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High-Temperature Hydrothermal Fe-Ti Oxide Mineralization in The Arızlı Ophiolitic Mélange, Western Anatolia

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Abstract - The Arızlı Ophiolitic Complex in western Anatolia provides a distinctive geological context for comprehending Fe-Ti oxide mineralization processes in ophiolitic settings. This research examines the geochemical and mineralogical properties of Fe-Ti oxides using extensive fieldwork and laboratory investigations, including X-ray fluorescence spectrometry (XRF), inductively coupled plasma mass spectrometry (ICP-MS), and X-ray diffraction (XRD). Ten samples were obtained from ultramafic and mafic rocks, displaying notable mineralization characteristics. The geochemical investigations indicated Fe_2O_3 concentrations between 10.52 % and 19.93 %, with TiO_2 contents ranging from 2.17 % to 13.63 %, suggesting hydrothermal and metasomatic processes. Discriminant diagrams, including Si-Al, Fe/Ti-Al/(Al+Fe+Mn), and Fe-Six2-Mn, validated the hydrothermal genesis of the deposit, supplemented by volcano-sedimentary processes Elevated Fe/Ti ratios and the clustering of samples within high-temperature hydrothermal domains (~300-500° C) suggest that hydrothermal fluids and metasomatic overprinting played a significant role in the formation of Fe-Ti oxide mineralization. A comparative analysis with other ophiolitic complexes, such as the Oman and Pindos ophiolites, underscores both common mineralogical-geochemical traits and unique attributes of Tthe Arızlı Ccomplex, notably its comparatively elevated aluminium enrichment. This work examines critical deficiencies in comprehending the genetic regulations and structural impacts on Fe-Ti oxide mineralization in ophiolitic environments. The findings offer a valuable foundation for subsequent research and resource evaluations, enhancing regional metallogenic models of hydrothermal Fe-Ti mineralization in ophiolitic environments.

Keywords: Arızlı Ophiolitic Complex, Fe-Ti oxide mineralization, geochemical analysis, hydrothermal processes, metasomatism, ophiolitic complexes

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Introduction

Iron-titanium oxides, including magnetite and ilmenite, are essential raw materials across several sectors, including pigment production, steel production, and titanium extraction (Charlier *et al*., 2015). Titanium is used in the aerospace, automotive, and energy industries (Salihu *et al*., 2019). Magnetite, an essential ingredient in steel manufacturing, meets global iron requirements (Berdnikov *et al*., 2023). The geochemical characteristics of these minerals elucidate their genetic processes and tectonic environments. Fe-Ti oxides are often linked to gabbroic and ultramafic rocks within ophiolitic systems, offering insights into tectonic processes and resource exploitation (Bhattacharjee and Mondal, 2021; Lee *et al*., 2022; Berdnikov *et al*., 2023). Understanding these deposits is crucial for scholarly research and industrial needs.

Ophiolitic complexes, relics of ancient oceanic lithosphere displaced onto continental margins, are significant geological formations owing to their distinctive tectonic environments and considerable mineralization potential (Okay 1996; Dilek and Furnes, 2011; Abuamarah *et al*. 2025). These formations often include commercially significant Fe-Ti oxides, chromites, and platinum-group elements, produced by intricate magmatic and hydrothermal processes (Rollinson, 1995; Rollinson, 2009; Nosova *et al*., 2024). Understanding these systems yields profound insights into geodynamic development and provides valuable resources for industrial applications.

The Arızlı Ophiolitic Mélange in western Anatolia demonstrates mineralization in a tectonically active area created during the Alpine orogeny (Okay and Tüysüz, 1999; Yılmaz and Gürer, 2023). The mélange, situated inside the Neotethyan suture zone, mainly consists of mafic-ultramafic rocks with extensive occurrences of Fe-Ti oxides. Despite substantial research on the region's chromite deposits and structural geology (Şengör and Yılmaz, 1981), comprehensive studies of its Fe-Ti oxide mineralization are few, resulting in significant knowledge gaps.

The origin of Fe-Ti oxides in ophiolitic systems is often associated with gabbroic and ultramafic lithologies, which occur as either magmatic cumulates or hydrothermal alteration products (Khedr *et al*., 2024; Wang *et al*., 2025). These deposits are especially abundant in tectonic zones where mantle dynamics and magmatic processes intersect (Rollinson, 2008). Examining their presence in the Arızlı mélange provides a comprehensive understanding of the region's's geochemical evolution and mineralization history, laying the foundation for future investigation.

Previous studies in the Arızlı area have focused on (i) high-resolution geophysical and geochemical methods for Cr-Ni exploration within the ophiolitic complex and (ii) the mineralogical and geochemical characterization of Mn mineralization, emphasizing diagenetic and supergene enrichment processes. However, the distribution and geochemical behaviour of Fe-Ti oxide mineralization within different structural levels of the ophiolite have not yet been systematically evaluated (Yalçın, 2025; Yalçın and Kara, 2026).

This work seeks to fill these gaps by thoroughly examining the Fe-Ti oxide mineralization in The Arızlı ophiolitic mélange. The study aims to clarify the origin, distribution, and industrial significance of these deposits through petrographic analyses, advanced geochemical analyses, and mineralogical investigations. The results enhance understanding of the geology of wWestern Anatolia and highlight the global economic potential of ophiolitic complexes.

Geological Regions with Iron Ore Deposits in Türkiye

The iron ore reserves of Türkiye are primarily located in the districts of Sivas, Malatya, Bingöl, Adana, and Kayseri. These regions are located within tthe Central Anatolian iron ore region and supply raw materials to Turkiye's integrated iron and steel facilities (Figure 1). Minor iron ore reserves are also found in areas such as Ankara, Balıkesir, and Adapazarı. Industries like cement production primarily use these low-grade resources (Tuncel *et al.*, 2017; Ünlü *et al*., 2019). Currently, Türkiye's known iron reserves, particularly the significant deposits in Divriği, Hekimhan, and Kangal, are deemed inadequate to meet the long-term requirements of the domestic iron and steel sector, given prevailing consumption rates and industrial growth (Öztürk *et al*., 2016; Özdemir and Kalkan, 2025). Previous studies indicate that ophiolitic complexes in Türkiye constitute important hosts for iron mineralization, where Fe enrichment is controlled by magmatic processes and high-temperature hydrothermal alteration

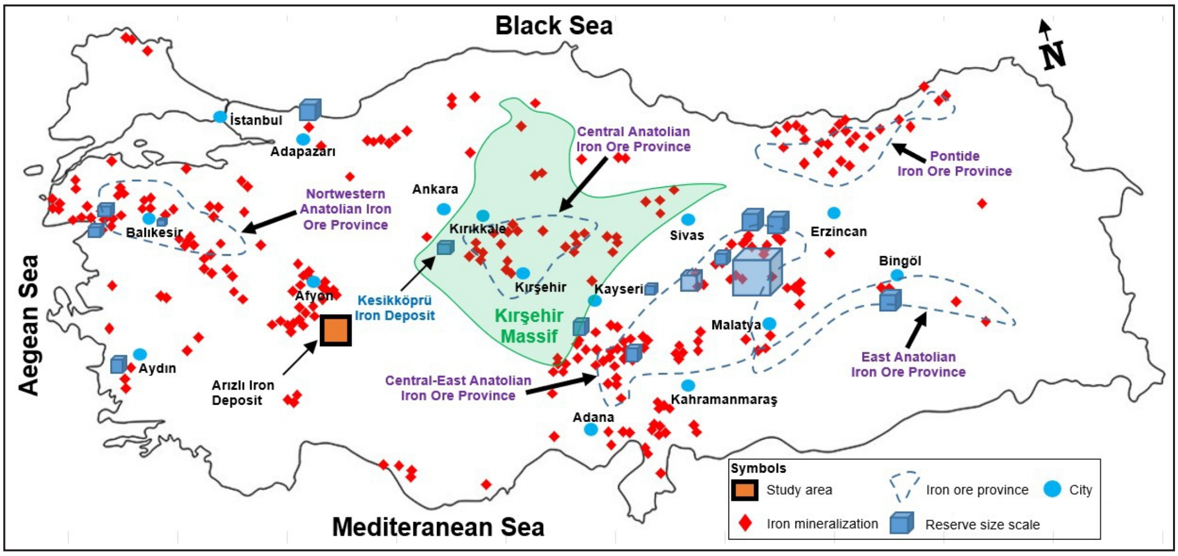

Figure 1. Geographical distribution of iron ore occurrences and deposits in Türkiye. The figure is derived from the archives of The General Directorate of Mineral Research and Exploration (MTA), as well as the works of Öztürk *et al.* (2016) and Ünlü *et al*. (2019).

