



Stockholm
University

Bachelor Thesis

Degree Project in
Geology 15 hp

Geochemical and mineral changes during Na-alteration, Bergslagen, Sweden

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Stockholm 2019

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Abstract

Bergslagen is a famous mining district in south-central Sweden which contains over 6000 mineral deposits with mining in operation for over a 1000 years. Because of strong hydrothermal alteration, metamorphism and deformation in the Bergslagen district the formation of the ore deposits is not well known. Hydrothermal alkali alteration in the district is pervasive with large areas characterised by enrichment of either Na, K or Mg. The aims of the project were to evaluate whether chemical elements are mobilised during Na-alteration at Björnhället, a well-known location in western of Bergslagen, and to investigate the mineral changes during alteration and their relationship to the geochemical mobility. To carry out this investigation low detection geochemical methods, that has the ability to detect the REEs which are enriched in some of Bergslagen ore deposits, were carried out. The main geochemical changes during alteration were losses of Fe, Mg, water, Sc, V, Li, which are minerals associated with chlorite and depletions in the REEs. Only one of the analysed samples showed the expected Na-alteration. This sample showed an increase in Na and depletions in the elements associated with chlorite loss and REEs and some few base metals. The depletions in the REEs during alteration may indicate a potential source for some of the REE enriched ore deposits in Bergslagen.

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Introduction

Bergslagen (Figure 1) is a mining district in south-central Sweden which contains over 6000 mineral deposits with a history of mining that stretches for more than 1000 years (Lagerblad and Gorbatshev 1985, Allen et al., 1996, Stephens et al., 2009, Jansson, 2011). The Bergslagen district is composed mainly of metamorphosed sedimentary and felsic volcanic rocks and intrusive rocks that together form a part in the Baltic Shield emerging from the Early Proterozoic (1.90 – 1.87 Ga) (Allen et al., 1996). The ore deposits in Bergslagen vary in style from banded iron formation, manganiferous skarn and carbonate hosted iron ore, magnetite-calc silicate skarn, apatite iron ore and stratiform and stratabound Zn-Pb-Ag-(Cu-Au) sulphide ores (Figure 1) (Allen et al., 1996, Stephens et al., 2009).

The strong diagenetic and hydrothermal alteration, deformation and metamorphism in the Bergslagen district strongly hinder attempts to investigate the formation of the ore deposits, the primary volcanic processes and the general geological evolution of the region (Allen et al., 1996, Jansson 2011). Large portions of the Bergslagen district are characterised by extensive hydrothermal alteration classified through the major element enrichments of either Na, K or Mg (Lagerblad and Gorbatshev 1985). It has been suggested, using geochemical and field evidence, that the formation of some of the ore deposits in the region may be related to this hydrothermal leaching (Lagerblad and Gorbatshev 1985). The hydrothermal leaching is thought to have been driven by penetration of saline brines into the volcano-sedimentary stratigraphy resulting in alteration, metal leaching and the production of metal bearing fluids which lead to mineralisation at the higher stratigraphic levels (Lagerblad and Gorbatshev 1985, Allen et al., 1996). Hydrothermally altered rocks have been shown to be depleted in metals including Cu, Zn and other metals with these depletions being interpreted as the sources of metals enriched in the ore deposits (Lagerblad and Gorbatshev 1985).

This project will investigate the mobility of chemical elements during hydrothermal alteration in a well-known location in western Bergslagen. The study uses modern low detection limit geochemical methods and analyses a wide range of chemical elements including for example the rare earth elements (REE's) that are also enriched in some of the Bergslagen ore deposits. The study also aims to link geochemical changes to mineralogical changes that occur during the alteration.

The aims of the project are:

- 1) Evaluate which chemical elements are mobilised during the Na-alteration at Björnhället, Bergslagen
- 2) Constrain the main mineral changes during alteration and attempt to link this to the geochemical mobility.

The main working hypothesis is that as the alteration has been called “Na-alteration” that Na will be amongst the mobile elements and that the main mineral reactions will involve plagioclase.

