



Title: Mineralogical and Textural Analysis of Serpentinites in the Major  
Ophiolite Belts of Kazakhstan

School of Mining and Geosciences, Nazarbayev University

Dana Sayat

## **Declaration**

I, Dana Sayat, hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at Nazarbayev University or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at NU or elsewhere is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.

Signed on 24.04.2026

## **Acknowledgements**

I would like to express my sincere gratitude to my supervisor, Professor George Mathews, for his guidance, support and valuable advice throughout the entire process. His input has been essential in shaping this work.

I am also grateful to Yerlan Kanattbayev for his assistance in preparing the thin sections, which played an important role in this study.

I would like to thank the School of Mining and Geosciences for providing access to facilities and an excellent academic environment. Also want to show my gratitude to NU Faculty Development Grant 201223FD8836 for funding the project and SEM lab in C4 for providing the lab for analysis.

Finally, I would like to express my heartfelt thanks to my parents for their constant support and encouragement and to my friends for their motivation and help throughout the journey.

## Table of Contents

|                                                                            |           |
|----------------------------------------------------------------------------|-----------|
| <b>1. Introduction .....</b>                                               | <b>5</b>  |
| <b>2. Literature review .....</b>                                          | <b>7</b>  |
| <b>2.1 Regional Geologic Context .....</b>                                 | <b>11</b> |
| <b>2.2 Petrological and Mineralogical Characteristics of Regions .....</b> | <b>15</b> |
| <b>2.3 Geochemical Signatures and Mantle Sources .....</b>                 | <b>18</b> |
| <b>2.4 Mantle Behavior and Tectonic Evolution during Paleozoic.....</b>    | <b>20</b> |
| <b>2.5 Petrography for Mineral Chemistry .....</b>                         | <b>21</b> |
| <b>2.6 Research Gaps and Objectives .....</b>                              | <b>22</b> |
| <b>3. Methodology .....</b>                                                | <b>23</b> |
| <b>3. 1 Fieldwork and Sample Collection.....</b>                           | <b>24</b> |
| <b>3. 2 Petrographic Analysis .....</b>                                    | <b>26</b> |
| <b>3. 3 X-Ray Diffraction Analysis.....</b>                                | <b>27</b> |
| <b>3. 4 Scanning Electron Microscopy Analysis.....</b>                     | <b>27</b> |
| <b>4. Results.....</b>                                                     | <b>29</b> |
| <b>4.1 Kempirsai Massif.....</b>                                           | <b>29</b> |
| <b>4.1.1 Petrographic Analysis Kempirsai Region .....</b>                  | <b>29</b> |
| <b>4.1.2 SEM Analysis of Sample 49 (Kempirsai massif) .....</b>            | <b>32</b> |
| <b>4.1.3 XRD Results- Kempirsai Massif Samples.....</b>                    | <b>37</b> |
| <b>4.2 Char Ophiolite Belt.....</b>                                        | <b>39</b> |
| <b>4.2.1 Petrographic Analysis Char Region.....</b>                        | <b>39</b> |
| <b>4.2.2 Sample GK2508 (Char ophiolite belt) .....</b>                     | <b>42</b> |
| <b>4.3 North Balkhash .....</b>                                            | <b>47</b> |
| <b>4.3.1 Petrographic Analysis Balkhash Region .....</b>                   | <b>47</b> |
| <b>4.3.2 XRD Results- North Balkhash Samples .....</b>                     | <b>49</b> |
| <b>5. Discussion .....</b>                                                 | <b>50</b> |
| <b>6. Conclusions .....</b>                                                | <b>54</b> |

## **1. Introduction**

Serpentinites are metamorphic rocks derived from ultramafic mantle protoliths and represent an important part of ophiolite complexes and subduction related tectonic events. They form through the hydration of peridotitic rocks, which mostly composed of olivine and pyroxene during the process of serpentinization. This process makes a major change in physical and chemical properties of mantle rocks. It leads to a decrease in density, an increase in volume and the development of pervasive fracturing, which helps fluid circulation (Fruh-Green et al., 2004; McCollm& Bach, 2009).

Serpentinization occurs in different types of geodynamic settings, including mid- ocean ridges, forearc regions and accretionary prisms. In these environments, the interaction between mantle rocks and water rich fluids leads to the formation of serpentinite minerals, magnetite and other secondary phases (Holm et al., 2015). These reactions are commonly associated with the oxidation of iron and the production of hydrogen (McCollm& Bach, 2009). The extent of serpentinization and the resulting mineral composition depend on such factors as fluid availability, temperature, deformation and tectonic setting.

Within the Central Asian orogenic belt (CAOB), serpentinites are widely distributed and are associated with ophiolite complexes representing parts of ancient oceanic lithosphere. The CAOB is one of the largest accretionary orogenic systems on Earth and formed through the long-term evolution and closure of the Paleo-Asian ocean, involving multiple stages of subduction, accretion and continental collision (Windley et al., 2007; Xiao et al., 2010). During these processes, ultramafic rocks derived from mantle were tectonically places into the crust and as a result exposed to varying degrees of deformation and alteration.

This study focuses on serpentinites from three distinct regions in Kazakhstan: the Kempirsai massif, the Char ophiolite belt and the North Balkhash ophiolite zone. These regions

represent different segments of the CAOBS and reflect different geological histories. The Kempirsai massif is characterized by relatively well-preserved mantle peridotites and significant chromite mineralization, which suggest that mantle section has undergone deformation (Saveliev et al., 2022). In contrast, the Char ophiolite belt and the North Balkhash zone are associated with accretionary complexes and serpentinite mélanges, where ultramafic rocks have been strongly affected by deformation, subduction related processes and fluid assisted alteration (Safonova et al., 2018; Safonova et al., 2012; Volkova et al., 2008).

Variations in mineral composition, texture and degree of serpentinization between these regions provide an important information about the processes that made an impact on ultramafic rocks during their geological evolution. In particular, the preservation of primary mantle minerals such as olivine as well as the secondary minerals such as spinel can be used to identify the differences in alteration intensity, fluid activity and tectonic conditions. These characteristics are vital for understanding the relationship between mineralogical composition and geodynamic setting.

The aim of this study is to compare the petrographic and mineralogical characteristics of serpentinites from the Kempirsai, Char and North Balkhash regions and to evaluate how these characteristics relate to their geological history. To achieve this, a combination of analytical methods was used. Petrographic microscopy of thin sections, scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS), and X-ray diffraction (XRD) analysis. Petrographic microscopy allows a detailed observation of mineral phases and XRD analysis allows to identify crystalline mineral assemblages.

By using these three methods, this study aims to identify differences in mineral composition, degrees of alteration and textural features between serpentinites from the three

regions. The results help to have a better understanding of serpentinization processes and provide information of tectonic evolution of ultramafic rocks within the Central Asian orogenic belt.

## **2. Literature review**

Serpentine is a metamorphic product of ultramafic mantle rocks, primarily harzburgite and dunite which were formed through the hydration of olivine and pyroxene-bearing peridotites (Holm et al., 2015).

This process, known as serpentinization, as shown in the Fig. 1, it occurs when the mantle lithosphere is exposed to water-rich fluids in environments such as oceanic lithosphere, forearc settings, fault zones and accretionary prisms. In all three regions of this study Kempirsai, Char and North Balkhash serpentinite commonly develop within mélangé complexes, tectonic slices and the shallow mantle ophiolite sequences.

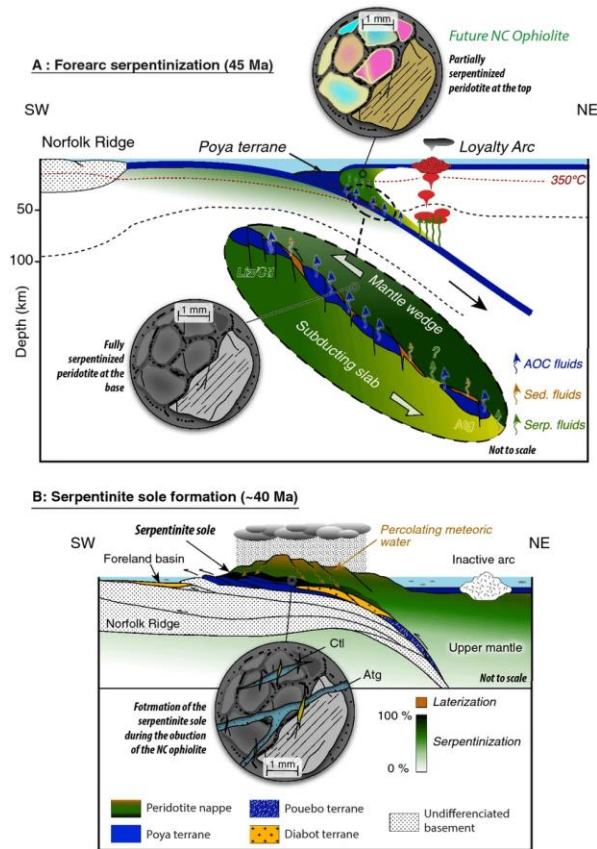


Figure 1. Serpentinization Process (unmodified copy of figure from Ulrich et al., 2020).

Serpentinization involves a set of mineral reactions that convert olivine and pyroxenes into serpentine group minerals such as brucite and magnetite. A typical reaction is:



These reactions increase rock volume, reduce density and generate extensive fracturing that enhances fluid flow, allowing serpentinization to spread through the ultramafic host. In forearc and supra-subduction environments such as Kempirsai and North Balkhash, petrological and geochemical studies interpret the strongly depleted harzburgites, high Cr-chromitites and associated serpentinite mélanges as residues of high degree melting in a supra-subduction zone mantle wedge, later hydrated by fluids derived from the subducting slab (Safonova et al., 2022;

Degtyarev et al., 2021). In contrast, the Char zone serpentinite mélanges host high pressure blocks and ocean plate stratigraphy units within an accretionary suture, suggesting that their serpentinization and tectonic incorporation are linked to underplating and exhumation processes in the collisional zone between the Siberian margin and the Kazakhstan collage (Volkova et al., 2008; Safonova et al., 2022).

Serpentinites in the Kempirsai massif, Char ophiolite belt and North Balkhash ophiolite zone are derived from mantle ultramafic rocks that experienced a complex sequence of tectonic, magmatic and hydrothermal processes during the evolution of the Paleo-Asian ocean and subsequent accretion within the Central Asian orogenic belt. These rocks represent fragments of the upper mantle that became the part of continental crust during oceanic spreading, subduction and collision.

The primary protoliths of serpentinites in these regions are mantle peridotites, mainly lherzolites, harzburgites and dunites, which formed as residues of partial melting within the upper mantle. In the Kempirsai massif, mineralogical and microstructural studies indicate that lherzolites experienced intensive mantle deformation associated with plastic flow and syntectonic recrystallization. These processes caused the change of distribution pattern of chemical components and the formation of new mineral phases within the mantle rocks (Saveliev et al., 2022).

During this stage, deformation of olivine and orthopyroxene produced microstructural features such as recrystallized neoblasts and exsolution lamellae of diopside, pargasite and spinel within grains. Plastic deformation made the segregation of chromium-rich spinel phases less complicated, which later contributed to the formation of chromite bodies within dunite channels

of the mantle section (Saveliev et al., 2022). These features indicate that the mantle peridotites went through significant solid-state deformation before serpentinization.

The ultramafic complexes of the Char and North Balkhash regions are interpreted as fragments of oceanic lithosphere formed within supra-subduction zone environments related to the evolution of the Paleo-Asian ocean. Geological and geochemical data indicate that the Char ophiolite belt records subduction related magmatism and the development of intra oceanic arcs during the Devonian-Carboniferous period (Safonova et al., 2018).

These ophiolitic complexes formed during accretionary processes associated with the closure of the Paleo-Asian ocean. Oceanic plate stratigraphy units including basalts, pelagic sediments and ultramafic mantle rocks were incorporated into accretionary complexes along suture-shear zones during subduction and following collision of continental blocks within the Central Asian orogenic belt (Safonova et al., 2018). In such tectonic environments, mantle peridotites were exhumed and tectonically placed into accretionary complexes where they later went through extensive hydration and serpentinization.

Serpentinities in the Char region mostly occur as *mélanges* that formed during accretionary and collisional processes. These *mélanges* contain blocks of ultramafic rocks, oceanic basalts and high-pressure metamorphic rocks, such as eclogites and blueschists. They were formed by the tectonic mixing of materials from the subducting oceanic plate and the overriding plate during subduction and exhumation processes (Volkova et al., 2008). The presence of high-pressure metamorphic blocks in serpentinite *mélanges* indicates that fragments of oceanic crust were subducted to higher depths and after exhumed during accretionary and collisional stages. These tectonic processes contributed to the structural complexity of serpentinites and caused extensive deformation and fracturing of ultramafic rocks.

