A field and laboratory study of suspected biotic features in Svecofennian rocks on Utö in the Stockholm Archipelago

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Abstract

This study examines Paleoproterozoic metasedimentary rocks from the island of Utö in the Stockholm Archipelago, a site of significant geological interest due to its well-preserved Svecofennian bedrock. The research focuses on identifying potential biogenic features, such as stromatolites and microbialites, which provide insights into early microbial ecosystems and environmental conditions during the Paleoproterozoic Era. Fieldwork was conducted at the Södra Sandvik locality, characterized by shallow-water depositions and alternating meta-arenite and meta-argillite beds. Samples were systematically collected, and detailed sedimentary logs and petrographic analyses were employed to document the geological context and identify potential signatures of early life.

Advanced analytical techniques, including Scanning Electron Microscopy (SEM) and fluorescence microscopy, were used to investigate microstructures and biomarkers in the collected samples. SEM imaging revealed mineralogical compositions and microtextures, such as filamentous structures and pyrite, that are often associated with microbial activity. Fluorescence microscopy identified areas of potential biogenicity through the detection of extracellular polymeric substances (EPS) and carbon-rich regions, suggesting microbial involvement in carbonate precipitation. However, challenges arose in distinguishing biotic from abiotic features due to extensive diagenetic and metamorphic overprints. The presence of calcite veins and skarn deposits further highlighted the complex interplay of tectonic, volcanic, and hydrothermal processes in shaping the region's geological history.

The findings indicate that stromatolite-like structures, along with potential biomarkers, are present in Utö's metasediments, supporting the hypothesis of microbial activity during the Paleoproterozoic. These results contribute to understanding the diversification of early cyanobacteria and microbial ecosystems during a period of significant environmental and geochemical change, including the Great Oxygenation Event (GOE). Further investigations, such as Raman spectroscopy, are required to validate these conclusions and explore the broader implications for the evolution of early life and its preservation in the fossil record.

Table of Contents

1. Abstract
2. Introduction
    - The Origin of Life
    - Paleoproterozoic Era and Redox Conditions
    - Biogenic Trace Fossils in the Paleoproterozoic
    - Study Area: Utö Island
3. Geological Setting
    - Svecofennian Orogeny and Fennoscandian Shield
    - Stratigraphy of Utö Island
    - Geological Formations
        - Lower Formation
        - Middle Formation
        - Upper Formation
    - Dolostone and Skarn Deposits
4. Microbialites
    - Overview and Definitions
    - Stromatolites: Formation and Identification
5. Methodology
    - Field Work and Sampling
    - Sedimentary Logging
    - Laboratory Techniques
        - Scanning Electron Microscopy (SEM)
        - Fluorescent Microscopy
        - Petrographic Microscopy
6. Results
    - Site Description

    - Sedimentary Log Observations
    - Petrographic Data
    - Microscopic Evidence
        - SEM Analysis
        - Fluorescence Microscopy
7. Discussion
    - SEM and Fluorescence Findings
    - Dolostone and Microbial Mediation
    - Stromatolite Identification
8. Conclusion
9. Acknowledgements
10. References

Introduction

The origin of life remains one of the most profound and unresolved questions in science. Despite extensive research, the exact mechanisms by which life first emerged on Earth continue to evade definitive understanding. Theories range from abiogenesis, where life began from non-living chemical precursors, to panspermia, which proposes that life, or its building blocks, may have originated elsewhere in the cosmos and arrived on Earth via meteorites or comets (Luisi, 2006). Experimental studies, such as the Miller-Urey experiment, have demonstrated that organic molecules can form under prebiotic conditions, yet the transition from simple molecules to self-replicating systems capable of evolution is still not fully understood. This field is further complicated by the lack of direct evidence from the earliest periods of Earth's history, as the geologic record has largely been erased or altered over billions of years. Consequently, the origin of life is a highly debated topic, though by 2.5 Ga life on Earth was already thriving, primarily in the form of photosynthetic microorganisms. Fossilized stromatolites, layered structures created by microbial communities, provide direct evidence of the widespread microbial activity during this period (Knoll, 2015).

The conditions in this Era, named the Paleoproterozoic (2.5-1.6 Ga) were characterized by intervals of variations in oxygenation, three ice ages, and intense magmatic activity. There were major sinks in O_2 from decreases in sub volcanism, which had great effects in life's diversification and the way that ecological niches developed, including the appearance of new organisms such as various cyanobacteria, gunflint-type benthic assemblages (microbial communities that thrived in shallow, seafloor environments) and eukaryotes. Gunflint-type assemblages are important because they provide evidence of ancient photosynthetic ecosystems and give insights into early microbial diversity and the environmental conditions of Earth's early oceans. While the gunflint-type photosynthetic biomasses disappeared after the Paleoproterozoic, the niches in cyanobacteria and eukaryotes continued developing (Javaux & Lepot, 2017).

Life at the time mainly consisted of simple morphological microbes such as sulphur and iron-tolerant prokaryotes, cyanobacteria, and eukaryotes. As stated in Javaux and Lepot (2017), the palaeobiological record of this Era exemplifies conditions varying from sulfidic, oxygenic, and ferruginous, which were difficult for the development of complex lifeforms.

Biogenic trace fossils in the Paleoproterozoic are difficult to find, and those that are found could be abiotic features mimicking biotic processes. The process of identifying them can be challenging, as they have gone through millions of years of diagenesis and metamorphic processes (Schiffbauer, et.al 2012). Additionally, early microfossils can differ from what we see today, so comparison might not be possible.

Redox conditions during the Paleoproterozoic make the documentation of these fossils important as they are the oldest records of cyanobacteria and eukaryotes. Additionally, unidentified microfossils in this Era can tell us more about the diversification of stromatolites, their morphology, and other environmental conditions. Furthermore, some of these unidentified microfossils may be evidence of a greater diversity in cyanobacteria than previously assumed (Javaux & Lepot, 2017).

In this study, we research the island of Utö which consists of Scovefannian bedrock originating in the Paleoproterozoic Era, and is composed mainly of metagranites and metasedimentary rocks (Larsson & Tullborg, 2015). Utö is situated 40km from the centre of Stockholm and is of interest to our study not only for its well-preserved outcrops but also for providing, in a relatively small area, the opportunity to observe supracrustal rocks characteristic of central Sweden and possible biogenic features in stromatolites and concretions.

In the context of this paper, we will look at meta sedimentary rocks and observe any traces of possible stromatolites and other biogenic features within them. The area we will be covering in Utö predominantly contains metasediments similar to greywacke, including areas with alternating beds in meta-arenite and meta-argillite (Morawiecki 2021).

More specifically, in terms of biogenic features, an area in Södra Sandvik is of greater interest for its shallow water depositions of meta-arenite. It contains fragments of argillitic sediments which are indicative of shallow waters and possible environmental characteristics needed for life. The metasediments in the area have evidence of graded bedding and crossbedding; illustrating the change from deep to shallow water depositions (Gavelin, et al. 1976). Utö has origins in a forearc created from subduction, therefore the metasediments in the area also have silicic pyroclastic rhyolitic and andesitic rocks (Talbot, 2008).

***Fig**. 1. Google Earth™ map showing the location of Utö, Sweden in the Southeast Stockholm archipelago*

Biogenic features in the island are present as stromatolites built by cyanobacteria and associated microbial communities in shallow sea conditions (Dupraz et al., 2006), where they can easily access sunlight. They are exemplified as layered up domes, created by tightly laminated structures as the cyanobacteria settles in sediment layers, sticks together, and new bacteria creates more layers on top of each other, giving them their distinctive structure (Lee 2021). During the Paleoproterozoic, stromatolites increased in morphological diversity and size, with conic forms in addition to their commonly found dome shapes. This is likely due to the Era's changes in hydrodynamic and chemical conditions, including intense environmental changes such as the GOE (Knoll, et al., 2013).

These phototrophic communities are highly recognized in the fossil record, although the preservation of its individual cells is most challenging due to burial and metamorphic processes they have gone through (Walsh 2010).
Thus, we must rely on specific biomarkers with compositions that can allow us to get to a diagnostic of what bacteria, if any, has created the structure. Conveniently, Archaea, Bacteria and Eukaryotes each have their specific individual signature lipids, and the diagnostic of these biomarkers are crucial to understanding the environment where they have developed.
The methods we use to find these diagnostics are various microscopic techniques, including light and fluorescent microscopy and SEM (Scanning Electron Microscope). Microscopy can give us a better understanding on the process of fossilization in biogenic structures and identify any microstructures related to biogenic-mimicking microfossils. Fluorescent microscopy along with SEM allows us to look closely at complex ultra-structures (Elbourne et al., 2019), such as the individual biomarkers mentioned earlier. We complement our methods in microscopy by gathering characterizations of the environmental and geological contexts of the island of Utö, allowing us a broader picture of the origins of these early microfossils.

While it is clearly challenging to partake in the endeavour of finding microfossils from the Paleoproterozoic, this paper's aim is to argue that biogenic features in Utö during this Era are present in Södra Sandvik. By observing different samples from the meta-sediments of the island, and using microscopy provided by Stockholm University and the University of Fribourg, the authenticity of the biomarkers will illustrate that cyanobacteria is present in our findings. We will attempt to identify the environmental context and possible metamorphic processes the samples have gone through that could affect their morphology. As the Paleoproterozoic is a complex historical time of ever-changing conditions, we find it important to learn more about how the chemistry in the atmosphere and the oceans could have altered life's diversity at the time. An increase in studies such as these will only help broaden the understanding of this somewhat misunderstood time in Earth's history, where there was indeed a diverse and varied growth in biodiversification including that of more complex life.

Geological Setting

Utö, located in the Stockholm archipelago, features a complex and well-documented geological history tied to the Svecofennian orogeny and the broader geological evolution of the Fennoscandian Shield. The Svecofennian domain, lies within the Bergslagen region, which is mainly in the southwestern section of the Svecokarelian orogen (Stephens et al., 2009; Stephens & Jansson, 2020).

The island's formation began with the deposition of greywackes by turbidity currents in a tranquil environment, resting atop an unidentified Pre-Svecofennian basement (Lundström et al., 1998). Exposed graded beds along the southeastern coastline are interpreted as having formed through accretion within a prism above a subduction zone, as stated in Talbot (2008). The prism then created banks of carbonate over siliclastic sediments, as melts composed of rhyolite and andalusite crystallized the prism over time.

The northeastern part of Utö, including the Södra Sandvik area where the study area is located, provides critical insights into metamorphic, sedimentary, and volcanic processes that have shaped the region.

The geology of the island is divided into three formations (lower, middle, and upper), each distinguished by lithological and metamorphic characteristics, as mentioned in Manfeld and Skelton (2023):

- **Lower Formation**: Features turbidites transitioning into ignimbrites, layered tuffs, and shallow marine or deltaic sediments. These rocks record early metamorphic events at high temperatures (540–580°C) and low pressures, producing minerals like cordierite and andalusite.

- **Middle Formation**: Composed primarily of carbonates (calcitic and dolomitic), interbedded iron-rich volcanic sediments and is the locality where our research takes place. This formation contains retrograde metamorphism, including the replacement of calcic pyroxene by amphibole, and the presence of skarns.

- **Upper Formation**: Southwest of the main island, this formation has higher-grade metamorphic rocks with sillimanite and migmatites, indicative of partial melting and more intense deformation. The Utö Shear Zone separates the upper formation from the others.

The area has been extensively studied due to its well-preserved geological features, with its bedrock primarily consisting of Palaeoproterozoic rocks that were either formed or altered by Svecokarelian orogenic processes. The bedrock on Utö has been dated at 1.90-1.87 Ga using the U-Pb technique, providing valuable insights into to the Paleoproterozoic era (Allen., et al., 1996, Lundström., et al., 1998).

The island's bedrock is made up of felsic volcanic rocks, interlayered with shallow-water limestones and variably deformed and metamorphosed siliciclastic sedimentary rocks (Stephens and Jansson, 2020). While its formation began with the sedimentation of greywackes, it was soon followed by sandstone and conglomerates, and later volcanic activity around 1904±4 Ma. The volcanic stage included rhyolitic and dacitic ash layers and pyroclastic flows. (Allen., et al., 1996)

The locality in this study is where much of the metamorphism in the area has occurred according to Talbot (2008). The limestone in the locality is chemically precipitated, with skarn intrusions and sandstone in the middle of a dolostone dune.

***Fig**. 2. Map shows the location of the study in relation to the northern part of the area*

Ref: Google Earth™

The rocks present deformations such as linear marks typical of carbonates, leucosome veins that are also observed around the central part of Hammnudden, circular holes from weathering, and coarse mud that has been metamorphosed. The weathered holes are filled with calcite and other crystals, possibly through mineral precipitation as the weathered holes formed from water flows.

The geological history of NE Utö involves interactions between sedimentation, magmatic activity, tectonic deformation, and metamorphism, that result in the current structure and composition of the region. Its complex deformation structures, including folded and refolded layers, offer a unique opportunity to study the Svecofennian orogeny and related metamorphic processes.