within mafic-ultramafic sequences (Akinci, 2009; Tanırlı and Rızaoğlu, 2016).

The distribution of iron-titanium oxide mineralizations in Türkiye has a strong genetic correlation with ophiolitic complexes formed during the Alpine-Himalayan orogeny linked to the closing of The Neotethys Ocean (Robertson, 2002; Dilek and Furnes, 2011). The ophiolites in Mersin, Arızlı, Guleman, and Kahramanmaraş frequently contain economically valuable Fe-Ti oxide mineralization, which is generated through magmatic differentiation and subsequent high-temperature hydrothermal alteration (Rollinson, 2008; Akinci, 2009; Tanırlı and Rızaoğlu, 2016). Recent studies demonstrate that high-temperature hydrothermal fluids interacting with ultramafic-mafic sequences can induce significant metasomatic modification, particularly affecting oxide mineral assemblages during post-magmatic and tectonically controlled fluid–rock interaction processes (Elitok, 2012; Ertürk *et al*., 2024). This intricate history illustrates the interaction between suprasubduction zone magmatism and subsequent tectonothermal processes that have influenced Türkiye's ophiolitic belts (Yılmaz and Gürer, 2023).

This research investigates The Arızlı Ophiolitic Complex in the tectonic context of western Anatolia. The Arızlı region, located southeast of Tthe Şuhut Ddistrict (Afyonkarahisar), is characterized by ultramafic-mafic lithologies and recrystallized limestones related to Alpine-Himalayan orogenic processes. The Fe-Ti oxide mineralization is genetically linked to magmatic differentiation within mafic-ultramafic sequences and subsequent high-temperature hydrothermal alteration (approximately 300-500° C), reflecting hydrothermal–metasomatic processes (Rollinson, 2008; Akinci, 2009; Khedr *et al*., 2024).

Similar iron enrichment has been recorded in the Kesikköprü iron deposit (Bala–Ankara), which has Upper Cretaceous ophiolitic intrusions and related granitoid formations. The Arızlı Fe-Ti oxide mineralization, by contrast, indicates high-temperature hydrothermal-metasomatic processes within an ophiolitic framework, devoid of diagnostic calc-silicate assemblages (Doğan *et al*., 1998; Ünlü *et al*., 2019). The Kesikköprü deposit is expected to contain approximately 3.8 million tonnes of ore, with iron concentrations ranging from 44 % to 60 % (Sözen, 1970; Ünlü *et al*., 2019). Recent studies (Öztürk *et al*., 2016; Özdemir and Kalkan, 2025) highlight that iron mineralizations in Türkiye are often associated with ophiolitic mélanges and exhibit geochemical signatures that suggest magmatic-hydrothermal development.

The Fe-Ti oxide assemblages in the Arızlı region, distinguished by high concentrations of Fe_2O_3 and TiO_2, indicate high-temperature hydrothermal-metasomatic processes influencing ophiolite-derived mafic-ultramafic rocks and underscore the considerable mineralization potential of ophiolitic domains in wWestern Anatolia (Tanırlı and Rızaoğlu, 2016; Ertürk *et al*., 2024).

Geology of The Studied Area

The Arızlı region lies within the tectonically complex framework of wWestern Anatolia and is notable for its extensive ophiolite coverage (Figure 2). In the area, several stratigraphic units are arranged chronologically from oldest at the bottom to youngest at the top. The most inferior unit consists of limestones from the Middle-Upper Triassic period (Yalçın, 2025). These units, often substantial and less porous, are distorted at elevated pressure and temperature conditions, resulting in a fragmented character. The superjacent Jurassic-Cretaceous limestones are lighter in hue, often consist of thinner strata, and exhibit folding. These units function as a tectonic overlay over the ophiolitic complex in the area.

The Upper Cretaceous ophiolitic complex in the Arızlı area is of significant stratigraphic relevance. This assemblage of rocks, including serpentine, dunite, gabbro, and basalt, was formed at the closing of the Neotetis Ocean. Serpentinization, prevalent in ophiolitic units, particularly in ultramafic rocks, was induced by hydrothermal fluids and contributed to rock deformation (Blakely, 1995). This activity established the foundation for geochemical enrichments in the area. Red pebble units are dated to the lower −Middle Oligocene in the higher strata of the ophiolitic complex. These clastic units are notable for their carbonate composition and constitute the youngest sedimentary formations in the area.

The structural characteristics of the Arızlı area are essential for comprehending its geological development. The east-west-orientated right-lateral strike-slip fault is the predominant structural feature of the area (Figure 2). This fault has influenced the area's geological structure by altering rock deformation and hydrothermal circulation. Deformation in fault zones has altered the physical and chemical characteristics of ultramafic rocks and initiated brecciation. Serpentinization and alteration processes have been

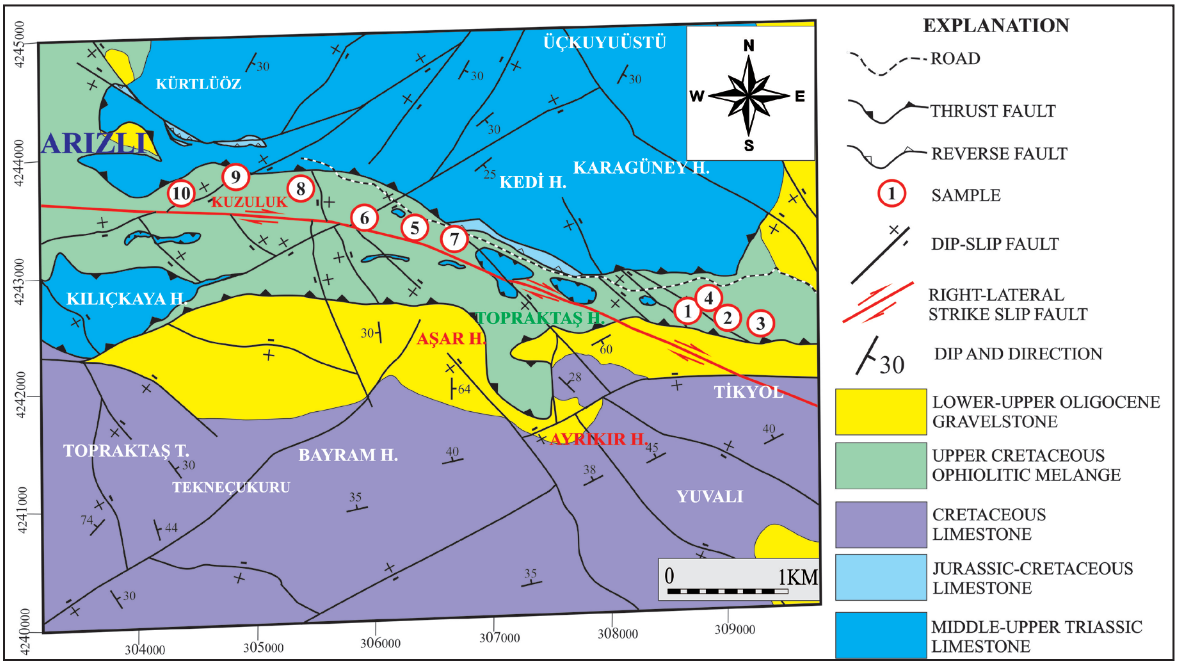

Figure 2. Geological map of the studied area (Modified after Yalçın, 2025).

well documented in these areas, and fault lines are believed to promote mineralization.