After ultramafic rocks became the part of continental crust, in all three regions underwent intense hydration reactions that caused conversion of primary mantle minerals into serpentine group minerals. This serpentinization process occurs when water-rich fluids infiltrate peridotites through fractures and shear zones. Hydration reactions involve the transformation of olivine and pyroxene into serpentine minerals, brucite and magnesite goes along with the release of hydrogen. Mineral reactions also lead to extensive fracturing, which enhances fluid flow and promotes continued serpentinization. In the investigated regions, serpentinization is strongly associated with tectonic structures such as fault zones, shear zones and fracture networks that were developed during subduction and collisional tectonics. These structures provided a way for hydrothermal fluids that went through ultramafic rocks and facilitated alteration.

## **2.1 Regional Geologic Context**

The Paleozoic orogenic evolution of Kazakhstan is mostly driven by interactions between the Kazakhstan, Siberian and East European plates, which shaped two major systems, such as the Central Asian orogenic belt and the Uralian orogen. These belts contain some of the most complete ophiolitic outcrops of the Paleozoic era, including the Kempirsai massif in the southern Urals, North Balkhash and the Char ophiolite belt in eastern Kazakhstan. Both complexes expose ultramafic rocks that record distinct, yet comparable episodes of mantle melting. (Puchkov, 1997; Volkova et al., 2008; Safonova et al., 2012)

According to Puchkov (1997), the Uralian orogen represents a Late Paleozoic collisional belt formed by the oblique convergence between the Laurasian passive margin and the Kazakhstan active continental margin. The orogen is composed of six tectonic zones placed longitudinally as shown on the Fig. 2, with the Main Uralian fault highlighting the suture where serpentinite mélanges and ophiolitic thrust sheets accumulated. These serpentinite-rich units,

often derived from forearc and supra-subduction peridotites, are widespread within the Kempirsai massif, making it an ideal locality for analyzing supra-subduction zone (SSZ) type mantle residues (Puchkov, 1997)

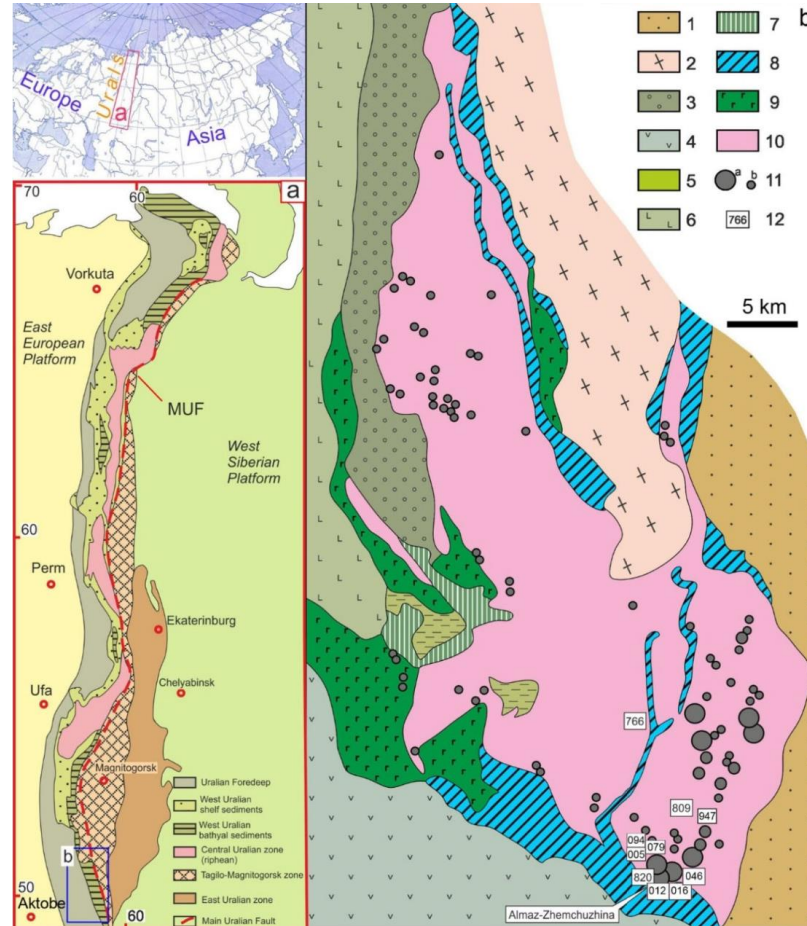


Figure 2. Kempirsai Massif map. Position of the Kempirsai ophiolite massif within Uralian fold belt (**b**): 1–6—Stratified rocks: 1—Yuzhnomugodzhary zone (basalts (S-D<sub>1</sub>, D<sub>2</sub>), flyschoids and olistostromes (D<sub>3</sub>-C<sub>1</sub>); 2—Ebeta zone (basalt-andesite-rhyodacite units, carbonaceous-silicite and greywacke formations (V?PZ<sub>1-2</sub>); 3–6—Sakmara zone: 3—basalt-andesite-dacite units, greywacke phthanite and carbonate formations (PZ<sub>1-2</sub>), 4—pillow lavas and pyroclastics of basalt-andesite-rhyodacite units with members of phtanites and clay-siliceous shales (PZ<sub>1-2</sub>), 5—phtanites and carbonaceous shales (O<sub>2</sub>), 6—tholeiite pillow basalts with

phtanite lenses (O<sub>2</sub>), 7–10—Kempirsay massif: 7—swarms of parallel diabase dykes and isotropic hornblende gabbro, 8—Kyzylkain unit of pyroxenite-gabbro rocks, 9—Kokpekta unit of olivine gabbro and troctolite, 10—upper mantle harzburgite, lherzolite and dunite, 11—chromitites (a—unique and large deposits; b—ordinary deposits and occurrences; icon size correlates with ore reserves), 12—numbers of holes from which samples were studied (unmodified copy of figure from Saveliev et al. 2022).

In contrast, the Char Ophiolite Belt forms part of the CAOBS accretionary system developed through the subduction and closure of the Paleo-Asian Ocean. As shown on the Fig. 3, the Char zone consists of multiple structural units, including olistostrome-melange complexes and tectonic parts of serpentinite melange (Volkova et al., 2008). The evolution of this zone has aligned with Late Carboniferous-Permian collision between the Siberian and Kazakhstan continents, which has resulted in the tectonic juxtaposition of island-arc, oceanic and continental fragments (Volkova et al., 2008; Safonova et al., 2012).

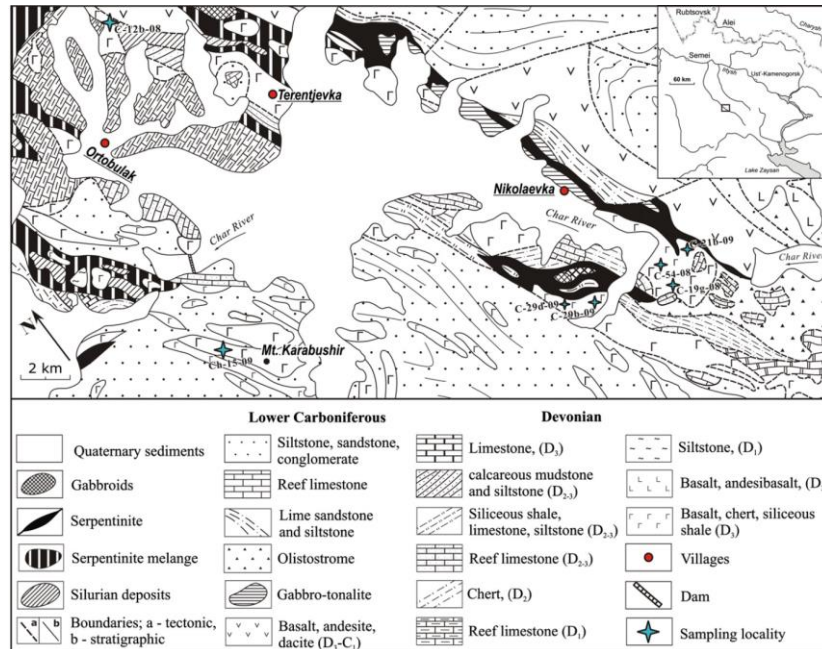


Figure 3. Char Study Area. (unmodified copy of figure 3 from Safonova et al., 2018).

The North Balkhash ophiolite zone (NBOZ) represents another major fragment of Paleozoic oceanic lithosphere within the western CAO. As shown on the Fig. 4, it forms a belt of serpentinite melange that contains blocks of residual dunite-harzburgite complexes and layered ultramafic-mafic sequences as well as chromitites, plagiogranites, eclogites and garnet blueschists (Milyukova & Skoblenko, 2022). Structurally these ultramafic blocks are interpreted as restitic mantle peridotites from the Junggar-Balkhash ocean, later incorporated into an accretionary prism, during Early Paleozoic suprasubduction tectonics (Degtyarev et al., 2021).

Thus, both Kempirsai (Uralian Orogen), Char (eastern CAO) and North Balkhash (central CAO) together formed a set of spatially separated but tectonically related fragments of Paleozoic oceanic lithosphere. Comparing their serpentinites and residual peridotites allows reconstructing changes in mantle depletion, melt extraction and refertilization across the Siberia-Kazakhstan plate boundary.

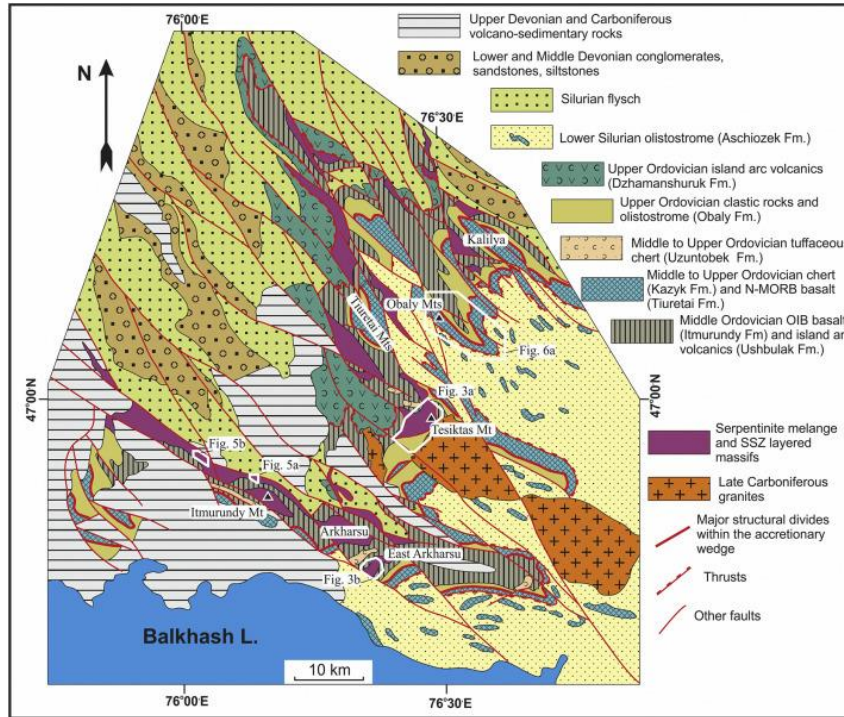


Figure 4. Geological Map of North Balkhash (unmodified copy of figure from Degtyarev et al., 2021).

## 2.2 Petrological and Mineralogical Characteristics of Regions

### 2.2.1 Kempirsai Massif

The Kempirsai massif represents one of the most chromite-rich ultramafic minerals of the southern Urals. Petrographically, the massif is mostly dominated by harzburgite, dunite and lherzolite, that were serpentinized in different ways and locally cut by chromite lenses (Saveliev et al., 2022). The mineralogy of the massif is largely residual, capturing high degrees of partial melting in a forearc or SSZ environment. The peridotites contain remains of olivine ( $Fo > 90$ ),

orthopyroxene and Cr-spinel with accessory clinopyroxene and secondary serpentine and magnetite.

Saveliev et al (2022) reported that silicate mineral compositions from lherzolites in the Kempirsai Massif are highly magnesian, and olivine Fo-and spinel Cr-values indicate strongly depleted mantle residues. Spinel compositions, particularly high Cr (0.6-0.8) and low TiO<sub>2</sub> (<0.1 wt.%), it shows the melt extraction under oxidizing conditions, which is typical of the SSZ-mantle. Chromitites that are present within the massif represent textural and compositional evidence of melt-rock interaction, suggesting the percolation of boninitic or island-arc tholeiitic melts through depleted harzburgitic residues.

The chromite-olivine-orthopyroxene mixtures provide information about mantle conditions. The Cr-Al variation in spinel correlates with the melt depletion and supports the notion that the Kempirsai peridotites are residual mantle wedge rocks, equilibrated at upper mantle pressures (10-20 kbar) and later went through a serpentinization process during exhumation (Saveliev et al., 2022). Petrographic features such as mesh textures, bastite pseudomorphs and magnetite veining indicate multiphase serpentinization during uplift, but the primary mineral chemistry remains diagnostic of forearc depletion.