Microbialites

As defined in Shapiro (2000), microbialites are organosedimentary structures that interact through their formation with microbial communities like cyanobacteria with sedimentary processes. These structures are created through the trapping, binding and precipitation of minerals in aquatic environments by microbes.

There is often confusion distinguishing between the various types of microbialites: thrombolites, stromatolites, leiolites and dendrolites. But understanding their differences is key in getting a better picture of the paleoenvironmental and biological information they can contain.

Therefore, it is important to identify their differences:

Feature	Stromatolites	Thrombolites	Leiolites	Dendrolites
Structure	Laminated (layered)	Clotted or mottled	Smooth, non-laminated, non-clotted	Branching or dendritic patterns
Formation	Predominantly microbial mat activity leading to layer-by-layer deposition	Microbial-induced clotted textures with little to no lamination	Smooth surface features, potentially microbial, with unclear internal textures	Branching structures formed by microbial and sedimentary interactions
Microbial Role	Strong microbial influence	Strong microbial influence	Likely microbial, but less understood	Strong microbial influence
Paleoenvironment	Common in shallow marine or hypersaline environments	Similar environments, but often distinct niches from stromatolites	Less well-defined environments	Varied environments, often indicative of dynamic conditions
Appearance	Fine, regular, planar layers	Irregular, clotted, or knobby	Non-layered, smooth surface	Branch-like structures

***Table** 1. Indicating the differences between stromatolites, thrombolites, leiolites and dendrolites and their various formations and structures alongside their environmental and microbial roles.*

According to Dupraz (2011), microbialites can be described using four structural levels: megastructures, which refer to the overall morphology and geometry of the microbialite (domal, columnar, or flat forms); macrostructures, which describe internal features such as lamination, clotted textures, or dendritic patterns; and mesostructures, which assess the finer organization of textures at the millimeter to centimeter scale. Microbialites are characterized by microstructures, including microbial filaments, mineral precipitates, or microfabric patterns, indicating the interaction between microbial activity and sedimentation.

Stromatolites

Södra Sandvik is of interest to this study as this is an area that literature has identified as having stromatolites.

Stromatolites are laminated structures formed primarily by cyanobacteria through the trapping and binding of intertwined filaments of their EPS (extracellular polymeric substances) and sheaths, which come together to form mat-like structures (Konhauser, 2006). First appearing around 3.45 Ga, they dominated the process of sedimentation through biogenic means from 2,800 to 1,000 Ma (Warren, 2006). With dynamic ecosystems, they go through an ever-changing process of upward accretion as the downward microbes decompose. This process varies with environmental conditions, such as rising sea levels. Thus, stromatolites can also tell us about developments in intertidal settings. Additionally, as discussed in Riding (2000), stromatolite’s laminations are disturbed by desiccation in intertidal to supratidal zones and by bioturbation. Their layering tends to be thicker and less refined when made up of large or upright components, such as in skeletal stromatolites and dendrolites. In agglutinated stromatolites, coarse sediment supply can directly lead to crude lamination, which can also indicate irregular and uneven accretion.

As stated in Konhauser (2006), colonization of the lithified surface of the mat is usual by epilithic-endolithic communities, which add to the microbial erosion of the stromatolite.

Cyanobacteria that form stromatolites are dominant in the early fossil record, possibly due to their metabolic role in early ecosystems. Their abundance aided them in their preservation in the fossil record, especially compared to organotrophic and chemolithotropic microorganisms that are dependent on the energy that the cyanobacteria produced (Golubic, 1980). In Utö, we find that the texture of their fossilized growth is noteworthy as the area is heavily metamorphosed and recrystallized, thus the rocks are vulnerable to maintaining their original shape, which can lead to wrong conclusions in the identification of a stromatolite.

Identification of Stromatolites

Several indicators must be present to confidently identify stromatolites: a particular morphology of wavy laminations, as well as conical and columnar structures exhibited in hand specimen. A stromatolite sample seen in microscopy should have chemical signatures, such as indicators of organic carbon isotopes ($\delta^{13}C$) and other geochemical markers, for example the presence of phosphorites and pyrite.

Filamentous microfossils and organic structures can also be seen with microscopy (Gulobic and Seo-Jool., 1999) and can be identified by analysing the presence of filamentous microfossils, which are indicative of microbial activity. These filaments are often preserved in the laminar structures of stromatolites and are key indicators of biogenicity. The following features are useful to aid identification:

- **Filament Morphology**: Filaments with a consistent size and shape, that reflect microbial sheaths or cells. They may have cylindrical or slightly curved shapes and can occur in patterns that could indicate microbial mat formations.
- **Laminations with Filaments**: Filaments can be embedded within the stromatolites' wavy or domal laminations. These filaments, in addition to laminar structures, strongly support microbial origins.
- **Micropeloid texture**: Uniformly small, rounded grains with homogeneous micrite or concentric zoning indicate precipitation. Stromatolites have

specific macroscopic forms that, when combined with micropeloidal textures, confirm their microbial origin.

Furthermore, as Riding (2011) discusses, the geological record of layered marine authigenic carbonate crusts is divided in three types of deposits commonly identified as stromatolites:

- **Isopachous Sparry Crust** – abiotic precipitates characterized by well-layered crusts with sparry microfabric
- **Fine-grained Crust** – microbial carbonates that are lithified with irregular and sometimes poorly defined layering, typically displaying fine-grained (e.g., clotted or peloidal) microfabrics but occasionally containing coarser textures
- **Hybrid Crust** – thinly interlayered combinations of the two preceding types, often exhibiting well-developed layering.

This criterion, alongside the use of microscopy for identification can help differentiate between abiogenic and microbial crusts.

Methodology

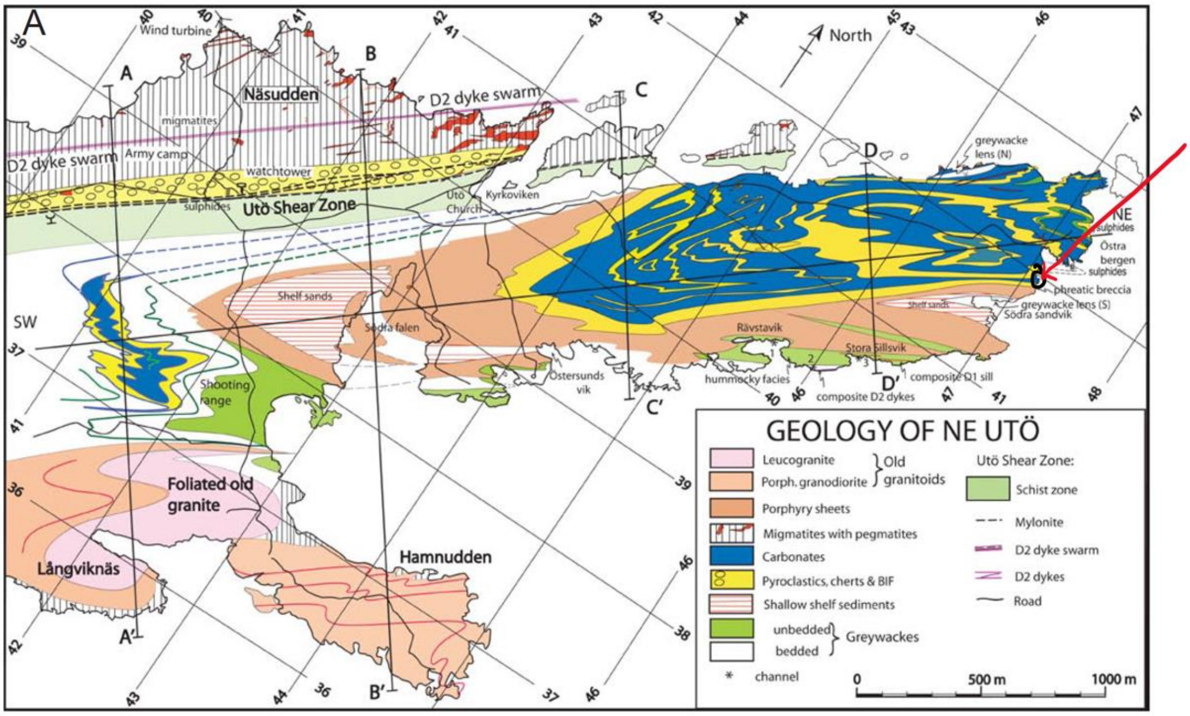


Fig. *3. Map adapted from Talbot et.al (2008) with arrow indicating location of study, legend specifies the carbonate geology of the area*

Sedimentary Log

A log was produced to define the observed layering and geological representation. The log was constructed through careful measurements of the structure, with photographs that examine closely the layering of the geological feature so that they could be highlighted. The process went as follows:

Recorded field observations:

- Types of observable rocks in the locality
- Grain size
- Sedimentary structures
- Colour
- Possible biogenic structures
- Thickness of layers or units

Environmental Context:

- Interpretations of depositional environments
- Presence of unconformities or changes in lithology

Vertical Sequence:

- Order and succession of the sedimentary units from bottom to top

Once these were recorded, a log was produced according to the observations.

Field Work

A week-long visit in Utö in the summer of 2024 was used to identify possible samples, gather specimens, and take detailed notes of the locality and its formation for a sedimentary log.

Around three days of field work were spent to designate several of the possible formations of the outcrop. Detailed photographs of the grain sizes and the skarn production in the middle of the structure were taken to further analyse mineral processes. Hand lenses were used to magnify and photograph pockets of crystals along with calcite and skarn veins that run through several parts on the dome.

Three main samples were identified, with 5 additional samples with similar morphological features for comparison; from which eight thin sections were produced.

Sample selection

Three main sites were identified for sample selection based on past descriptions of stromatolite morphology (Noffke, 2001). We sampled from observed geometric arguments for biogenesis such as wavy laminates.

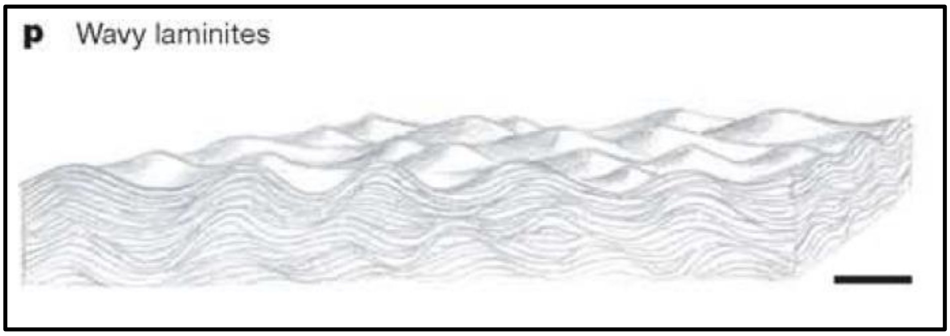


***Fig**. 4. from - Allwood, et al., 2006 showing a three-dimensional view of stromatolite facies*

The main sample site had been previously described as a stromatolite, and thus became the focus of the study since testing of the specimen had not been produced before. This is named Sample 1. Sample 2 is of similar morphology just to the left of the main sample, and sample 3 is from the back side of the dome facing North, which had similar morphology but much more metamorphosed. Other samples were taken in smaller domes which included dark and lighter layering, to compare to Sample 1 and Sample 2. Specimens were also taken from the skarn to look at their composition more clearly using SEM and petrographic microscopy.

Sample 1

***Fig**.5. Main sample site, clear coarse layering and morphological features noted in stromatolites*

Sample 2

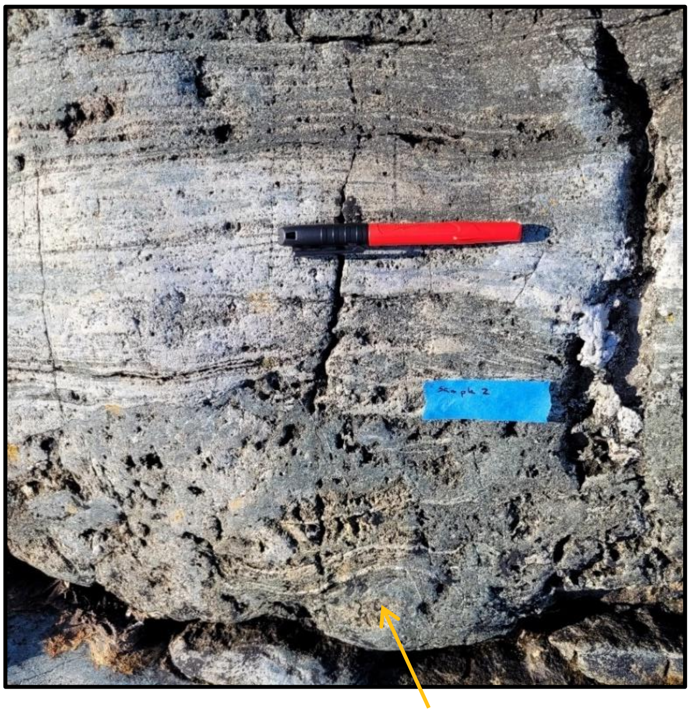


***Fig**. 6. Sample 2 with similar morphology to known stromatolites on left side of main sample site*

Sample 3

Fig. *7. Extra sample showing layering on the opposite side of main sample site*

Microscopy

Over the course of a week at the University of Fribourg in Switzerland, the samples, now in thin section, were taken from the field and studied through SEM and Fluorescent microscopy to find evidence of possible biological origins. A reference sample was used in SEM to check for standard beam currents and help identify known minerals.

