

## Tectonic Setting of the Serow-Torshab Ophiolite Related Mafic Rocks, NW-Iran: Implications from Minerals and Whole-Rock Geochemistry

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### Abstract

In this paper, focused on the Late Cretaceous Serow ophiolite related gabbros from the Torshab area, NW Iran, to enhance our understanding on the tectonic setting of ophiolite formation in terms of pressure-temperature and fluid conditions. The applied methods encompassed field geological observations, petrographic and mineralogical analyses, and whole-rock chemistry assessments. The findings revealed that the calc-alkaline gabbros predominantly consist of hornblende gabbro, olivine gabbro, and minerals such as amphibole, ortho-/clinopyroxene, olivine, and plagioclase. According to geochemical signatures such as the depletion of high field strength elements (Hf, Zr, Nb, and Ta) and the enrichment of large ionic lithophile elements (Ba and K) the Serow-Torshab gabbro is considered in relation to an arc setting indicating their origin from a mantle wedge, potentially enriched by subducting crust-derived melts/fluids. The mineral chemical study on mafic phases also suggests a supra-subduction zone (SSZ, fore-arc) environment for the Serow ophiolite, offering valuable insights into the region's geodynamic evolution.

**Keywords:** Ophiolite-Related Gabbro; Fore-Arc Setting; Mineral Chemistry; Serow-Torshab; NW Iran Ophiolites.

### Introduction

The ophiolitic fragments cropped out in Neo-Tethyan suture zones spanning from NW Iran through Iraqi Zagros to the Baer-Basit (border of Türkiye - Syria) exhibit numerous correspondences in their tectonic settings of generation (supra-subduction zone or mid-ocean ridge), age (predominantly Late Cretaceous, around 100-90 million years), and lithologies (1, 2 and references therein). Most of the Late Cretaceous Neo-Tethyan ophiolites, especially in NW Iran, are believed to have formed in an SSZ environment (3) or an abyssal setting (4). These

ophiolites were formed during the collision between the Arabi-Eurasian (Central-Iranian) plates in various locations such as Kermanshah (Harsin), Kamyaran (Garmab), Marivan (Sarvabad), Piranshahr, Sardasht, Silvana (Gysian), and Serow near Urmia (1). In many instances, mafic bodies, particularly gabbros, are found alongside ultramafic rocks or within ophiolitic melanges. Investigating these gabbros aids in enhancing our comprehension of the ophiolites. The chemical characteristics of mafic minerals in these gabbros, particularly amphibole and pyroxene, can offer valuable insights into interpreting the physicochemical nature and conditions of the source magma (5). The

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hornblende-bearing gabbros are a common rock type in subduction-related magmatic assemblages and indicate fractional magmatic processes in an arc setting (6, 7). The hornblende in subduction-related ophiolitic gabbros may form as the primary phase from hydrous mafic magma (8) or as a reaction product of primary mafic minerals (9).

Additionally, due to the constant companionship between ophiolites and gabbros (layered or massive types), the study of the Serow ophiolite-related gabbros concerning their mineral and whole rock chemistry accompanied with petrogenetic and tectonic setting indications, could help to evaluation the Neo-Tethyan characteristics in this part of the suture, at NW Iran.

Our study has specifically focused on the Serow-Torshab ophiolite-related gabbros found in the Torshab area as a small stock in NW Iran (Figure 1). Field geological observations, petrographic analyses, and mineralogical and whole-rock chemistry data were utilized to delve into the pressure-temperature (PT) conditions and petrogenesis of these gabbros. While whole-rock chemistry and crystal size distribution have already been studied in these gabbros (10), to the best of our knowledge, mineral chemistry data have not been investigated yet.

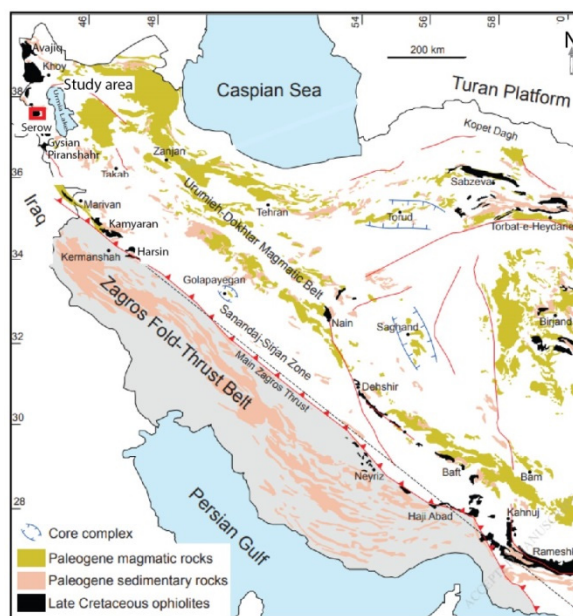
### Geological setting

The study area is situated in the northwest of Urmia

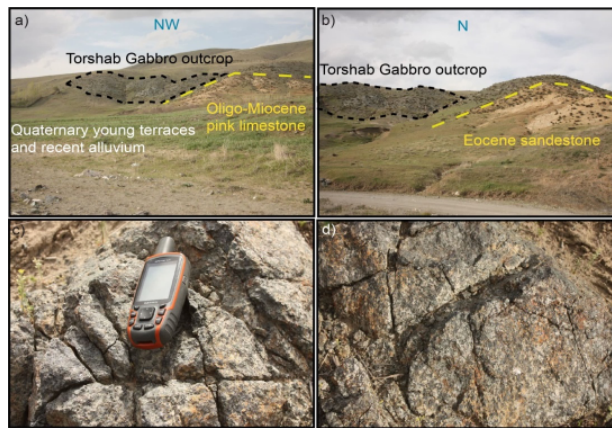
(Figure 2) on the Serow 1:250,000 sheet scaled geological map of the Geological Society of Iran (12) and the 1:100,000 scaled Gangechin map (13). The mafic stocks in the vicinity of Urmia are part of the Urmia-Dokhtar magmatic arc (14), associated with the subduction and closure of the Neo-Tethyan ocean. Within the study area, small gabbroic patches have intruded metamorphic and sedimentary rocks dating back to the Early Paleozoic era (12, Figure 3).

A notable characteristic surrounding the medium to coarse-grained gabbroic rocks is the presence of high-Ti placer deposits in the Serow area. These deposits contain significant quantities of Ti-rich minerals such as ilmenite, diopside, and amphiboles, which were abundant phases found within the historical drainage pattern of the area.

