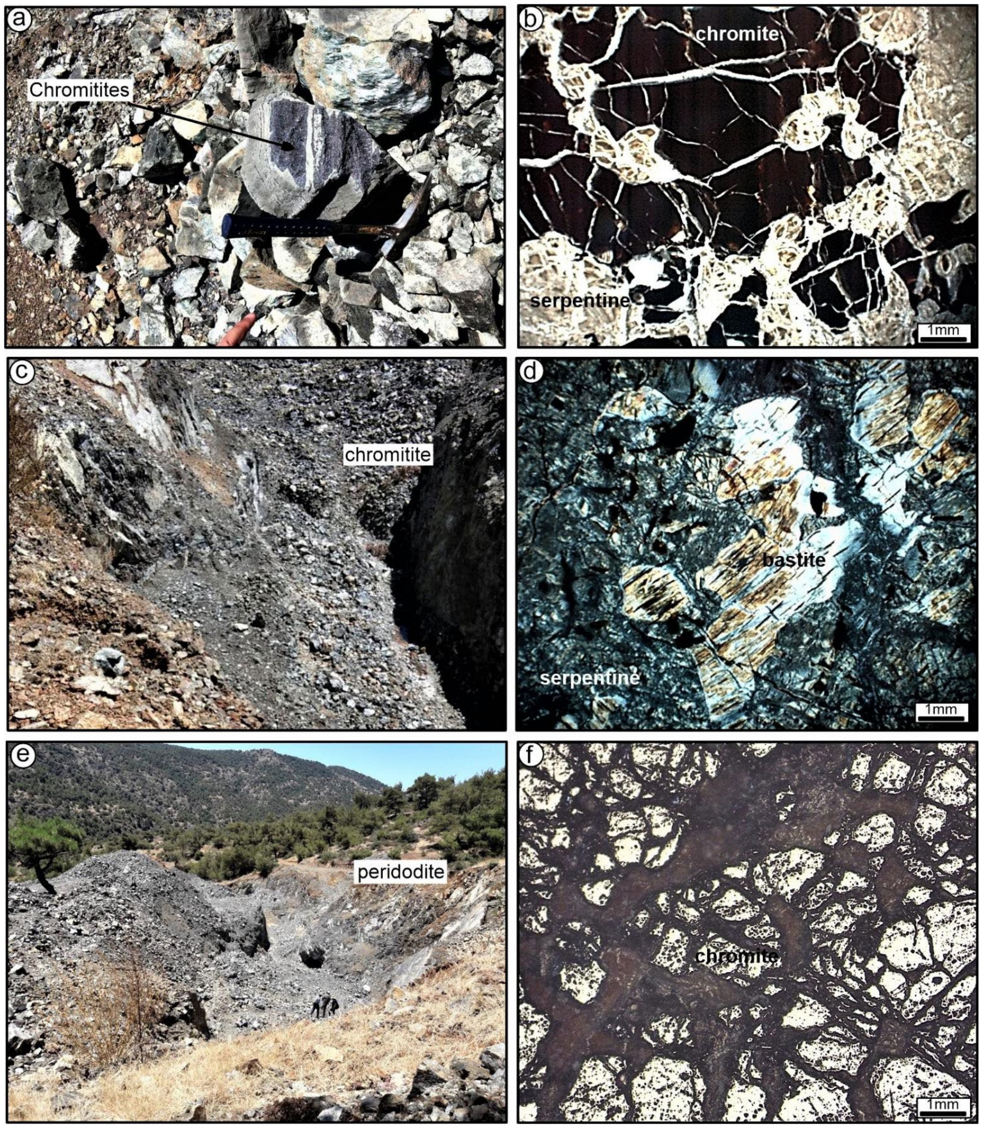

Fig. 3 Petrographic views of ophiolitic rocks and chromite, (A) Chromitite ore surrounded by dunites, (B) Thin section of chromite, (C) Serpentinized harzburgites and chromitite, (D) Thin section of serpentinized harzburgites, (E) General view of Islahiye peridotites, (F) Polished section of chromite

dunite. The modified harzburgites are serpentinised, exhibiting light green, yellow, and brown colours. Microscopic examinations of the thin sections of the rocks show the presence of olivine, orthopyroxene, clinopyroxene, and major chromite. The serpentinised harzburgites exhibit mesh to granular textures and consist of olivine (70 %), orthopyroxene (20 %), and opaque minerals (magnetite and chromite). Serpentinites mainly consist of minerals from the serpentine group (bastite and chrysotile) (Fig. 3a–d).

Dunites Fewer dunites occur in the study area relative to harzburgites, and in most places, they are completely serpentinised, having undergone mineral transformations. The dunites have a grainy texture and consist of olivine (97–98 %), partially serpentinised orthopyroxenes, and rare chromite crystals that are fixed in olivines. The serpentinised dunites exhibit mesh to granular textures and mainly consist of olivine (90–95 %), clinopyroxene (1–2 %), and chromite. The olivines (forsterites) have been strongly deformed through cataclasis. A dunite rock in the form of envelopes occurs on the outer surfaces of the chromite mineralisations, and the mineralisations have developed from this ultramafic rock. The transition contact between the harzburgite and dunite units represents the outer part of the lithology and the inner part of the harzburgite. It is sometimes difficult to differentiate the foliation plans in cases where the dunite samples are unaltered (Fig. 3).