The present study employed field, laboratory, and analytical approaches to evaluate iron-titanium mineralization in the Arızlı Ophiolitic Complex and its geological structure. The primary goal of the research is to identify the mineralogical, petrographic, and geochemical characteristics of the rocks and to disclose the link between these qualities and the geological processes in the area.

Methods and Materials

Field Studies

During field research, rock samples were collected from several lithologic units in the Arızlı area. The sampling focused on the region's's primary rock types, including ultramafic rocks (serpentinite, dunite), gabbro, basalt, and carbonate units. Samples were collected from ten locations distributed across different structural and lithological levels of the ophiolite, focusing on Fe-Ti-bearing mineralized zones (Figure 2). The sample locations were selected based on strike-slip faults and alteration zones.

Field observations included detailed mapping of rock structural features, alteration levels, fault systems, and preparation of geological cross-sections. In addition, thorough field notes were taken, concentrating on the rock deformation features and alteration processes. Samples from alteration zones along fault lines are useful for studying the effects of hydrothermal activity.

Laboratory Studies

Thin, polished sections were produced and examined under a microscope to analyze the rock sample'ss' mineralogical composition and textural features. X-ray diffraction (XRD) studies were used to detect mineral phases and assess them semiquantitatively. The investigations were carried out using a Bruker D8 Advance apparatus with Cu Kα radiation. The data were analyzed using the X'Pert HighScore Plus v. 3.0 program. XRD studies provided precise information on the crystalline structures of the minerals and the regional alteration processes.

The samples were examined using X-ray fluorescence spectrometry (XRF) to identify the primary oxide constituents. The materials were pulverized into a fine powder with a RETSCH RS-200 model grinder at the Geochemistry Research Laboratory of Istanbul Technical University. The powder samples were examined with a Siemens XRF apparatus. XRF studies disclosed the overall composition of the rocks and furnished precise data on the concentrations of the primary oxides.

Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) was used to ascertain the amounts of trace components. Each sample was entirely dissolved in a blend of 37 % hydrochloric acid (HCl), 65 % nitric acid (HNO_3), and 38-40 % hydrofluoric acid (HF) inside teflon containers. The leftover HF acid was eliminated by adding 5 % boric acid (H_3BO_3), and the resultant solutions were transferred to 50 ml flasks containing distilled water. The reference blank solution was made using the same approach. ICP-MS studies provide essential insights into the area of elemental enrichments and mineralization processes.

Results

Fe-Ti mineralization in the Arızlı area is intricately linked to ultramafic and mafic rocks of the ophiolitic complex. The mineralization in these rocks is dominated by Fe-Ti oxide minerals, including magnetite and ilmenite. Figure 3 illustrates that these minerals were mainly located inside brecciated gabbro and dunite formations. These rocks were augmented by hydrothermal processes and modification along fault zones.

Figure 3a illustrates the surface features of the ophiolitic complex, whereas the brecciated gabbro and dunites include mineralization zones with magnetite and ilmenite (3b). The brecciation of gabbro and dunites following hydrothermal alteration has enhanced the mineralization potential of these rocks. Figures 3c, 3d, 3e, and 3f demon-

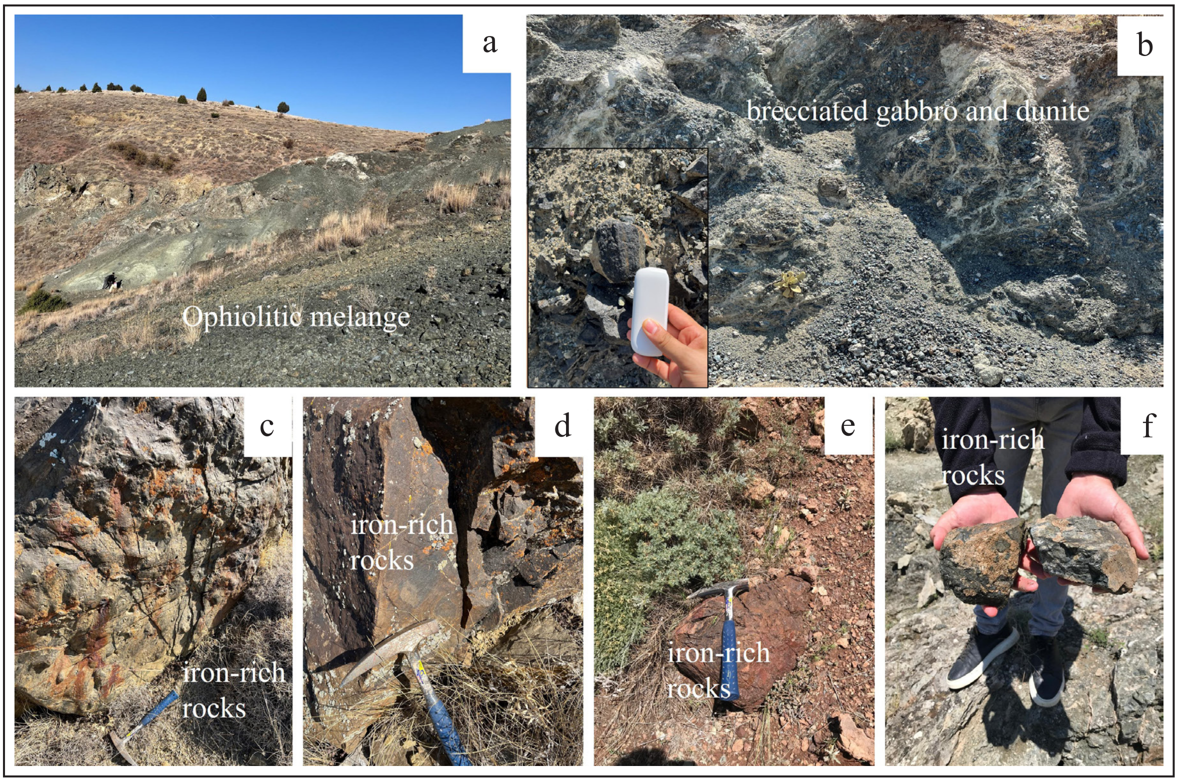

Figure 3. General view of ophiolitic mélange-related iron-rich rocks.

strate unequivocal evidence of iron enrichment in samples collected from these zones.

Thin-section examinations meticulously examined the lithological components of the materials. Pyroxenes (cpx), plagioclases (plg), and amphiboles (amp) were prevalent in gabbro and dunite specimens (Figures 4a, b). Microscopic examination reveals that granular structures are prevalent in the gabbro units. Intense evidence of serpentinization was identified in the ultramafic rocks, with serpentine minerals (ser) and opaque minerals (opq) occurring simultaneously (Figures 4c, d). These minerals indicate that the rocks underwent significant hydrothermal alteration and serpentinization.