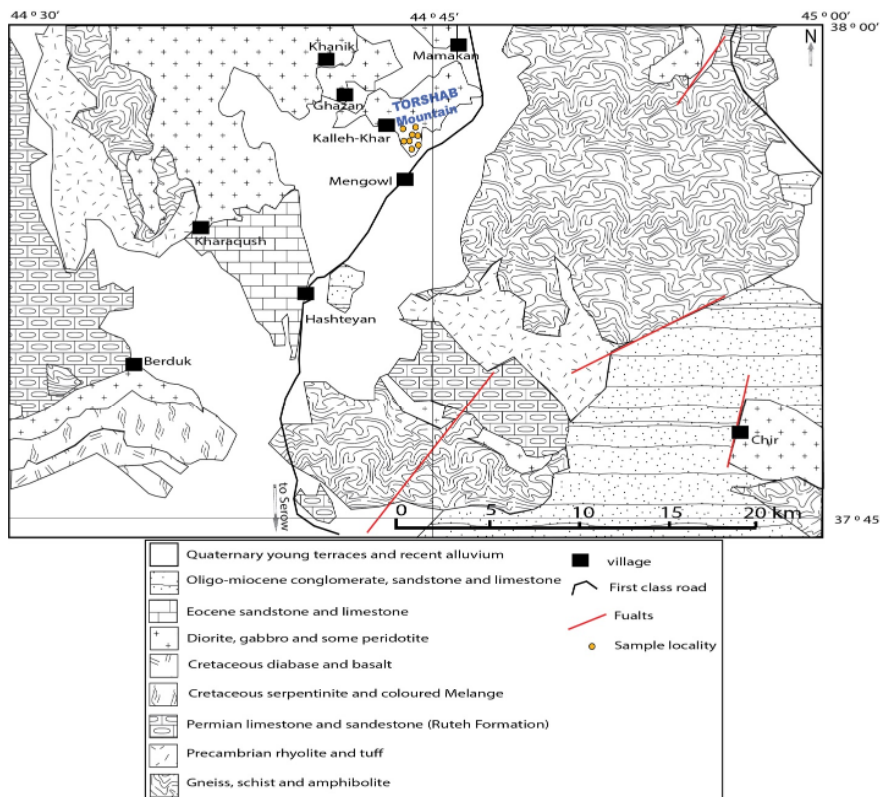
The igneous rocks (both mafic and acidic) in the Serow region intruded during the Late Mesozoic to Early Cenozoic periods due to the collision between the Iranian and Arabian plates (15). The Serow ophiolitic fragment, situated in northwest Iran near the Iran-Türkiye border, shares similarities with other Neo-Tethyan Mesozoic ophiolites in northwest Iran (e.g., Gysian), manifesting as a tectonic mélange which is predominantly composed of serpentized ultramafic rocks (lherzolitic-harzburgites and some dunites), basaltic lavas, diabases, Upper Cretaceous limestones (pelagic and radiolarite/globotruncana-bearing), as well



**Figure 1.** Geological map of Iran depicting Paleogene magmatic and sedimentary rocks as well as Late Cretaceous ophiolites (modified after 11). The study area, Serow (highlighted in a red box), along with other ophiolitic fragments in West Azarbaijan Province including Avajiq, Khoy, Serow, Gysian, and Piranshahr are situated in this region. Notable well-recognized fragments like Marivan, Kamyaran (Garmab), and Harsin in the Zagros Ophiolite Belt (ZOB) are also indicated.



**Figure 2.** a, b) Field photos of the Serow, Torshab region and related units. c, d) The mesoscopic scale of the Torshab coarse-grained gabbro.



**Figure 3.** The simplified geological map of Serow-Torshab area (modified after 12; 1:250.000 scaled map), showing the location of the analyzed samples indicated by blue, yellow and black stars.

as sedimentary rocks such as sandstone and shale.

Triassic and Jurassic sedimentary rocks are not exposed in the area; instead, Cretaceous units are prevalent. Contact metamorphic aureoles have developed around the basic intrusions and near the Permian limestones, leading to the formation of some garnet, wollastonite, and diopside-bearing skarn deposits, notably encompassing the Ghazan patch. Gabbroic rocks within the Serow-Torshab area intruded

the ultramafic unit in the form of several intrusive stocks in the Serow area (Figure 3), including Ghazan (16), Khanik (17), Chir, Moskin (10), and Torshab (from this study). The studied rocks, appearing as stocks (small patches), exhibit dark green-brownish-black colors, with the feldspar-bearing portions appearing lighter.

### Materials and Methods

Numerous mafic rocks were sampled from the Serow-Torshab Mountain, located near the Iran-Türkiye border, following thorough fieldwork conducted during the summers of 2019 and 2020. After initial petrographic assessments, a careful selection of samples was made for electron microprobe analysis (EPMA). Subsequently, three mafic thin sections underwent detailed examination. The EPMA were carried out at the Department of Earth and Environmental Sciences at Ludwig Maximilian University in Munich, Germany, by utilizing a Cameca SX-100 system equipped with a LaB6 cathode. This fully automated instrument incorporates five wavelength dispersive spectrometers for nondestructive analysis. Various phases, such as olivine, pyroxenes, plagioclase, and amphibole, among others, were analyzed and reference materials were employed to calibrate the EPMA. The data obtained

from the EPMA are outlined in Table 1.

After conducting petrographic and EPMA studies on mineral assemblages and textures, eight representative samples from the Serow-Torshab (near the Chir village) were selected for geochemical analysis (Table 2). Whole-rock major- and trace-element ICP-OES analysis utilizing a radial 735 model and V-Groove nebulizer with a detection limit of 0.05% dl, was performed using a spectro-analytical instrument at the ZarAzma Laboratory in Tehran, Iran. The aqua-regia digestion method involving hydrochloric and nitric acids, which is suitable for various exploration applications and provides a cost-effective multi-element analysis solution for most base-metal explorers, was employed for the analyses (Table 2).

**Table 1.** Representative mineral chemical compositions, along with cation distributions, for various phases analyzed from the Serow-Torshab gabbros, including olivine, orthopyroxene, clinopyroxene, plagioclase, amphibole, and serpentine. Mineral abbreviations follow the conventions outlined in reference 18 (Ol:olivine, opx: orthopyroxene, Cpx: clinopyroxene, Pl: plagioclase, Amp: amphibole, Srp: serpentine), with the analyzed point numbers denoted by "N." bdl: below detection limits.