Chromitites The chromitites in the study area consist of dunitic sheaths and podiform chromites in harzburgites. The chromites in the area are related to tectonic movements and the outcrop points are very few. The faults are NE–SW-oriented and the mineralisations have been displaced in the region due to these faults. The fault has resulted in an irregular distribution of mineralisations in the area making it difficult to establish the presence of ores and to determine their reserves. The contact between the chromite ore and the harzburgites in which the ore is located is tectonic, creating a brief transition zone between the ore and the harzburgites. There are problems of fragmentation and ore loss in areas where the ore occurs. The area is highly tectonically active. There are lenticular chromite formations. It is difficult to see all the massive, scattered, nodular, and banded chromite ores in the same regions. Structural irregularities are related to changes in the physicochemical conditions in the ophiolite magma chamber and the conditions of the ophiolite's obduction onto the continent (Fig. 3b).

4.2 Mineral chemistry of chromitites

Fourteen electron microprobe analysis (EMPA) spot measurements were performed on two chromitite samples (Table 1) to determine the primary distributions of oxidised elements in the ore. According to Fig. 4, the Islahiye chromites are located in the region of samples containing high Cr contents, compared to the high Al and high Cr ores produced in the Kahramanmaraş–Gaziantep line (Akmaz et al. 2014). Moreover, the chromite crystals exhibit a wide range of compositional variations ($Cr_2O_3 = 58.91–59.74$ wt%, $Al_2O_3 = 10.85–11.20$ wt%, and $TiO_2 = 0.09–0.13$ wt%) that plot within the ophiolitic podiform chromitite field in Fig. 4. The values of Cr# vary from 0.7802 to 0.7844, and those of Mg# from 0.55 to 0.60 (Table 1). The investigated chromitites are Cr-rich (Cr# $\geq$ 0.7). For the chromites of the Cr-rich chromitites, the Cr# values range between 0.70 and 0.81 (Akmaz et al. 2014). Some minor and trace elements of the chromites are listed in Fig. 2. The Ni, Mn, Ti, and Zn values were also determined (4–7; 9–11; 4–6; 0–4 ppm, respectively). The diagrams in Fig. 4a-b show that all chromitites from the Islahiye ophiolites are plotted into the subfield of podiform chromitites according to their mineral chemistry data. The overlapping sector of stratiform and podiform chromitites on the Mg# vs. Cr# variogram was plotted through the analyses. The studied chromite grains consist of magnesiochromite (Fig. 4d). Therefore, we use the term "magnesiochromite" instead of "chromite". These samples have low Ti contents and high Cr# values suggesting that the chromites crystallised from a typical boninitic melt (Fig. 5a). The Islahiye chromites fall in the arc field according to the TiO_2–Al_2O_3 diagram (Fig. 5b). According to the diagrams, when the estimated chemical compositions of the primer melts crystallizing the chromites are examined, the Cr-rich chromitites are believed to have crystallised by boninitic fusion in a subduction environment.

4.3 PGE geochemistry

A total of eight samples of whole chromite ores were analysed for the presence of PGEs. The results of the PGE analysis for the Islahiye chromitites are shown in Table 2. The PGE contents of samples taken from the Islahiye chromitites are low and range from 97 to 214 ppb in total (average 169 ppb). In the examined samples, the Ru, Ir, Os, and Rh contents range between 90 and 130, 3 and 40, 9 and 50, and 6 and 11 ppb, respectively, showing a positive correlation among the Os–Ir ($R^2 = 0.52$), Ir–Ru ($R^2 = 0.92$), and Os–Ru ($R^2 = 0.56$) pairs. Gold and Pt were always below the detection limit, except for samples from PGE 7; the chromitites show enrichment in IPGE with the occasional presence of Ru and Ir, and higher Os contents in chromite. In addition, no PGMs were associated with the serpentinised silicate matrix of this sample, indicating a secondary enrichment in PGE. The results of the analysis are normalised to the chondrite–normalised values and the data are evaluated in spider diagrams (Fig. 6). The Ir values of the analysed chromites in Islahiye ophiolite (3–40 ppb) are significantly lower compared to the Ir contents (2.92–64.9 ppb) in the chromites of the Kizildağ ophiolite (Su et al. 2021). In contrast, the Ru values (48–130 ppb) of the Islahiye ophiolite are higher than the reported Ru content (6.11–92.6) of the Kizildağ ophiolite (Su et al. 2021).

The chondrite-normalised PGE trends of the Islahiye region chromitites compared with the distinct chromitites are shown in Fig. 6. Almost all samples from the Islahiye ophiolite present similar PGE trends as worldwide chromitites, and mostly, these samples exhibit negatively tilted chondrite-normalised PGE trends together with Ru anomalies. All examined samples are represented by a positive slope or almost flat one from Os to Rh, with a negative tilt from Ru to Ir (Fig. 6). Furthermore, the PGE patterns show a negative trend toward positive Ru to Rh in general and present a near–horizon trend from Os to Ir. The samples obtained from the PGE samples collected in the Islahiye ophiolite present a positive correlation between Ir, Ru, and Rh and Os; Rh also shows a positive correlation with Ru, Rh, and Ru. The samples that were taken from the studied region exhibit values between the plutonic chromites and podiform chromites of NATO and fall closer to the podiform