Analyses of polished sections were conducted to ascertain the distribution and mineralogical characteristics of iron and titanium oxide minerals. Magnetite (mag) and ilmenite (ilm) minerals were extensively disseminated throughout the gabbro and dunite units (Figures 5a, b, and d). Magnetite is distinguished by its granular structure, while ilmenite is noted for its finer texture and veinlets. Chromite minerals (chr) are prevalent in ultramafic rocks and were identified in areas linked to brecciation and alteration (Figure 5c). Goethite (goe) is often identified in alteration zones and is a significant indicator of hydrothermal circulation activities.

XRD investigations were conducted to verify and ascertain the mineralogical composition of the samples. The analytical findings indicated that the samples primarily contained magnetite and ilmenite (Figure 6a). Magnetite peaks were seen at high intensity, while ilmenite peaks were identified at lesser intensity but were still conspicuous. The XRD pattern in Figure 6b is dominated by magnetite and ilmenite, indicating Fe-Ti oxide mineralization within the ophiolitic sequence. The data indicate that the XRD results align with the findings from the thin and polished sections.

The findings indicate that Fe-Ti mineralization in the Arızlı Ophiolitic Complex originated from magmatic and hydrothermal processes and is closely linked to the regional rocks. Petrographic and mineralogical observations indicate

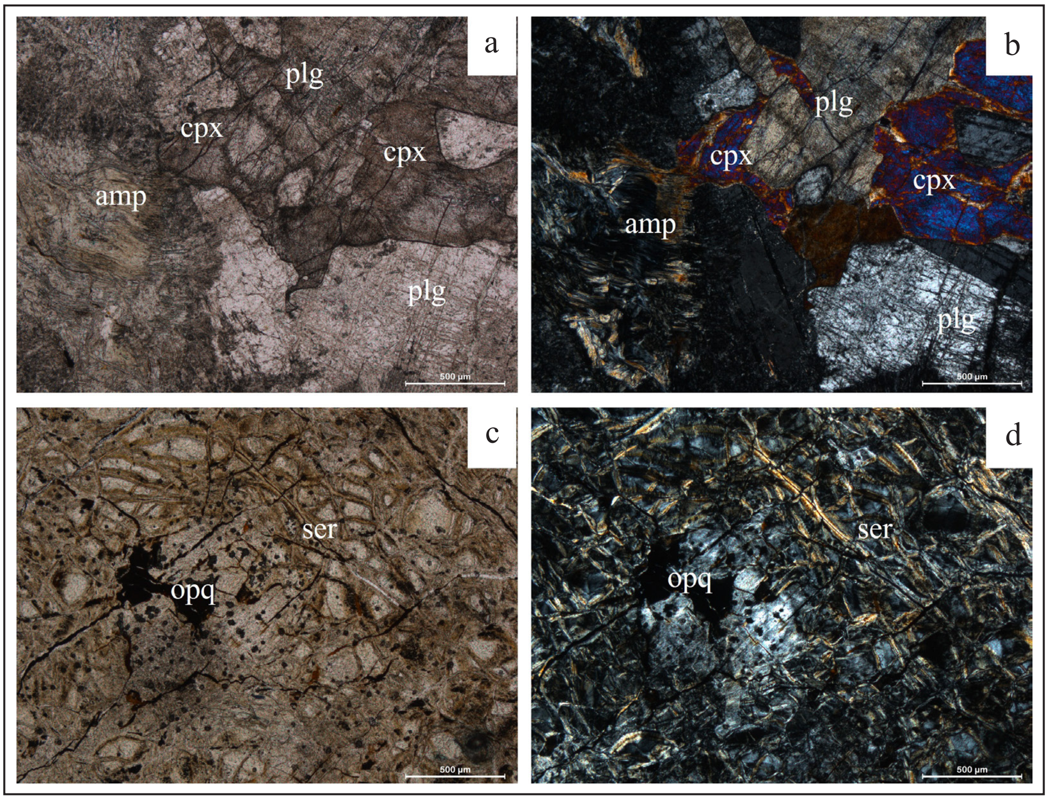

Figure 4. Views of microscopy examinations. a-b: Thin sections of the host rock (gabbro); c-d: thin section of the iron-titanium opaque minerals (serpentinized dunite). Abbr. amp: amphibole; cpx: clinopyroxene; plg, plagioclase; ser: serpentine; opq: opaque mineral.

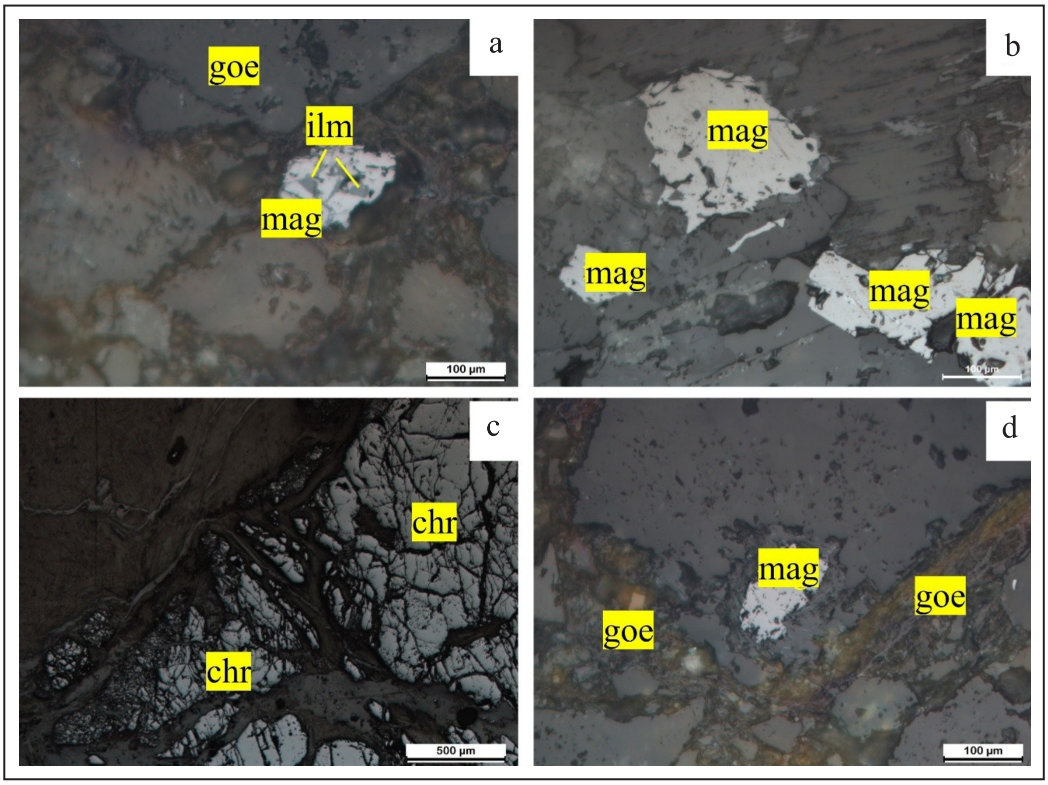

Figure 5. Views of polished sections. Abbr. geoe:gethite, chr: chromite; ilm, ilmenite; mag: magnetite.