Sample Name	Ol S10 N=11	Opx S9, S10 N=4	Cpx S9, S10 N=15	Pl S9, S10 N=9	Amp S9, S10 N=45	Srp S9 N=8
SiO <sub>2</sub>	37.03	54.42	53.06	43.30	43.29	35.03
TiO <sub>2</sub>	bdl	0.15	0.29	0.03	0.08	0.03
Al <sub>2</sub> O <sub>3</sub>	bdl	1.52	1.93	32.86	12.60	0.24
Cr <sub>2</sub> O <sub>3</sub>	0.03	0.00	0.01	0.00	0.00	0.01
NiO	0.05	0.03	0.01	bdl	0.03	bdl
FeO	26.34	17.45	6.48	0.35	10.24	33.01
MgO	36.48	26.39	15.71	0.04	15.91	0.68
MnO	0.50	0.52	0.23	0.02	0.17	25.91
CaO	0.02	0.89	23.21	21.49	11.29	0.48
Na <sub>2</sub> O	bdl	bdl	0.09	1.44	1.95	bdl
K <sub>2</sub> O	bdl	0.02	bdl	0.03	0.28	0.01
P <sub>2</sub> O <sub>5</sub>	bdl	0.01	0.01	0.02	0.00	bdl
Cl	bdl	0.01	0.01	0.61	0.02	bdl
Total	100.45	101.41	101.07	100.23	95.97	95.44
	<u>3C/4Q</u>	<u>4C/6Q</u>	<u>4C/6Q</u>	<u>5C/8Q</u>	<u>15C/23Q</u>	<u>5C/7Q</u>
Si	0.977	1.949	1.935	2.040	6.270	1.706
Ti	-	0.004	0.008	0.001	0.012	-
Al	-	0.063	0.083	1.826	2.150	-
Cr	-	-	-	-	-	-
Fe <sup>3+</sup>	0.029	0.031	-	0.014	0.901	0.015
Fe <sup>2+</sup>	0.553	0.492	0.198	-	0.343	1.668
Mn	0.011	0.016	0.007	0.001	0.020	0.032
Mg	1.435	1.409	0.854	0.003	3.441	1.832
Ca	0.001	0.035	0.907	1.085	1.750	3.198
Na	-	-	0.007	0.133	0.553	-
K	-	-	-	0.002	0.051	-
Total	3.006	3.999	3.999	5.105	15.491	8.451
Al <sup>(IV)</sup>	-	0.051	0.065	-	1.73	-
Al <sup>(VI)</sup>	-	0.013	0.019	-	0.43	-
Mg #	72.2	74.1	81.2	-	90.9	52.3

**Table 2.** Whole-rock major oxides (wt. %) and trace element (ppm) contents as well as some ratios for the Serow-Torshab gabbros.

Sample	S1	S2	S3	S4	S5	S6	S7	S8
SiO <sub>2</sub>	51.93	47.44	49.69	50.80	45.87	47.49	45.20	45.99
TiO <sub>2</sub>	1.21	0.90	0.54	0.78	3.95	2.60	1.25	0.61
Al <sub>2</sub> O <sub>3</sub>	15.14	14.90	15.48	14.73	13.00	13.95	14.15	15.64
Fe <sub>2</sub> O <sub>3</sub>	10.00	10.72	9.46	8.95	15.98	13.87	13.43	9.18
MnO	0.15	0.19	0.17	0.16	0.20	0.28	0.20	0.16
MgO	6.45	9.18	7.45	8.52	5.64	6.77	8.19	12.02
CaO	8.27	11.03	10.89	11.15	9.79	9.56	10.91	12.17
Na <sub>2</sub> O	3.41	2.68	3.34	2.72	3.73	3.49	3.16	1.83
K <sub>2</sub> O	1.20	0.78	0.69	0.58	0.54	0.45	0.45	0.10
P <sub>2</sub> O <sub>5</sub>	0.31	0.11	0.15	0.18	0.19	0.30	0.26	0.12
LOI	1.74	1.86	1.92	1.32	0.9	1.06	2.43	1.92
Total	99.81	99.79	99.78	99.89	99.79	99.82	99.63	99.74
Ba	1491	187	456	324	243	305	172	51
Rb	23.37	16.54	12.19	14.63	10.04	8.28	9.67	3.13
Sr	252	171	329	190	421	336	222	120
Y	25.4	16.65	26.83	21.08	11.59	18.86	19.32	10.95
Zr	15.36	12.39	62.57	11.88	17.23	12.83	17.85	28.45
Nb	7.93	1.26	5.85	2.27	8.32	14.18	1.8	0.74
Th	1.02	<0.01	0.28	0.84	2.14	0.37	0.16	<0.01
Pb	1.49	3.02	<0.01	<0.01	0.24	<0.01	<0.01	<0.01
Ga	19.72	15.49	17.23	15.12	18.57	16.13	15.19	12.23
Cu	9.79	26.85	9.84	19.71	35.28	36.94	12.46	53.79
Ni	21	110	91	49	12	69	76	166
V	2.7	2.2	1.7	2.2	4	1.7	2.2	1.7
Hf	0.65	0.59	2.01	0.62	0.91	0.73	0.83	0.74
Cs	0.3	0.25	0.27	0.21	0.1	<0.01	0.2	0.12
Ta	0.32	<0.001	0.3	<0.01	0.56	1.26	<0.01	<0.01
Co	36.08	44.86	31.37	37.53	41.11	38.34	39.16	49.94
U	0.16	<0.01	<0.01	0.22	0.3	<0.01	<0.01	<0.01
W	1	0.67	1.33	0.4	0.91	1.8	2.64	0.88
Cr	89	303	231	426	49	183	160	529
La	24.13	1.4	8.28	5.86	8.74	5.63	3.45	1.31
Ce	61.71	4.07	18.31	12.76	16.16	12.97	8.09	3.1
Pr	7.95	1.02	3.52	2.42	2.64	2.57	1.7	0.72
Nd	35.46	7.32	21.93	15.08	15.09	16.36	11.12	4.75
Sm	7.58	2.04	4.82	3.31	2.77	3.55	2.64	1.24
Eu	2.34	0.76	1.98	1.03	1.25	1.81	1.24	0.51
Gd	6.56	2.41	4.93	3.52	2.8	3.82	3.12	1.56
Tb	1.16	0.57	1.06	0.78	0.53	0.78	0.7	0.36
Dy	6.08	3.62	6.32	4.68	2.72	4.3	4.04	2.2
Ho	1.29	0.83	1.35	1.05	0.56	0.93	0.91	0.5
Er	3.13	2.1	3.29	2.63	1.32	2.31	2.34	1.29
Tm	0.68	0.47	0.71	0.59	0.26	0.49	0.51	0.29
Yb	3.39	2.38	3.44	2.92	1.26	2.43	2.57	1.46
Lu	0.39	0.24	0.34	0.29	0.13	0.25	0.25	0.14
Nb/Yb	2.34	0.53	1.7	0.78	6.6	5.84	0.7	0.5
Th/Yb	0.3	0.004	0.081	0.29	1.7	0.15	0.06	0.007
Zr/Y	0.6	0.74	2.33	0.56	1.49	0.68	0.92	2.6
Nb/Y	0.31	0.076	0.22	0.1	0.72	0.75	0.09	0.07
Sm/La	0.31	1.46	0.58	0.56	0.32	0.63	0.77	0.95
Th/La	0.04		0.03	0.14	0.24	0.07	0.05	
Zr/Nb	1.94	9.83	10.7	5.23	2.07	0.9	9.9	38.4