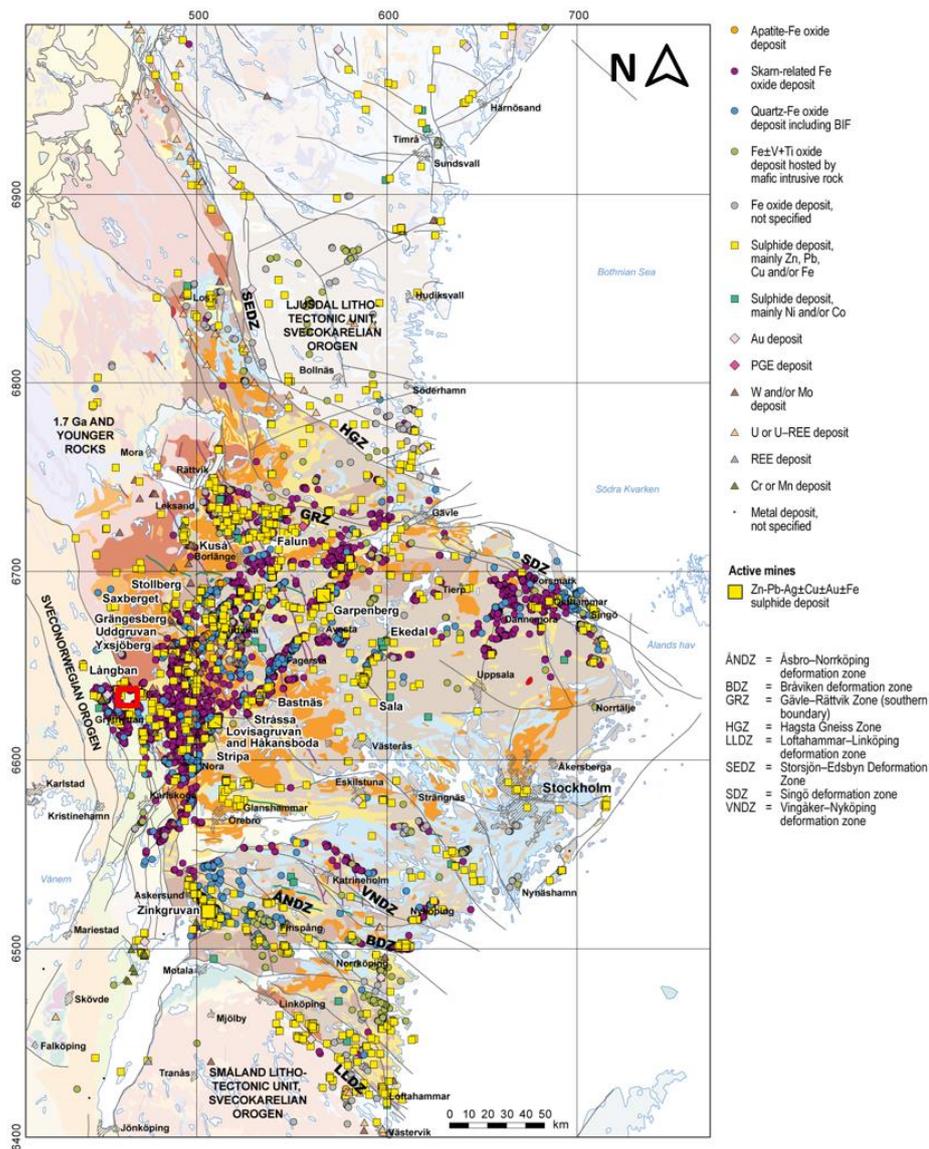


Figure 1. Map of the Bergslagen district, showing the mines and the different deposits, taken from Stephens et al., 2009. The area marked in red is where the samples were collected.

Geological setting

The Bergslagen district has evolved through numerous tectonic events that has resulted in intense magmatism, crustal extension and thermal doming (Allen et al., 1996). The area and the rocks hosting the ore deposits developed under extensional active continental margin conditions, in a mixed terrestrial and marine environment interpreted as a back-arc felsic caldera built on continental crust (Allen et al., 1996, Jansson 2011).

