

# Role of Alteration in the Alaskan-Type Turnagain Complex, North-Central British Columbia (Parts of NTS 104I/07, 20)

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## Introduction

Although numerous studies have investigated the magmatic processes producing sulphide mineralization in mafic–ultramafic igneous complexes, fewer studies have examined the influence of hydrothermal processes on this type of mineralization. Most of the latter studies have focused on the serpentinization of the olivine and pyroxene in these complexes and rarely have considered the effect of this alteration on the distribution of the metals. Notable exceptions are the studies by Keays and Jowitt (2013) and Kamenetsky et al. (2016) that documented the mobilization of nickel during the serpentinization of olivine in the McIvor Hill mafic–ultramafic complex of Tasmania, in Australia.

The Turnagain Complex, situated in northern British Columbia (BC; Figure 1), is an example of an Alaskan-type mafic–ultramafic complex containing a potentially economic concentration of magmatic nickel-sulphide mineralization. Serpentinization resulted in the replacement of some of the magmatic olivine by serpentine and the remobilization of the primary sulphides to form secondary sulphides. In addition, deserpentinization led to the formation of secondary olivine that replaced serpentine and locally created a near-complete pseudocumulate texture.

Owing to the presence of nickel in both the sulphide and silicate minerals, as well as to the complex interplay between magmatic and hydrothermal processes, the nickel-to-sulphur ratio within the deposit varies considerably (Ni:S = 0.5–14.2; Broda et al., 2024), posing challenges for metallurgical recovery. The Turnagain Complex, with the highest known nickel-sulphide endowment of any Alaskan-type complex (1574 Mt of ore grading 0.21 wt. % Ni; Giga Metals Corporation, 2023), is an ideal natural laboratory in which to

study the processes leading to the development of economic concentrations of nickel-sulphide.

Preliminary results of a petrographic study of representative samples from the Horsetrail-Northwest zone of the Alaskan-type Turnagain mafic–ultramafic complex undertaken to investigate the role of alteration on the nickel-to-sulphur ratio are presented in this paper. These results show that the rocks of the Turnagain Complex experienced two stages of alteration: 1) early serpentinization related to fluids introduced along faults and 2) subsequent dehydration of the serpentine as a result of thrusting of the complex to higher crustal levels.