SEM

Fig. *8. Sample with half coating, aluminium taping and reference sample*

Scanning electron microscopy (SEM) is used to look at the pores of the minerals to better aid in identification.

This is done through an electron beam focused on the sample, with acceleration voltages of up to 30 kV (Inkson, 2016). The electron beam then emits signals from the specimen that are recorded to form an image.

The microscope's ability to resolve fine structures is useful for identifying particle shapes, fibre arrangements, or biological microstructures. Paired with EDS, SEM identifies mineral phases like carbonates and silica, which are associated with stromatolite formation.

For our samples, we coated the sides with aluminium tape to save time as we only had a week, and half of the samples were covered with carbon threads using a Leica EM ACE600 coating device. Once coated, the samples were placed in the sample chamber and evacuated to high vacuum (around 2x 10^{-6}torr). Both back-scatter and SEM micrograph were visualized using FEI XL 30 Sirion FEG SEM (Thermo Fisher Scientific, Waltham, MA, USA) in the Department of Geosciences. This microscope is equipped with an EDAX NEW-XL30 EDS detector (FEI Com- pant, Hillsboro, OR, USA).

The SEM sampling was focused on units 06, 13, 04 and 14. These were chosen due to their location; either on the alleged stromatolite or laminations nearby it. Photographs and mapping of their chemical compositions were taken, with emphasis on a search for structures near carbonates. Element maps were also produced in the specific sample regions with the above technique and 25 keV, 12 nA, dwell time of 50 ms per pixel, 5ml spot size.

Fluorescent microscopy

Combs (2010) details the importance of fluorescence microscopy in identifying biogenicity. By using fluorophores, a binding of specific biomolecules takes place and cellular components, microbial activity, and organic materials can be better detected in geological samples. In our study of possible stromatolites, fluorescence microscopy can reveal the presence of microbial communities, EPS, and other organics and biomarkers such as nucleic acids or proteins.

The microscope used is the Wavelength dispersive X-ray fluorescence (WD-XRF) spectrometer (Malvern Panalytical Zetium), also in the Department of Geosciences. This spectrometer is able to identify elements from Be (4) up to U (92). Different filters were used, such as TexRed, Green light and Bright light, to be able to enhance any possible organic markers. TexRed in particular was used to highlight filaments, and is mainly used to see structures inside of cells, molecules and proteins in samples.

The samples used for fluorescent microscopy were the ones that had already shown evidence of Carbon and in some cases, sulphur; mainly 04, 06 and 14.

This allowed us to zone in the samples that had hand-specimen indicators of biogenicity and SEM indicators.

After going through sample Uto_04 and Uto_06, further analysis was required through the University of Fribourg, and Raman microscopy was intended to follow up on the results, but unfortunately the microscope was not available to be used on time for this paper.

Petrographic Microscopy

Lastly, petrographic microscopy was used on all eight samples on a Leica Microsystems microscope at Stockholm University. As the samples were kept coated only halfway through for SEM, one side was always in its original form. For this process, the samples were observed both in Plain Polarized Light and in Crossed-Polar Light, to annotate their optical characteristics and arrive at possible evidence for their minerology. For all samples, relief, pleochroism, and cleavage were written down in PPL, as well as in XPL in addition to extinction angles and birefringence. Deformations in the overall section, such as layering or cracks were also noted.

Emphasis was put on the sections of the samples that had exhibited fluorescence in Fluorescent microscopy, in an effort to identify opaque minerals or any other markers for biogenicity.

MAP ADC-3 from Microsystems was used to take photographs for thin section 05 and 03, but the resolution was not desirable, and this method was discarded for the rest of the samples.

Results

Site description

Fig. *9. Skarn banding along the top of the dome in between the dolostone*

***Fig**. 10. Skarn and dolomite banding*

***Fig**. 11. Crystal pocket with skarn and tremolite alongside the top of the dome*

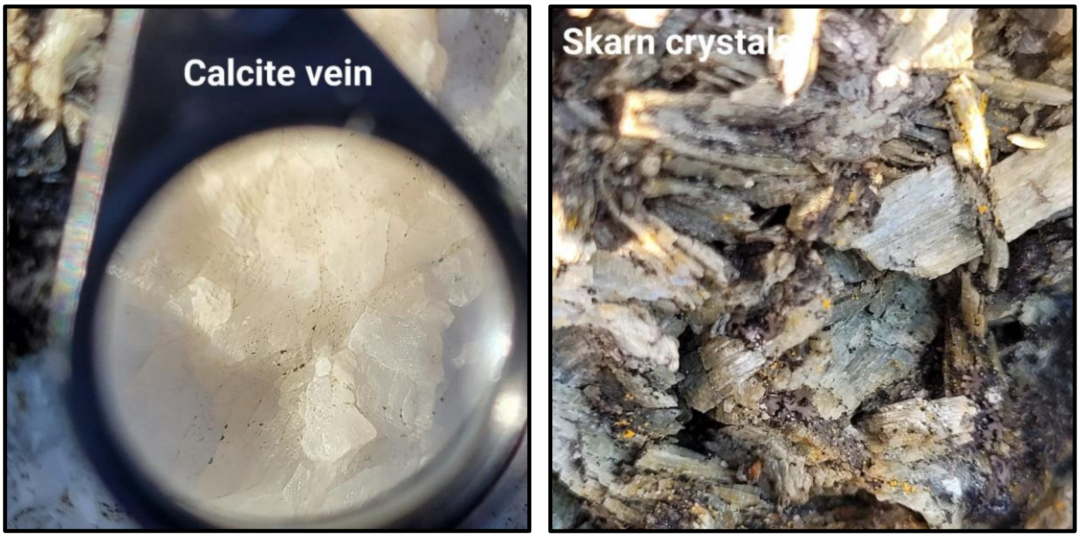


Fig. *12. Calcite veins along the dolostone seen through a hand lens 10x magnification on the left and skarn and tourmaline crystals through hand lens magnification at 10x, seen in various pockets on the top of the dome*

Sedimentary Log

Fig.*13. Measurement of the structure using a measuring tape and noting banding length differences and any variations in sedimentology*

***Fig.**14. Measurement of the main sample site to note any coarseness variations and size of possible stromatolite*

***Fig.**15. One meter measurement from waterline to top of the skarn vein, as variations between layering seem more prominent at this height*

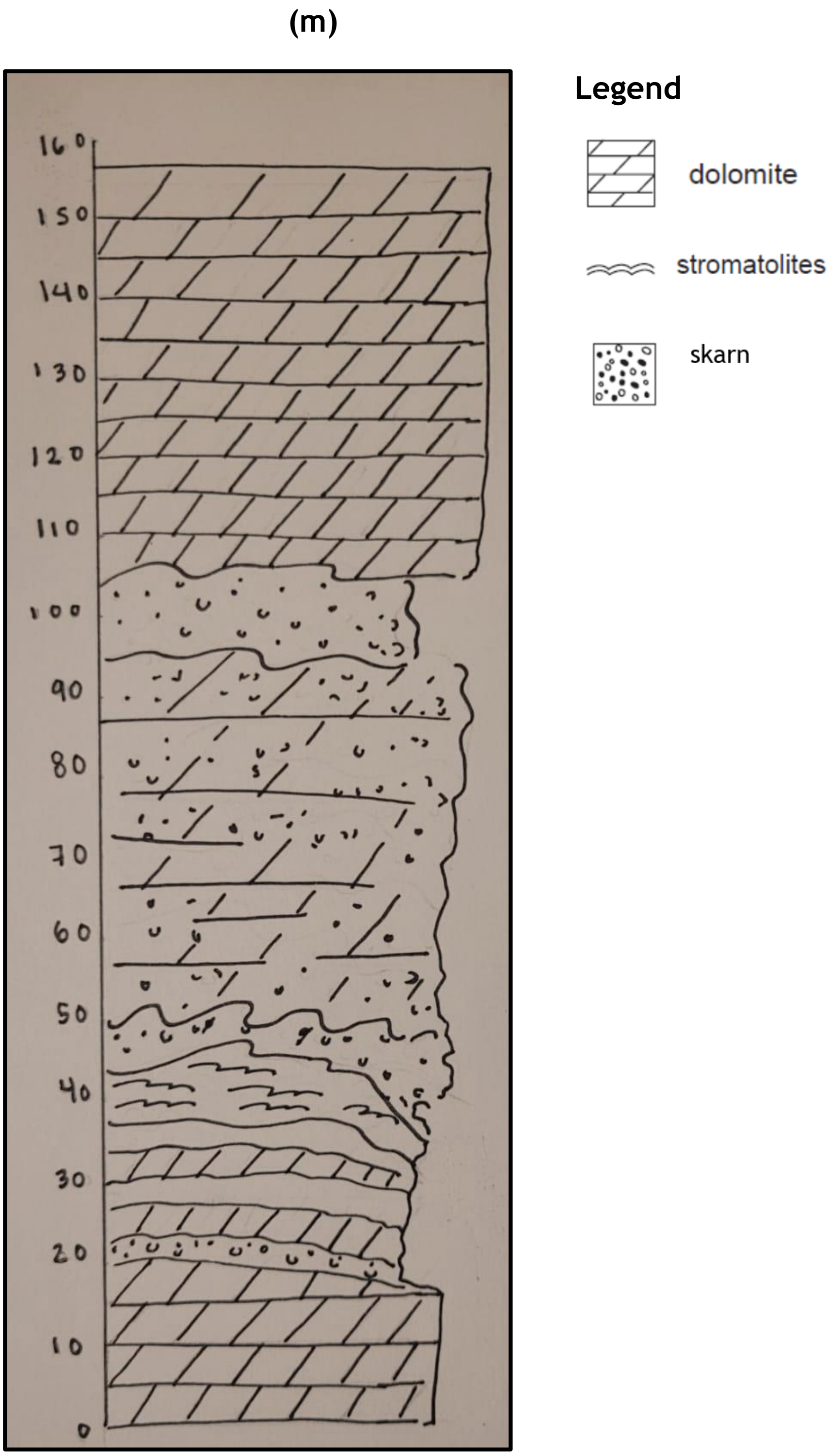


Fig. *16. Medium to coarse grained throughout with slightly finer grains in skarn from 90-100m*

Geological Formation

Metamorphic deformations such as fractures are seen in the lower parts of the dome-like structure and are increased due to erosion from smaller to larger. These deformations are typical of carbonates. The dome presents many coarse exposed areas, with fine silt-like textures in eroded holes from weathering. The porosity was identified as evidence of chemical weathering, with clear coarseness at the bottom of the dome. No shells were found in the limestone, which backs the chemical precipitation hypothesis in addition to the geological time which corresponds to limestone and dolostone chemically precipitating. The calcium, magnesium and CO_2 needed for the dolostone could have carried down from rivers. Warm climate at the moment of formation could explain the amount of CO_2.

The mudstone in the dome is found as recrystallized, as is evident through the observations of the specimen containing larger, interlocked crystals.

There are episodes of pyroclastic eruptions through the interbedded layers in the carbonate structure, reenforcing the geological setting of the area as back-arc metamorphism, as Talbot (2008) noted in his study. Observations note that the carbonate banks were indeed episodically smothered by falls of silicic pyroclastic rocks. These pyroclastic deposits are indicative of explosive volcanic activity associated with the magmatic arc.

The structure is in majority chemically precipitated dolostone, composed of skarn and dolostone in differentiated layers. The limestone formed after the volcanic eruption of the area, as limestone forms after volcanic eruptions when calcium and carbonate ions interact, often mediated by biological, chemical, or physical processes in marine, freshwater, or hydrothermal environments.

Dolostone

The structure in this study is a carbonate rock, consisting mainly of calcite, aragonite and dolomite. The locality has been further identified as dolostone, which can be produced by transforming $CaCO_3$ minerals through precipitation, into the mineral dolomite $CaMg(CO_3)_2$. In addition, Vasconcelos (1995) investigates the role of microbial mediation in the formation of dolomite at low temperatures, a process that has puzzled geologists due to the "dolomite problem"; the rarity of modern dolomite formation compared to its abundance in the geologic record. Vasconcelos highlights how microbial processes, specifically the metabolic activities of sulfate-reducing bacteria (SRB), can promote dolomite precipitation in low-temperature environments. As Dupraz et.al (2009) discusses, other microbial metabolic pathways such as photosynthesis, respiration and fermentation can also alter the local chemical environment within microbial mats. These metabolic activities can change pH levels and the saturation state of carbonate minerals, thereby promoting or inhibiting carbonate precipitation.