### **2.2.2 Char Ophiolite Belt**

The Char ophiolite belt, in contrast to Kempirsai massif, represents a wider lithological range and a more complex metamorphic history. It contains serpentinite melanges that host blocks of harzburgite, lherzolite, gabbro, basalt and high-pressure metamorphic rocks such as eclogite and blueschist (Volkova et al., 2008). The serpentinite matrix represents hydrated

peridotite, while the enclosed HP-rocks provide direct evidence for subduction-related burial and exhumation processes.

Volkova et al. (2008) classified three main *mélange* types within the Char zone: (1) *mélanges* containing HP metamorphic blocks (type I), (2) *mélanges* with metagabbros and peridotites (type II) and (3) tectonic *mélanges* incorporating fragments of both. The HP inclusions are dated at  $\sim 450 \pm 5$  Ma (Ar-Ar ages) and display trace element patterns consistent with enriched mid-ocean rich basalt (E-MORB), normal mid-ocean rich basalt (N-MORB) and ocean island basalt (OIB) affinities, showing that the protoliths originated from a heterogeneous mantle source. Amphiboles and garnets from these rocks have Cr-poor, Al-rich compositions, which leads to derivation from oceanic crust subducted beneath an accretionary prism.

In the work by Safonova et al. (2012) identified three basaltic suites MORB-like, transitional plateau type and OIB-like revealing different types of degree of melting and enrichment, possibly reflecting plume-ridge interaction. Peridotites range from lherzolite to harzburgite, with spinel Cr# = 0.3-0.6 and TiO<sub>2</sub> up to 0.3 wt.%, representing a more fertile mantle source than Kempirsai.

### **2.2.3 North Balkhash ophiolite zone**

The ultramafic rocks of the North Balkhash ophiolite zone occur as blocks within a serpentinite *mélange* and are dominated by serpentinitized harzburgites with subordinate dunites (Milyukova & Skoblenko, 2022). Harzburgites are composed of anhedral porphyroclasts of olivine separated by smaller, stainless recrystallized olivine grains and display high modal orthopyroxene ( $\sim 10$ -26 vol%) with very low clinopyroxene contents ( $<3$  vol%). Dunites consist mainly of olivine ( $\sim 90$  vol%) with minor spinel (1-2 vol%). Primary structures show strong deformation, while secondary loop like and mesh textures reflect pervasive serpentinitization;

bastite replaces orthopyroxene and magnetite overgrows chromium spinel and filled sieve-like textures, suggesting last stage of hydration.

The mineral chemistry of non-basaltic oceanic zone (NBOZ) peridotites correlates with a strongly depleted mantle residue. Olivine is magnesian with relatively high NiO-contents (~0.39-0.40 wt.%), characteristic of mantle-derived olivine. Orthopyroxene is mainly enstatite with high Mg# (0.91-0.92) and low  $\text{Al}_2\text{O}_3$ , CaO,  $\text{TiO}_2$  and  $\text{Cr}_2\text{O}_3$ , while clinopyroxene is diopside with Mg# of 0.95-0.97 (Milyukova & Skoblenko, 2022). Chromium spinel is present as small euhedral to anhedral grains with  $\text{Cr\#} = \text{Cr}/(\text{Cr}+\text{Al}) \sim 0.63\text{-}0.67$ , very high  $\text{Cr}_2\text{O}_3$  (48-52 wt.%) and elevated FeO, corresponding to chromite-alumochromite compositions typical for residual SSZ peridotites.

### **2.3 Geochemical Signatures and Mantle Sources**

The geochemical context of both belts reveals essential differences in mantle composition and melting history. Safonova et al. (2012) showed that basalts from the Char Suture-Shear Zone display three geochemical groups distinguished by trace element and rare-earth elements (REE) patterns.

1. Group 1- MORB-like tholeiites: flat REE-profiles, low Nb- and Ti- and positive Nd-values (+7 to +9), consistent with melting of a depleted upper mantle under mid-ocean ridge or forearc conditions.
2. Group 2- Transitional basalts are moderately enriched in incompatible elements and contain lower Nd (+4 to +6), showing a lower degree of melting of a heterogeneous mantle source.

3. Group 3- OIB like basalts are strongly enriched with REE and high field strength elements HFSE with negative Nb-Ta representatives and low Nd (+1 to +3), indicating a possible plume or enriched lithospheric mantle input.

The geochemical diversity shows that the mantle beneath the Char ezone evolved from initially depleted to progressively enriched, indicating the change of geodynamic regimes from spreading ridge to plume affected back-arc. Volkova et al. (2018) further showed that HP metamorphic rocks in the Char mélange share HFSE patterns with the basalts, confirming that both derive from variably depleted oceanic crust subducted beneath an accretionary prism.

In contrast, Saveliev et al. (2022) noted that the Kempirsai peridotites show mineral chemistries matches with highly depleted mantle residues formed after extensive melt extraction. The spinel Cr# up to 0.8 and the TiO<sub>2</sub> contents suggest a melting degree of 20%, while high Mg-content in olivine and orthopyroxene (>0.9) implies equilibration with tholeiitic arc melts. The chromitites of the Kempirsai massif show a localized melt-rock interaction, where ascending melts modified residual harzburgites to dunites, precipitating Al-Cr spinels and accessory sulfides.

In the North Balkhash ophiolite zone, geochemical data from residual peridotites support a depleted mantle source modified in a supra-subduction environment. Whole rock trace-element patterns show low concentrations of incompatible elements and Ni-, Cr- and Co- contents fall within the range of depleted MORB. Combined with low modal clinopyroxene, high Mg# in olivine and pyroxenes and elevated Cr# in spinel, these features indicate partial melting of ~18-22% in forearc setting (Milyukova & Skoblenko, 2022; Degtyarev et al., 2021). The suprasubduction affinity is also reflected in high Cr spinels (Cr#>60) associated with Fo-rich olivine, comparable to peridotites from modern forearc basins.

When the Kempirsai, Char and North Balkhash are considered together, localities outline a spectrum of mantle domains from highly depleted, oxidized and chromite rich forearc (Kempirsai), through differently depleted to enriched mantle affected by plume-related magmatism, (Char), to strongly depleted, SSZ type peridotites in Balkhash that document Early Paleozoic suprasubduction in the Junggar- Balkhash ocean. This three-way comparison provides a canvas for interpreting mineral chemistry data from serpentinites in terms of both degree of depletion and tectonic position along the Paleozoic plate boundary.

#### **2.4 Mantle Behavior and Tectonic Evolution during Paleozoic**

The mantle beneath the CAOBS and the Uralian belts during the Paleozoic behaved as a dynamically heterogeneous system. In the Char ophiolite belt, different types of melting degrees and mixed MORB-OIB signatures (Safonova et al., 2012; Volkova et al., 2008) suggests that plume upwelling repeatedly rejuvenated already depleted lithospheric mantle, producing enriched and transitional basaltic magmas. The Char mantle represents a transitional domain, where plume-derived melts and subduction fluids coexisted.

In contrast, the Kempirsai mantle segment of the southern Urals represents a steady-state subduction mantle wedge. Puchkov (1997) suggested that the Uralian orogen formed during oblique convergence, with serpentinite mélanges marking deep sutures and forearc domains. The high-Cr spinel, refractory olivine and boninitic melt interactions reported by Saveliev et al., (2022) confirm that the Kempirsai peridotites are analogous to modern forearc harzburgites like those from the Izu-Bonin-Mariana arc. Mantle behavior here was dominated by dehydration, melt extraction and oxidation, resulting in highly depleted residues and Cr-rich chromitite pods.

The North Balkhash ophiolite zone preserves an earlier stage of this evolution. Residual dunite-harzburgite complexes and supra-subduction geochemical signatures indicate that the

NBOZ formed in a forearc setting above the Junggar-Balkhash subduction zone during the Early Paleozoic (Degtyraev et al, 2021; Milyukova & Skoblenko, 2022). These peridotites capture high degree melt extraction, which is possible to compare to Kempirsai, but in a different segment of the CAO, implying that strongly depleted forearc mantle domains were widespread along the Paleo-Asian ocean margins,

This comparison suggests that the Paleozoic mantle beneath Kazakhstan was heterogeneous, having evolved through one time subduction, plume interaction, and continental collision, as a result producing complex lateral variations in mantle chemistry along the Siberian-Kazakhstan boundary.

## **2.5 Petrography for Mineral Chemistry**

Petrographic assessment is a crucial step for completing the comparative mantle studies. Such assessment is applied on the serpentinite and ultramafic rocks before detailed mineral-chemical interpretation is conducted. Both the Kempirsai and Char serpentinites show extensive serpentinization, but relict textures provide information about the primary mineral assemblages. In Kempirsai, mesh and bastite textures overprint a coarse-grained harzburgitic texture, while in Char, serpentinites often show tectonic mixing of ultramafic clasts and metamorphic fragments (Volkova et al., 2008).

Petrographic evidence of Saveliev et al., (2022) suggests that in Kempirsai olivine and orthopyroxene maintain equilibrium textures, supporting minimal metasomatic modification before serpentinization. In contrast, the Char peridotites (Char Ophiolite, 2018) represent recrystallization and melt impregnation features, suggesting on the recrystallization process by mafic melts. These textural differences need to be correlated with mineral chemistry to accurately draw mantle depletion or enrichment histories.

In the North Balkhash ophiolite zone, serpentinites derived from harzburgites and dunites show a combination of deformation and hydration microstructures that are also suitable for petrographic chemical coupling. Large, deformed olivine porphyroblasts are surrounded by strainless neoblasts, indicating high temperature solid state flow prior to serpentinization. Mesh and loop textures in serpentine, bastite pseudomorphs after orthopyroxene and magnetite overgrows around chromian spinel record multistage hydration and oxidation (Milyukova & Skoblenko, 2022). These textures together with mineral chemistry can be used to assess how deformation, melt extraction and fluid percolation interacted during the evolution of the NBOZ mantle section.

## **2.6 Research Gaps and Objectives**

Despite significant progress in regional petrology and geochemistry, only a limited number of studies have conducted a direct comparative analysis of serpentinites from the Kempirsai massif, the Char ophiolite belt and the North Balkhash ophiolite zone using a consistent methodological approach. Existing research mainly focuses on whole rock geochemistry or high pressure metamorphic compositions. Mineral scale and textural data are often neglected or studied separately. This leads to several important gaps:

1. Direct comparison between these regions does not exist. Even if the ophiolitic belt has been studied individually, there is a lack of integrated studies that compare mineralogical composition, textures and degree of serpentinization of all three regions using the same analytical approach.
2. Connection between petrography and mineral chemistry is not fully developed. Petrographic analysis commonly describes textures such as mesh, fibrous and foliated serpentinite, but these observations are rarely combined for mineral data. A study that uses both textural

observations with mineralogical and chemical analyses would provide a clearer interpretation of the serpentinization process.

By using an approach that combines field observations, petrographic analysis with their mineralogy contributes to a better understanding of serpentinization processes in different tectonic settings. The results help to differentiate between partially preserved mantle derived ultramafic rocks and highly altered serpentinites.

The major objectives of this study are:

1. To collect serpentinite samples from three designated study areas: the Kempirsai massif, the Char ophiolite belt, and the North Balkhash ophiolite zone.
2. To understand the mineralogy and the various textures in the serpentinite through petrographic analysis.
3. To compare and contrast mineralogy and textural characteristics of the serpentinite samples to deduce their difference.

### **3. Methodology**

This study was aimed to investigate and compare the petrographic characteristics of serpentinites from three different ultramafic complexes in Kazakhstan: the Kempirsai massif, the Char ophiolite belt and the North Balkhash ophiolite zone. The research is focused on identifying differences in mineral composition, alteration patterns and textural features that developed during serpentinization.

The methodological workflow of this study included four main stages. First, representative serpentinite samples were selected during the fieldwork in three study areas. Second is petrography that includes using a polarizing microscope in order to identify mineral

composition and texture from thin sections. Third, XRD analysis was carried out to confirm the mineral composition of the samples. As the last part of analysis, selected thin sections from each region were analyzed by SEM to obtain detailed information on mineral chemistry and exact mineral composition based on microscopic image. Together these methods provided information for interpretation the processes responsible for serpentinization and the differences between serpentinites from three regions.

### **3. 1 Fieldwork and Sample Collection**

Fieldwork was conducted in three geological regions of Kazakhstan that host ultramafic rocks associated with ophiolite complexes. These three representative regions are : the Kempirsai massif, the Char ophiolite belt and the North Balkhash ophiolite zone. These regions represent fragments of oceanic lithosphere that were part of the evolution of Paleo-Asian ocean and the formation of the Central Asian orogenic belt.

The purpose of the fieldwork was to collect representative serpentinite samples and document the geological setting of sampled rocks.