## Geology of the Turnagain Complex

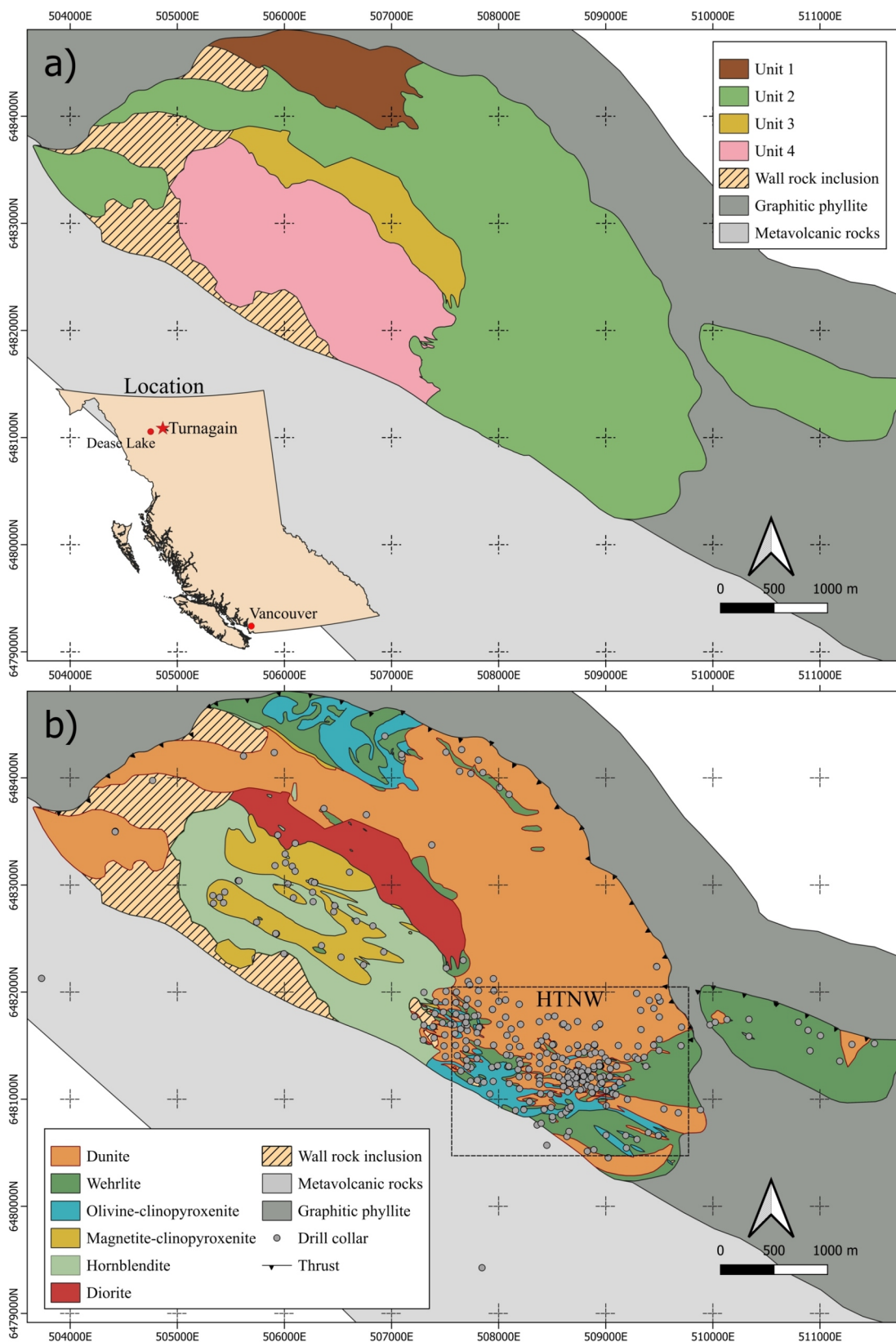
The Turnagain Complex is located approximately 70 km east of Dease Lake in northern BC and comprises four spatially and temporally distinct mafic–ultramafic intrusions (units 1–4; Figure 1a) that were emplaced in the late Paleozoic Road River metavolcanic-metasedimentary succession between 189 and 185 Ma (Scheel, 2007; Jackson-Brown, 2017; Nixon et al., 2020). These intrusions comprise, from north to south (Figure 1a, b): wehrlite, olivine-clinopyroxenite and minor dunite in unit 1; dunite and wehrlite in unit 2; diorite in unit 3; and clinopyroxenite and hornblendite in unit 4. The complex is bounded to the north and east by a major thrust fault and juxtaposed against pyrite-bearing graphitic phyllite along its northern and eastern margins; it is also in intrusive contact with metavolcanic and metasedimentary rocks on its southern boundary (Scheel, 2007; Jackson-Brown, 2017; Nixon et al., 2020). Enclaves of pyrite-bearing graphitic phyllite and metavolcanic rock are found in all the intrusions except the diorite (Figure 1b). All of the intrusive rocks have undergone varying degrees of alteration, mainly serpentinization, particularly close to faults and shear zones that are present in the complex (Clark, 1980).