Virtually all dolostones were at one point limestones (Schwab, 2003), and because limestone is formed from seawater organisms by their crystallization of dissolved calcium to form shells or through their mere presence in seawater, its geological setting will depend on such factors.

The formation of dolostone will then depend on how carbonate deposited when limestone was formed. The factors include the salinity of water, warm water temperature for higher organic activity, and depth. As stated in Schwab (2003), shallow waters are more adept at carbonate formation.

Layering

Alternating light and dark laminae are found in several areas of the dome. The white layering could be evidence of precipitation of aragonite during summers and consequent sinking. As Garber et al. 1987 suggests, the darker laminae could also be due to storm floods that have washed in clay, quartz grains and dolomite from surrounding areas.

These laminae aren’t necessarily indications of microbial binding, as Warren (2016) indicates that they can be indications of fluctuations in subaqueous deposition depending on surface water chemistries; and can be in turn evidence of water depths instead.

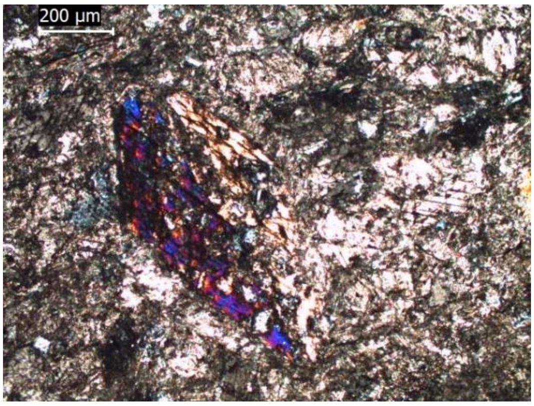
Skarn

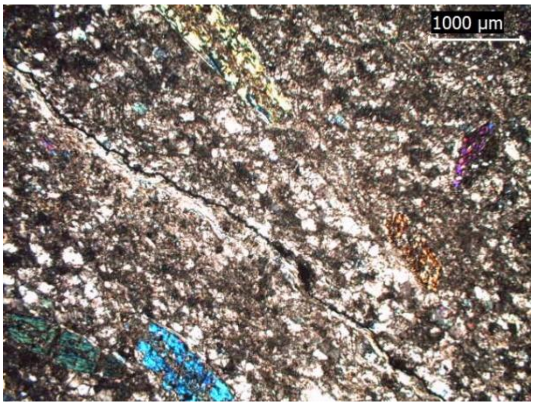
The formation of skarn in this area could have formed from the cooling of the magma from the nearby volcanic eruption. As the magma cooled, fluid infiltration occurs with metals and silica interacting with the carbonate rocks. Another possibility could be metasomatism: a chemical exchange between the carbonate rock and hydrothermal fluids. As we see further down in the mineralogy, garnet and pyroxenes are common in the samples, which is standard in this process.

Additionally, as we know the area has gone through retrograde alterations, the presence of hydrous materials in this deposit is also evidence of a high temperature assemblage.

Petrographic Microscopy Data

Uto 02





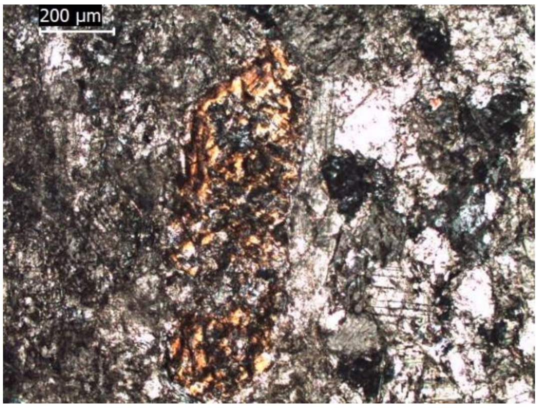
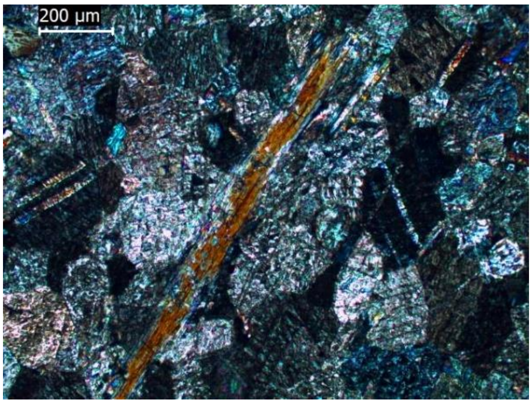
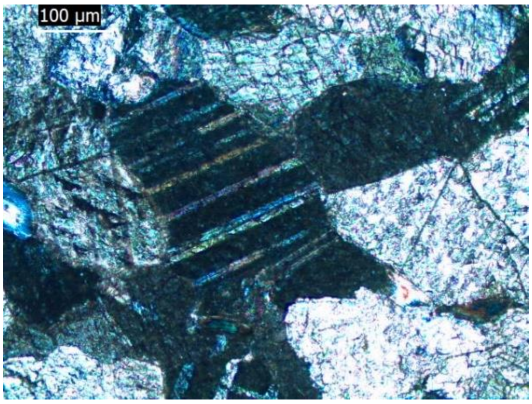


Fig. *17. Thin sections in crossed-polars showing evidence of metamorphism and deformation. From left to right- Pyroxene porphyroblast embedded in a fine-grained matrix with some curved boundaries indicating possible strain. Next thin section has seemingly fractured grains, indicating brittle deformation along with a prominent crack. Aligned elongated grains could indicate ductile deformation. Lastly, bottom sample shows an amphibole, with elongated grains that could indicate foliation under direct pressure. Finer grains around the mineral are typical of recrystallized metamorphic environments.*

Uto 03





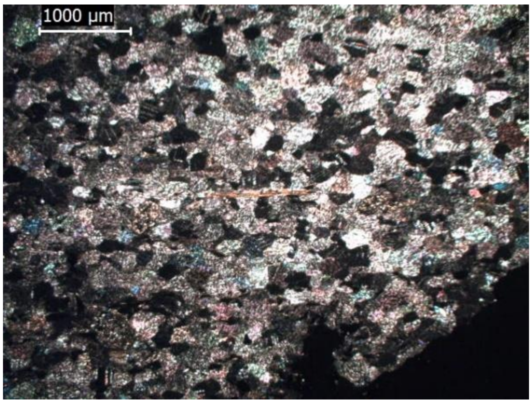
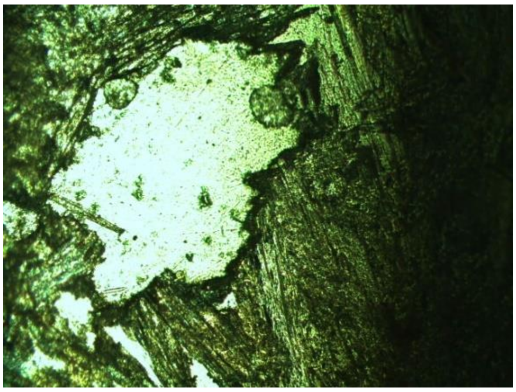
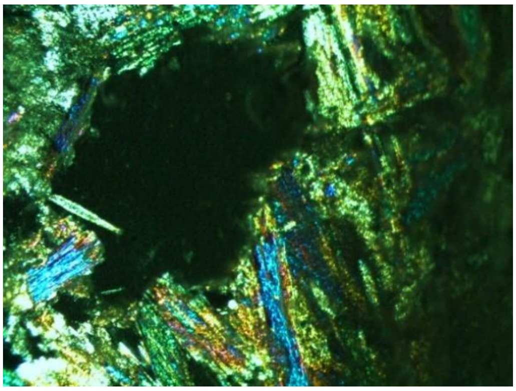


Fig. *18. Thin section in XPL from left to right- Inclusion surrounded by calcite, next is calcite in extinction showing clear twinning, and a mosaic of interlocking grains mostly composed of quartz and weathered feldspar.*

Uto 04





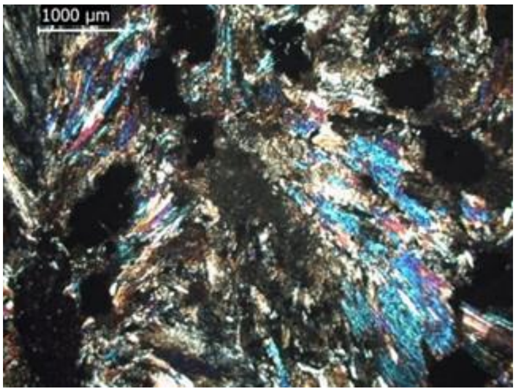


Fig. *19. Left Garnet in PPL, next Garnet in XPL and lastly garnet surrounded by muscovite, indicating retrograde metamorphism.*

Uto 06

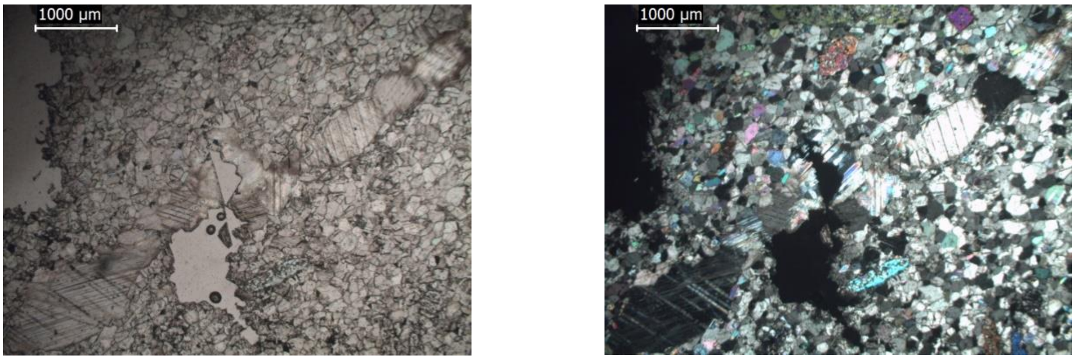


Fig. *20. Left (PPL) and right(XPL)- microcrystalline quartz matrix with visible calcite vein along the middle*

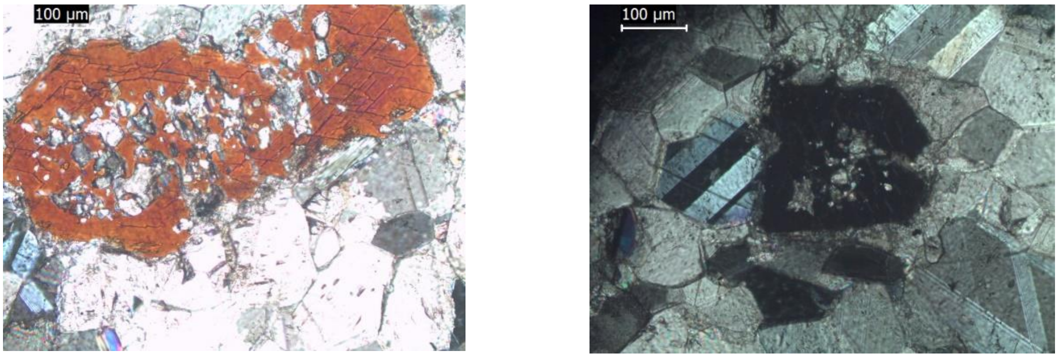


Fig. 21. Left and right (XPL) - amphibole and classic twinning of plagioclase

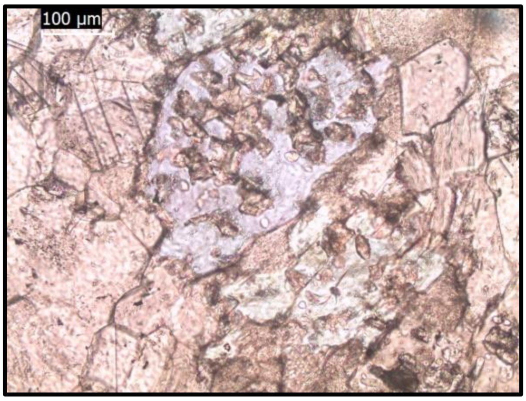


Fig. *22. Plane polarized light shows a glaucophane in pale blue- indication of a high pressure and low temperature environment.*