Figure 5. Serpentinite exposures around Mt. Itmurandy, North Balkhash.

Representative rock samples as shown on Fig. 5, 6 and 7 were collected from different outcrops in each region to identify different types of serpentinite textures. During sampling, key field observations were recorded to have an information on the geological context of each sample. These observations included general appearance of the outcrop and visible structural features. All collected samples were labeled in the field and later used for laboratory analysis to get further information based on them.



Figure 6. Serpentinites exposures at Char village, Char ophiolite belt.



Figure 7. Serpentinite exposure inside a chromite mine, Chromtau, Kempirsai massif.

### 3. 2 Petrographic Analysis

Petrographic analysis was conducted by using an optical polarizing microscope in transmitted light at the petrological microscope lab in the School of Mining and Geosciences as shown on the Fig. 8. Thin sections prepared from collected samples were examined under plane-polarized light. Observations under plane-polarized light allow to identify color, relief and alteration features of a mineral. Cross-polarized light was used to observe birefringence, interference colors and extinction patterns which are crucial for mineral identification. By using these two observation models, it allowed to obtain a more complete characterization of mineral and textures.



Figure 8. Polarizing microscope.

The petrographic analysis focused on identifying the dominant serpentine minerals and determining preserved primary mantle minerals or replaced during serpentinization. Several

types of serpentinization textures were examined. Mesh textures commonly formed by replacement of olivine as well as fibrous serpentine crystals which form by network interlocking. Vein structures were also examined as they reflect the movement of hydrothermal fluids through fractures in the rock. Deformation features were also examined as in some thin sections serpentine minerals show a shape preferred orientation which forms a weak foliation. They may indicate deformation during or after serpentinization and can provide information about the possible tectonic history of the ultramafic rocks. Observations from the petrographic studies are included in the results.

### **3. 3 X-Ray Diffraction Analysis**

X-Ray diffraction (XRD) analysis was conducted to determine mineralogical composition of the serpentine samples and to support the data carried out by other methods. XRD is an analytical technique for identifying crystalline phases in rocks and is very useful for distinguishing minerals that are difficult to differentiate by using optical microscopy.

For this analysis, selected serpentine samples from the studied areas were crushed and grounded into fine homogeneous powder. This powder was further analyzed with an X-ray diffractometer. During this analysis, X-rays interact with the crystal lattice of the minerals present in the sample, producing patterns characteristic of specific crystalline phases. The analysis was done in the Sample Solution Laboratory, in Wuhan, in China and the results are presented in Section 4.

### **3. 4 Scanning Electron Microscopy Analysis**

Selected samples were also examined using scanning electron microscopy (SEM) coupled with energy dispersive spectrometry (EDS) to get higher resolution information on

mineral composition with high resolution images (Fig. 9). One representative thin section from each study area was selected for the analysis based on the preservation of serpentinization features. The analytical conditions were as follows: the acceleration voltage was 15kV, the working distance 10 mm, and the probe current 60 pA.

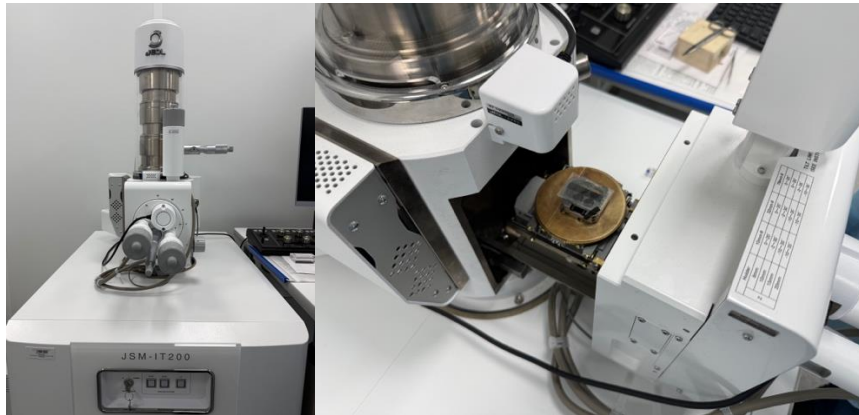


Figure 9. The SEM machine used in our studies.

Prior to SEM analysis, the thin sections were cleaned and coated with a thin conductive carbon layer (Fig. 10). They are layered with carbon layer in order to ensure proper imaging and results. SEM analysis was conducted to obtain higher quality petrographic analysis. It provided detailed imaging of mineral phases.



Fig 10. Sputter Machine for carbon coating

Chemical composition of two thin sections was identified with the help of this method. Point analyses were performed to obtain the major element composition of both silicate and opaque phases. This analysis provided an important link between petrographic observations and mineralogical interpretation.

## **4. Results**

### **4.1 Kempirsai Massif**

#### **4.1.1 Petrographic Analysis Kempirsai Region**

Eight thin sections from the Kempirsai massif were studied, namely section number 40, 42, 47, 49, 51, AKM-1, AKM-2 and AKM-3. The Kempirsai samples display advanced serpentinization, but are distinguished by the widespread development of vein-dominated textures, and locally better preservation of relict olivine. In these samples, olivine occurs as subhedral to anhedral grains (Fig.11). In some cases, olivine is preserved as isolated fragments enclosed within serpentine-rich zones or intersected by veins, reflecting progressive replacement. Minor pyroxene relics are locally present, typically occurring near opaque minerals or at the margins of altered domains, but are significantly less abundant than olivine.

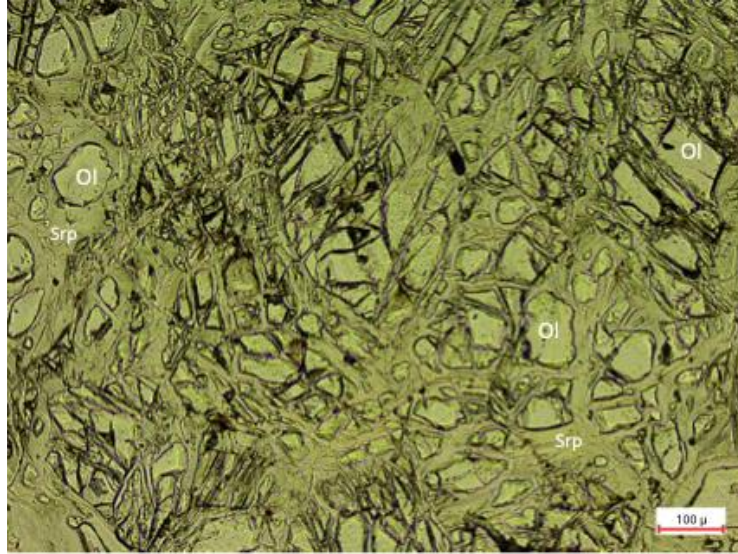


Figure 11. Olivine grains (Sample 40). Srp=serpentine, Ol=olivine.

Serpentinite textures in the samples of the Kempirsai massif range from well-developed mesh structures to massive and fibrous. In many thin sections, mesh structures are partially preserved, whereas in others they are completely overprinted by fine-grained serpentine. Fibrous to platy serpentine commonly forms elongated, interconnected networks and in some samples these minerals show a degree of alignment, producing a weakly developed planar fabric,

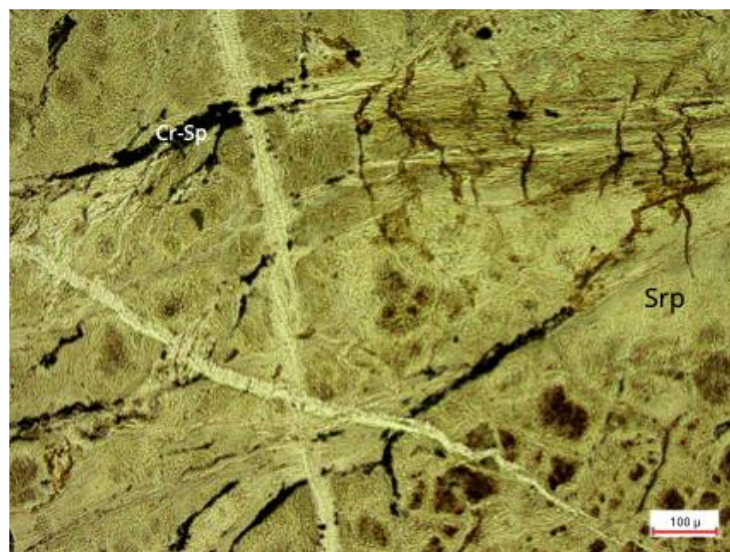


Figure 12. Vein structure (Sample AKM3). Srp=serpentine, Cr-Sp= Cr-spinel.

A defining feature of the Kempirsai serpentinites is the abundance and scale of veins that forms during serpentinization process (Fig. 12, 13). These veins vary from thin, fracture-controlled features to thick irregular bands that locally dominate the rock fabric. Veins commonly cross-cut both primary and secondary textures.

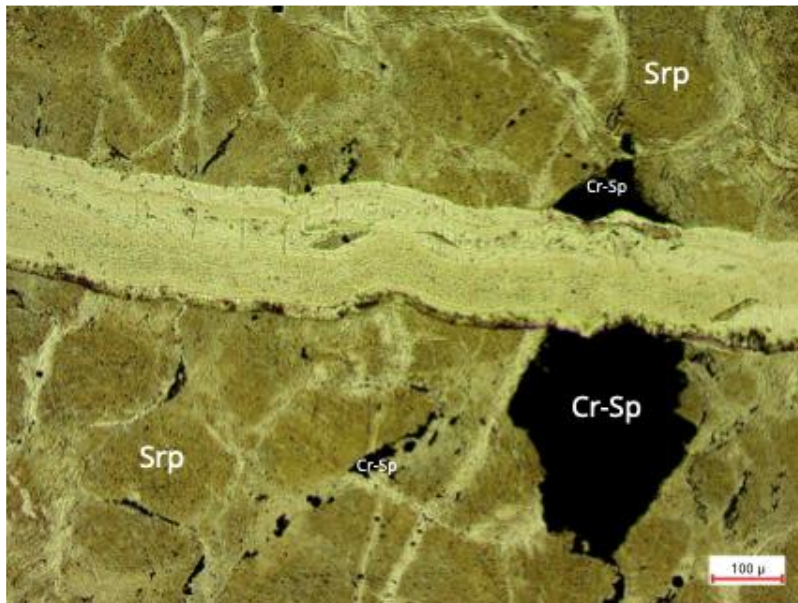


Figure 13. Serpentine vein (Sample AKM3). Srp=serpentine, Cr-Sp= Cr-spinel.

Opaque minerals are present in all Aktobe samples as euhedral to anhedral grains distributed throughout the matrix along veins (Fig.14). These grains are commonly unaffected by serpentinization and occur both as isolated and as clustered crystals. In addition, dark spots occur as isolated crystals and as clusters. And dark spots are locally observed in association with serpentine-rich zones and veins. These phases show no interference colors and occur intergrown with serpentine. Brownish to reddish domains identified as rutile are also present and are typically associated with fractures and alteration zones.

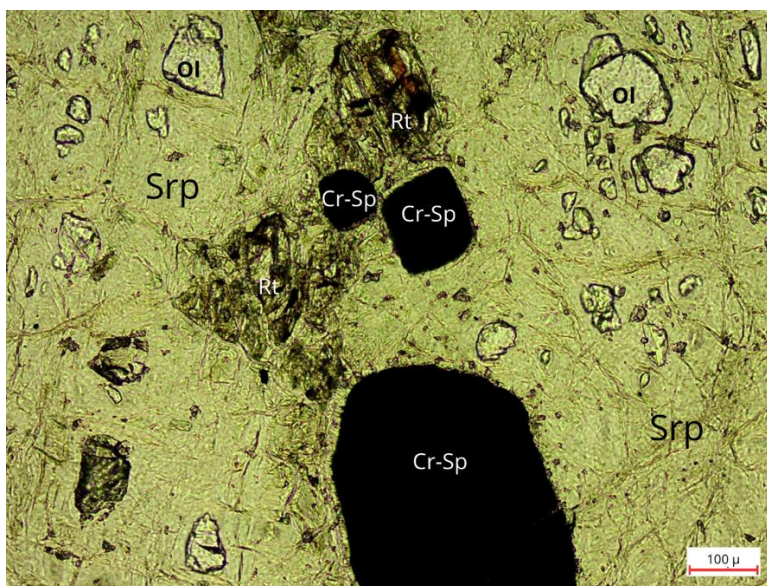


Figure 14. Opaque minerals (Sample 49). Srp=serpentine., Rt=rutile, Cr-Sp= Cr-spinel, Ol=olivine.

Across the Kempirsai region, the degree of serpentinization is consistently high. Some samples retain well-defined mesh textures with recognizable olivine, whereas others are completely recrystallized into massive or foliated serpentine with no identifiable primary minerals. In all cases, serpentine group minerals constitute the dominant phase, and primary silicates are either partially or completely replaced.