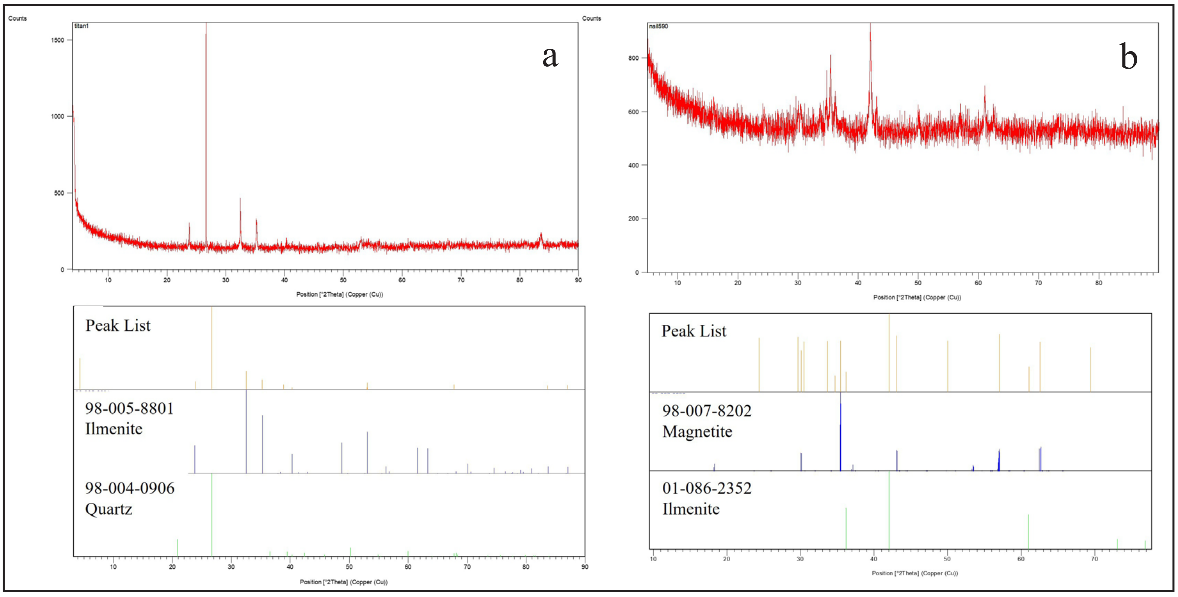

Figure 6. XRD patterns of ore samples collected from the mineralization area.

that iron–titanium oxides occur as volumetrically significant and texturally continuous phases, suggesting potential commercial relevance.

Petrographic analyses indicate that Fe-Ti oxide minerals primarily manifest as magnetite with lesser amounts of ilmenite, found in disseminated, vein-associated, and breccia-hosted textures. In ultramafic samples, magnetite frequently substitutes for primary silicate minerals such as olivine and clinopyroxene, indicating significant hydrothermal alteration. In mafic lithologies, Fe-Ti oxides are interstitial between plagioclase and pyroxene or occur along fracture networks, indicating fluid-assisted remobilization. Analyses of polished sections further indicate that magnetite typically occurs as anhedral to subhedral aggregates linked with secondary alteration phases, suggesting a hydrothermal-metasomatic origin rather than primary magmatic crystallization. The microscopic characteristics align with the geochemical discrimination diagrams, suggesting a predominance of hydrothermal activity with isolated volcano-sedimentary effects.

The paragenetic sequence, derived from textural connections in thin and polished sections, initiates with the synthesis of primary silicate minerals in mafic-ultramafic host rocks, succeeded by fracturing and fluid infiltration. Subsequent hydrothermal alteration led to the precipitation of magnetite ± ilmenite, occasionally accompanied by serpentinization and the production of secondary silicates. Late-stage hydrothermal activity is characterized by vein-hosted Fe–Ti oxides along fault-controlled conduits.

The hydrothermal fields identified by the Si-Al and Fe/Ti discrimination diagrams align completely with the petrographic and mineralogical observations detailed in Table 1, where Fe-Ti oxides primarily manifest as fracture-controlled and replacement textures linked to secondary alteration phases.

Geochemistry

XRF and ICP-MS analyses of the samples taken for this investigation were conducted to ascertain the chemical and mineralogical composition of the region mineralization. The study findings were assessed based on primary oxide concentrations, trace element contents, and ratios derived from these data (Tables 1-3).

The XRF analysis indicates the chemical composition of samples from the Arızlı area, with high concentrations of silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and titanium dioxide (TiO_2). The results indicate that SiO_2 concentrations range from 12.35 % to 36.62 %, which is consistent

Table 1. The Mmajor Ooxide Cconcentration of Tthe Oore Ssample

Sample	Host rock / lithology	Major silicate minerals	Fe-Ti oxide phases	Relative abundance	Textural features	Genetic interpretation
AR-1	Serpentinized peridotite	Olivine (relict), serpentine, clinopyroxene	Magnetite ± ilmenite	Major	Disseminated and vein-related	Hydrothermal replacement
AR-2	Mafic ophiolitic rock	Plagioclase, clinopyroxene, amphibole	Magnetite ± ilmenite	Major	Brecciated, fracture-controlled	Fault-controlled hydrothermal
AR-3	Altered gabbro	Plagioclase, clinopyroxene	Magnetite	Moderate	Interstitial, partially recrystallized	Hydrothermal overprint
AR-4	Serpentinized ultramafic	Serpentine, relic olivine	Magnetite	Major	Massive to vein-filling	Hydrothermal metasomatism
AR-5	Mafic volcanics	Plagioclase, pyroxene	Magnetite–ilmenite	Moderate	Disseminated	Hydrothermal–volcanogenic
AR-6	Ultramafic tectonite	Serpentine, talc	Magnetite	Major	Shear-related aggregates	Structural-fluid control
AR-7	Mafic intrusion	Plagioclase, amphibole	Magnetite	Minor–moderate	Disseminated	Weak hydrothermal
AR-8	Altered gabbro	Plagioclase, clinopyroxene	Magnetite–ilmenite	Moderate	Interstitial	Hydrothermal modification
AR-9	Ultramafic rock	Serpentine, chlorite	Magnetite	Major	Vein-hosted	Late hydrothermal
AR-10	Mafic ophiolitic unit	Plagioclase, pyroxene	Magnetite	Minor	Disseminated	Hydrothermal

Table 2. The Major Oxide Concentration of The Ore Sample

XRF	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3	Cr_2O_3	SO_3	LOI	TOTAL
SAMPLE	%	%	%	%	%	%	%	%	%	%	%	%	%	
AR- 1	1.12	8.42	8.85	29.29	0.69	0.52	13.3	**3.01**	0.2	19.1	0.12	0.03	15.12	**99.77**
AR-2	<0.01	9.97	11.82	32.35	<0.01	0.03	9.66	**4.13**	0.14	14.63	0.35	0.02	16.31	**99.41**
AR- 3	1.18	10.42	12.22	36.62	0.78	0.85	13.53	**3.92**	0.22	18.65	0.08	<0.01	1.52	**99.99**
AR- 4	1.64	10.76	9.83	30.95	0.62	0.64	8.65	**2.17**	0.98	11.49	20.19	<0.01	1.92	**99.84**
AR- 5	0.05	12.88	11.65	12.35	0.06	0.19	8.66	**12.31**	1.99	13.02	22.32	0.01	4.1	**99.59**
AR- 6	<0.01	16.73	13.38	19.82	<0.01	<0.01	2.92	**8.03**	0.66	16.19	19.11	<0.01	2.58	**99.42**
AR- 7	0.64	9.49	11.26	26.17	0.52	0.27	18.13	**2.88**	0.2	14.53	10.29	<0.01	5.49	**99.87**
AR- 8	1.03	4.56	14.46	19.38	0.16	0.26	12.56	**7.11**	0.82	17.88	10.85	0.02	10.52	**99.61**
AR- 9	0.1	0.85	11.23	21.92	<0.01	0.65	9.43	**13.63**	1.12	19.93	10.03	0.03	10.83	**99.75**
AR- 10	<0.01	9.28	12.29	30.54	<0.01	<0.01	10.14	**8.83**	<0.01	10.52	2.34	0.01	16.02	**99.97**

with an ultramafic protolith, and reflects dilution effects related to Fe-Ti oxide enrichment and alteration processes (Table 2). Similarly, Al_2O_3 concentrations varied from 8.85 % to 14.46 %, and the alumina content is believed to be associated with metasomatic influences from the host rocks.