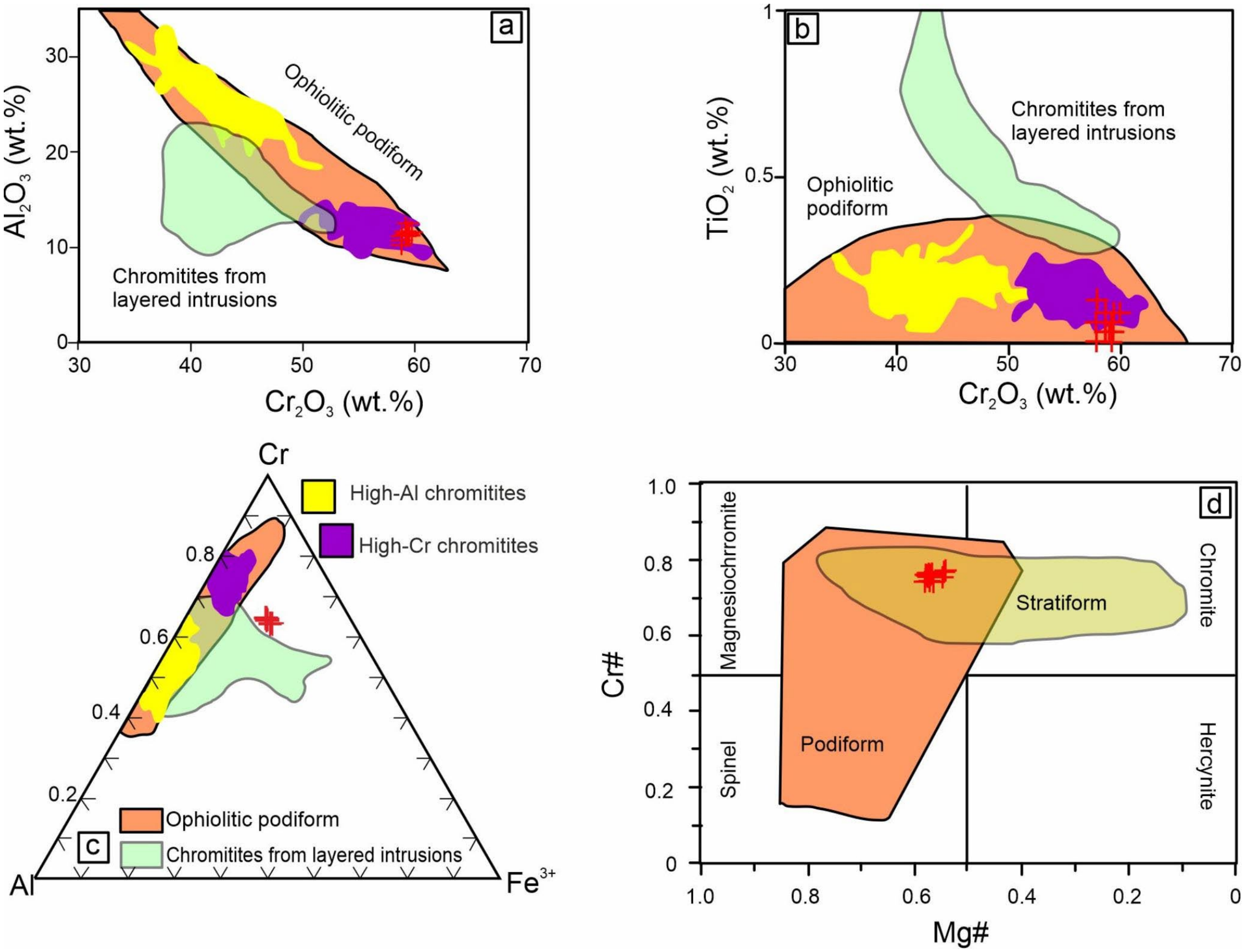

Fig. 4 Composition of chromite crystals drawn on Al_2O_3 versus Cr_2O_3 (a), TiO_2 versus Cr_2O_3 (b). Data for plotting the ophiolitic podiform and layered intrusions chromitite subfields were taken from Pagé and Barnes (2009); Barnes and Roeder (2001). (c) The ternary discrimination diagram of Fe^{3+}–Cr–Al (Barnes and Roeder 2001 d) Data for plotting the stratiform and podiform chromitite subfields were taken from Bonavia et al. (1993) and high-Al/high-Cr chromitites data from Uysal et al. (2015)

chromite zone of the mantle (Fig. 7). The total PGE contents of Islahiye ophiolitic chromites are additionally enriched in IPGEs. The PPGE (Pd, Pt, Rh) concentrations and PPGE/IPGE ratios are very low.

4.4 Platinum group minerals (PGM)

A total of eight samples of PGMs fall into the laurite subfield, whereas in the Ru–Rh–Ir triple diagram, the samples obtained from the region are called ruarsite. The PGE samples enter the laurite subfield, while in the Ru–Rh–Ir triple chart, samples obtained from the region are called ruarsite. The Ir, Ru, and Rh contents exhibit a positive correlation with Os and Ir against Ru, Rh and Ru against also a positive correlation with Rh. Laurite is the most abundant PGM among the studied chromite samples, as is commonly seen in other ophiolitic bodies. Chromites, and in some cases, irarsite and Os–Ir alloys, have been seen to be associated with laurite. The laurite grains in chromites with high Cr contents have higher Ru contents (Fig. 8).