Records of two separate major tectonic cycles first one ranging between 1.91 – 1.86 Ga and the other one occurring between 1.86- 1.82 Ga, both in a transtentional setting, can be recognised in the Bergslagen district (Stephens et al., 2009, Jansson, 2011). The first cycle occurred during 1.91-1.86 Ga with an episode of penetrative ductile deformation (Holtstam et al., 2014) taking place 1.87-1.86 Ga (Stephens et al., 2009, Jansson 2011). This transtentional tectonic setting with back-arc environment condition occurred again between 1.86-1.82 Ga (Stephens et al., 2009, Jansson, 2011). The rocks were later affected by the Svecokarelian orogeny where they underwent compression with folding and shearing (Allen et al., 1996, Jansson, 2011). The metamorphism of the Bergslagen district ranges from greenschist to upper amphibolite facies (Lagerblad and Gorbatshev 1985, Allen et al., 1996, Jansson 2011, Holtstam et al., 2014).

The metasedimentary rocks, the felsic metavolcanic and the underlying syn-volcanic intrusions that were emplaced between 1.91 and 1.89 Ga, in the western, central and northern parts of the region are metamorphosed and deformed (Stephens et al., 2009, Jansson 2011). Together they form a 7000 thick layer in the stratigraphy of the Bergslagen district (Allen et al., 1996, Lundström et al., 1998, Jansson 2011).

The volcanic rocks in the region have a dominantly rhyolitic composition, with volcanic rocks occurring as quartz-feldspar or feldspar porphyries and also reworked volcanoclastic rocks (Allen et al., 1996, Jansson 2011). Early pre-tectonic intrusions consist of granites, granodiorites and tonalites, syn-volcanic and post-volcanic plutons that were placed before peak metamorphism (Allen et al., 1996). The overall composition in the region varies from granite to gabbro however, towards the east the rocks tend to be of a more intermediate composition (Allen et al., 1996).

Stratigraphically the lower unit constitutes of poorly stratified felsic rocks such as quartzite, meta-greywacke, meta-arkose, pelite and meta-turbidite which is overlain by rhyolitic metavolcanic rocks (Allen et al., 1996). At the top of the sequence meta-turbidites, meta-pelites

and marbles occur, and it is these marbles that commonly host the base metal sulphide deposits (Lagerblad and Gorbatshev 1985, Allen et al., 1996, Jansson 2011).

Ore deposits of the Bergslagen district

Over 6000 metallic ore deposits reside in the felsic metavolcanic and metasedimentary rocks (Stephens et al., 2009, Jansson et al., 2011). Bergslagen contains a diverse range of ore deposits such as stratiform and strata bound Zn-Pb-Ag-(Cu-Au), banded iron-formation, apatite bearing iron ore, magniferous skarn- and carbonate-hosted iron ore, magnetite-calc-silicate skarn and banded iron formation (Allen et al., 1996, Stephens et al., 2009, Jansson et al., 2011). The district also contains deposits enriched in REEs, Mn, W, O, Mo, Cl, Ni, Co, Ba and Li (Jansson, 2011). The majority of the ores reside in the upper volcanic succession hosted in carbonate or skarn rocks (Allen et al., 1996, Jansson 2011).

Two main types of base metal sulphide deposits can be distinguished in the region based on their character, host rock and metal content (Allen et al., 1996, Stephens et al., 2009). The first type is stratiform ash siltstone hosted Zn-Pb-Ag rich deposit appearing in Zinkgruvan (Allen et al., 1996, Stephens et al., 2009). The second one involves stratabound volcanic associated marble skarn massive and berated Zn-Pb-Ag-(Cu-Au) ores that appear in Garpenberg, Stollberg, and Falun deposits (Figure 2) (Allen et al., 1996, Stephens et al., 2009).