The total iron was reported by XRF as Fe_2O_3 (T) (*i.e.*, total Fe expressed as Fe_2O_3), and FeO was not determined separately. Fe_2O_3 values varied from 10.52(?) % to 19.93 %, indicating the significance of iron enrichment in the mineralization processes of the area. This study indicates that hydrothermal processes are predominant and contribute to iron enrichment., Iin contrast to Fe-Mn enrichment models, the findings are supported by the geochemical discriminant diagrams discussed below. Furthermore, TiO_2 values ranging from 2.17 % to 13.63 % indicate significant titanium

Table 3. The Trace Element Concentration of The Ore Sample

ICP-MS	Sc	V	Co	Ni	Cu	Zn	As	Sr	Zr	Nb	Mo	Ba	Pb
SAMPLE	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
AR- 1	6	261	12	51	23	36	13	130	79	11	<1	28	<1
AR-2	10	279	14	627	20	24	12	93	26	11	<1	35	<1
AR- 3	20	260	25	350	17	27	14	65	27	10	<1	46	<1
AR- 4	25	209	33	439	32	10	11	103	47	13	<1	30	<1
AR- 5	5	246	25	30	20	19	20	139	79	14	<1	33	<1
AR- 6	<1	255	43	502	17	33	19	151	54	<1	<1	19	<1
AR- 7	19	245	35	235	22	27	17	150	13	25	<1	31	<1
AR- 8	18	241	44	42	25	21	16	153	46	15	<1	28	<1
AR- 9	11	258	11	28	18	19	12	141	35	12	<1	<1	<1
AR- 10	5	221	12	245	19	19	11	122	19	12	<1	16	<1

enrichment, consistent with the hydrothermal and volcano-sedimentary signatures observed in the discriminant plots.

The data suggest that the area mineralization arises from hydrothermal processes and a volcano-sedimentary origin, augmented by chemical contributions from adjacent rocks. Elevated levels of Fe_2O_3 and TiO_2 suggest that iron and titanium might be commercially significant in the area. The chemical data are essential for understanding the chemical evolution of the ultramafic rocks in the Arızlı area and for assessing the mineralization processes within them.

The ICP-MS study findings indicated differences in trace elements. The maximum vanadium (V) concentration in the samples was recorded at 279 ppm. Nickel (Ni) concentrations ranged from 28 to 627 ppm, indicating hydrothermal activity associated with ultramafic rocks (Table 3).

Tthe genesis and geochemical properties of mineralization were examined by calculating various ratios (Table 4) and using several diagrams. These studies provide a comprehensive knowledge of the mineralization processes in the area.

The Si-Al diagram is extensively utilized to differentiate hydrothermal from sedimentary contributions in iron-rich systems (Crerar *et al*., 1982). The majority of samples from the Arızlı area are located within the hydrothermal field, with a restricted distribution towards elevated Al concentrations along the hydrothermal-sedimentary interface (Figure 7). This distribution suggests a

Table 4. Calculated Various Ratios

%	Al	Si	Fe	Mn	Ti	V	Ca	Al (Al+Fe+Mn)	Fe/Ti	Ti+V	Ca+Al+Mn	Al+Mn
AR- 1	4.68	13.69	13.34	0.15	1.80	0.026	9.51	0.26	7.41	1.83	14.34	4.83
AR-2	6.26	15.12	10.22	0.11	2.48	0.028	6.90	0.38	4.12	2.51	13.27	6.37
AR- 3	6.47	17.12	13.02	0.17	2.35	0.026	9.67	0.33	5.54	2.38	16.31	6.64
AR- 4	5.2	14.47	8.02	0.76	1.30	0.021	6.18	0.37	6.17	1.32	12.14	5.96
AR- 5	6.17	5.77	9.09	1.54	7.38	0.025	6.19	0.37	1.23	7.40	13.90	7.71
AR- 6	7.08	9.26	11.31	0.51	4.81	0.026	2.09	0.37	2.35	4.84	9.68	7.59
AR- 7	5.96	12.23	10.15	0.15	1.73	0.025	12.96	0.37	5.87	1.75	19.07	6.11
AR- 8	7.65	9.06	12.49	0.64	4.26	0.024	8.98	0.37	2.93	4.28	17.27	8.29
AR- 9	5.94	10.25	13.92	0.87	8.17	0.026	6.74	0.29	1.70	8.20	13.55	6.81
AR- 10	6.51	14.27	7.30	0.01	5.29	0.022	7.250	0.47	1.38	5.31	13.77	6.52

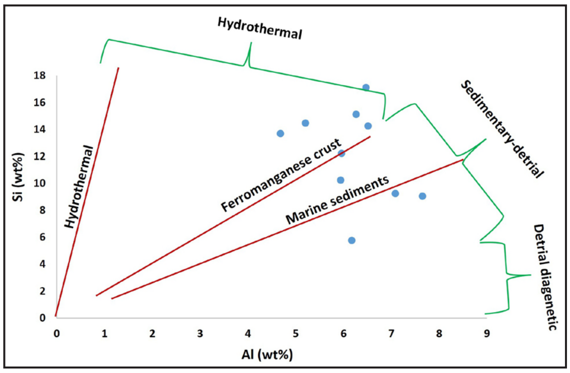

Figure 7. The position of ore samples from the studied region on the Si-Al diagram (adapted from *Crerar et al*., 1982).

mostly hydrothermal origin for the mineralization, with minimal aluminium enrichment regarded as indicative of restricted detrital input or wall-rock interaction rather than main sedimentary deposition. This placement in the diagram facilitates interaction between the ultramafic rocks in the area and hydrothermal solutions.

Increased Fe/Ti ratios, up to 7.41, indicate a predominant hydrothermal influence on the mineralization, comparable to that observed in contemporary and historical hydrothermal systems (Barrett, 1981). The Al/(Al+Fe+Mn) ratios, which range from 0.26 to 0.47, suggest minimal detrital or pelagic contribution (Figure 8). The geochemical fingerprints collectively indicate that the mineralization is mostly hydrothermal, with minimal sedimentary contribution.

In the Ca+Al+Mn against Ti+V discrimination map, all samples from the Arızlı region are situated inside the Fe-Ti–V field, distinctly

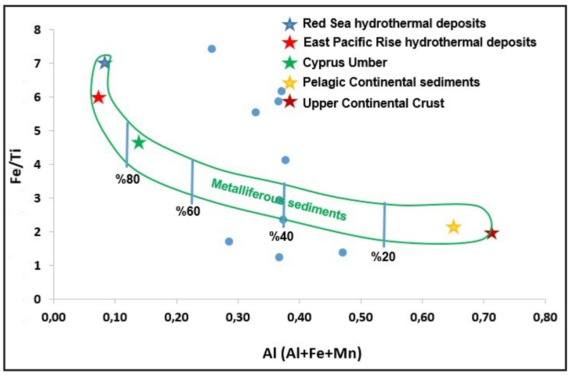

Figure 8. Fe/Ti - Al/(Al + Fe + Mn) diagram of the outcrop samples from the studied area. (diagram: from Barret, 1981).

separated from the skarn, IOCG, and porphyry domains (Figure 9). The Ti+V-Al+Mn diagram suggests production at elevated temperatures (>300 °C), which pertains to the thermal conditions of hydrothermal fluids rather than carbonate-hosted skarn metasomatism (Figure 10). The persistent grouping of samples in high-temperature hydrothermal fields across several discrimination diagrams corroborates a genetic model that entails fault-controlled, high-temperature hydrothermal–metasomatic processes within an ophiolitic context.