#### 4.1.2 SEM Analysis of Sample 49 (Kempirsai massif)

SEM analysis of representative sample 49 from the Kempirsai massif show a complex mineralogical composition. The analyzed points indicate the presence of Mg-rich silicates, Cr-rich spinel, Fe-rich phases and locally Ca-bearing silicate material. Images show strong compositional contrast between different phases, reflecting mineralogical heterogeneity in the sample.

The silicate phases have a high MgO and SiO<sub>2</sub> contents, consistent with Mg-rich mantle derived minerals and serpentized phases (Table 1). Several analyses show MgO values in the range approximately 51-53 wt.% and SiO<sub>2</sub> values around 41-42 wt.%, with relatively low FeO contents of 4-6 wt.%

| Spot    | MgO (wt.%) | SiO <sub>2</sub> (wt.%) | FeO (wt.%) |
|---------|------------|-------------------------|------------|
| Spc_010 | 52.5       | 41.91                   | 5.59       |
| Spc_009 | 53.48      | 42.38                   | 4.14       |
| Spc_008 | 51.41      | 42.31                   | 6.29       |
| Spc_007 | 52.45      | 42.05                   | 5.5        |
| Spc_006 | 52.14      | 41.7                    | 6.16       |
| Spc_004 | 52.14      | 42.09                   | 4.77       |
| Spc_012 | 52.04      | 41.77                   | 6.19       |

Table 1. SEM-EDS analyses of Sample 49, Kempirsai Massif.

The compositions are typical of Mg-rich silicate phases such as serpentinite and can also reflect partially preserved olivine compositions. These analyses show consistent Mg-Si ratios with a more uniform silicate matrix (Fig. 15).

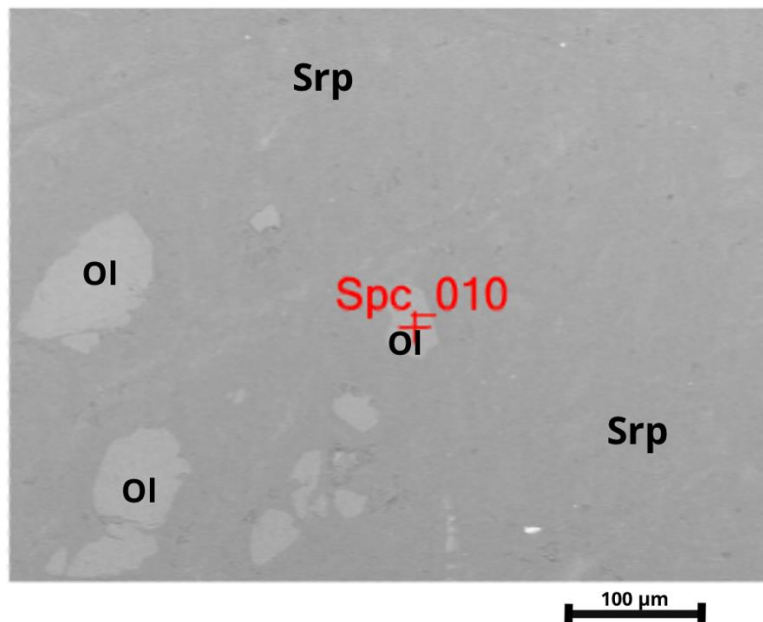


Figure 15. Representative olivine from Kempirsai sample 49 around the spot Spc\_010.

Srp=serpentine., Ol=olivine.

In addition, one analyzed point (Spc\_015) (Fig. 16) shows a distinct Ca-bearing composition, with 57.55 wt.% SiO<sub>2</sub>, 23.88 wt.% MgO and 18.58 wt.% CaO. This composition differs significantly from the serpentinite matrix and likely represents a secondary Ca-bearing phase at localized compositional difference associated with the alteration process. Clinopyroxene was found at that spot, and it led to a new finding about the composition of the rock. Since clinopyroxene is present in it, this rock is wehrnite.

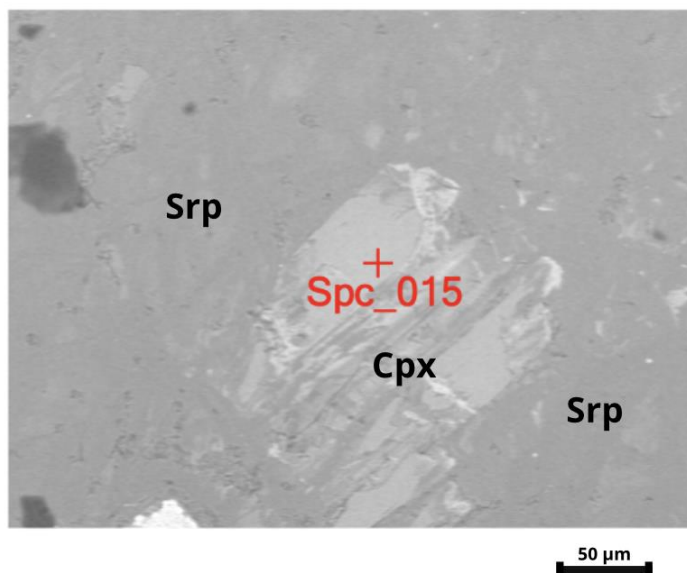


Figure 16. Representative clinopyroxene from Kempirsai sample 49 around spot Spc\_015. Srp=serpentine., Cpx=Clinopyroxene.

The opaque minerals in this sample show two distinct compositional types. The first type is represented by Cr-rich spinel group minerals, described by high  $\text{Cr}_2\text{O}_3$  contents of approximately 57 wt.% along with FeO (~ 24 wt.%) and minor  $\text{Al}_2\text{O}_3$  and MgO. These compositions are consistent with chromite or Cr-spinel minerals.

| Spot    | Cr <sub>2</sub> O <sub>3</sub> (wt.%) | FeO (wt.%) | Al <sub>2</sub> O <sub>3</sub> (wt.%) | MgO(wt.%) |
|---------|---------------------------------------|------------|---------------------------------------|-----------|
| Spc_003 | 57.22                                 | 24.41      | 9.27                                  | 9.09      |
| Spc_002 | 57.32                                 | 24.54      | 8.89                                  | 9.26      |

Table 2. SEM-EDS analyses of Sample 49, Kempirsai Massif

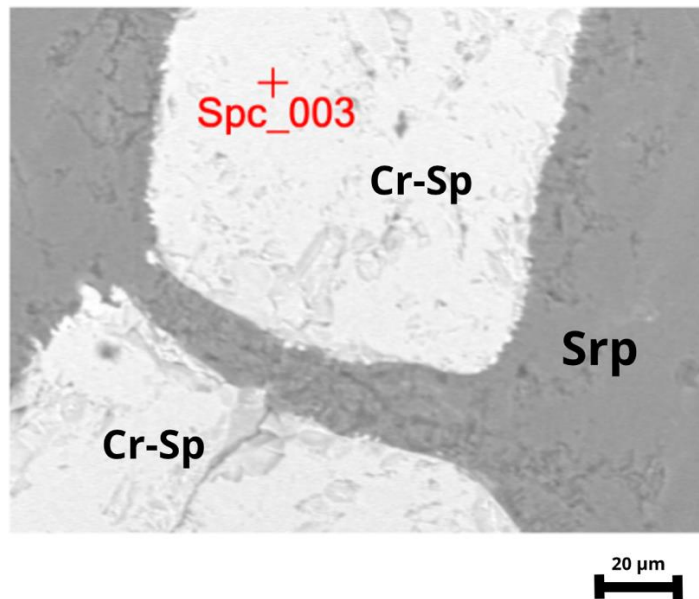


Figure 17. Representative Cr-spinel from Kempirsai sample 49 around spot Spc\_003.

Srp=serpentine, Cr-Sp= Cr-spinel.

A second type of opaque phase is represented by Fe-dominated compositions. One analyzed point (Spc\_001) shows 61.99 wt.% FeO, 32.84 wt.% MgO, 2.21 wt.% Cr<sub>2</sub>O<sub>3</sub> and 2.96 wt.% SiO<sub>2</sub>. This composition suggests Fe-rich phase with minor chromium, possibly representing altered spinel or Fe-rich oxide material.

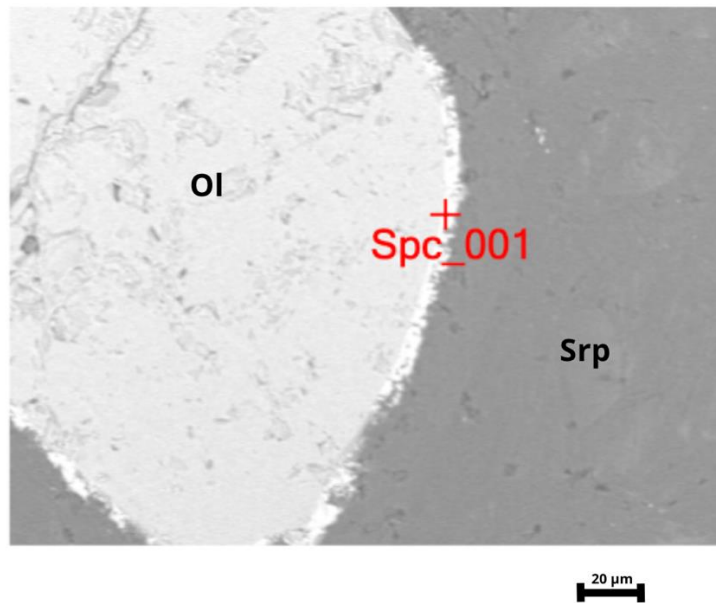


Figure 18. Representative olivine from Kempirsai sample 49 around spot Spc\_001.

Ol=olivine, Srp=serpentine.

SEM imaging shows that the silicate matrix is relatively uniform and fine-grained, while opaque minerals appear as bright and well-defined grains within the matrix. The SEM results indicate that the Kempirsai sample preserves a more diverse mineral composition with Mg-rich silicates, Cr-rich spinel, Fe-rich phases and locally Ca-bearing mineral. Well-defined Cr-rich spinel and consistent Mg-rich silicate compositions suggests a better preservation of primary mantle minerals.

#### 4.1.3 XRD Results- Kempirsai Massif Samples

X-ray diffraction analysis of Kempirsai serpentinite samples shows that all samples are strongly dominated by serpentinite minerals, primarily lizardite. The diffraction patterns are

characterized by a very intense basal reflection at  $\sim 7.3 \text{ \AA}$  ( $\sim 12^\circ 2\theta$ ), which is typical for lizardite and shows an extensive serpentinization of the ultramafic protolith.

Quantitative phases identification shows that lizardite is the main minerals phase in all samples and ranges approximately from 76.6% to 93.5%. The high amount of lizardite in samples suggests a continuous alteration and most likely homogeneous serpentinization conditions in the Kempirsai massif.

Minor amounts of forsterite ( $\text{Mg}_2\text{SiO}_4$ ) are present in all samples, and they range from  $\sim 6\%$  to  $15\%$ . The presence of forsterite indicates the partial preservation of the original ultramafic composition, suggesting that serpentinization was not complete and relic olivine remains in the rock, like observed in the petrography.

In some samples as AKM-2 and AKM-3, talc ( $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$ ) is identified in small amounts of  $\sim 3\text{-}4\%$ . It reflects localized silica-rich alteration conditions. In AKM-1  $\sim 12.6\%$  of pyroxenite was observed and it indicates the formation of secondary Mg-Fe hydroxide phases during alteration.

All diffraction patterns show consistent peak positions, mostly at  $\sim 24\text{-}25^\circ 2\theta$  and  $\sim 35\text{-}37^\circ 2\theta$ , which corresponds to lizardite reflections. It basically confirms its mineralogical homogeneity across the samples. No significant peaks corresponding to primary pyroxene were observed, indicating their almost complete replacement during serpentinization.

Overall, the XRD results demonstrate that the Kempirsai samples are highly serpentinized ultramafic rocks. They are dominated by lizardite with minor amount of forsterite and accessory minerals as talc and pyroxenite. The similarity of each samples in mineral composition suggests similar alteration conditions across the samples locations.

## 4.2 Char Ophiolite Belt

### 4.2.1 Petrographic Analysis Char Region

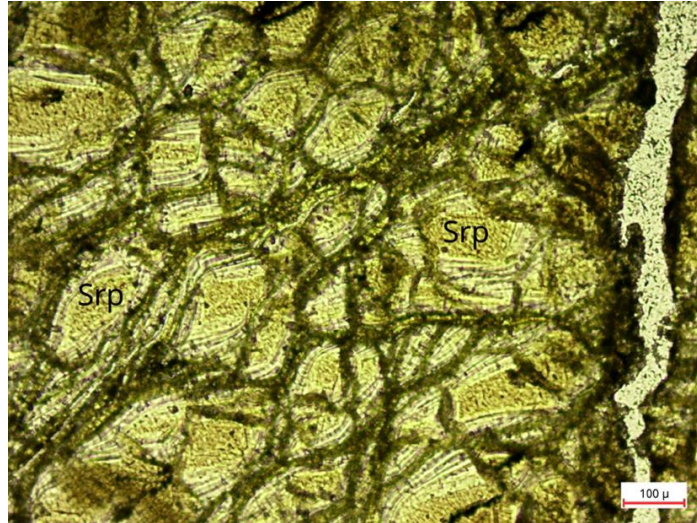


Figure 19. Mesh texture serpentinite (Sample GK2507\_24).