Hydrothermal leaching and magmatic hydrothermal fluids have been suggested as the two main sources of metals for the formation of Fe-oxides and sulphides (Baker and De Groot, 1983, Lagerblad and Gorbatshev 1985, Allen et al., 1996). The former model proposes that saline brines infiltrated the volcano-sedimentary rocks which resulted in large-scale hydrothermal leaching of different rock types which produced metal rich fluids that caused mineralisation at the higher stratigraphic levels in form of replacement of limestone interbeds in the volcanic succession (Baker and De Groot, 1983, Lagerblad and Gorbatshev 1985, Allen et al., 1996). Na- and Mg-altered metavolcanics rocks have been shown to be depleted in elements including Fe, Mn, K, Rb, Ba, Cu, Zn and Pb (Lagerblad and Gorbatshev 1985). Mg-altered rocks have also been shown in a separate study to be depleted in REE's (Baker and De Groot 1983).

The magmatic hydrothermal model proposes that the metal rich fluids that formed certain ore deposits were produced by sub-volcanic magmatic intrusions (Holtstam et al., 2014). This model was developed by interpretations of stable isotopes analysis of O, S and C from Bastnäs (Holtstam et al., 2014). It is, however, unclear if these results are typical of the Bastnäs mineralisation or if they apply for the whole Bergslagen region (Holtstam et al., 2014).

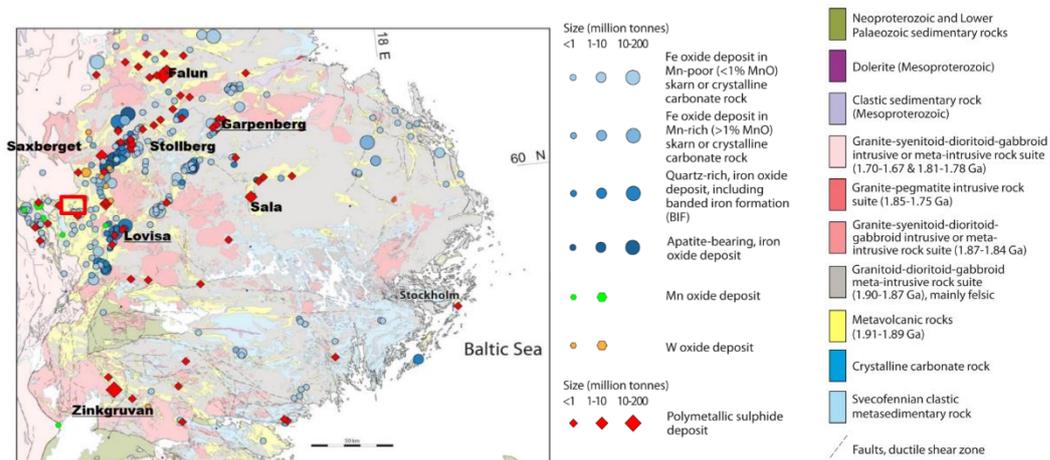


Figure 2. A geological map showing the location of ore deposits and host rock types in Bergslagen (From Stephens et al., 2009). The red area is the location of Björnhället.

Hydrothermal alteration and secondary alteration

Metasomatism is hydrothermally-driven recrystallisation of a rock that leads to changes in its chemical composition (Winter 2014). One type of metasomatism, where igneous rocks intrude carbonate bearing sedimentary rocks, is skarn alteration which is abundant in the Bergslagen (Allen et al., 1996). In metamorphic rocks the metasomatism is represented by mass transfer due to recrystallization driven by changes in T or P where the hydrothermal fluid acts as the medium that transports the mass (Winter 2014). Metasomatic rocks are recrystallised and therefore commonly exhibit a change in colour such as bleaching (Winter 2014).

Regional alteration of areas in Bergslagen has resulted in differentiations of the alkali content of the volcanic rocks that were emplaced 1.91 and 1.89 Ga before they were deformed and metamorphosed (Lagerblad and Gorbatshev 1985, Jansson 2011). Volcanism occurred in a submarine environment which resulted in extensive amount of sea water and possibly more saline basinal brines infiltrating the volcanosedimentary sequence causing extensive metasomatism (Lagerblad and Gorbatshev 1985, Allen et al., 1996, Holtstam et al., 2014). Extensional faulting helped the infiltration of water to reach greater depths (Lagerblad and Gorbatshev 1985). This extensive alteration has led to enrichment in Na and locally Mg in the rocks residing at lower stratigraphic levels (Lagerblad and Gorbatshev 1985, Jansson 2011).