The Fe-Si×2–Mn ternary diagram is frequently employed to differentiate hydrothermal, nodular, and Mn-enriched depositional settings

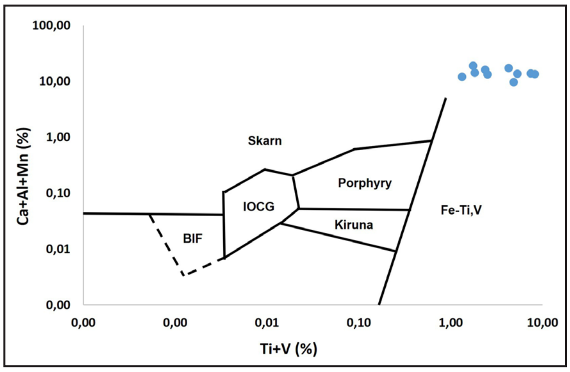

Figure 9. This figure depicts the position of the outcrop samples within the (Ca+Al+Mn) - (Ti+V) diagram of the researched region. This diagram, a key tool in our analysis, is adapted from the works of Dupuis and Beaudoin (2011), Nadoll *et al*. (2014), Huang *et al*. (2015, 2016), and Bonda *et al*. (2022).

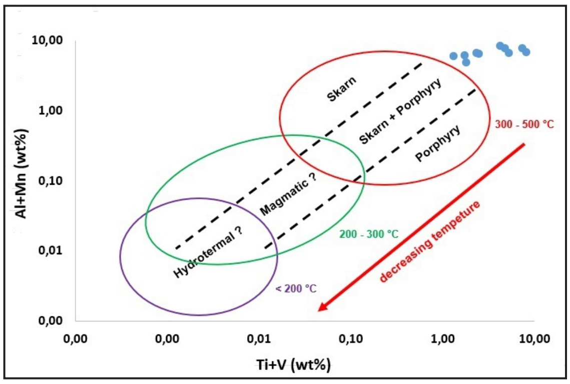

Figure 10. Position of the outcrop samples inside the (Al+Mn) - (Ti+V) diagram of the researched region (graphics taken from Dupuis and Beaudoin (2011), Nadoll *et al*. (2014), Huang *et al*. (2015, 2016), and Bonda *et al*. (2022)).

(Corliss and Dymond, 1975). The Arızlı samples are primarily located inside the Fe-rich hydrothermal field in this diagram, distinctly separated from the nodular and Mn-rich crust domains (Figure 11). This pattern indicates a predominant role of Fe-enriched hydrothermal fluids in mineralization development.

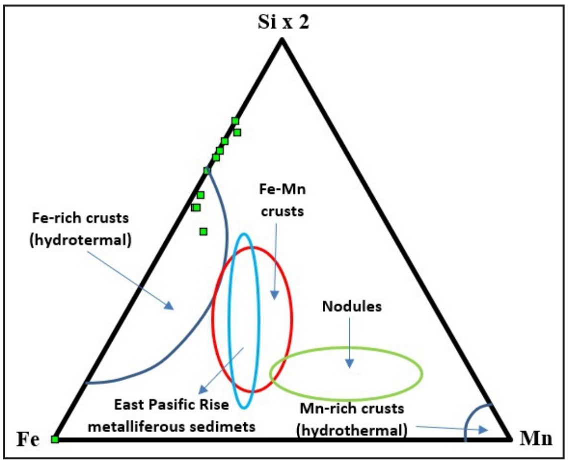

Figure 11. Locations of the outcrop samples inside the Fe-Six2-Mn triangular diagram (Source: Corliss and Dymond, 1975).

The Al-Fe-Mn ternary diagram is frequently employed to differentiate hydrothermal from nonhydrothermal (sedimentary or detrital) contributions in iron-rich systems (Adachi *et al*., 1986). The majority of samples from the Arızlı area are distinctly categorized within the hydrothermal field, separate from the non-hydrothermal domain (Figure 12). This distribution suggests that sedimentary contributions to mineralization are minimal and that iron enrichment is primarily governed by hydrothermal processes.

The consolidated geochemical data and schematic analyses suggest that the mineralization in the Arızlı region is primarily hydrothermal in origin. The concentrations of Fe, Ti, and Mn consistently indicate that hydrothermal–metasomatic processes are the primary mechanism governing mineralization. While slight geochemical dispersion may suggest some limited interaction with the wall rock, it is not significant. There is no indication of primary sedimentary or carbonate-hosted mineralization.

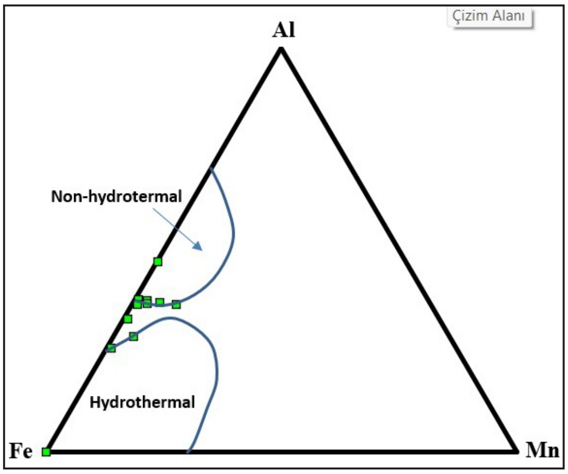

Figure 12. Position of the researched region outcrop samples inside the Al-Fe-Mn diagram (diagram: from Adachi *et al*., 1986)

This paper offers a thorough evaluation of hydrothermal Fe-Ti oxide mineralization within an ophiolitic context, a subject that is still inadequately addressed in existing literature. The findings indicate that mineralization is intricately linked to hydrothermal fluid circulation through ultramafic rocks and structurally governed conduits, notably fault zones, in alignment with regional tectonic development (Dilek and Furnes, 2011; Huang *et al*., 2015). These findings enhance the comprehensive understanding of hydrothermal mineralization processes in global ophiolitic complexes.

Discussion

Globally, analogous hydrothermal Fe-rich mineralization has been recorded in ophiolitic complexes originating from mid-ocean ridges, back-arc basins, and supra-subduction zone environments, where fluid-rock interactions are crucial for metal redistribution (Dilek and Furnes, 2011; Rollinson, 2020). Within this paradigm, the Arızlı mineralization indicates a similar tectono-magmatic environment where hydrothermal circulation altered mafic-ultramafic rocks.

The mineralization processes seen at Arızlı differ from those documented in other extensively researched ophiolitic complexes. The Oman ophiolite and the Pindos ophiolite exhibit mineralization types that highlight magmatic differentiation or sedimentary-hydrothermal interaction on a regional scale (Robertson, 2002; Kapsiotis *et al*., 2024). Conversely, the Arızlı system is characterized by a more pronounced overprint of hydrothermal precipitation and localized metasomatic alteration.