## Results

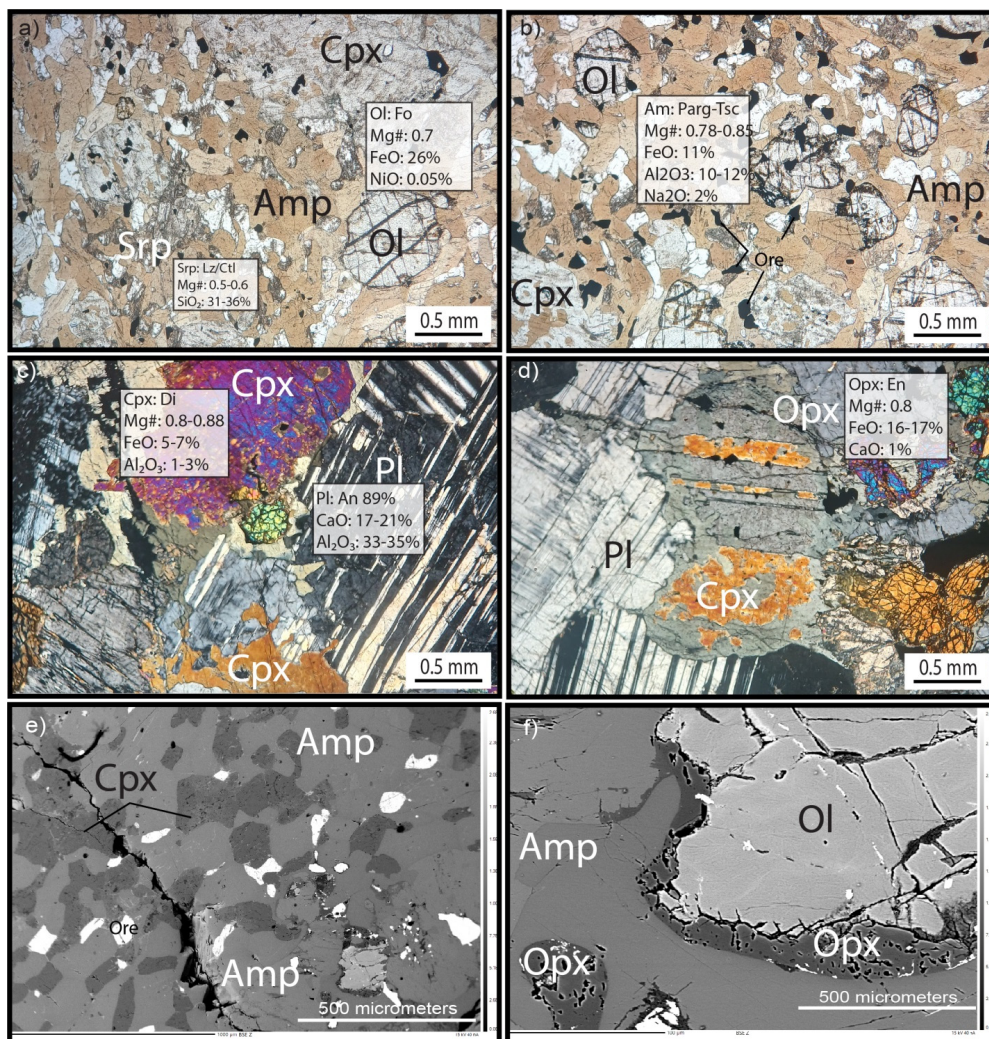
### *Petrographic descriptions and mineral composition*

The intrusive rocks in the Serow-Torshab region primarily consist of gabbros, categorized into hornblende gabbro and olivine gabbro based on the modal percentage of the main phases and

microstructures. The grain sizes are predominantly medium to coarse, displaying sub-/anhedral granular, intergranular, and poikilitic (sub-ophitic) textures (Figure 4).

The prevalent minerals in the Serow-Torshab gabbros are amphibole, clino-/ortho-pyroxene, olivine, and plagioclase, with occasional occurrences of





**Figure 4.** Microphotographs (a, b; plain-polarized and c, d; cross-polarized) and BSE images (e, f) of the Serow-Torshab gabbros. Summary of the mineral compositional data are shown on thin section photos (a-d). Mineral abbreviations are after 18. The EPMA data are presented in Table 1.

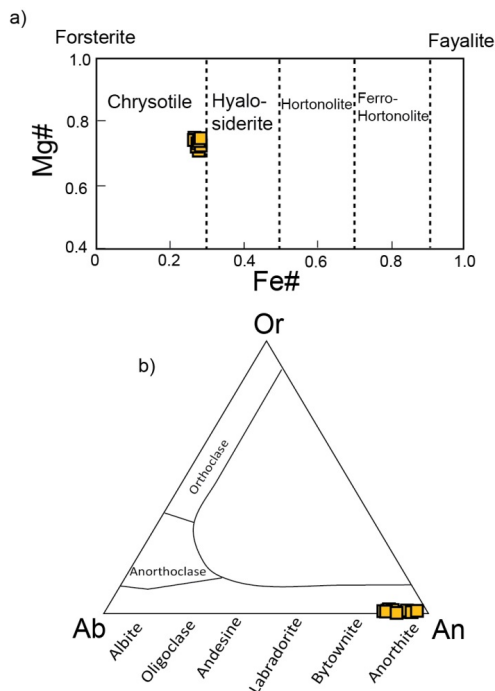
serpentine. Polysynthetic twinning is common in relatively fresh, plagioclases, while pyroxenes primarily consist of clinopyroxene as individual crystals (heterogeneous crystallization) or as exsolution lamellas within orthopyroxenes. Alteration to serpentine group minerals can be observed in the cracks of olivine. BSE images reveal narrow orthopyroxene rims forming around the olivines. In some samples, amphibole coarse grains encase clinopyroxenes intermittently. Following detailed petrographic studies, three representative thin sections underwent EPMA.

Olivine crystals are predominantly forsterite-rich (chrysotile; Fo: 74, <10 modal%, Figure 5a), and altered to serpentine (Mg#: 0.52-0.60, <10 modal%), in most cases. Orthopyroxenes are primarily enstatite (Mg#:

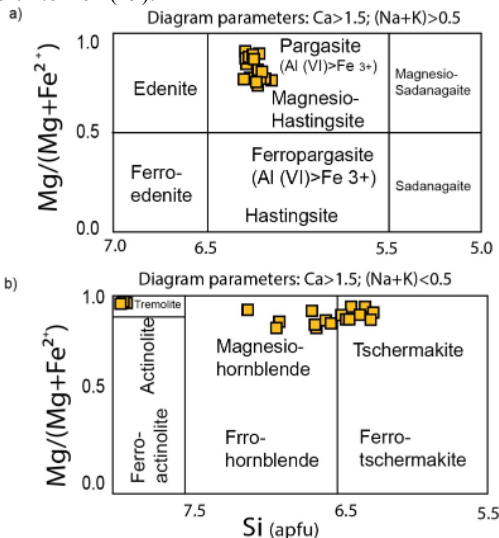
0.76-0.79, Al<sub>2</sub>O<sub>3</sub>: 1.2 wt.%, <10 modal%), in direct association with diopsidic clinopyroxene crystals (Mg#: 0.85-0.89, Al<sub>2</sub>O<sub>3</sub>: up to 2 wt.%, 10-15 modal%). Anorthite contents in the plagioclases (An: 88-94, 15 modal%, Figure 5b) are high. Predominantly, hornblende gabbros encompass pargasite to magnesiohornblende-tschermakite amphiboles (Figure 6a; Mg#: 0.91, Al<sup>IV</sup>: 1.7, Al<sup>VI</sup>: 0.43, Na: 0.55 apfu, 40 modal%) within the rock matrix. Additionally, secondary tremolites, identified as the alteration products of pyroxenes, are present in some samples (Figure 6b).