Uto 12

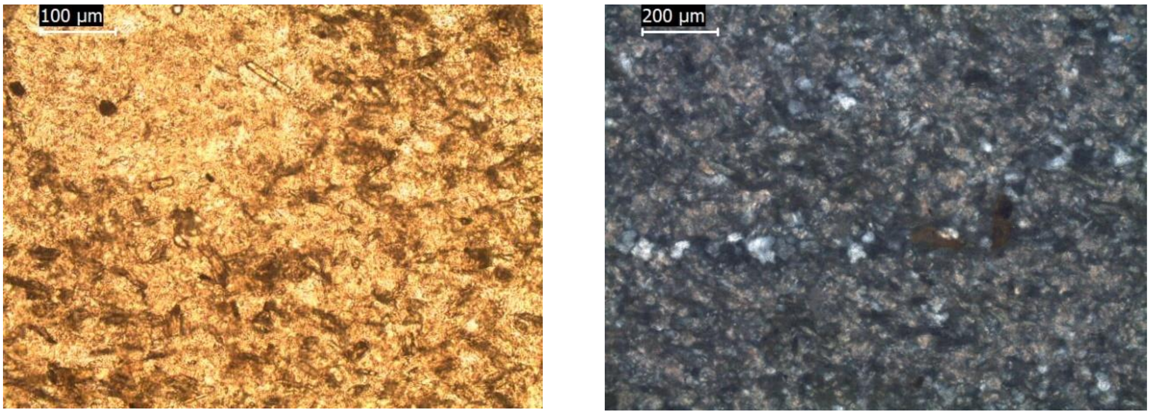
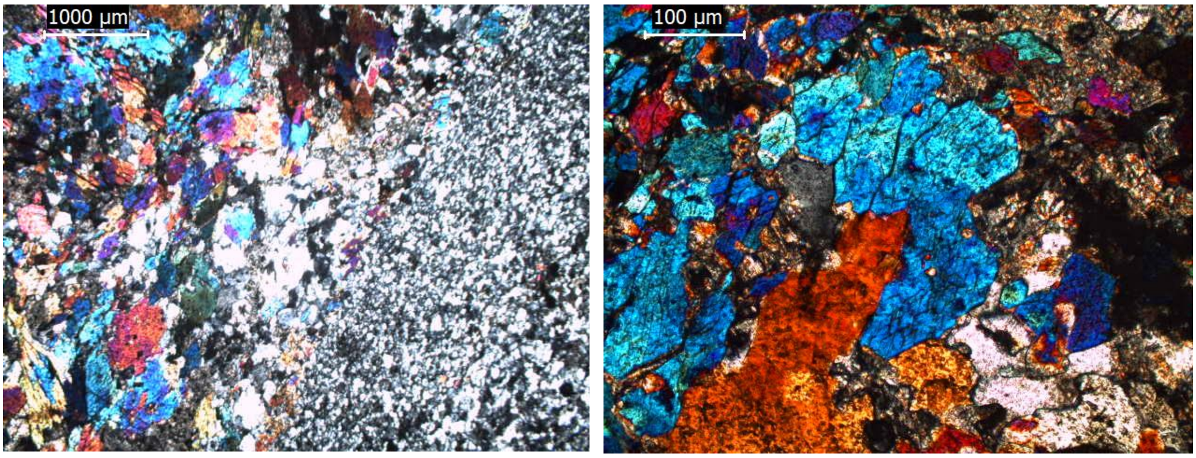


Fig. *23. Left shown in PPL with clear tourmaline needles. Right in XPL shows an aligned quartz vein with biotite*

Uto 13



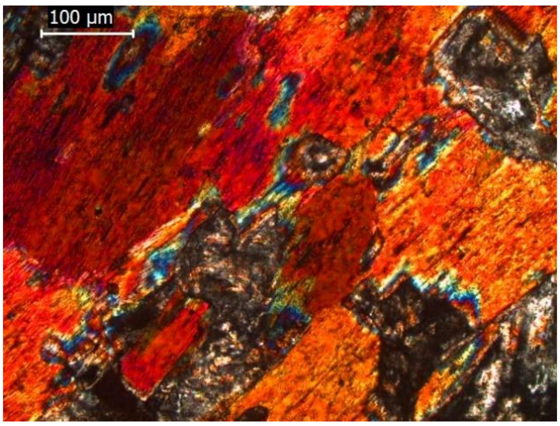


Fig. *24. Left- XPL thin section with angular clasts embedded in a finer matrix, high birefringence pyroxenes mixed with fine quartz. Deformation and recrystallization could indicate tectonic activity. Undulose extinction is observed and strongly deformed zones.*

Uto 14

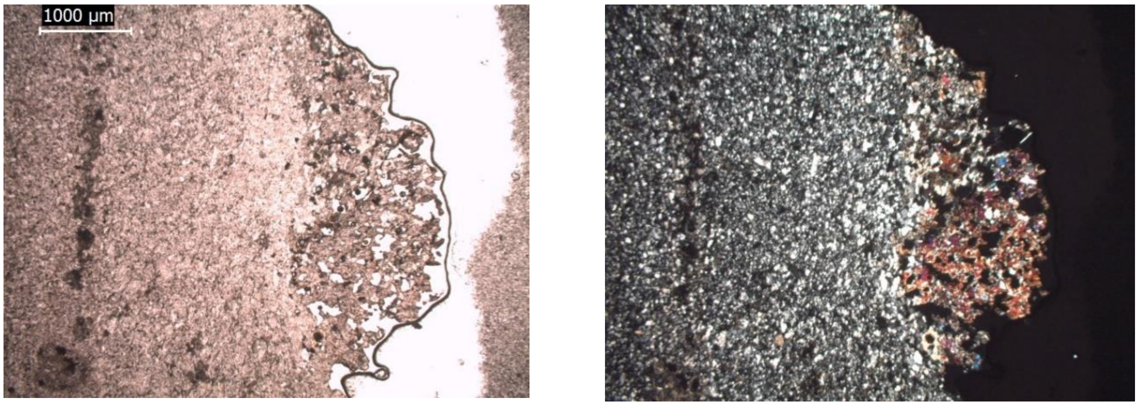
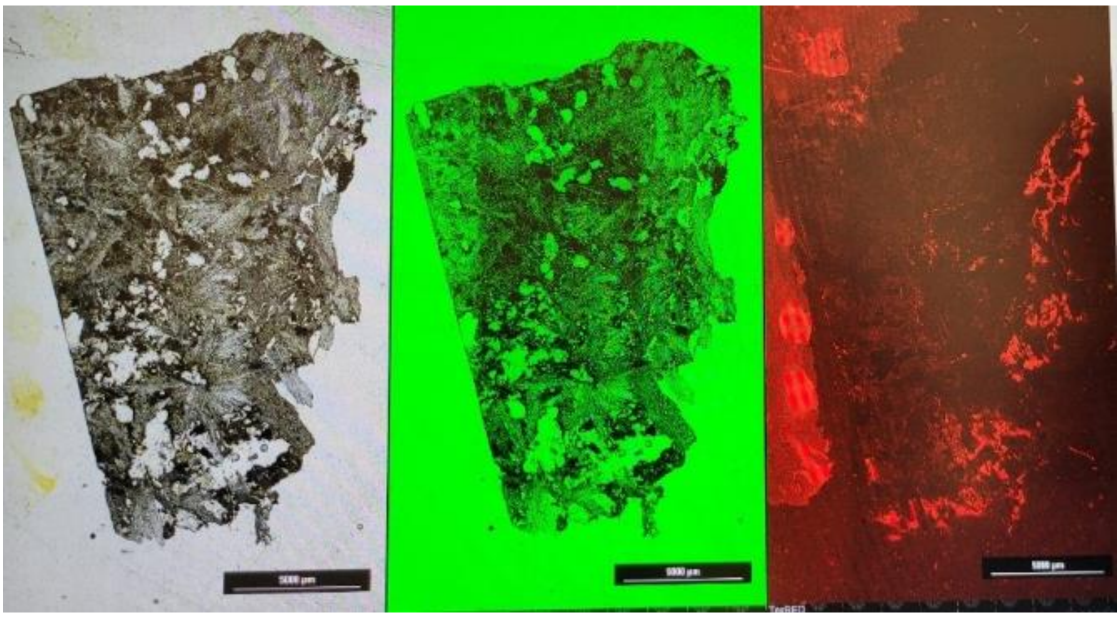


Fig. *25 Fine grained thin section in XPL, recrystallized with low-grade metamorphism. Lamination could be from original sedimentary bedding. Fragmented grains could be from mechanical breakage during metamorphism. Brittle deformation at the edges of the sample, possibly from tectonic or fault-related stresses.*

Samples show high temperature minerals surrounded by low temperature assemblages, indicating retrograde metamorphism as stated in past literature.