Four thin sections from the Char ophiolite belt were investigated during petrography with samples GK2507, GK2508, GK2509 and GK2511. Serpentine in the Char samples occur in a range of textural forms. Mesh textures are common where olivine is well preserved (Fig.19), while fibrous to bladed serpentinite form a well-developed foliation, producing a planar fabric defined by elongated or platy crystals. In other cases, the texture is mostly massive, with no clear preservation of primary structures (Fig. 20). It is common for different textures to coexist within a single thin section.

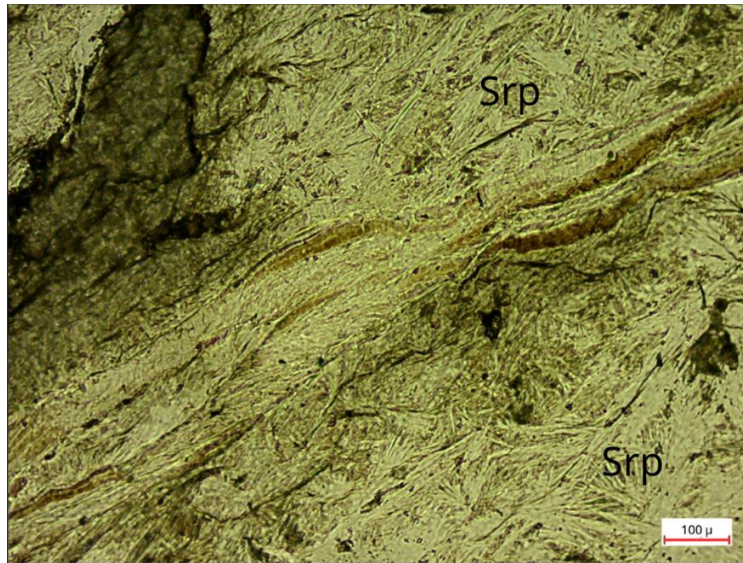


Figure 20. Fibrous texture (Sample GK2511(2)). Srp=serpentine.

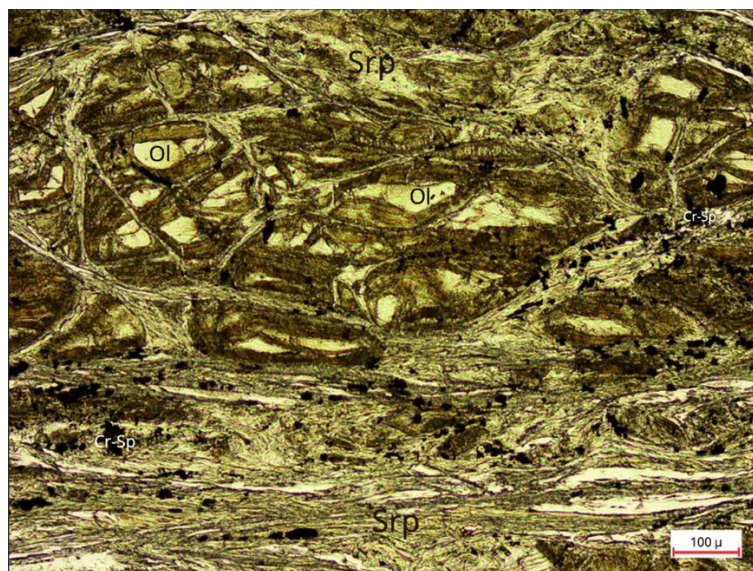


Figure 21. Preserved olivine grains (Sample GK2508). Ol=olivine, Srp=serpentine.

Deformation features are noticeable in a couple of Char samples. These are expressed as a well-developed foliation defined by the preferred orientation of serpentinite minerals as well as the presence of lens shaped domains. Opaque minerals are frequently concentrated along

foliation planes and microfractures, showing the planar fabric (Fig. 21, 22, 23). Cross cutting serpentinite veins are also abundant and occur as thin fractures, irregular vein networks and locally interconnected systems.

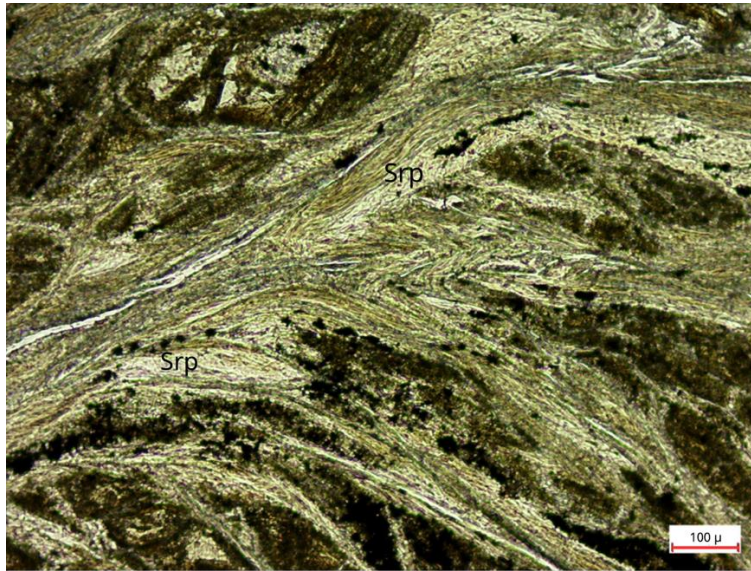


Figure 22. Foliated texture (Sample GK2508). Srp=serpentinite.

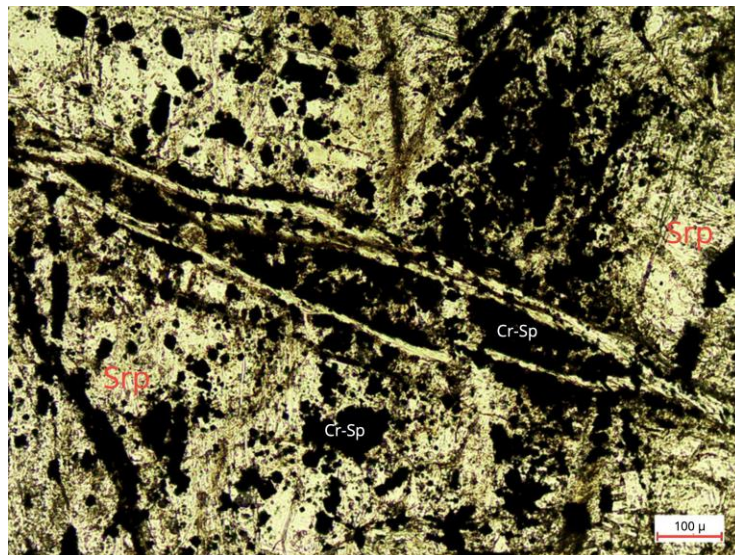


Figure 23. Veins (Sample GK2509)

#### 4.2.2 Sample GK2508 (Char ophiolite belt)

The SEM analyses of sample GK2508 show presence of Mg-Si silicate material and opaque Fe-Cr bearing spots. Images show clear contrast between the darker silicate matrix and brighter opaque grains, suggesting compositional heterogeneity in the sample. The silicate parts are characterized by high MgO and SiO<sub>2</sub> contents, consistent with serpentinite group minerals. Representative analyses show MgO values ranging from 48.21 to 49.95 wt.% and SiO<sub>2</sub> values between 50.05 and 50.59 wt.%, with only minor Al<sub>2</sub>O<sub>3</sub> present (Table 3.).

| Spot    | SiO <sub>2</sub> (wt.%) | MgO (wt.%) | FeO (wt.%) | Al <sub>2</sub> O <sub>3</sub> (wt.%) |
|---------|-------------------------|------------|------------|---------------------------------------|
| Spc_011 | 50.05                   | 49.95      | -          | -                                     |
| Spc_009 | 50.59                   | 48.21      | -          | 1.2                                   |

Table 3. SEM-EDS analyses of Sample GK2508, Char Ophiolite

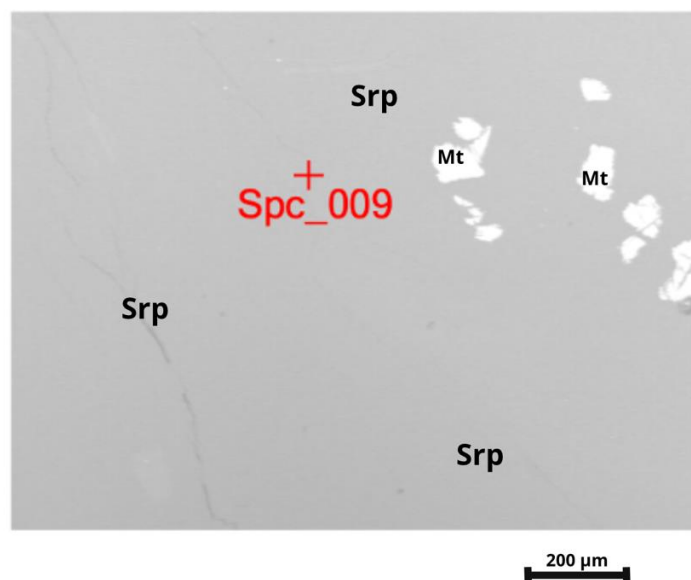


Figure 24. Representative serpentine spot Spc\_009 from sample GK2508 from the Char region. Srp=serpentine, Mt=magnetite.

These compositions are typical of Mg-rich serpentinite minerals formed during the hydration of ultramafic rocks. The absence of Fe-rich silicate compositions and the lack of olivine like chemistry in the analyzed points, indicates that the primary mantle minerals have been replaced (Fig. 25). Also, several more analyses show  $\text{Al}_2\text{O}_3$  contents of 15.22-16.72 wt.%, MgO-values of 40-42 wt.% and  $\text{SiO}_2$ -values of around 37 wt.% (Table 4).

| Spot    | FeO (wt.%) | SiO <sub>2</sub> (wt.%) | MgO(wt.%) | Al <sub>2</sub> O <sub>3</sub> (wt.%) |
|---------|------------|-------------------------|-----------|---------------------------------------|
| Spc_004 | 5.46       | 37.32                   | 40.5      | 16.72                                 |
| Spc_005 | 4.99       | 37.76                   | 42.03     | 15.22                                 |

Table 4. SEM-EDS analyses of Sample GK2508, Char Ophiolite.

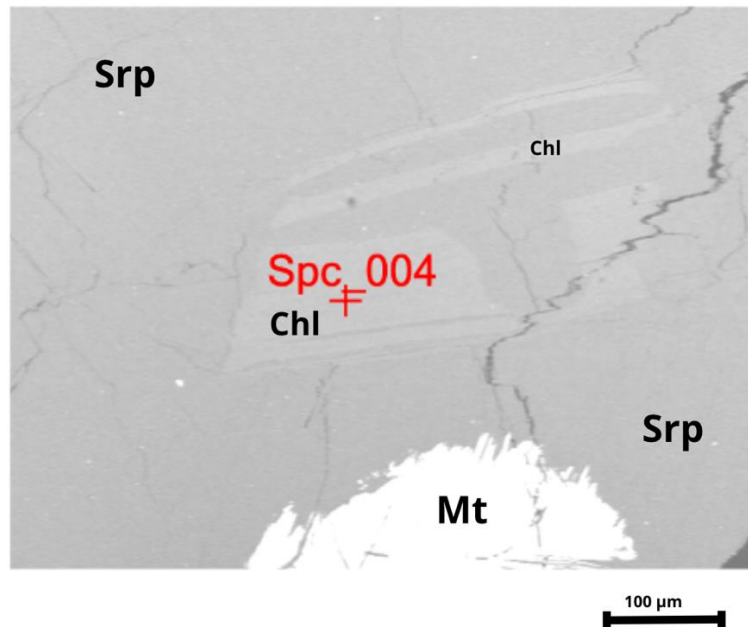


Figure 25. Representative chlorite spot Spc\_004 from sample GK2508 from the Char region. Srp=serpentine, Mt=magnetite, Chl=chlorite.