#### Whole rock chemistry

The gabbros found in the Serow-Torshab area



**Figure 5.** Mineral classification diagrams for olivine a) and feldspar. b) The olivines in Serow-Torshab gabbros are Mg-rich chrysotile, and their plagioclases are anorthite-rich (19).



**Figure 6.** Classification diagrams for the amphiboles from Serow-Torshab gabbros. Si vs. Mg# diagram for low alkali (a) and alkaline amphiboles (b) (after 20). All amphiboles present are primarily pargasite, magnesiohornblende, transitioning to tschermakite, with occasional occurrences of secondary tremolite.

originate from basaltic magma (Figure 7a, diagram from 21) and typically exhibit SiO<sub>2</sub> contents ranging from 45-52 wt.% and MgO contents of 6.5-12 wt.% (Table 2). These gabbros display relatively high TiO<sub>2</sub> contents,

approximately in the range of 0.5-4 wt.%. Additionally, their CaO content falls between 8 wt.% and 12 wt.%. Al<sub>2</sub>O<sub>3</sub> ranges from 13 wt.% and 15.5 wt.%, and FeO<sub>(T)</sub> is around 9-16 wt.%. The levels of Al<sub>2</sub>O<sub>3</sub> and CaO are linked to the substantial modal proportions of plagioclase and clinopyroxene in these rocks. Furthermore, their Co content falls within the range of approximately 30-50 ppm, and Zr is between 12 ppm and 62 ppm. In addition Ni ranges from 20ppm and 160 ppm, and Y contents are between 11 ppm and 26 ppm. The high field strength elements (HFSE) like Hf, Ta, Th, and U contents are relatively low, ranging below 1-2 ppm.

Moreover, all Serow-Torshab gabbros exhibit a calc-alkaline to tholeiitic character (Figure 7b) mostly with an SSZ related affinity, as determined by trace element ratios such as Nb/Yb vs. Th/Yb and Nb<sub>(N)</sub> vs. Th<sub>(N)</sub> (Figure 7b, c). An arc setting is confirmed by other discrimination diagrams such as FeO<sub>(T)</sub>-Alk-MgO ternary (Figure 7d), and Ti/40-Si/1000-Sr (Figure 7e) diagrams.

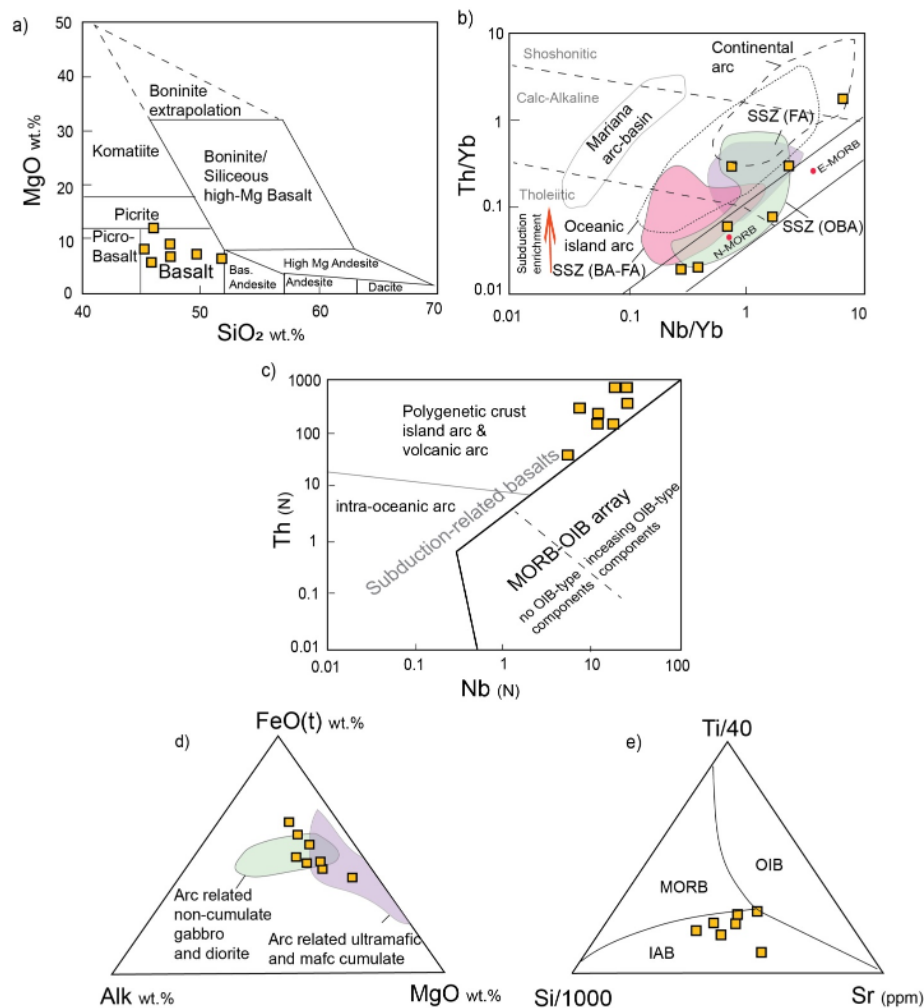
The chondrite-normalized Rare Earth Elements (REE) diagram (Figure 8a) of the Serow-Torshab gabbros exhibits a slight light REE/heavy REE (HREE) enrichment. In the N-MORB normalized multi-element diagram of the analyzed rocks (Figure 8b), there is notable enrichment in Large Ion Lithophile Elements (LILE), such as Ba, K, Sr, and Pb contents in contrast to depletion in HFSE.