Fluorescent Microscopy

Uto 04 Overview



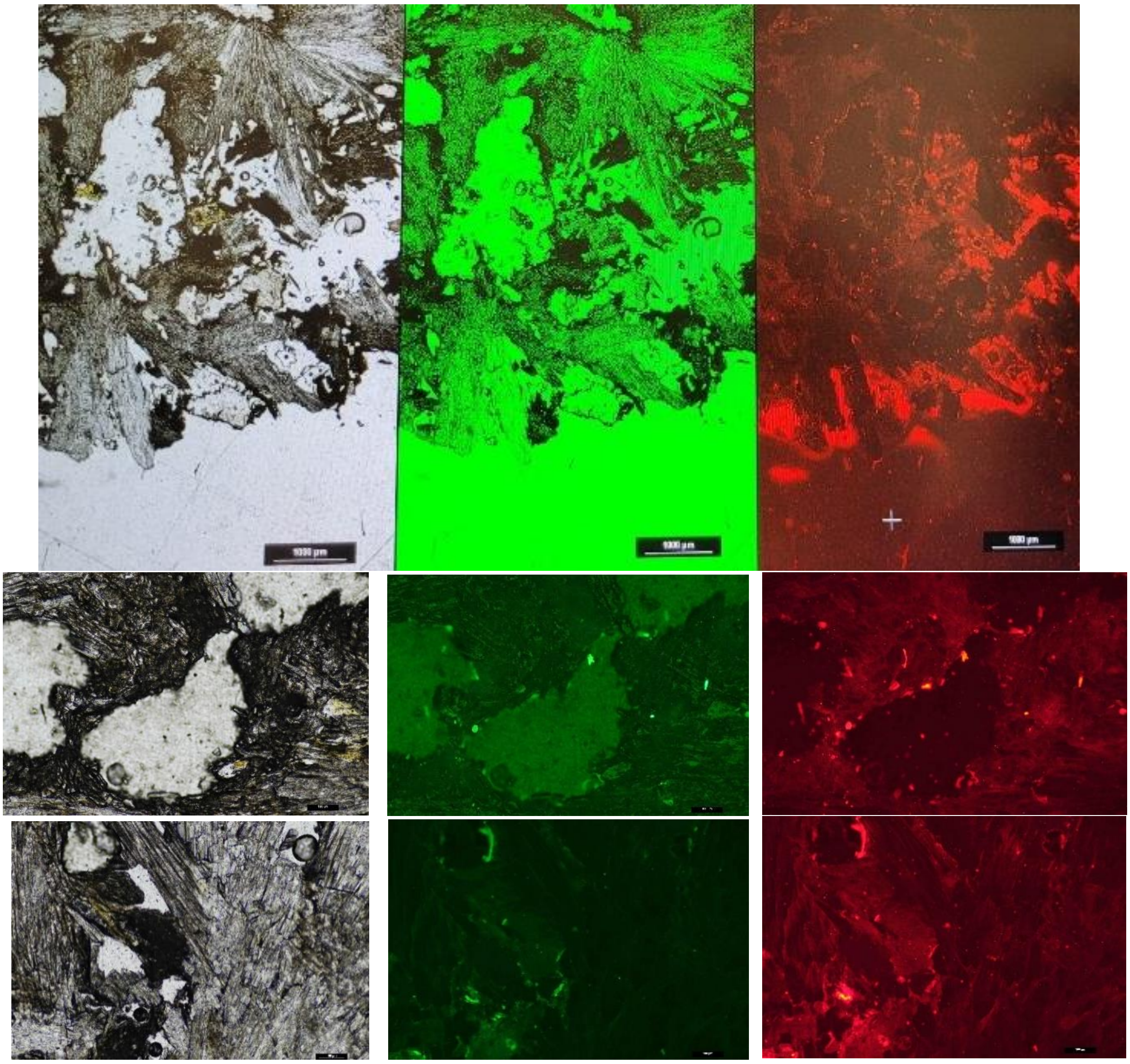


Fig. *26. From left to right: brightfield fluorescence, FITC and TxRed*

Uto 14 Overview

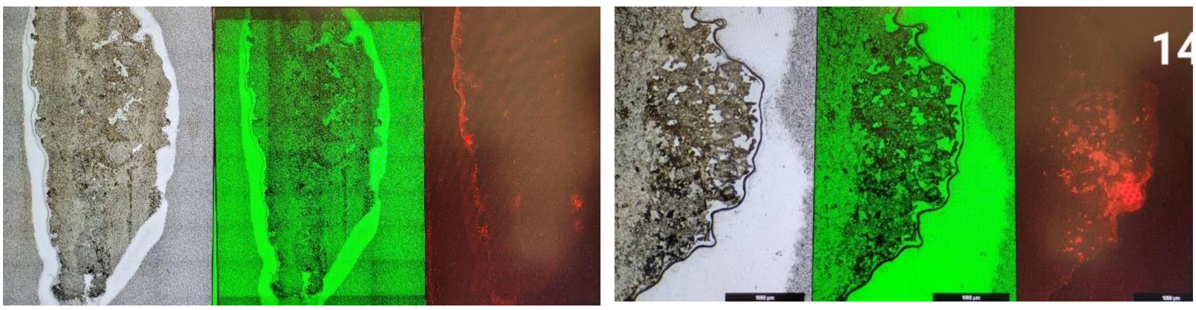


Fig. *27. Key interest mid-right side of the sample showing fluorescence*

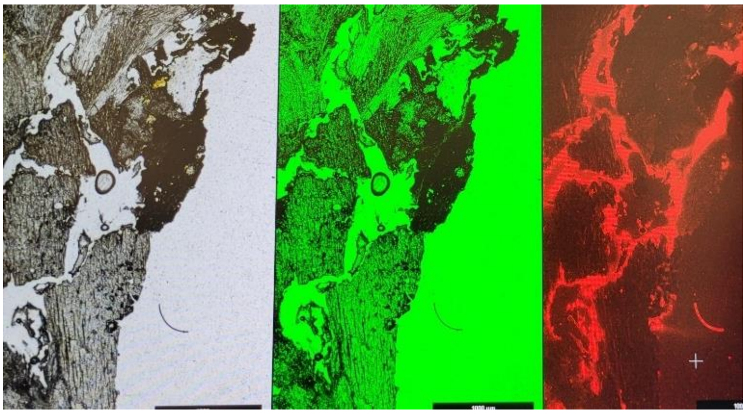


Fig. *28. Secondary key interest showing bright fluorescence*

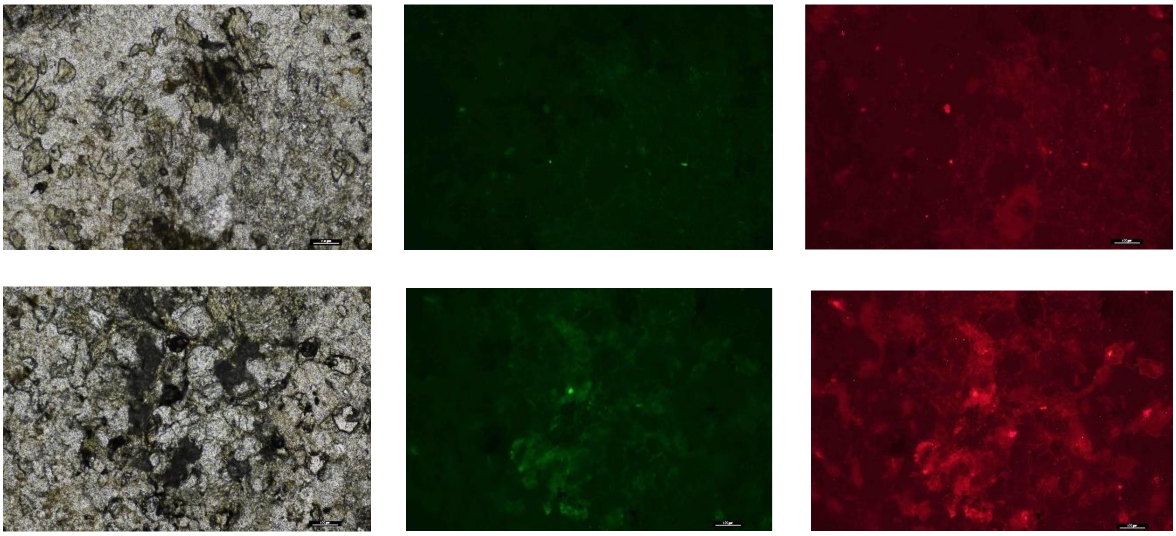


Fig. *29. Brightfield, FITC and TxRed from left to right in both key interest samples in further detail*

Uto 06 Overview

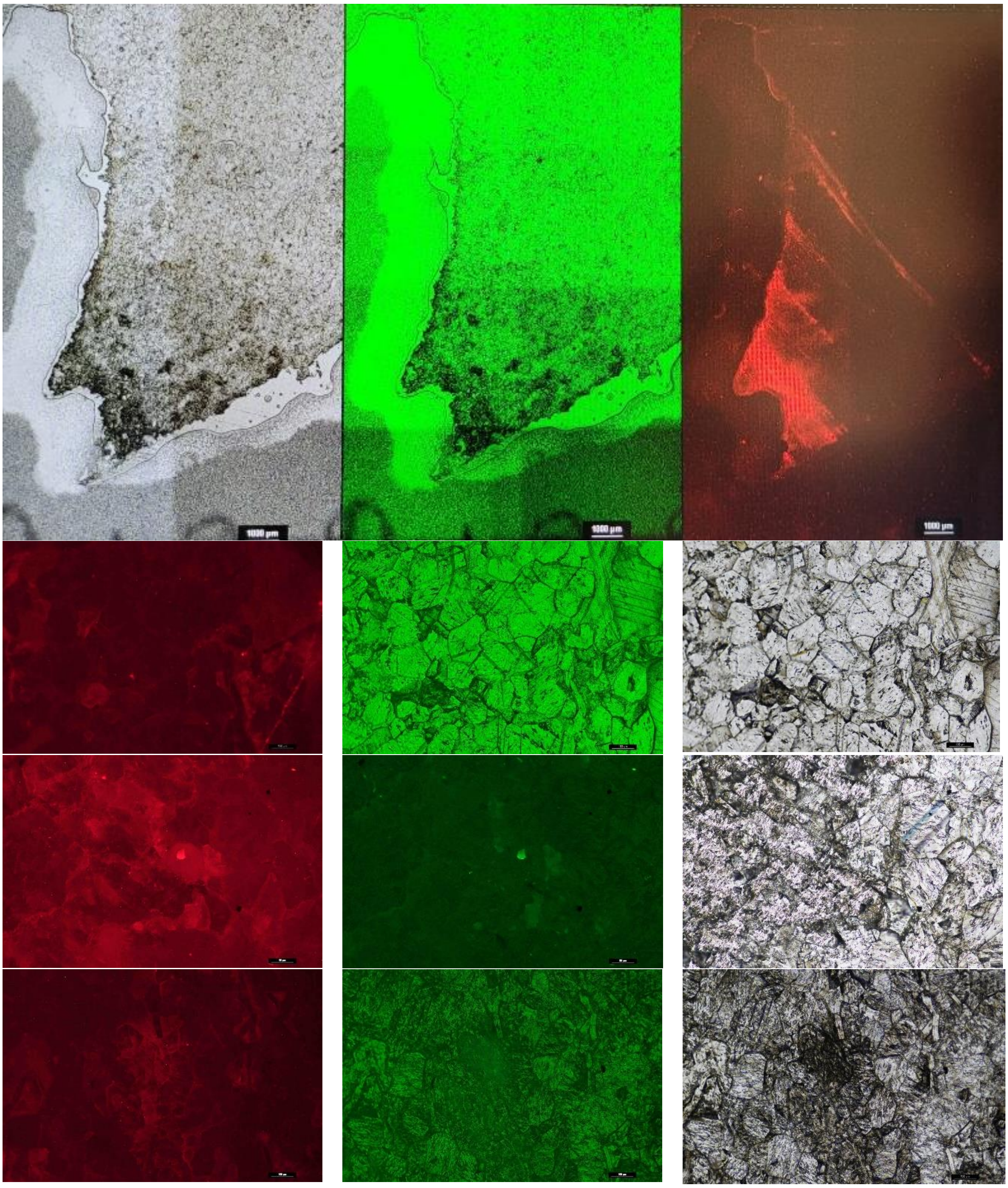


Fig. *30. Brightfield, FITC and TxRed from left to right, showing fluorescence from the bottom left side of the sample*

SEM

Uto 06

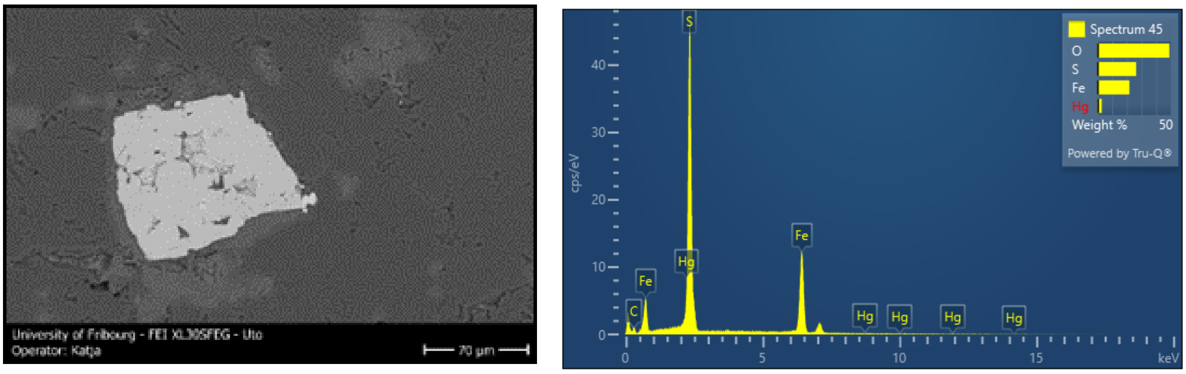


Fig. *31. Pyrite in sample Uto_06 surrounded by dolomite*

Element	Signal Type	Wt%	Wt% Sigma
O		49.05	
S	EDS	26.38	0.26
Fe	EDS	21.73	0.28
Hg	EDS	2.84	0.50
Total		100.00	