5 Discussion

New geochemical (PGE mineral chemistry) and petrographic data provided in the investigation of chromitites, dunites, and harzburgites from the Islahiye ophiolite of the Gaziantep region suggest that distinct magmatic and ore affinities composed in the prominent geodynamic environment. Accordingly, the formation conditions and petrogenesis of chromitites will be discussed below.

Approximately 2000 large-scale and economically important podiform type chromitite deposits can be widely observed from west to east in Turkey. Most of these

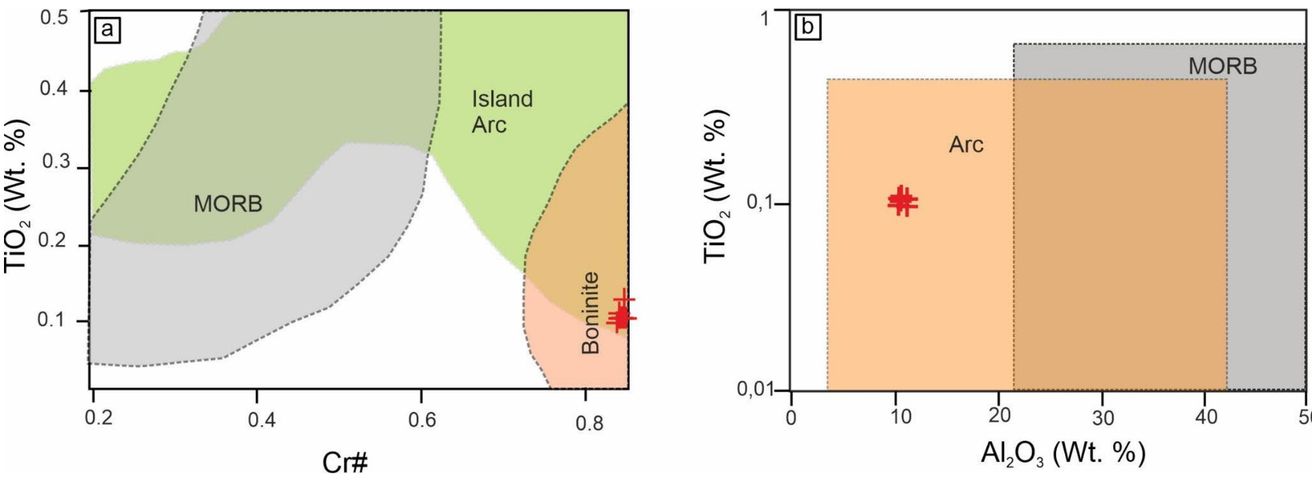

Fig. 5 (a) Composition of magnesiochromite plotted on Cr# vs. TiO_2 (Arai 1992). (b) Composition of magnesiochromite plotted TiO_{2}_ Al_2O_3 arc fields and MORB Kamenetsky et al. (2001)

chromites are found within the mantle unit of the ophiolitic succession, which is thought to represent the remnants of the Tethys Ocean (Kozlu-Erdal and Melcher 2007a; Akbulut 2009; Uysal et al. 2005). Around 83% of Turkey's known chromite resources (sources identified in 140 deposits) come from deposits with a grade of less than 10% Cr_2O_3, and grades of 5% are deemed to be directly saleable. The chromites (Cr_2O_3 = 58.91–59.74 wt%, Al_2O_3 = 10.85–11.20 wt%, and TiO_2 = 0.09–0.13 wt%) in the research area (Islahiye/G.Antep) have a 5% direct sale potential (Kozlu-Erdal and Melcher 2007a; Kozlu-Erdal and Melcher 2007b; Akbulut 2009). As examples of Turkey's deposits with significant PGE concentrations, the total PGE values of Pozanti–Karsanti chromitites in the Taurus Ophiolite Belt are between 38.2 and 2730 ppb, while the total PGE contents of the Mersin chromitites (S Turkey) range between 105 and 204 ppb. The total whole-rock PGE concentrations of chromitites from the Pinarbaşi (Central Anatolia) region are between 67.5 and 253 ppb. The PGE concentrations of the chromitites in this study area were in the range of 0.07–50.19 ppb, and Ru yielded a high concentration of 50.19 ppb. These similar PGE values, which were found in some samples of Pozanti–Karsanti chromitites, have been recorded in the literature as one of the highest PGE concentrations determined in Turkish chromitites (Kozlu-Erdal and Melcher, 2006b). High concentrations of Pd (144–6877 ppb) and Pt (0.18–57.20 ppb) have been reported in the Pozanti-Karsanti chromitites. In addition, a very high PPGE enrichment (Pt and Pd from 1155 to 2518 ppb) was detected in the rutile–bearing, high Al chromitites of the Berit Meta–ophiolite Massif (Kahramanmaraş, SE Turkey) (Kozlu-Erdal and Melcher 2007a; Kozlu-Erdal and Melcher 2007b; Akbulut 2009). The Islahiye region chromites have ΣPGE values of 97–214 ppb, which were found to fit with Turkey's average. These values are low and it has been concluded that they do not have economic importance in terms of PGE mining today. The chromite mineralisations examined in this study are located in the Islahiye area (SE Turkey). Chromite mineralisations, which form the basis of this study, are located within the Lower Cretaceous Islahiye Ophiolite. Recent studies have confirmed that chromites with a high Cr content in the mantle sequence of a single ophiolite