The Turnagain deposit is located along the southern margin of intrusive unit 2, in the Horsetrail-Northwest zone (Figure 1b). This zone consists predominantly of dunite,

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**Figure 1.** Geology and location of the Alaskan-type Turnagain mafic-ultramafic complex: **a)** map showing the generalized geology, the boundaries of intrusive units (1–4) that represent separate intrusive units composed of the rock types identified in the legend of panel (b), the Horsetrail-Northwest resource zone (HTNW) study area outlined by the dashed rectangle in the southeastern part of the complex and the location of the complex (bottom right inset); **b)** detailed geology of the Turnagain Complex study area. All co-ordinates are in UTM Zone 9N, NAD83.

wehrlite, olivine-clinopyroxenite and clinopyroxenite. A distinguishing feature of the Horsetrail-Northwest zone is the association of a large body of low-grade nickel-sulphide mineralization with abundant pyrite-bearing graphitic phyllite enclaves.

The primary silicate and sulphide textures in the Horsetrail-Northwest zone have been described in Broda et al. (2024). The fresh dunite, wehrlite and olivine-clinopyroxenite consist primarily of equigranular, 1–3 mm (locally up to 15 mm in diameter), euhedral to anhedral cumulus olivine, with varying proportions of interstitial clinopyroxene comprising mainly diopside (Clark, 1980; Scheel, 2007); and subhedral to euhedral cumulate spinel clusters, less than 1 mm in diameter. In the clinopyroxene-dominant rocks, the clinopyroxene occurs as 1–3 mm subhedral cumulate crystals.

The main sulphide minerals are disseminated to net-textured interstitial pyrrhotite ( $\{(Ni,Fe)_xS\}$ ;  $x = 0-0.2$ ) and pentlandite  $\{(Ni,Fe)_9S_8\}$ , the primary ore mineral. They are concentrated in the dunite and wehrlite. The pyrrhotite occurs as aggregates of 50 to 500  $\mu m$  subhedral to euhedral crystals. Two types of pentlandite are present: subhedral to euhedral blocky crystals, ranging from  $<20$  to 150  $\mu m$  in diameter and occurring as aggregates (up to 1500  $\mu m$ ) enclosed within pyrrhotite or as isolated crystals; and fine lamellae within pyrrhotite. The blocky pentlandite is interpreted as a product of peritectic reaction between monosulphide solid solution (MSS) and sulphide liquid, whereas the fine lamellae likely exsolved from MSS (Broda et al., 2024). The presence of significant interstitial pyrrhotite and pentlandite in the cumulus olivine is consistent with their crystallization from an immiscible sulphide liquid (Scheel, 2007; Jackson-Brown, 2017; Nixon et al., 2020; Broda et al., 2024).

The rocks of the Horsetrail-Northwest zone have undergone varying degrees of serpentinization of the primary olivine and clinopyroxene. This alteration generally proceeded along microfractures, crystal cleavages and grain boundaries. In weakly altered rocks, serpentine formed fibrous, lath-like crystals perpendicular to the olivine grain boundaries. In more strongly altered rocks, the olivine has been completely replaced by serpentine. Veinlets of magnetite and fibrous serpentine are commonly concentrated along grain boundaries, mantling the olivine and preserving the original cumulate texture. Magnetite, produced during serpentinization, is disseminated as anhedral crystals intergrown with serpentine. The clinopyroxene was more resistant than the olivine, with alteration typically restricted to grain boundaries, fractures and cleavages, where it manifests itself as prismatic to tabular tremolite and minor serpentine. The sulphide mineral pyrrhotite was replaced extensively by magnetite and the pentlandite, much less so by magnetite, heazlewoodite and millerite (Broda et al., 2024).

## Methodology

A total of 30 drillcore samples, representative of both altered and unaltered rocks from the Horsetrail-Northwest zone, were selected for petrographic analysis. The selection was based on the degree of alteration and the textural relationships of the minerals in the sulphide ores. The petrographic analyses were performed at the Department of Earth and Planetary Sciences of McGill University using polished thin sections. An Olympus BX51-P polarizing microscope and a Hitachi High-Tech Canada, Inc. SU5000 field-emission scanning electron microscope, equipped with an X-Max<sup>N</sup> 80 silicon drift detector from Oxford Instruments plc, were employed for this purpose.