Table *2. Elemental composition for Spectrum 45*

Uto 13

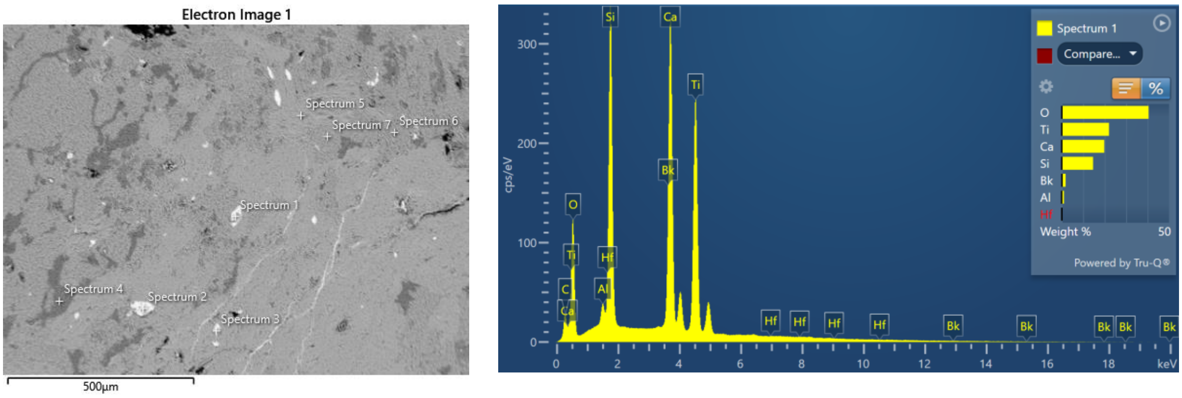


Fig. *32. Spectrum 1, 2, 3- Same composition - Titanite*

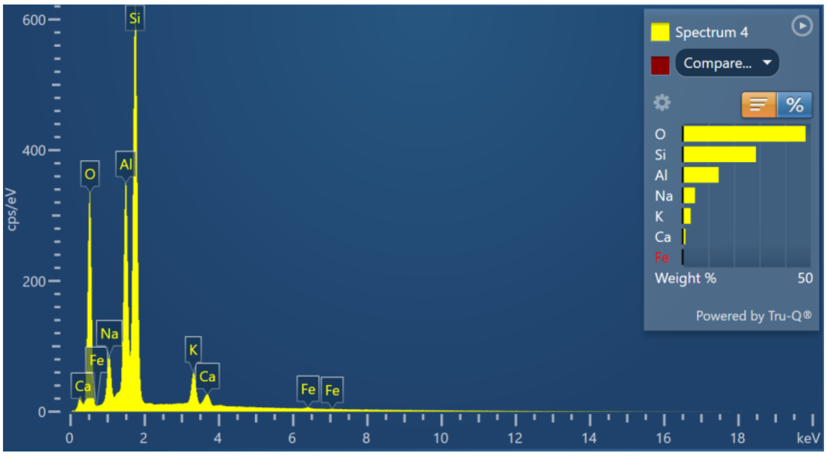


Fig. 33. Spectrum 4 – Feldspar

Uto 14

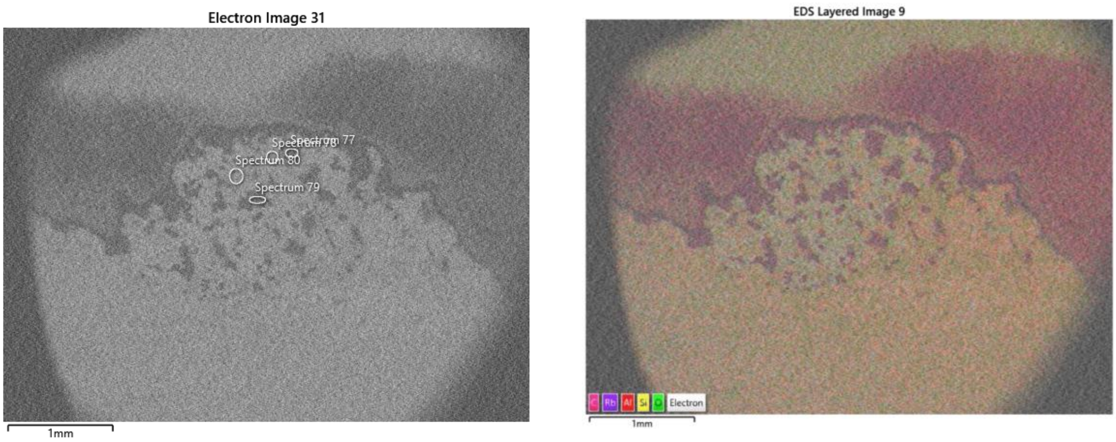


***Fig**. 34. Key interest sample seen again in SEM*

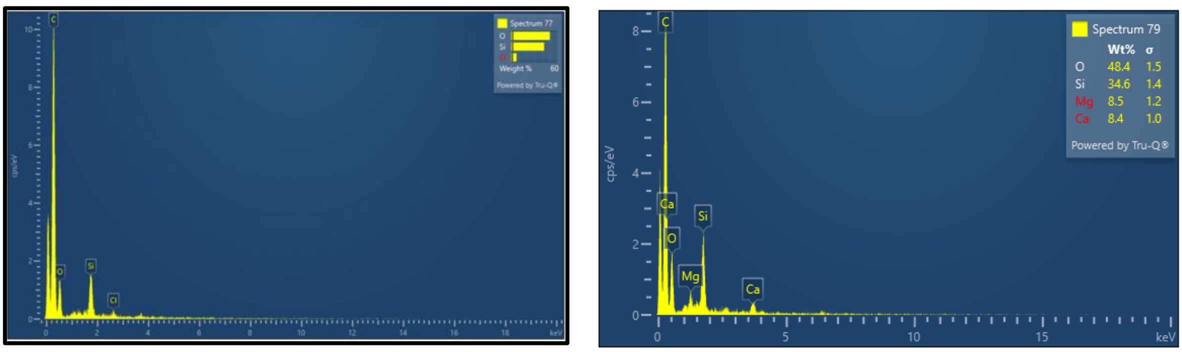
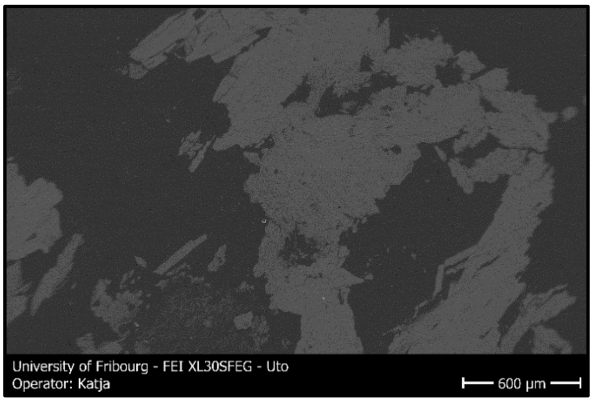


***Fig**. 35. Left and right top images show Uto_14 sample in SEM and in EDS layered image. Right image visualizes the sites elements with Red as Carbon. Further elemental analysis in lower elemental map corroberates carbonaceous elements.*

Uto 04



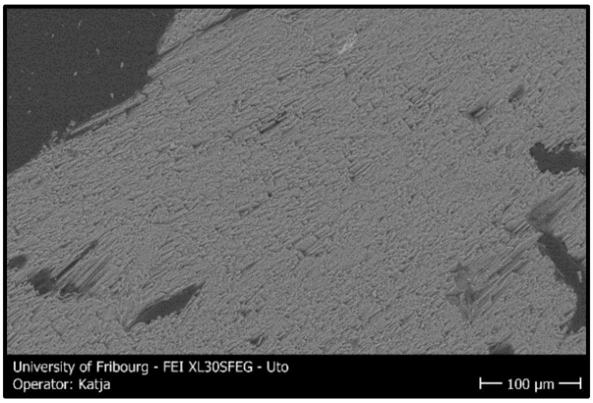
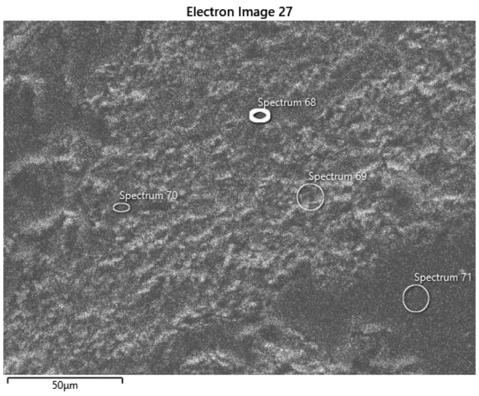


Fig. *36. Textures in SEM from skarn sample, including needle-like texture on right image.*



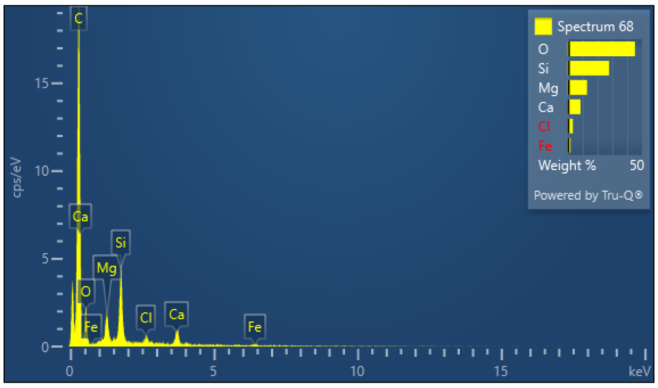


Fig. *37. Carbon in Spectrum 68*

Element	*Signal Type*	*Wt%*	*Wt% Sigma*
O		*45.26*	
Mg	*EDS*	*12.98*	*0.72*
Si	*EDS*	*27.82*	*0.83*
Cl	*EDS*	*3.45*	*0.53*
Ca	*EDS*	*8.63*	*0.58*
Fe	*EDS*	*1.87*	*0.58*
Total		*100.00*	

Table *3. Elemental composition for Spectrum 68*

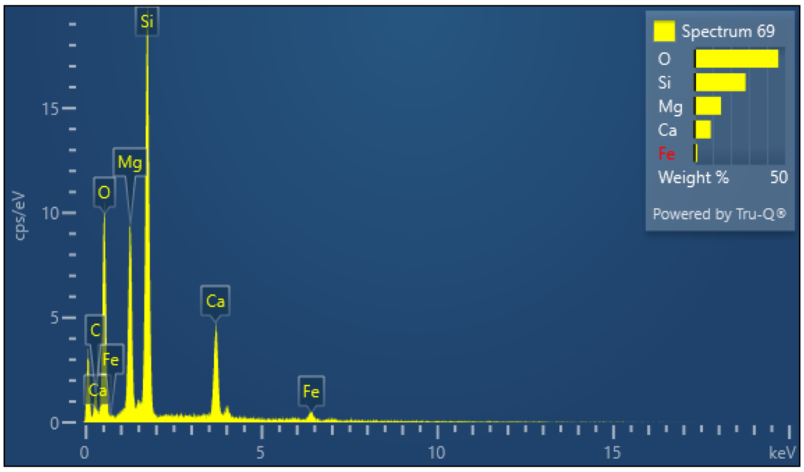


Fig. 38. Comparison of elements in surrounded areas in Spectrum 69

Element	Signal Type	Wt%	Wt% Sigma
O		44.15	
Mg	EDS	11.57	1.09
Si	EDS	27.33	1.20
Cl	EDS	7.87	0.95
Ca	EDS	9.08	0.89
Total		100.00	