The presence of elevated  $\text{Al}_2\text{O}_3$  in these spots shows chemical variability within the serpentinite matrix and suggests interaction with fluids during alteration (Fig.26). The opaque parts are strongly dominated by iron, with FeO contents ranging from 88.69 to 98.48 wt.% and contain minor amounts of  $\text{Cr}_2\text{O}_3$  and MgO (Table 5).

| Spot    | Feo (wt.%) | Cr <sub>2</sub> O <sub>3</sub> (wt.%) | MgO (wt.%) |
|---------|------------|---------------------------------------|------------|
| Spc_002 | 90.19      | 7.41                                  | 2.4        |
| Spc_012 | 90.72      | 7.19                                  | 2.1        |
| Spc_010 | 88.69      | 8.91                                  | 2.4        |
| Spc_008 | 93.79      | 4.46                                  | 1.75       |
| Spc_003 | 94.18      | 4.13                                  | 1.7        |

|         |       |   |      |
|---------|-------|---|------|
| Spc_006 | 98.48 | - | 1.52 |
|---------|-------|---|------|

Table 5. SEM-EDS analyses of Sample GK2508, Char Ophiolite

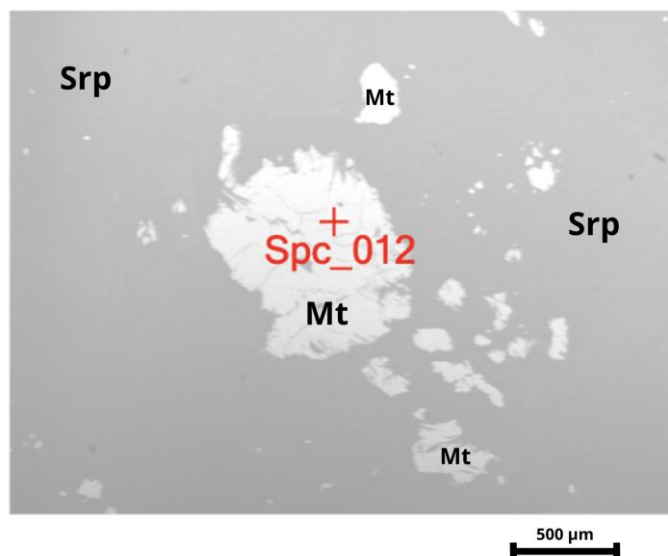


Figure 26. Representative magnetite spot Spc\_012 from sample GK2508 from the Char region. Srp=serpentine, Mt=magnetite.

These compositions show Fe-rich opaque minerals with little amounts of chromium content. Compared to typical chromite compositions, the relatively lower  $\text{Cr}_2\text{O}_3$  and high FeO values suggest modification of primary spinel phases during alteration.

SEM imaging shows that the silicate matrix consists of fine-grained material with relatively uniform contrast while opaque phases are bright, irregular grains distributed through the matrix. In several areas, opaque minerals are close to microfractures and boundaries between altered zones. It indicates that fluid pathways played an important role in their formation and distribution.

Overall, the SEM result of this region is strongly dominated by serpentinite minerals and Fe-rich opaque phases with no clear preservation of primary mantle silicate compositions. The

chemical variability observed in both silicate and opaque phases reflects the heterogeneous composition of the alteration processes.

#### **4.2.3 XRD Results- Char Samples**

Char region samples show that all of them are dominated by lizardite, showing that serpentinite minerals form the key component of the studied rocks. Strongest basal reflection occurs at about 7.28-7.30 Å ( $\sim 12^\circ 2\theta$ ) and it shows a high degree of serpentinization. Additional strong reflections near 3.62-3.65 Å and 2.5-2.52 Å are also consistent with the lizardite phase and appear in all samples.

The simplest mineralogical composition belongs to GK2511 with 97.19% of lizardite and 2.81% magnetite, showing that this sample is strongly serpentinized and relatively uniform. The very high lizardite content and only little amount of magnetite suggest extensive replacement of the original ultramafic minerals with little preservation.

Sample GK2507 is also dominated by lizardite with about 91.51%, but is different from sample GK2511 by the presence dolomite of  $\sim 5.09\%$  and magnetite  $\sim 3.39\%$ . The presence of dolomite suggests localized carbonate formation. Magnetite was most likely formed during iron redistribution associated with change of composition.

Samples GK2508 and GK2509 are slightly more complex in composition compared to the previous two samples. In these samples, lizardite is the most common mineral with contents of about 85.57% in sample GK2508 and 84.77% in sample GK2509. Both samples also contain tridymite as a secondary mineral, reaching about 10.6% in GK2508 and 11.79% in GK2509. Also, with little magnetite amount of 3.82% and 3.44% respectively. The presence of tridymite

indicates silica enrichment in both samples and suggests some local chemical change during or after serpentinization.

Char region samples are all strongly serpentinized and dominated by lizardite, but they show mineralogical diversity. Some samples as GK2511 represents a nearly pure lizardite serpentinite with minor magnetite, GK2507 contains carbonate in form of dolomite and GK2508-GK2509 show silica related secondary minerals represented by tridymite.

### **4.3 North Balkhash**

#### **4.3.1 Petrographic Analysis Balkhash Region**

The thin section from sample GK2516 from the Balkhash regions is characterized by abundant fibrous and lath-shaped, dense and intertwined serpentinite. The serpentine occurs as elongated blades and clusters, locally forming fan-like structure (Fig. 27). These textures suggest extensive replacement of primary ultramafic minerals, most likely olivine.

A large central opaque area appears completely black under transmitted light, indicating an opaque mineral. This region is irregular in shape and surrounded by dense packed serpentinite fibers, indicating spatial association between chrome spinel formation and serpentinization.

The matrix shows a typical mesh texture, with polygonal outlines of olivine grains. Chrome spinel is characterized as fine and irregular scattered across the section.

High degree of serpentinization with well-developed fibrous serpentine texture and chrome spinel can be observed on this thin section spot.

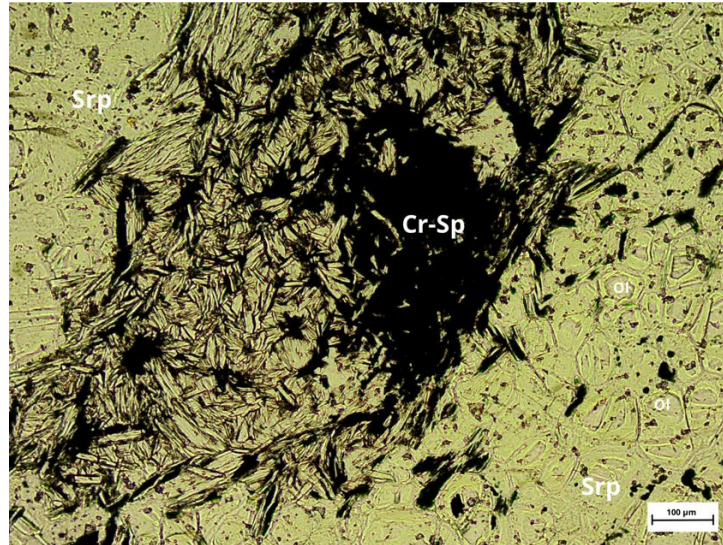


Figure 27. Thin section of Balkhash serpentinite (Sample GK2516). Srp=serpentine, Cr-Sp= Cr-spinel, Ol=olivine.

The next thin section from Balkhash area is dominated by mesh- like texture with clear opaque mineral surrounded by serpentine. Olivine has been largely replaced by serpentine minerals, forming an irregular shape as mesh boundaries. Fibrous serpentine suggests recrystallization during alteration within the rock.

An opaque mineral observed in the thin section is labeled as a chrome spinel, and it appears completely black under the transmitted light. Smaller parts of chrome spinel grains are distributed throughout the matrix. The brownish area is identified as orthopyroxene. It shows an irregular and patchy textures. No well-preserved primary silicate minerals are visible; it suggests a high degree of alteration. The overall texture and mineral composition are consistent with strongly serpentinized ultramafic rock (Fig. 28).

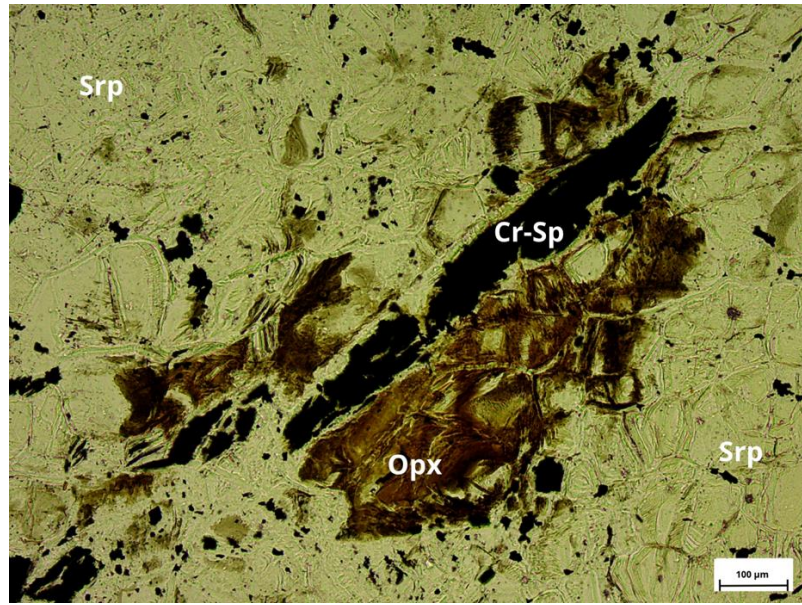


Figure 28. Thin section of Balkhash serpentinite (Sample GK2516). Srp=serpentine, Cr-Sp= Cr-spinel, Ol=olivine, Opx=orthopyroxene.

#### 4.3.2 XRD Results- North Balkhash Samples

X-ray diffraction analysis of the Balkhash region samples shows that both samples are strongly dominated by serpentinite minerals, mostly with lizardite. In both diffraction patterns, the most important reflection occurs at about  $\sim 7.26\text{-}7.29 \text{ \AA}$  ( $\sim 12^\circ 2\theta$ ), which is characteristic of lizardite and shows that these rocks are highly serpentinitized.

The mineral composition of sample GK2516B is represented as the simplest and has its mineral uniformity at its peak. Mineralogical phase analysis results show that the composition consist of 99.21% lizardite containing aluminum and only about 0.79% magnetite. Given the presence of lizardite in the composition in the sample without any other silicate minerals, it suggests that the rock sample has undergone strong alterations due to metamorphism. Also, most of the original minerals have undergone through replacement reactions.

Sample GK2516A also contains lizardite as the dominant mineral, but its mineralogical composition is more diverse compared to previous sample. About 88.37% lizardite with clinochlore of ~6.62% and magnetite of ~5%. Compared to previous sample, this one contains a slightly more complex secondary mineral composition. The presence of clinochlore suggests localized chlorite composition or bulk chemistry. The higher magnetite content also indicates stronger development of iron oxide in this sample.

These results show that the Balkhash samples are dominated by lizardite and shows a high degree of serpentinization. However, small differences between two samples suggest minor local difference in alteration within the Balkhash area.

## **5. Discussion**

Results obtained from the fieldwork, petrographic, XRD and SEM analyses allowed to have a direct comparison of three regions: the Kempirsai massif, the Char ophiolite belt and the North Balkhash ophiolite zone. Fieldwork involved sampling of ultramafic outcrops representing different structural settings. Rock samples were selected based on the visible visual similarity and identifiable composition to original serpentinite rocks. Petrographic analysis of thin sections which were made from collected rocks from the field confirmed that all samples are strongly serpentinized, but with clear difference in preservation. The Kempirsai samples contained olivine and locally pyroxene in mesh and vein- dominated textures, while Char and Balkhash samples are dominated by fibrous, mesh and foliated serpentine with almost complete replacement of primary minerals. XRD analysis of powdered samples was used to identify crystalline phases and shows that all regions are dominated by lizardite. The Kempirsai samples contains minor forsterite (up to ~15%), indicating incomplete serpentinization. Samples from the Balkhash area contained up to ~99% lizardite and samples from the Char belt represent more advanced

alteration with additional secondary minerals such as magnetite, clinochlorite and tridymite, reflecting localized chemical processes. SEM analysis provided mineral-scale chemical composition and confirmed all observation made before. Sample 49 from Kempirsai shows Mg-rich silicate compositions consistent with partially preserved mantle minerals. Cr-rich spinel and importantly a Ca- bearing phase identified as clinopyroxene, allowed to classify this rock as wehrlite. Samples from the Char are characterized as uniform Mg-Si serpentinite compositions and Fe-rich altered spinel phases, suggesting complete replacement of primary silicates. The combined dataset shows that Kempirsai preserves primary mantle characteristics and incomplete serpentinization, whereas Char and Balkhash have higher degrees of alteration.

One of the primary findings is identification of sample 49 from the Kempirsai massif as wehrlite. Fieldwork, petrographic and XRD analyses did not show this fact and only with the help of SEM analysis such finding was discovered.