The Si-Al discrimination method suggested by Crerar *et al.* (1982) reinforces this interpretation. Most Arızlı samples are situated inside the hydrothermal field; however, a slight dispersion towards elevated Al concentrations is noted. This dispersion is understood to indicate minimal volcanic-sedimentary input or wall-rock interaction, rather than a primary sedimentary origin. Comparable volcano-sedimentary contributions have been proposed for further ophiolitic complexes in Türkiye (Parlak and Robertson, 2004), suggesting that such hybrid signatures are prevalent in tectonically active ophiolitic environments.

The Ca+Al+Mn against Ti+V curve (Figure 10) delineates the temperature conditions of mineralization. The placement of samples within the 300-500° C range suggests formation under medium- to high-temperature hydrothermal settings. Similar temperature ranges have been documented in high-temperature hydrothermal systems within the Neyriz ophiolite in Iran and tthe Rogaland Anorthosite Complex, despite differences in lithological context and predominant mineralization processes (Modjarrad *et al*., 2024).

The Fe–Si×2–Mn ternary diagram (Figure 9) offers supplementary evidence for hydrothermal control, with Arızlı samples being inside the Fe-rich hydrothermal domain. This pattern signifies predominant Fe enrichment due to hydrothermal fluids. In contrast to the iron enrichment observed in the Red Sea and the Oman ophiolite, the Arızlı mineralization has a comparable degree of hydrothermal influence, while it has evolved within a distinct tectonic and structural context (Robertson, 2002; Ahmed *et al*., 2025).

The Al-Fe–Mn triangle diagram (Figure 11) indicates that sedimentary contribution to the Arızlı mineralization system is negligible. The majority of samples reside within the hydrothermal domain, indicating that Fe-Ti enrichment is predominantly influenced by hydrothermal processes rather than sedimentary accumulation (Hamade *et al*., 2003). This observation aligns with the conclusions derived from the Si-Al and Fe/Ti-based discrimination diagrams.

From a comprehensive metallogenic viewpoint, Fe–Ti mineralization in ultramafic–mafic rocks inside ophiolitic complexes is frequently associated with magmatic-hydrothermal interactions (Dilek and Furnes, 2011; Rollinson, 2020). Comparisons with substantial Fe-Ti deposits like Panzhihua (China) and Bushveld (South Africa) underscore essential distinctions, as those systems are primarily governed by magmatic processes. While the Arızlı mineralization is marked by hydrothermal predominance (Zhou *et al*., 2013; Khedr *et al*., 2024; Liu *et al*., 2024; Wang *et al.,* 2025; Chaumba *et al*., 2026).

Additional distinctions can be made with Fe-Ti oxide deposits in Egypt, such as El-Baroud and Abu Ghalaga, where liquid immiscibility and fractional crystallization significantly influence metal concentration (Nosova *et al*., 2024; Chen *et al*., 2024). The Arızlı mineralization does not exhibit geochemical markers characteristics of magmatic processes but rather reflects a more pronounced influence of hydrothermal alteration.

Recent high-resolution investigations of Fe-Ti oxide mineralization in mafic–ultramafic systems highlight the significance of open-system magmatic evolution followed by hydrothermal alteration, rather than solely closed-system magmatic segregation. Comprehensive mineral-chemical analyses of Tthe Nuasahi and Mayurbhanj Ccomplexes (India) reveal that the enrichment of Fe-Ti oxides is initially facilitated by magma replenishment, redox variations, and cumulate differentiation. While subsequent fluid-rock interactions substantially alter oxide chemistry and metal distribution (Bhattacharjee and& Mondal, 2026; Bhattacharjee *et al*., 2026). Clinopyroxene zoning patterns from the Wajilitag mafic-ultramafic intrusion in NW China indicate recurrent magma recharging and melt-fluid interaction, underscoring the significance of dynamic magmatic–hydrothermal coupling in Fe-Ti-(V)-bearing systems (Luan *et al*., 2026). In this context, the Arızlı Fe–Ti oxide deposit differs from extensive layered intrusions by exhibiting a more pronounced hydrothermal-metasomatic signature within an ophiolitic mafic framework, consistent with fault-controlled fluid circulation and elevated Fe/Ti ratios. The comparisons indicate that Arızlı exemplifies a structurally oriented, hydrothermally dominated end-member of Fe-Ti enrichment in ophiolitic settings, rather than a traditional magmatic cumulate system.

The geochemical attributes, including high Fe_2O_3/TiO_2 ratios and comparatively low V/Cr values at Arızlı, align with those of other high-temperature hydrothermal systems linked to mafic complexes globally (Bhattacharjee and Mondal, 2021; Berdnikov *et al*., 2023). Similar iron enrichment patterns have been documented in hydrothermal iron deposits, including the Sanaga occurrence in Cameroon and Fe-Ti-(V) mineralization inside gabbroic intrusions such as Tthe Gonamsan Ccomplex in South Korea (Bonda *et al*., 2022; Lee *et al*., 2022). The structural influence of fault zones and lithological boundaries reinforces the suggested genetic model, as evidenced in the Mersin ophiolite and additional ophiolitic belts in Türkiye (Omer, 2014; Çavdar, 2019). Regionally, these characteristics align with tectonic development associated with the closure of Tthe Neo-Tethys Ocean and the multi-stage magmatic-hydrothermal overprints recorded in adjacent areas (Karsli *et al*., 2008; Charlier *et al*., 2015; Bernard *et al*., 2024; Modjarrad *et al*., 2025).

The Fe-Ti oxide mineralization in the Arızlı region significantly enhances the comprehension of hydrothermal enrichment mechanisms in ophiolite-hosted systems. The geochemical attributes indicate deposition from elevated-temperature hydrothermal fluids, with minimal wall-rock interaction and slight volcano-sedimentary impact. These results provide a significant reference framework for assessing the Fe-Ti mineralization potential of ophiolitic complexes with analogous tectonic and lithological characteristics.

Conclusion

This study suggests a new perspective into the formation of Fe-Ti oxide mineralization within Tthe Arızlı Ophiolitic Complex and enhances the comprehension of mineralization processes in ophiolitic mélanges. Combined geochemical and mineralogical data suggest that mineralization is primarily controlled by high-temperature hydrothermal processes, with minimal contribution from volcano-sedimentary processes. The increased Fe/Ti and Al/(Al+Fe+Mn) ratios, along with geochemical discrimination diagrams and structural data, indicate that Fe-Ti enrichment occurred at 300-500° C under dynamic tectono-hydrothermal conditions.

Unlike traditional magmatic Fe-Ti deposits like Rogaland, Panzhihua, and Bushveld, the Arızlı mineralization exhibits hydrothermal predominance and significant structural influence, rather than fractional crystallization or liquid immiscibility. These findings fill a significant void in the literature, as Fe-Ti oxide systems in Turkish ophiolites have been far less studied than chromitite deposits. The Arızlı occurrence exemplifies a thoroughly documented instance of hydrothermal-metasomatic Fe-Ti enrichment within the extensive tectonic context of Neo-Tethyan ophiolitic evolution.

The findings elucidate the mineralization potential of the Arızlı region and serve as a regional benchmark for subsequent investigations into the metallogenic development of wWestern Anatolia and other ophiolitic belts. It is advisable to conduct additional research utilizing isotopic analyses, comprehensive fluid-inclusion studies, and high-resolution structural investigations to enhance the proposed genetic model and to more accurately delineate the sources and pathways of mineralizing fluids.

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Author contributions:

CY: fieldwork, data analysis and interpretation, manuscript drafting, and critical revision. The author read and approved the manuscript.

AO: geochemistry, data curation, interpretation, and drafting.

Availability of data and materials:

This published article includes all data generated or analyzed during this study.

Declarations:

Conflict of interest: The authors declare they have no competing interests.

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