***Table** 4. Elemental composition for Spectrum 69*

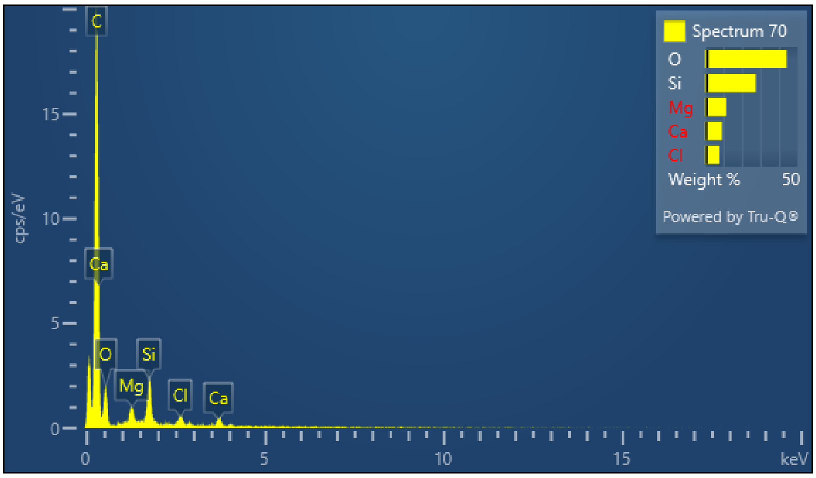


***Fig.** 39. Spectrum 70, once again showing Carbon*

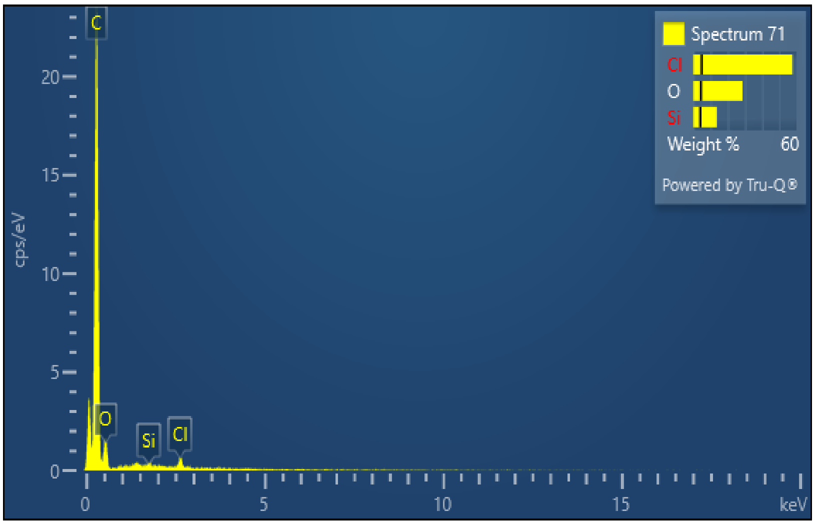


Fig. *40. Spectrum 71 with levels of Carbon*

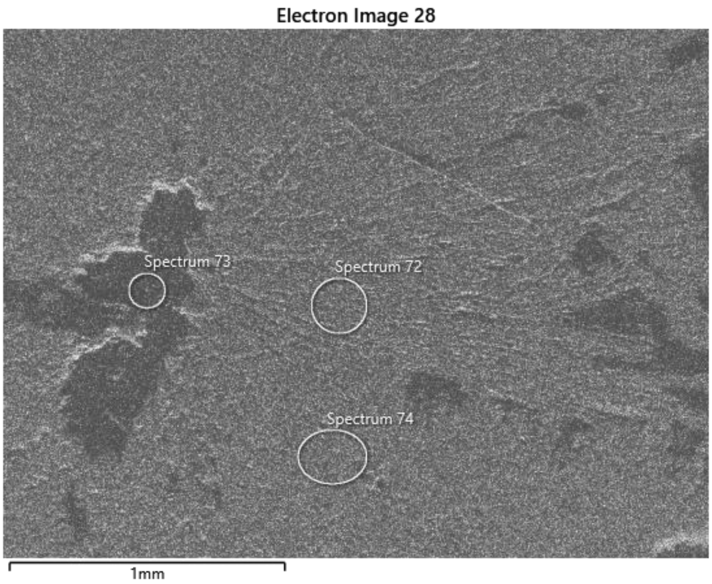


Fig. *41. Skarn sample*

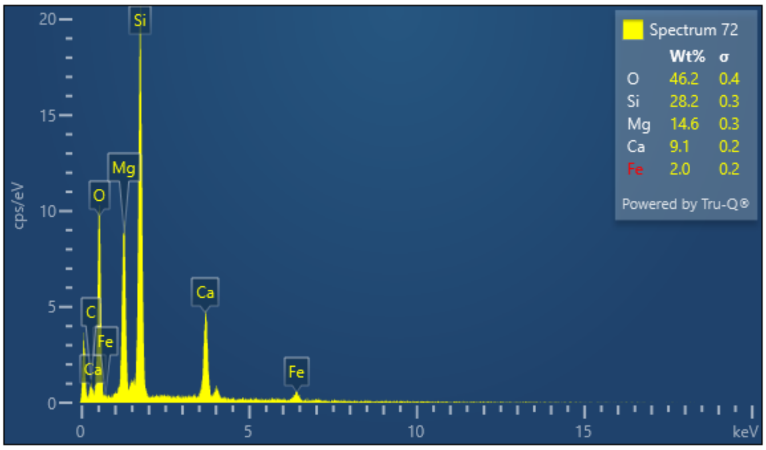


Fig. *42. Spectrum 72*

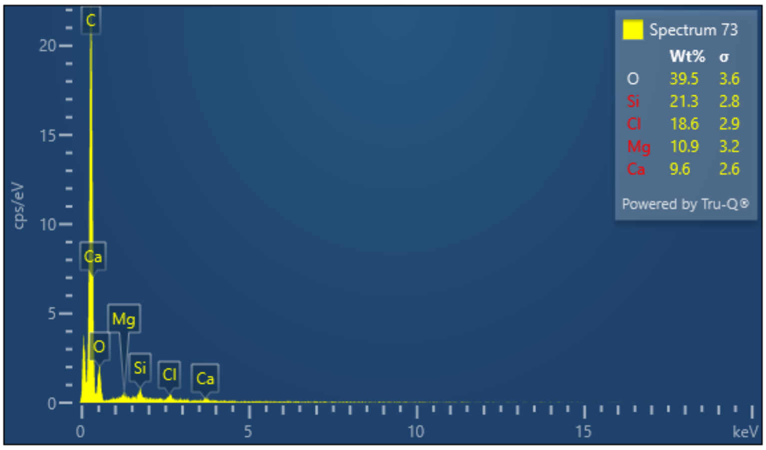


Fig. *43. Spectrum 73*

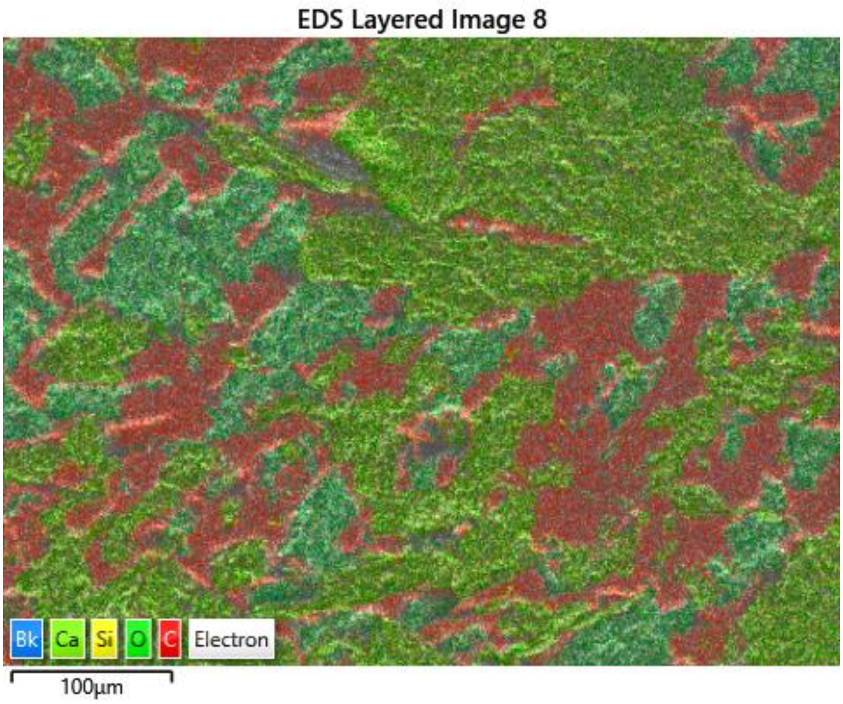


Fig. *44. EDS Image for Skarn sample, with red indicating Carbon, green as Oxygen and Calcium and yellow as Silicate*

Element	Signal Type	Wt%	Wt% Sigma
O		41.67	
Mg	EDS	12.29	0.09
Si	EDS	21.35	0.10
Cl	EDS	0.43	0.04

Ca	EDS	20.60	0.11
Mn	EDS	0.24	0.05
Fe	EDS	1.60	0.06
Bk	EDS	1.80	0.26
Total		100.00	

***Table** 5. Elemental composition for EDS layer in skarn sample*

Discussion

SEM

The presence of pyrite in Sample Uto_06 is of importance as pyrite often forms through microbial sulfate reduction, where microorganisms reduce sulfate to sulfide, leading to pyrite precipitation. The formation of $Fe - Cr - Ni$ alloys may indicate high-temperature hydrothermal processes that introduce these metals into the surrounding sediments. The combination of these minerals within chert matrices points to a dynamic interplay between biological activity and hydrothermal geochemistry, creating niches favorable for early life forms (Alleon, et. Al, 2019) Samples in the SEM elemental mapping often showed high levels of Carbon. This could be taken as a biomarker, though there might be other reasons such as epoxy or other possible pollutants in the making of the thin section that could give off this result.

Filamentous and organic structures were identified as micropeloids in at least one of the samples (e.g. 14) and had the elemental composition to indicate biogenicity.

Petrographic Microscopy

Calcite veins in dolostone provide valuable insights into past geological processes, such as fluid migration, tectonic activity, and diagenesis.

Their presence could be from tectonic stress or fractures in dolostone that are commonly caused by tectonic forces, such as faulting or folding. These fractures provide pathways for fluid movement (Twiss and Moores, 2007).

Another explanation could be fluid migration and how dolostone reacts with infiltrating fluids, often leading to the leaching of magnesium and enrichment of calcium in the fluid (Machel, 2004). Additionally, as Morse and Mackenzie (1990) state, the amount of calcite could be from a supersaturation of the fluid with calcium carbonate from cooling, pressure decrease and/or pH changes which make calcite precipitate and fill these fractures.

The samples also contained amphiboles, which can form in limestone or dolostone under specific metamorphic or hydrothermal conditions where suitable chemical compositions, pressure, and temperature are present. Dolostone (rich in dolomite, $CaMg(CO_3)_2$) provides the carbonate framework. Furthermore, we see the regularly associated minerals like garnet, pyroxene, and plagioclase, in addition to amphiboles being commonly found in skarn deposits where carbonate rocks interact with magmatic fluids (Meinert, 1992). In a manner similar to Mansfeld and Skelton(2023) we see evidence of the earlier stated replacement of calcic pyroxene by amphibole. Evidence of retrograde metamorphism and deformations are observed in the thin sections, in accordance to past literature of the site.

Fluorescence Microscopy

All the samples showed a level of fluorescence in TxRed, which indicates carbon. While fluorescence can be indicators of biogenicity, this result could also be explained by possible contamination and/or the coating the samples were made of. However, it's interesting to note we see the fluorescence more strongly in the areas that have opaques and in the same areas that have shown levels of carbon in SEM.

Dolostone

As Vasconcelos (1995) states, Inorganic dolomite formation under natural low-temperature conditions is rare because it requires a high magnesium-to-calcium (Mg: Ca) ratio, specific pH levels, and the removal of sulfate ions, which inhibit dolomite precipitation. Magnesium ions are strongly hydrated in water, making it difficult for them to integrate into the carbonate structure. Microbial biofilms and EPS can bind magnesium ions, reducing kinetic barriers. The EPS also serves as a template that facilitates the organization of ions into the dolomite structure, effectively bypassing the kinetic challenges of magnesium incorporation.

SRBs metabolize organic matter by reducing sulfate (SO_4^{2-}) to sulfide (H_2S) during anaerobic respiration. This process increases alkalinity (carbonate ion concentration) in the microenvironment, raising the saturation state of dolomite.

Microbial mediation is crucial for understanding both modern dolomite occurrences and the extensive ancient dolomite deposits in the geological record.

Stromatolite Identification

Experimental studies show that hydrothermal processes can create organo-mineral microstructures similar to microorganisms and abiotically reduce inorganic carbon into organic molecules (Alleon, et al., 2019).

However, filamentous evidence on sample 14 is consistent with what Dupraz et.,al (2023) identifies as micropelodial texture. There are distinct internal structures such as micrites that are seen in this sample, in the same location that shows fluorescence in microscopy and opaques in light microscopy, altogether indicating possible biological activity.

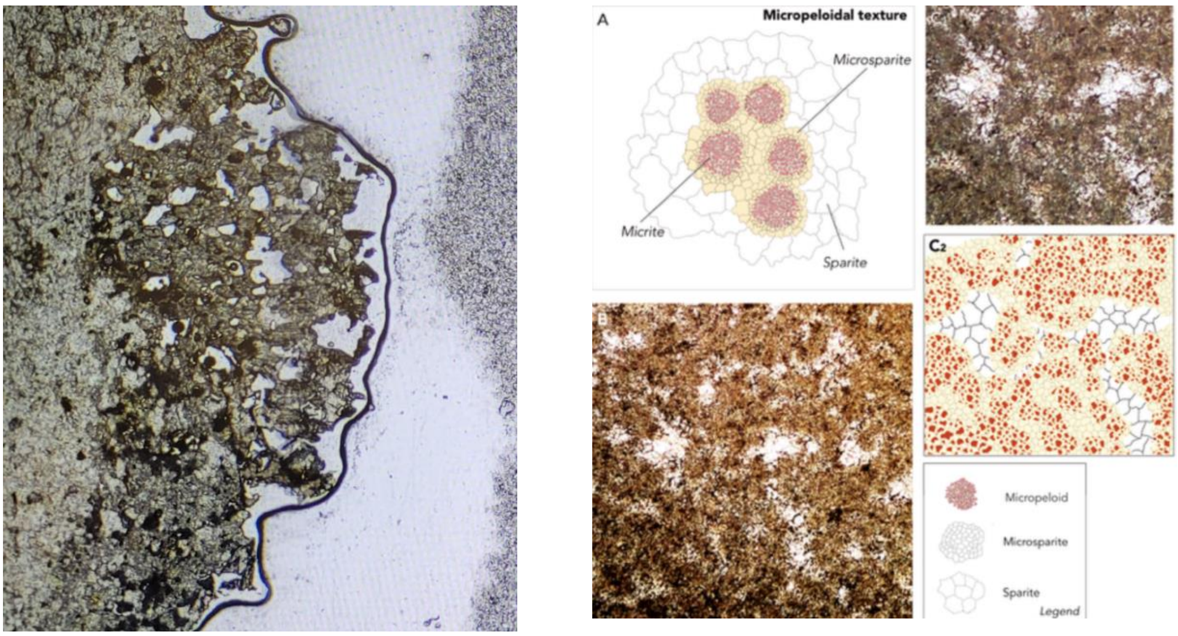


***Fig.** 45. Uto 14 in comparison with micropeloidal textures, adapted from Dupraz et.al(2023)*

While some abiotic processes can mimic micropeloidal morphologies, the combination that we have seen in morphology, geochemistry (appearance of elemental composition such as $Mg/Ca, Sr/Ca$ and layering strengthens their identification as biosignatures.

Laminated authigenic crusts can form through purely chemical processes, making it challenging to confirm a biological origin for ancient stromatolites. Additionally, the extensive morphological diversity of stromatolites peaked in the Proterozoic, which would add to the difficulty of identifying biotic from abiotic structures.

However, the morphology matches accounts of identified stromatolites and carbon and pyrite were also found through microscopy. We have to consider these as evidence in the samples as a possibility that these are biogenic.

Conclusion

It is very difficult to gather any valid information on samples as old as the ones in this study. The process of diagenesis and metamorphism alters the original isotopic signatures and as these samples are over a billion years old, they have gone through thermal, chemical and physical processes that have recrystallized their minerals to a point where the primary isotopic ratios have been obscured. It is therefore difficult to distinguish primary from secondary alterations. In addition, there is difficulty in differing between biogenic and abiogenic structures, due to how stromatolites accrete. However, their dominance in Precambrian times needs to be considered as they were not limited as modern stromatolites are, and were abundant in hypersaline, normal marine and nonmarine settings.

Furthermore, we need to take into account the abundance of Carbon in the samples and the morphology of the structure, which in light of the presented information evidence points to a lithified microbial carbonate.

Further studies would need to be done to fully identify biogenicity, specifically in Raman microscopy, as the levels of carbon can not without a doubt be direct evidence. While our data points in a biotic direction, we take into consideration that further studies would need to be done to fully identify biogenicity, specifically in Raman microscopy, as the levels of carbon cannot without a doubt be direct evidence.

Acknowledgements

I would like to thank Professor Dupraz for his patience and support throughout this thesis and for encouraging me to stay balanced in my work. The University of Fribourg for allowing me to be a guest at their university and for their generosity. Many thanks to my husband for his incredible support and for a second set of scientific eyes. My field-trip partner Katja, for her enthusiasm, attention to detail and beautiful drone shots.

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