## Discussion

### Tectonic setting

All the discrimination diagrams show an arc related setting for the Serow gabbros (Figure 7). The LREE/HREE enrichments at the Serow-Torshab gabbros (Figure 8a) could potentially reflect the enrichment of the mantle source of gabbros with subducted oceanic crust-derived components. Consequently, the gabbro could represent a segment of the lithospheric mantle enriched in incompatible elements (e.g., LREE; Figure 8b). The island arc basalt (IAB)-like pattern in the multi-element diagram of the Serow-Torshab gabbros, especially enrichment in LILE may indicate the generation at an arc tectonic setting of the source magma (e.g., 29). The depleted HFSE such as Zr, Hf, Ta and Nb may indicate arc setting formation for the studied rocks (30). While, the positive Eu anomaly (Figure 8a) indicates the high abundance of plagioclase in the rock, a convex up pattern (Middle REE enrichment) can be interpreted by the dominant phase of amphibole presence (31).

The composition of the pargasitic-tschermakitic



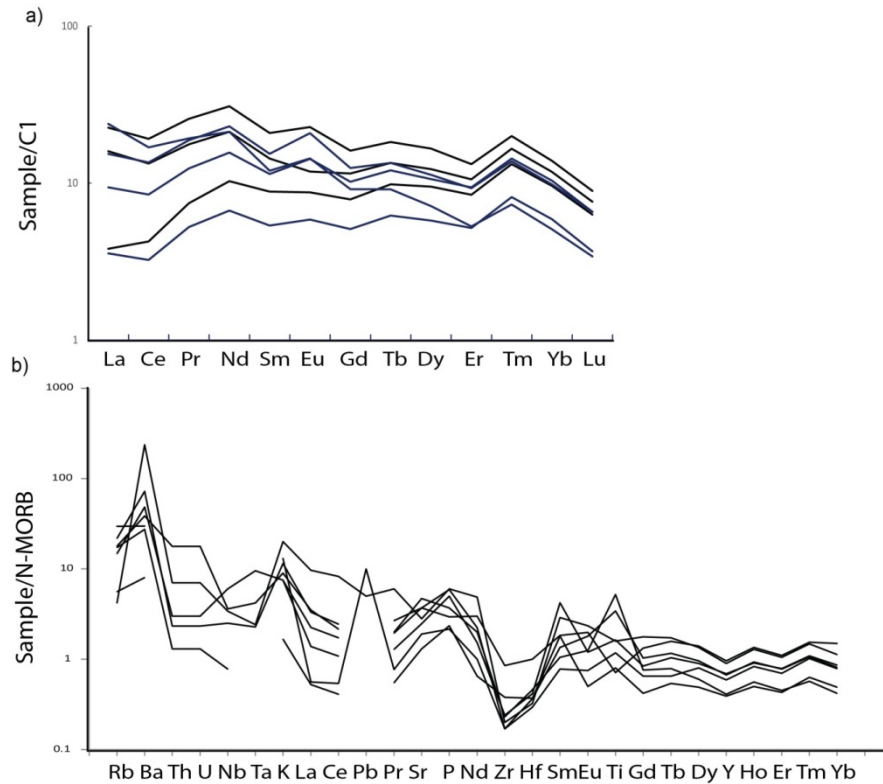
**Figure 7.** a) Distribution of MgO wt.% and SiO<sub>2</sub> wt.% contents of the Serow-Torshab gabbro on a high-Mg mafic to ultramafic-mafic rock discrimination diagram (21), all samples falling within the basalt field. b) The discrimination diagram of the Nb/Yb vs. Th/Yb (22), which shows a SSZ (OBA) affinity for the studied rocks. The SSZ setting fields are determined by colors and abbreviations are as following: SSZ (BA-FA): supra subduction zone back-arc to fore-arc, SSZ (OBA): supra subduction zone oceanic back-arc and SSZ (FA): supra subduction zone fore-arc setting. c) The Nb<sub>(N)</sub> vs. Th<sub>(N)</sub> diagram (23) which are normalized to the primitive mantle (PM values after 24). The diagram shows polygenetic crust island arc setting for the studied rocks. d) AFM discrimination ternary diagram for the Serow-Torshab gabbroic rocks. Fields of cumulate and non-cumulate rocks are from (25). e) The tectonic setting discrimination diagram (26), all the samples are located in the IAB field. The abbreviations are: OIB: oceanic island basalt, MORB: middle oceanic ridges basalt, IAB: island arc basalt. Complete whole rock data results are presented in Table 2.

amphibole in the Serow-Torshab gabbro demonstrates a magmatic origin (Figure 9a) and suggests formation within an SSZ setting (Figure 9b). Similar conclusions are drawn from the clinopyroxene composition (Figure 10a-c), indicating characteristics consistent with the SSZ environment. Moreover, clinopyroxenes from the Serow-Torshab gabbros point toward moderate pressure crystallization within the SSZ setting (Figure 10c). The clinopyroxenes in the Serow-Torshab gabbros also display an arc-related trend based on their Al and Ti

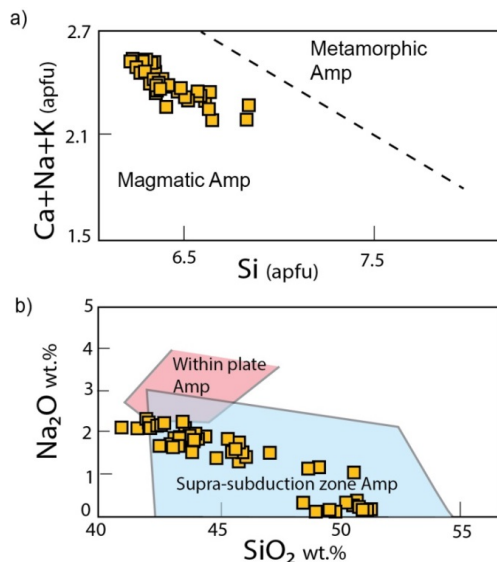
contents (Figure 10d).

Mineral chemistry examinations of the serpentinized peridotites of the Serow ultramafics in the southwestern part of the Serow-Torshab gabbroic patch indicate an SSZ setting for the Serow ophiolite (38). Nonetheless, the absence of comprehensive data on the whole-rock chemistry, particularly the REEs of the peridotites, hinders making definitive conclusions about them.





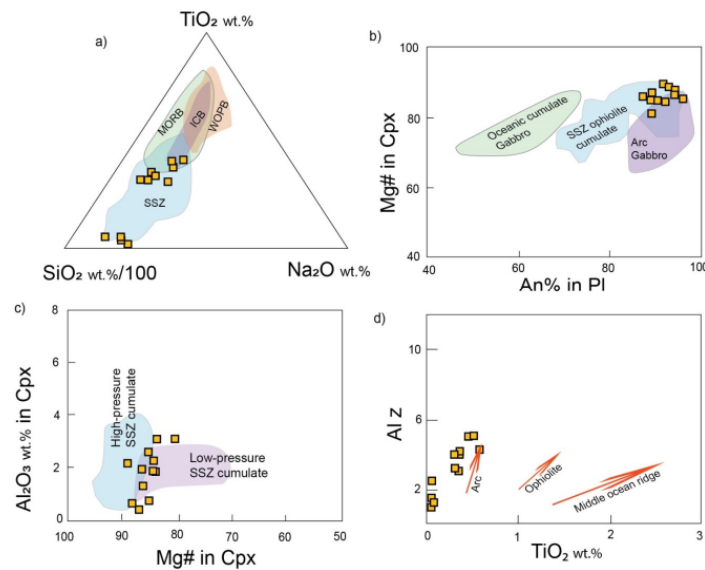
**Figure 8.** a) Chondrite normalized REE patterns (normalizing values are after 27) and b) N-MORB normalized multi-element diagram (normalizing values are from 28) for the Serow-Torshab gabbros.