Table 2 The PGE contents (ppb) in examined chromitites and calculated Pd/Ir values. bdl = below detection limit

Sample	IN1	IN2	IN3	IN4	IN5	IN6	IN7	IN8
Au	bdl	bdl	bdl	bdl	bdl	5	5	bdl
Ir	40	38	37	24	32	27	3	38
Os	33	22	50	13	24	14	9	35
Pd	bdl	bdl	bdl	bdl	bdl	bdl	5	bdl
Pt	bdl	bdl	bdl	bdl	bdl	bdl	20	bdl
Rh	11	11	6	9	8	8	7	10
Ru	130	120	120	92	90	91	48	127
ΣPGE	214	191	213	138	154	140	97	210
IPGE	203	180	207	129	146	132	60	200
PPGE	11	11	6	9	8	8	32	10
PPGEN/IPGEN	0.054	0.061	0.029	0.07	0.055	0.061	0.533	0.05

BDL = below detection limit

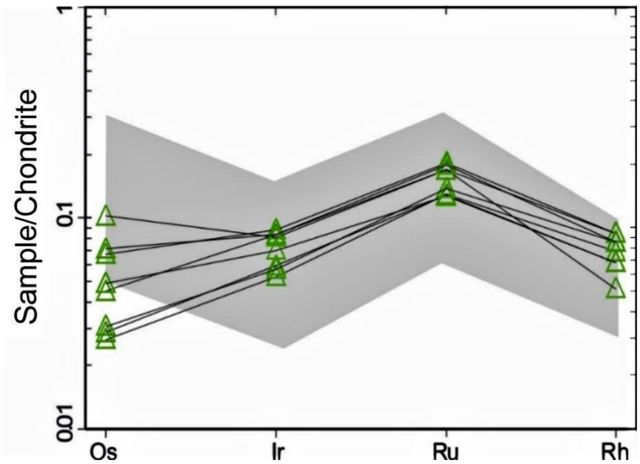

Fig. 6 Spider diagram presenting the comparison of mantle peridotites and chromites with the PGE content of chromites from the Islahiye ophiolite. The data source for the gray field after Bonavia et al. (1993), Bacuta et al. (1990), Yang and Seccombe (1993), Leblanc (1997), Augé and Maurizot (1995), Graham et al. (1996), Uysal et al. (2005) and Prichard et al. (2008)

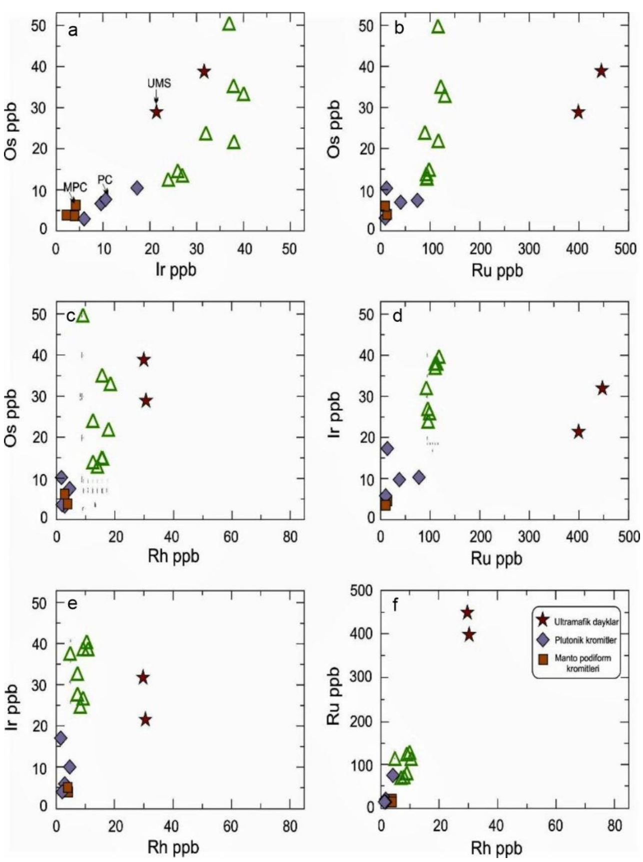

Fig. 7 Diagram Os, Ir, Ru, Rh/Ir, Rh, Ru, and Ru versus Rh shows the location of the PGE sample chart comparison values were obtained from Page et al. 2009 and Hirose and Kawamoto 1995.

complex may have a polygenic origin from various fuses with depleted signatures, but do not necessarily represent a homogeneous group of minerals (Stowe 1994; González-Jiménez et al. 2014a, b; Kapsiotis et al. 2011; Uysal et al. 2015). Furthermore, we report no PGMs associated with the serpentine silicate matrix of the samples, which would also have indicated a secondary enrichment in PGE; in addition, the PGE contents of the samples obtained from the Islahiye ophiolite were low and ranged from 97 to 214 ppb in total (average 169 ppb). The values of Cr# varied from 0.7802 to 0.7844, and those of Mg# from 0.55 to 0.60.