## Results

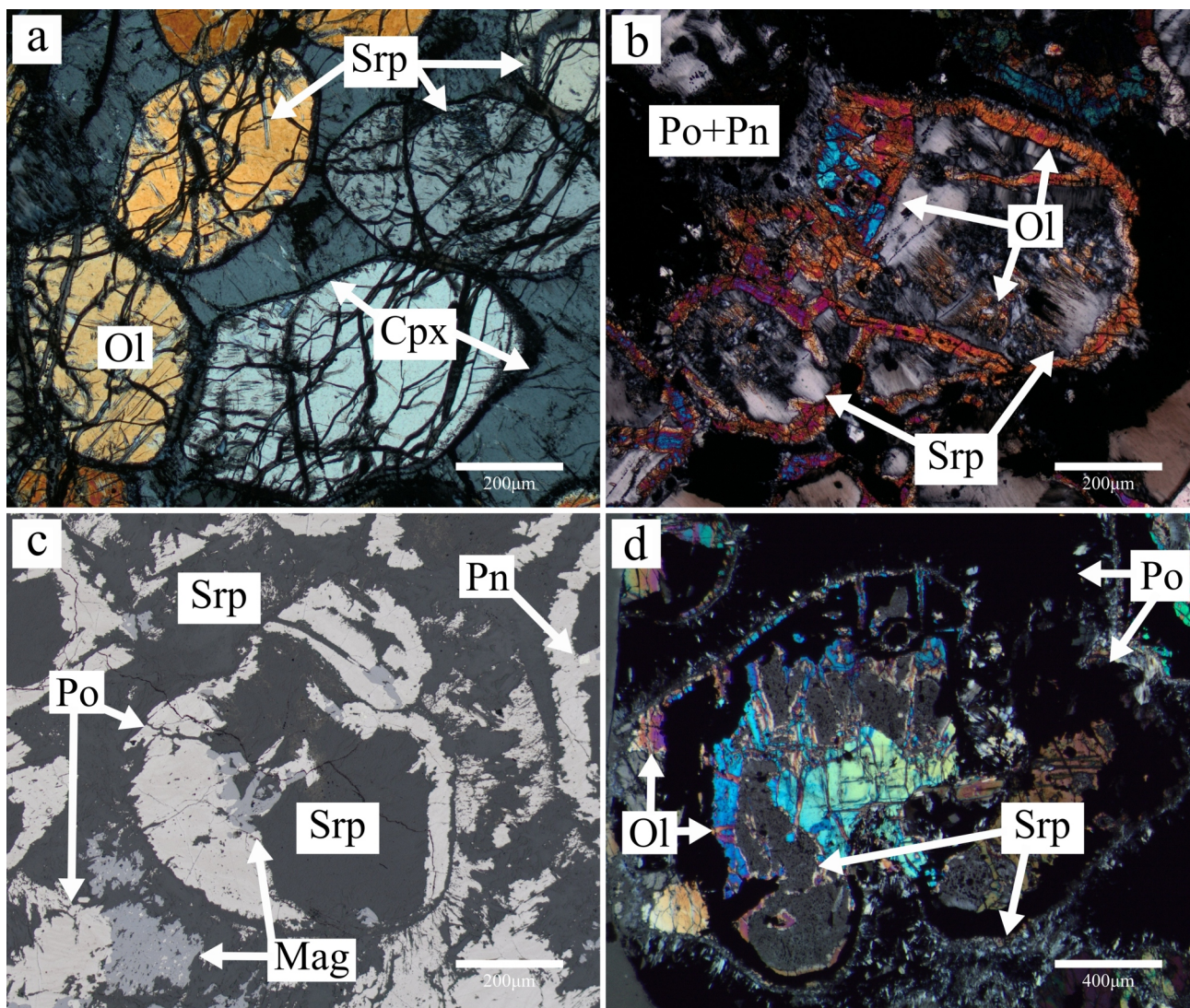
### Alteration

Alteration in the Horsetrail-Northwest zone of the Turnagain Complex is evident by the variable replacement of cumulus olivine by serpentine, magnetite and minor brucite. In weakly altered samples, serpentine replaced olivine along crystal boundaries and microfractures (Figure 2a). However, in samples or parts of samples in which the alteration was intense (samples taken closer to faults), cumulus olivine crystals were completely replaced by serpentine (Figure 2b). Magnetite occurs as disseminated anhedral crystals that are intergrown with serpentine along relict grain boundaries and microfractures; minor brucite is intergrown with serpentine, but due to its fine-grained nature, is hard to discern.

The alteration of interstitial diopside to tremolite, and locally serpentine, is only evident where the alteration was intense. Replacement of the diopside by tabular tremolite grains ( $<100 \mu m$ ) is patchy and localized to grain boundaries, microfractures and cleavage planes.

Locally, secondary olivine replaced serpentine along relict grain boundaries, producing veins as well as rims on the serpentine pseudomorphs after primary olivine (Figure 2b). Additionally, rare disseminated anhedral grains of secondary olivine replaced mesh-to hourglass-textured serpentine. The grain size of the olivine pseudomorphs is erratic and varies according to alteration intensity. In rare cases, secondary olivine is juxtaposed with relict cumulus olivine.

The alteration of the sulphide minerals, pyrrhotite and pentlandite, occurred mainly along grain boundaries, fracture surfaces and cleavage planes. Where the alteration was strong, pyrrhotite was partially to almost completely replaced by magnetite (Figure 2c). In contrast, pentlandite was replaced only locally by magnetite and, to a lesser extent, by heazlewoodite, millerite and violarite.



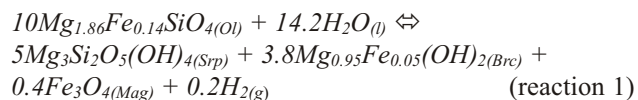