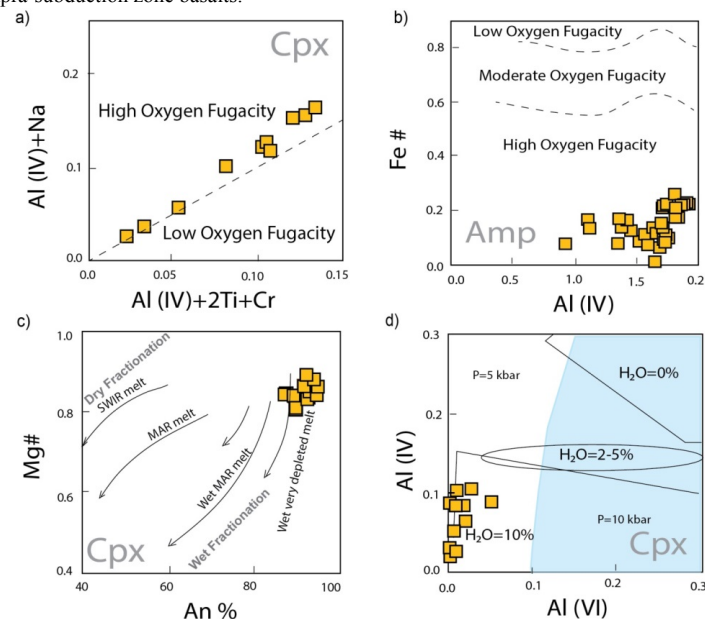
**Figure 9.** a) Si vs. CNK (apfu) diagram (32), used for distinguishing between magmatic and metamorphic amphiboles, demonstrating the magmatic nature of the examined amphiboles. b) SiO<sub>2</sub> vs. Na<sub>2</sub>O diagram in amphiboles (33), indicating that the studied amphiboles belong to the SSZ type.

#### *Oxygen fugacity and water contents*

The elevated presence of amphibole modal percentage in the Serow-Torshab gabbros suggests a notable abundance of H<sub>2</sub>O as the primary fluid constituent in the parent magma of the studied rocks. This crucial factor likely influenced the temperature of the liquidus and the composition of the melt. In order to assess the fluid fugacity parameter, mineral chemistry-based diagrams utilizing clinopyroxene and amphibole were employed for analysis (Figure 11a-d). These diagrams, incorporating Al, Na, Ti, Cr, and Mg# values of clinopyroxene, Fe#, and Al content in the amphibole, along with the anorthite content of plagioclases, provide insight into the fluid fugacity of the magma. The fluid content may either originate from inherent source characteristics or be a result of heightened levels due to metasomatic events. Both scenarios are considered relevant in this context. The relatively high anorthite content of plagioclases is typically linked to the crystallization of plagioclase from water-rich magmas, suggesting derivations from a melt with high water content during crystallization (39).



**Figure 10.** a)  $\text{TiO}_2$ – $\text{Na}_2\text{O}$ – $\text{SiO}_2/100$  diagram (34), utilized for differentiating clinopyroxenes in basalts/gabbros from various oceanic settings. b) Anorthite content of plagioclase vs. Mg# of clinopyroxene diagram (35). c) Mg# vs.  $\text{Al}_2\text{O}_3$  contents of clinopyroxene (34) aiding in determining the pressure conditions of the Serow-Torshab mafic rocks. The samples align within the overlap area between high-pressure (8-10 kbar) SSZ-type cumulates field and low-pressure (2.5-3.5 kbar) SSZ field (diagram sources: 36). All three diagrams indicate the rocks examined are within an SSZ environment. d)  $\text{TiO}_2$  vs.  $\text{Al}_2$  diagram, where  $\text{Al}_2 = \text{Al}^{\text{IV}} \times 100/2$  (37), indicating an arc-related setting for the Serow-Torshab gabbro. Abbreviations: E-MORB - enriched mid-ocean ridge basalt; N-MORB - normal mid-ocean ridge basalt; WOPB - within oceanic plate basalts; ICB - Iceland basalts; SSZ - supra-subduction zone basalts.

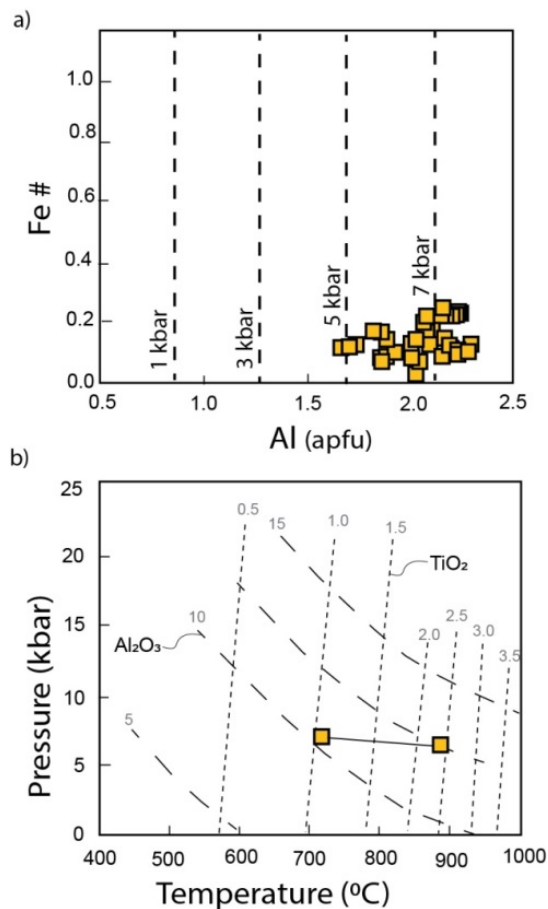


**Figure 11.** Estimation of oxygen fugacity for the parental magma of the Serow-Torshab gabbro. a) Based on clinopyroxene (40) and b) Based on amphibole (41), both indicating high oxygen fugacity; c) Plagioclase anorthite content vs. Mg# (42) revealing a highly depleted melt with a wet composition for the gabbro magma; d) Al content in clinopyroxene (43) indicating a high water abundance (10%) in the magma, suggesting emplacement in a low-pressure setting (5 kbar).