6 Conclusions

Mantle tectonites are the most extensive ophiolite rocks in the Islahiye region and consist of dunite, serpentinised dunite, serpentinised harzburgite, and serpentinite and the study area consists mainly of peridotites (dunite and harzburgite) of Islahiye region ophiolite. The Islahiye (Gaziantep, SE Anatolia) chromitites are primarily linked with harzburgites and dunites and a massive nodular structure with a thin layer and a disseminated layer were present in the investigated tectonites consisting of dunite and harzburgites. The Islahiye chromites present an enrichment in IPGE with the occasional presence of Ru and Ir and higher Os contents in chromite. According to the results of the chemical analysis (mineral chemistry), the chromites exhibit a wide range of compositional variations (Cr_2O_3 = 58.91–59.74 wt%, Al_2O_3 = 10.85–11.20 wt%, and TiO_2 = 0.09–0.13 wt%). All the chromites in the study area have high Cr and low Ti values, and are defined as magnesiochromites that crystallised from a typical boninitic melt based on the TiO_2–Al_2O_3 diagram; the studied rocks fall into the arc subfield. The PGE contents of the examined Islahiye chromitites were low and varied from 97 to 214 ppb in overall (average 169 ppb). The crucial geochemical distinctions in the boninitic magma may also be caused by an interaction with the mantle country rock. In the Islahiye region, the chemical attitude of PGEs and the mineralogical features of the original PGM inclusions provide robust evidence for the effect of a rock/melt reaction process.

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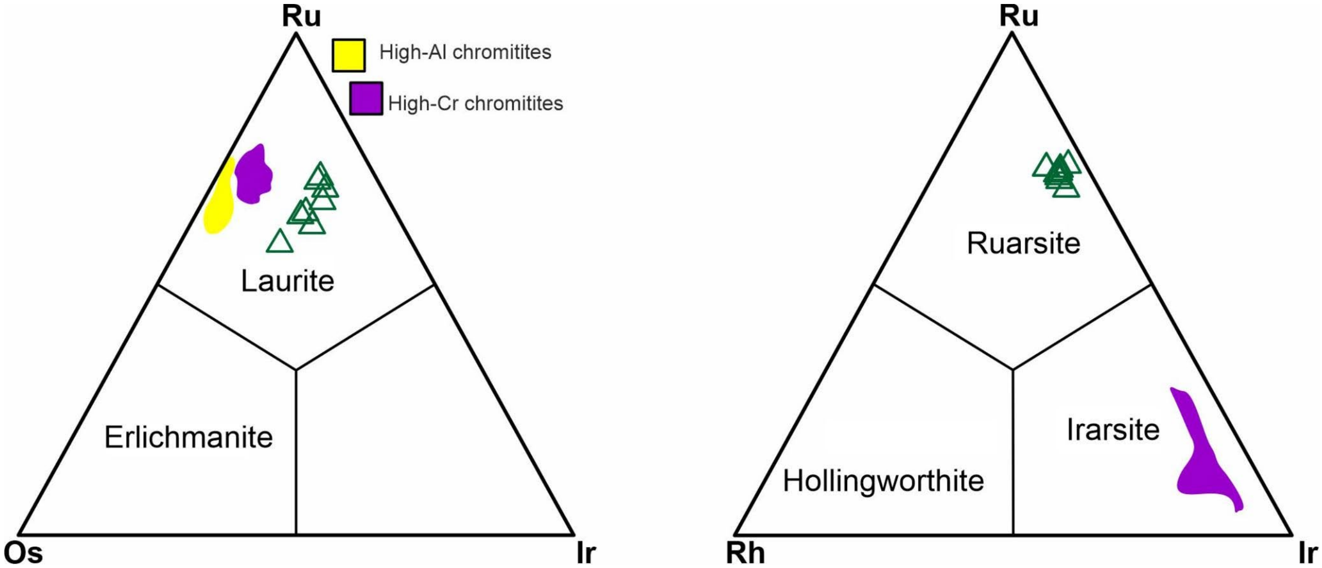

Fig. 8 Ir–Ru–Os (at %) discrimination diagram (Harris and Cabri 1991) for the composition of Os–Ir alloy, laurite, and irarsite drawn in the ternary diagram Ru–Rh–Ir, and Ru–Os–Ir and respectively (High-Al/ high-Cr chromitites data from Uysal et al. 2015)

Conceptualization, data collection, writing original draft, formal analysis, and methodology.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Akbulut M (2009) Güneybati Anadolu Kromit Yataklarinin Platin Grubu Element (PGE) Potansiyelleri, Dokuz Eylül Üniversitesi Fen Bilimleri Enstitüsü Doktora Tezi, Ankara, 181 syf (in Turkish with English abstract)

Akmaz RM, Uysal I, Saka S (2014) Compositional variations of chromite and solid inclusions in ophiolitic chromitites from the southeastern Turkey: Implications for chromitite genesis. Ore Geol Rev 58:208–224. https://doi.org/10.1016/j.oregeorev.2013.11.007

Arai S (1992) Chemistry of chromian spinel in volcanic rocks as a potential guide to magma chemistry. Mineral Mag 56:173–184. DOI: https://doi.org/10.1180/minmag.1992.056.383.04

Armstrong JT (1988) Quantitative analysis of silicates and oxide minerals: Comparison of Monte-Carlo, ZAF and Phi-Rho-Z procedures, Microbeam Analysis, 239-246.