**Figure 2.** Photomicrographs of primary and secondary silicate and sulphide minerals of samples from the Turnagain Complex illustrating their textural relationships: **a)** image in cross-polarized light of subhedral-euhedral cumulus olivine (Ol), with traces of serpentine (Srp) along the fractures, completely encased in interstitial clinopyroxene (Cpx); **b)** image in cross-polarized light of secondary olivine that has been completely replaced by serpentine and is surrounded by pyrrhotite (Po) and pentlandite (Pn); **c)** image in reflected light of magnetite (Mag) locally replacing pyrrhotite, and of pyrrhotite and pentlandite replacing serpentine, which itself has replaced primary olivine, encased in interstitial pyrrhotite and serpentine; **d)** image in cross-polarized light of secondary olivine and secondary pyrrhotite replacing serpentine, which itself has replaced primary olivine (the secondary olivine and pyrrhotite occur in net-textured pyrrhotite).

The secondary sulphides, pyrrhotite and pentlandite, are disseminated in serpentine and magnetite veinlets. Additionally, olivine and serpentine were replaced along their crystal boundaries by pyrrhotite and minor pentlandite, which take the form of irregularly shaped dendrites (Figure 2c, d).

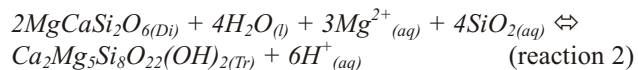
### Discussion

The silicate and sulphide textures observed in the Horse-trail-Northwest zone of the Turnagain Complex record two distinct alteration events. The first event was marked by the alteration of primary silicate and sulphide minerals by hydrothermal fluids. In this event, olivine was variably re-

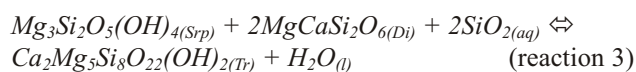
placed by serpentine+magnetite±brucite (Brc), according to the following reaction assuming an olivine composition of Fo<sub>93</sub> (preliminary microprobe data):



and clinopyroxene (as diopside [Di]) by tremolite (Tr) plus or minus serpentine via the following reactions:

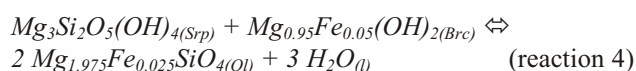


and/or



In addition, pyrrhotite was replaced by magnetite, and pentlandite by magnetite or, less commonly, by heazlewoodite, millerite and violarite. These findings are consistent with the textures and reactions previously described and reported in Broda et al. (2024). An increase in the intensity of the serpentinization with increasing proximity to faults suggests that this alteration was due to the interaction of the ultramafic rocks of the complex with fluids focused along these faults.

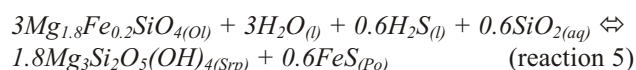
The second alteration event involved the dehydration of serpentine to form secondary olivine, according to the following reaction:



As magnetite produced during serpentinization was not involved in this reaction, the secondary olivine is predicted to exhibit a higher magnesium content than the primary magmatic olivine (Filippidis, 1982). Indeed, semiquantitative scanning electron microscope–energy dispersive spectrometry (SEM-EDS) analyses show this to have been the cause. Additionally, nickel was mobilized from olivine during serpentinization to form secondary sulphide minerals, implying that the secondary olivine should have a lower concentration of nickel than the primary olivine.

As the Turnagain Complex and its hostrock are part of a thrust sequence, it appears that this dehydration event was triggered by the decrease in pressure that accompanied the displacement of the complex to higher crustal levels. This decrease in pressure would have favoured the product (low volume) side of Reaction 4, leading to the replacement of the serpentine and brucite by olivine.

During one of these alteration events, pyrrhotite (with minor pentlandite) pseudomorphs may have formed via the reaction:



as proposed in Broda et al. (2024), and may indicate that sulphur fugacity was high during serpentinization (Filippidis, 1982).

## Conclusions and Future Work

The Alaskan-type Turnagain mafic–ultramafic complex experienced two distinct stages of alteration: 1) hydrothermal alteration causing the serpentinization of olivine, the alteration of diopside to tremolite and the replacement of sulphides by magnetite, followed by the remobilization of sulphide; and 2) the dehydration of serpentine to form sec-

ondary olivine. The first event is attributed to the introduction of hydrothermal fluids along faults within the complex and the second event, to the decrease in pressure that accompanied the thrusting of the complex to higher crustal levels.

The interplay between magmatic processes and the mobilization of nickel and sulphur during alteration events was likely responsible for the observed variability and unpredictability in nickel-to-sulphur ratios. A deeper understanding of these processes will be crucial in developing a comprehensive genetic model for mineralization in Alaskan-type complexes. The preliminary interpretations presented above, which are based on petrographic observations of textural relationships, will be tested by detailed analyses of the compositions of the primary and secondary silicate and sulphide minerals using a combination of electron probe microanalysis (EPMA) and laser-ablation inductively coupled plasma–mass spectrometry (ICP-MS) methods. Proven correct, they should show, among other things, that the secondary olivine is depleted in both iron and nickel. In addition, the analyses will help in assessing spatial and temporal variations in mineral compositions during alteration. Sulphur isotope compositions will be measured using laser-ablation, multiple-collector inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) to evaluate sulphur mobilization and physicochemical parameters such as oxygen fugacity in hydrothermal fluids. Furthermore, ultraviolet femtosecond laser-ablation, multiple-collector inductively coupled plasma–mass spectrometry (UV-fs-LA-MC-ICP-MS) will be employed to measure in situ iron and nickel isotope compositions in rock-forming minerals. This will aid in the evaluation of the sources of iron and nickel and their isotopic fractionation between minerals during the primary magmatic and secondary alteration processes. The resulting data will be used to constrain temperature and redox conditions during magmatism and serpentinization.

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