### Geothermobarometry

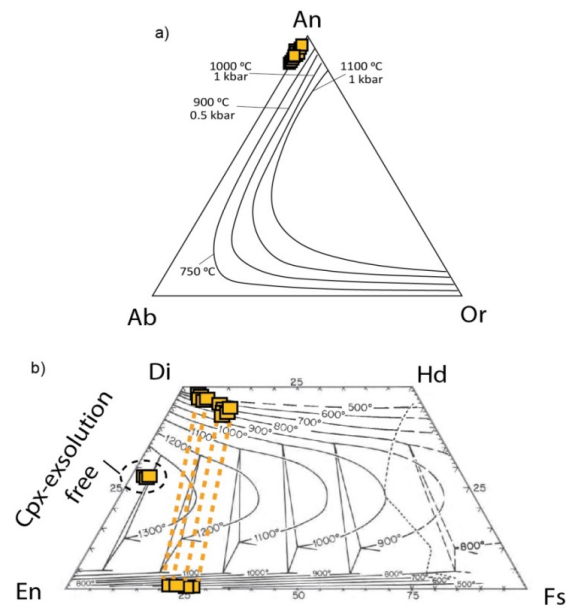
Amphibole and pyroxene chemistry serve as valuable parameters for assessing crystallization pressure and temperature. Various geothermobarometers were applied to estimate the

crystallization conditions of the Serow-Torshab gabbros. The plot of total Al content (apfu) against Fe# in amphiboles represents a crystallization pressure range of 5-8 kbar (Figure 12a, b), corresponding to a temperature range of 700-900°C (Figure 12b).



**Figure 12.** a) Pressure estimation for the Serow-Torshab gabbro utilizing total Al content vs. Fe# in amphiboles (44), indicating a pressure range of 5-8 kbar. b) Pressure-Temperature (PT) grid based on amphibole Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> content (45; max and min values), corroborating the aforementioned pressure range and temperature of 700-900°C.

The feldspar diagram suggests temperatures below 750°C for mineral formation in the Serow-Torshab gabbroic rocks (Figure 13a, following reference 46). Utilizing solvus curve-based pyroxene thermometry (as proposed by 47) indicates temperatures ranging from 800°C to 1000°C (Figure 13b) for the exsolution lamellas of clino-/orthopyroxene, which aligns well with the findings of other thermometers. However, exsolution-free clinopyroxenes exhibit slightly higher temperatures (>1300°C; Figure 13b), implying that the individual clinopyroxenes were crystallized at higher temperatures than the others. However, the exsolution-bearing ones equilibrated at 300-400 °C lower than the exsolution free ones, during the sub-solidus events. An alternative calibration method (as described in 48) provides temperatures of 1150 °C at pressures of 2-5



**Figure 13.** a) Thermometry diagrams for the feldspars (46) suggesting a crystallization temperature of 1000°C for the Serow-Torshab gabbro. b) Solvus thermometry for pyroxene in the Serow-Torshab gabbro (47). Exsolution-free clinopyroxenes crystallized up to 1300°C, whereas clinopyroxenes equilibrated with orthopyroxenes exhibit temperatures of 800-900°C.

kbar for the crystallization of clinopyroxene in the Serow-Torshab gabbros (Figure 14). Such conditions were confirmed for the other ophiolite related mafic (gabbroic) intrusions in the Neo-Tethyan suture like, in the Chaldoran, south of Maku (49) or in the west of Maku region (50).

### Conclusions

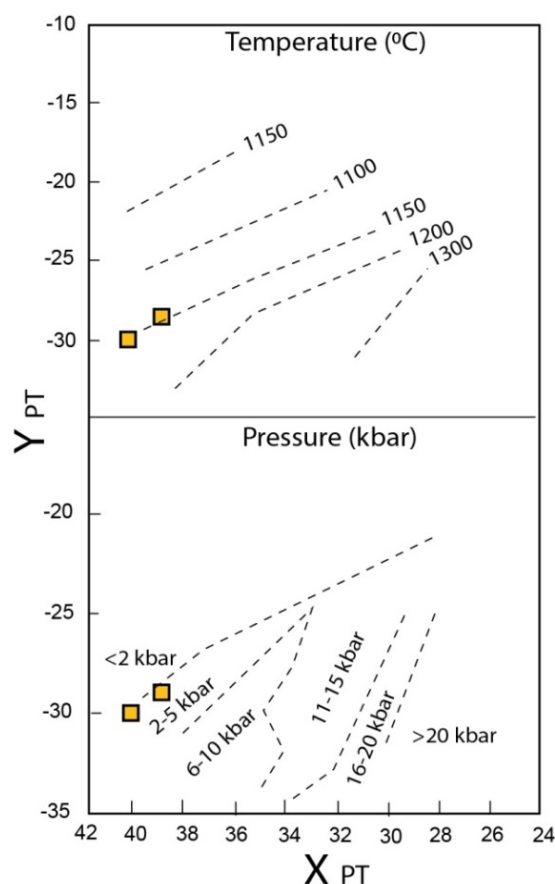
The Serow ophiolite-related gabbro in the Torshab area, situated in northwest Iran near Urmia, is part of the Mesozoic Neo-Tethyan ophiolitic belt.

The examined gabbros exhibit characteristics of arc-related rocks and display signs of metasomatic enrichment, likely originating from oceanic slab-derived melt/fluids.

Mineral chemistry studies on the gabbros offer insights into the geodynamic setting, formation conditions, and magmatic processes, providing valuable information for understanding the tectonic evolution of the region.

The geochemical signatures suggest that the derivation of the Torshab gabbro occurred from a melt with high water content during crystallization.

The formation pressure-temperature conditions, fluid



**Figure 14.**  $X_{PT}$  vs.  $Y_{PT}$  diagram (by 48), based on clinopyroxene composition (max and min values), suggests a pressure of 2-5 kbar and temperature of 1150 °C for Serow-Torshab gabbro. The factors are calculated as below:

$$\begin{aligned}
 X_{PT} = & 0.446\text{SiO}_2 + 0.187\text{TiO}_2 - \\
 & 0.404\text{Al}_2\text{O}_3 + 0.346\text{FeO} - \\
 & 0.052\text{MnO} + 0.309\text{MgO} + 0.431\text{CaO} - 0.446\text{Na}_2\text{O} \\
 Y_{PT} = & -0.369\text{SiO}_2 + 0.535\text{TiO}_2 - \\
 & 0.317\text{Al}_2\text{O}_3 + 0.323\text{FeO} + 0.235\text{MnO} - 0.516\text{MgO} - \\
 & 0.167\text{CaO} - 0.153\text{Na}_2\text{O}
 \end{aligned}$$

fugacity, and geochemical feature, points to a supra-subduction setting for the Serow-Torshab ophiolitic gabbros. The Serow Late Cretaceous ophiolite was generated within an SSZ situation, exhumed, and emplaced in the Late Cenozoic, throughout collisional events.

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