Atan OR (1969) Eğribucak-Karacaören (Hassa)-Ceylanlı-Dazevleri (Kırıkhan) arasındaki Amanos dağlarının jeolojisi [The geology of the Amanos mountains among the Eğribucak-Karacaören (Hassa)-Ceylanlı-Dazevleri (Kırıkhan)]. General Directorate of Mineral Research and Exploration (MTA) Publication: 139 (in Turkish with English abstract)

Augé T, Maurizot P (1995) Stratiform and alluvial platinum mineralization in the New Caledonia ophiolite complex. Can Mineral 33:1023–1045

Bacuta GC, Kay RW, Gibbs AK, Lipin BR (1990) Platinum–group element abundance and distribution in chromite deposits of the Acoje block, Zambales ophiolite complex Philippines. J Geochem Explor 37:113–145. https://doi.org/10.1016/0375-6742(90)90086-P

Bağcı U (2013) The geochemistry and petrology of the ophiolitic rocks from the Kahramanmaraş region, Southern Turkey. Turk J Earth Sci 22:536–562. https://doi.org/10.3906/yer-1203-1

Barnes SJ, Roeder PL (2001) The range of spinel compositions in terrestrial mafic and ultramafic rocks. J Petrol 42:2279–2302. https://doi.org/10.1093/petrology/42.12.2279

Bonavia FF, Diella V, Ferrario A (1993) Precambrian podiform chromitites from Kenticha Hill, Southern Ethiopia. Econ Geol 88:198–202. https://doi.org/10.2113/gsecongeo.88.1.198

Çiftçi Y, Dönmez C, Parlak O, Günay K (2019) Chromitite Deposits of Turkey in Tethyan Ophiolites. In: Pirajno F., Ünlü T., Dönmez C., Şahin M. (eds) Mineral Resources of Turkey. Modern Approaches in Solid Earth Sciences, 73–157. https://doi.org/10.1007/978-3-030-02950-0_3

Donovan JJ, Snyder DA, and Rivers ML (1993) An improved interference correction for trace element analysis in microbeam analysis, 2, 23-28.

Dubertret L (1955) Géologie des roches vertes du nord-ouest de la Syrie et du Hatay (Turquie). Notes Mémoires Moyen-Orient 6:227

Engin T, Özkoçak O, Artan U (1986) General geological set ting and character of chromite deposits in Turkey. In: Pe-trascheck W, Karamata S, Kravchenko GG, Johan J, Economou M, Engin T (eds) Chromites. Theophrastus Publ. S.A., Athens, pp 199–228

González-Jiménez JM, Griffin WL, Gervilla F, Proenza JA, O'Reilly SY, Pearson NJ (2014a) Chromitites in ophiolites: how, where, when, why?, Part 1. A review and new ideas on the origin and significance of platinum–group minerals. Lithos 189:127–139. https://doi.org/10.1016/j.lithos.2013.06.016

González-Jiménez JM, Griffin WL, Proenza JA, Gervilla F, O'Reilly SY, Akbulut M, Pearson NJ, Arai S (2014b) Chromitites in ophiolites: how, where, when, why? Part II. The crystallization of chromitites. Lithos 189:140–158. https://doi.org/10.1016/j.lithos.2013.09.008

Graham IT, Franklin BJ, Marshall B (1996) Chemistry and mineralogy of podiform chromitite deposits, Southern NSW, Australia: a guide to their origin and evolution. Mineral Petrol 37:129–150. https://doi.org/10.1007/BF01162355

Harris DC, Cabri LJ (1991) Nomenclature of platinum–group–element alloys: Review and revision. Can Mineral 29:231–237

Hirose K, Kawamoto T (1995) Hydrous partial melting of lherzolite at 1 GPa: The effect of H_2O on the genesis of basaltic magmas. Earth and Planetary Science Letters Volume 133:(3–4):463–473. https://doi.org/10.1016/0012-821X(95)00096-U

Kamenetsky VS, Crawford AJ, Meffre S (2001) Factors controlling chemistry of magmatic spinel: an empirical study of associated olivine, Cr–spinel and melt inclusions from primitive rocks. J Petrol 42:655–671. https://doi.org/10.1093/petrology/42.4.655

Kapsiotis A, Grammatikopoulos AT, Tsikouras B, Hatzipanagiotou K, Zaccarini F, Garuti G (2011) Mineralogy, composition and PGM of chromitites from Pefki, Pindos ophiolite complex (NW Greece): evidence for progressively elevated fAs conditions in the upper mantle sequence. Mineral Petrol 101:129–150. https://doi.org/10.1007/s00710-010-0140-8

Kozlu-Erdal H, Melcher F (2007a) Mineralogy and geochemistry of platinum-group element enrichments in Berit (Maraş) chromitites, southeastern Turkey. European Geosciences Union General Assembly, abs

Kozlu-Erdal H, Melcher F (2007b) Berit (Kahramanmaraş) metaofiyoliti kromititlerindeki platin grubu elementler ve mineral zenginleşmesinin jeokimyası, mineralojisi ve petrolojisi, Güneydoğu Türkiye. 60. Türkiye Jeoloji KurultayıBildiri Özleri, 16–22 Nisan 2007, Ankara, pp. 205–208. (in Turkish with English abstract)