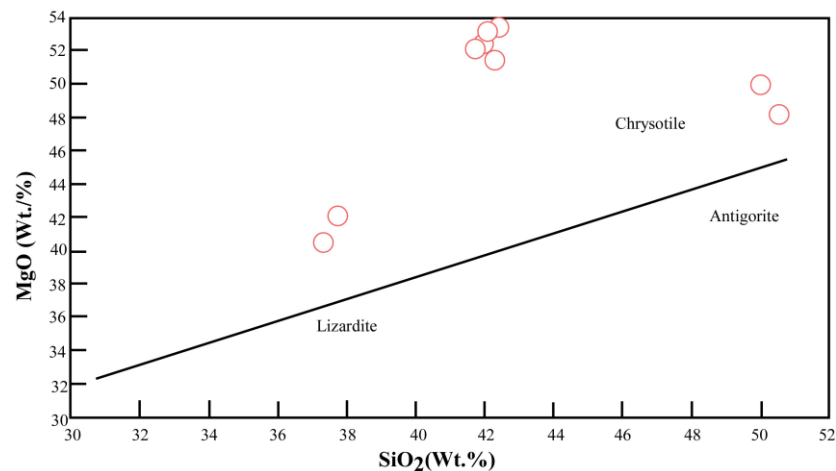


Figure 29. Composition of serpentinite from the SEM data from representative samples from the Kempirsai and Char regions.

The SEM data plotted for samples GK2508 (Char) and 49 (Kempirsai) show that analyzed Mg-Si silicate spots accumulate within the field of chrysotile, which is contradictory to

the XRD results. However, a chrysotile variety of serpentinite was reported from Kempirsai by a recent study (Leila et al., 2025). These authors point out that chrysotile serpentinization forms during the carbonation process in the sampled mineral from Chromtau, in the Kempirsai massif. It is also noteworthy that SEM analyses are based on internal standards so the Mg/Si content may vary considerably. In sample 49, this is particularly important because clinopyroxene was identified. Presence of such minerals indicates a wehrlitic protolith, so the silicate matrix has been largely transformed due to serpentinization, although relicts of mantle mineral like clinopyroxene are found.

Sample GK2508 shows tight grouping points in the lizardite field. It shows a slightly wider spread of values, which indicates a richer chemical variability in the silicate phases of the sample. Such variability shows more heterogeneous alteration conditions or redistributed composition during serpentinization. Despite such difference, both datasets follow the expected Mg/Si trend for chrysotile, leading to the conclusion that serpentinite is the dominant serpentine phase in both samples.

| No | Analysis No. | Sample ID    | Location | Serpentine | Olivine | Clinopyroxene | Magnetite | Chrome spinel |
|----|--------------|--------------|----------|------------|---------|---------------|-----------|---------------|
| 1  | 40           | Serpentinite | Aktobe   | +          | +       | -             | -         | +             |
| 2  | 42           | Serpentinite | Aktobe   | +          | +       | -             | -         | +             |
| 3  | 49           | Serpentinite | Aktobe   | +          | +       | +             | -         | +             |
| 4  | 51           | Serpentinite | Aktobe   | +          | +       | -             | -         | +             |
| 5  | AKM-1        | Serpentinite | Aktobe   | +          | +       | -             | -         | +             |
| 6  | AKM-2        | Serpentinite | Aktobe   | +          | +       | -             | -         | +             |
| 7  | AKM-3        | Serpentinite | Aktobe   | +          | +       | -             | -         | +             |
| 8  | GK2516A      | Serpentinite | Balkhash | +          | +       | -             | -         | +             |
| 9  | GK2516B      | Serpentinite | Balkhash | +          | -       | -             | -         | +             |
| 10 | GK2511       | Serpentinite | Charsk   | +          | +       | -             | +         | -             |
| 11 | GK2507       | Serpentinite | Charsk   | +          | -       | -             | +         | -             |
| 12 | GK2508       | Serpentinite | Charsk   | +          | +       | -             | +         | -             |
| 13 | GK2509       | Serpentinite | Charsk   | +          | +       | -             | +         | -             |
| 14 | 47           | Serpentinite | Aktobe   | +          | +       | -             | -         | +             |

Table 6. Summary of mineralogical composition.

| Sample ID | Lizardite (%) | Forsterite (%) | Magnetite (%) | Tridymite (%) | Dolomite (%) | Talc (%) | Clinochlore (%) |
|-----------|---------------|----------------|---------------|---------------|--------------|----------|-----------------|
| 40        | 85,8          | 14,2           | -             | -             | -            | -        | -               |
| GK2507    | 91,51         | -              | 3,39          | -             | 5,09         | -        | -               |
| GK2509    | 84,77         | -              | 3,44          | 11,79         | -            | -        | -               |
| GK2511    | 97,19         | -              | 2,81          | -             | -            | -        | -               |
| GK2508    | 85,57         | -              | 3,82          | 10,6          | -            | -        | -               |
| AKM-3     | 89            | 6,84           | -             | -             | -            | 4,17     | -               |
| AKM-1     | 76,61         | 10,75          | -             | -             | -            | -        | -               |
| 49        | 92,26         | 7,74           | -             | -             | -            | -        | -               |
| 51        | 93,47         | 6,53           | -             | -             | -            | -        | -               |
| GK2516A   | 88,37         | -              | 5             | -             | -            | -        | 6,62            |
| GK2516B   | 99,21         | -              | 0,79          | -             | -            | -        | -               |

Table 7. XRD results of each sample.

The mineralogical data in the table above show a clear variation in serpentinization degree and accessory minerals across the studied regions. All samples are characterized by the consistent presence of serpentine, which confirms the serpentinization process across the locations. In the Aktobe samples serpentine comes along with olivine and chrome spinel, while clinopyroxene is present only in the sample 49. This suggests incomplete serpentinization in this sample. Balkhash samples show serpentine with chrome spinel, but some samples without olivine and clinopyroxene, indicating a more advanced stage of alteration where primary minerals have been replaced. Char samples show serpentine with magnetite and in some cases minor olivine, showing intense serpentinization and magnetite formation. The absence of chrome spinel in this area differentiates it from samples from Aktobe and Balkhash, possibly reflecting differences in protoliths or metasomatic conditions. These variations suggest that the studied serpentinites have different degrees of serpentinization and conditions across the three regions.

## 6. Conclusions

This study investigated serpentinites from the Kempirsai massif, Char ophiolite belt and North Balkhash ophiolite zone using an integrated approach that combined field observations, petrographic analysis, XRD and SEM. The results show that all studied samples are strongly serpentinized ultramafic rocks derived from mantle peridotites and dominated by lizardite as the main alteration product. However, differences between regions are clear in degree of alteration, protolith composition and tectonic setting.

Kempirsai samples preserve the most primary mantle characteristics. Petrography shows relict olivine and vein-dominated textures, while XRD confirms the presence of minor forsterite, which indicated incomplete serpentinization. SEM analysis reveals Mg-rich silicates, Cr-rich spinel and the presence of clinopyroxene, which allowed to identify sample 49 as wehrilite. These features suggest that Kempirsai serpentinites have a partially preserved mantle signature and experienced relatively less intense alteration compared to other regions.

Serpentinites from the Char ophiolite belt and North Balkhash ophiolite zone show more advanced stages of serpentinization. Petrographic analysis showed the presence of mesh, fibrous and foliated textures with almost complete replacement of primary minerals. XRD results from Char samples show additional secondary phases such as magnetite, dolomite and tridymite, while Balkhash samples showed very high lizardite content, reaching nearly pure compositions. SEM data confirm the dominance of serpentine compositions and the absence of preserved primary silicate chemistry.

SEM based analysis shows that all Mg-Si silicate data points from samples GK2508 and 49 fall in the compositional range of chrysotile, which is not in line with the XRD results. However, it was confirmed that it is the dominant serpentine polymorphs, but slight differences in data

distribution indicate that Kempirsai has more compositional consistency, whereas Char shows higher variability. It has happened most likely due to more complex fluid-rock interaction.

Future work could expand this study by including a larger number of samples from each region in order to improve reliability and for better understanding of the regions. Additional mineral chemical analyses with standardized methods would lead to new findings that includes the interpretations such as the wehrlitic composition of sample 49 from the Kempirsai massif.

Overall, the results from all these analyses demonstrate a progression from partially preserved mantle derived ultramafic rocks in the Kempirsai massif to highly altered serpentinites in the Char and Balkhash belts. These differences show the influence of tectonic setting, deformation and fluid activity during the process of serpentinization in the Central Asian orogenic belt. The study highlights the importance of combining petrography, mineralogical and chemical analyses for better understanding of the ultramafic rocks and the process of serpentinization in different environments.

## References

1. Degtyarev, K. E., Ryazantsev, A. V., & Yakubchuk, A. S. (2021). Tectonic evolution of the Balkhash region in the Central Asian Orogenic Belt. *Geotectonics*, 55(3), 243–260
2. Früh-Green, G. L., Connolly, J. A. D., Kelley, D. S., Grobéty, B., & Karson, J. A. (2004). Serpentinization of oceanic peridotites. *Geochemistry, Geophysics, Geosystems*.  
[https://www.researchgate.net/publication/27246576\\_Tectonic\\_models\\_for\\_accretion\\_of\\_the\\_Central\\_Asian\\_Orogenic\\_Belt](https://www.researchgate.net/publication/27246576_Tectonic_models_for_accretion_of_the_Central_Asian_Orogenic_Belt)
3. Holm, N. G., Oze, C., Mousis, O., Waite, J. H., & Guilbert-Lepoutre, A. (2015, July). *Serpentinization and the formation of H<sub>2</sub> and CH<sub>4</sub> on celestial bodies (planets, moons, comets)*. *Astrobiology*.  
<https://pmc.ncbi.nlm.nih.gov/articles/PMC4523005/#:~:text=Serpentinization%20involve%20the%20hydrolysis%20and,wide%20range%20of%20environmental%20conditions.>
4. Leila, M., Hazlett, R., Mathews, P.-G., Šegvić, B., & Fustic, M. (2025). *Low temperature carbonation and CO<sub>2</sub> mineral trapping in altered hydrotalcite-rich ultramafic rocks*. *Scientific Reports*, 15, 31133.
5. McCollom, T. M., & Bach, W. (2009). Thermodynamic constraints on hydrogen generation during serpentinization of ultramafic rocks. *Geochimica et Cosmochimica Acta*, 73(3) <https://pmc.ncbi.nlm.nih.gov/articles/PMC4523005/>
6. Milyukova, A. G., & Skoblenko, A. V. (2022). Structures and compositions of the residual dunite–harzburgite complex of the North Balkhash ophiolite zone. In *Proceedings of the Siberian Early Career GeoScientists Conference*. Novosibirsk State
7. O’Hanley, D. S. (1996). *Serpentinites: Records of tectonic and petrological history*. Oxford University Press.  
<https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/97EO00088>
8. Plumper, O., Botan, A., Los, C., Liu, Y., Iyer, K., & Killian, R. (2015). Formation and breakdown of serpentinite during subduction: A review of petrology, mineralogy, and geochemistry. <https://doi.org/10.1098/rsta.2014.0168>
9. Puchkov, & V. N. (1997). Structure and geodynamics of the Uralian orogen. Geological Society, London, Special Publications. <https://doi.org/10.1144/GSL.SP.1997.121.01.09>
10. Safonova, I., Santosh, M., Kojima, S., Komiya, T., Kurganskaya, E., & Koizumi, K. (2018). Supra-subduction igneous formations of the Char ophiolite belt, East Kazakhstan. *Gondwana Research*, 59, 159–179.
11. Safonova, I., Simonov, V., Buslov, M., & Obut, O. (2012). Late Paleozoic oceanic basalts hosted by the Char suture-shear zone, East Kazakhstan; Implications for plume-ridge interaction in the Paleo-Asian Ocean. *Journal of Asian Earth Sciences*, 51, 10-25.
12. Saveliev, D. E., Nikitin, V. N., & Tatarinov, A. V. (2022). Silicates from lherzolites in the Kempirsai Massif: A source of chromite. *Lithology and Mineral Resources*, 57(5), 427-444
13. Sazanova, M. (2023). Structure and evolution of the Char Ophiolite Belt (Eastern Kazakhstan) <https://ora.ox.ac.uk/objects/uuid:50df3f10-2de8-429e-b615-7b1f23885f9f>

14. Ulrich, M. et al. (2020). Serpentinization and tectonic evolution of the New Caledonia ophiolite.
15. Volkova, N. I., Tarasova, E. N., Polyanskii, N. V., Vladimirova, A. G., & Khromyakov, V.D. (2008). High-pressure rocks in the serpentinite melange of the Char zone, Eastern Kazakhstan: Geochemistry, petrology, and age. *Geochemistry International*, 46(4), 386-401.
16. Windley, B. F., et al. (2007). Tectonic models for accretion of the CAO. *Earth-Science Reviews*.  
[https://www.perplex.ethz.ch/papers/frueh-green\\_agu\\_04.pdf](https://www.perplex.ethz.ch/papers/frueh-green_agu_04.pdf)