Leblanc M (1997) Chromitite and ultramafic rock compositional zoning through a paleotransform fault, Poum, New Caledonia. Econ Geol 92:503–504. https://doi.org/10.2113/gsecongeo.92.4.503

MTA (General Directrorate of Mineral Research and Exploration) (2015) Vertical stratigraphic section and Geological Map of Islahiye, Ankara–Turkey

Nurlu N, Parlak O, Robertson AHF, Quadt A (2016) Implications of Late Cretaceous U–Pb zircon ages of granitic intrusions cutting ophiolitic and volcanogenic rocks for the assembly of the Tauride allochton in SE Anatolia (Helete area, Kahramanmaraş region, SE Turkey). Int J Earth Sci 105:283–314. https://doi.org/10.1007/s00531-015-1211-1

Prichard HM, Neary CR, Fisher FC, O'Hara MJ (2008) PGE–rich podiform chromitites in the Al'Ays ophiolite complex, Saudi Arabia: an example of critical mantle melting to extract and concentrate PGE. Econ Geol 103:1507–1529. https://doi.org/10.2113/gsecongeo.103.7.1507

A. H. F., Robertson O., Parlak T., Rízaoğlu Ü., Ünlügenç N., İnan K., Tasli T., Ustaömer (2007) (2007) Tectonic evolution of the South Tethyan ocean: evidence from the Eastern Taurus Mountains (Elaziğ region SE Turkey). Geological Society London Special Publications 272(1) 231-270 10.1144/GSL.SP.2007.272.01.14

Robertson AHF, Ustaömer T (2009) Formation of the Late Palaeozoic Konya Complex and comparable units in southern Turkey by subduction-accretion processes: Implications for the tectonic development of Tethys in the Eastern Mediterranean region. Tectonophysics 473:113–148. https://doi.org/10.1016/j.tecto.2008.10.027

Pagé P, Barnes SJ (2009) Using trace elements in chromites to constrain the origin of podiform chromitites in the Thetford Mines Ophiolite, Quebec, Canada. Econ Geol 104:997–1018. https://doi.org/10.2113/econgeo.104.7.997

Sengör AMC, Yilmaz Y (1981) Tethyan evolution of Turkey: Plate tectonic approach. Tectonopysics 75:181–241. https://doi.org/10.1016/0040-1951(81)90275-4

Stowe CW (1994) Compositions and tectonic settings of chromite deposits through time. Econ Geol 89:528–546. https://doi.org/10.2113/gsecongeo.89.3.528

Su B, Liu X, Chen C, Robinson PT, Xiao Y, Zhou M, Bai Y, Uysal İ, Zhang P (2021) A new model for chromitite formation in ophiolites: Fluid immiscibility. Sci China Earth Sci 64:220–230. https://doi.org/10.1007/s11430-020-9690-4

Tanırlı M, Rızaoglu T (2016) Whole–rock and mineral chemistry of mafic cumulates from the Low–Ti ophiolite in the southern part of Kahramanmaras, Turkey, Russian Geology and Geophysics Volume 57, Issue 10, October 2016, pp. 1398–1418. https://doi.org/10.1016/j.rgg.2016.01.018

Uysal I, Akmaz RM, Kapsiotis A, Demir Y, Saka S, Avci E, Müller D (2015) Genesis and geodynamic significance of chromitites from the Orhaneli and Harmancık ophiolites (Bursa, NW Turkey) as evidenced by mineralogical and compositional data. Ore Geol Rev 65:26–41. https://doi.org/10.1016/j.oregeorev.2014.08.006

Uysal I, Sadiklar MB, Tarkian M, Karsli O, Aydin F (2005) Mineralogy and composition of the chromitites and their platinum–group minerals from Ortaca (Muğla SW Turkey): evidence for ophiolitic chromitite genesis. Mineral Petrol 83:219–242. https://doi.org/10.1007/s00710-004-0063-3

Uysal I, Tarkian M, Sadıklar MB, Sen C (2007) Platinum group–elementgeochemistry and mineralogy of ophiolitic chromitites from the Kop Mountains, Northeastern Turkey. Can Mineral 45:355–377. https://doi.org/10.2113/gscanmin.45.2.355

Yang K, Seccombe PK (1993) Platinum–group minerals in the chromitites fromthe Great Serpentinite belt, NSW, Australia. Mineral Petrol 47:263–286. https://doi.org/10.1007/BF01161571

Yilmaz Y, Demirkol C, Yalçin N, Yiğitbaş E, Gürpınar O, Yetiş C, Günay Y, Saritaş B (1984) Amanos Dağlarinin Jeolojisi, II Ofiyolit [The geology of the Amanos mountains, II Ophiolite]. İstanbul Teknik Üniversitesi Mühendislik Fakültesi Publication 351. (in Turkish with English abstract)

Yilmaz Y, Yigitbas E, Genc SC (1993) Ophiolitic and metamorphic ssemblages of Southeast Anatolia and their significance in the geological evolution of the orogenic belt. Tectonics 12:1280–1297. https://doi.org/10.1029/93TC00597

Zhou M, Robinson PT, Su B, Gao J, Li J, Yang J, Malpas J (2014) Compositions of chromite, associated minerals, and parental magmas of podiform chromite deposits: The role of slab contamination of asthenospheric melts in suprasubduction zone environments. Gondwana Res 26:262–283. https://doi.org/10.1016/j.gr.2013.12.011