Both Na and Mg are elements that can be derived from seawater (Lagerblad and Gorbatshev 1985). The upper levels of the stratigraphy show enrichment in K (Lagerblad and Gorbatshev 1985, Allen et al., 1996, Jansson 2011). The altered felsic metavolcanic rocks in the region have been previously called Leptite rocks (Figure 2) (Lagerblad and Gorbatshev 1985, Allen et al., 1996).

The hydrothermal leaching occurred under relatively high temperatures in the deeper parts of the stratigraphy before termination of volcanic activity (Lagerblad and Gorbatshev 1985). The Na-enriched meta-volcanics are remarkably depleted in Fe, K, Mn, Rb, Ba, Cu, Zn and Pb (Lagerblad and Gorbatshev 1985). This indicates an occurring event where Na got precipitated and elements were leached, forming the Na-rich porphyries (Lagerblad and Gorbatshev 1985). The rocks enriched in K are depleted in Na, Ca and Sr (Lagerblad and Gorbatshev 1985). The study by Baker and De Groot (1983) showed that REE's are mobile during Mg-alteration of felsic meta-volcaniclastic rocks. In this alteration style oxides such as K_2O , SiO_2 and Al_2O_3 are relatively immobile while the REEs (with the exception of the HREEs that are not mobile) are depleted (Baker and De Groot, 1983).

[Björnhällen, 59°48'24.37"N, 14°36'16.88"E](#)

Björnhällen is a small locality north east of Hällefors, that got its name as it was a favourite locality of Björn Lagerblad for demonstrating an example of the extensive alkali alteration in Bergslagen. The rock type is a porphyritic rhyolitic volcanoclastic rock that has been recrystallised during greenschist facies metamorphism and has also been intensely hydrothermally altered. Figure 3 shows the clear difference in colour between the darker, chlorite bearing "least" altered rocks and the lighter coloured altered rocks. The alteration style at the locality is classified as being Na-alteration.

A suite of 9 samples were collected, 5 of the least-altered chlorite bearing rock and 4 of the altered rock with one sample demonstrating the reaction front.



Figure 3. Photo showing the difference in colour of the altered rock and least altered rock. Photo taken by Dr. Iain Pitcairn, 2018.

Methods

Thin sections description in transmitted light microscopy

The mineral assemblages in the thin sections were all observed using transmitted light microscopy. The minerals were identified by observation of their several properties such as the colour, pleochroism, birefringence and so on. For this project the microscope LEICA DMLSP was used and for the thin section scans in the appendix Nikon SUPERCOOLSCAN9000 was utilised.

Point count was not used because samples were too fine grained to differentiate some of the components.

ALS geochemical data and mass change analyses

Whole-rock chemical analyses for major, trace and rare earth elements were carried out at the ALS analytical laboratories in Sweden. The major oxides were measured using the code ME-ICP06 in which 2 grams of the samples were analysed for the major oxides using the ICP-AES following lithium borate fusion and acid digestion. The detection limits for the major oxides

are between 0.01% and 0.002%. Trace and rare earth elements were measured using the code MS61L-REE which provides REE analyses at low detection limits of between 0.005 – 0.002 ppm. Loss on ignition (LOI) was measured using the OA-GRA05 method by measuring the difference in weight after heating to 1000 °C using the WST-SEQ instrument. The used methods are ISO 17025:2005 accredited and the precision and accuracy are controlled through analysis of multiple international reference materials.

Mass change analysis was carried out using “Isocon” diagrams - a method for analysis of changes in volume and concentration during metasomatism (James, 1986). The isocon is a linear relationship of the concentration of elements in the altered rock compared to the original one (James, 1986). The immobile elements define the “isocon” which is a straight line going through the origin (James, 1986). Those elements significantly above or below the line show either mass gain or mass loss and the slope of the line from the origin to the position of any specific chemical element determines the mass change for this element (James, 1986). In this project this method was used to investigate mass change between the average concentrations of most altered samples (5B, 6, 7) and the least altered (1, 2, 3, 5A).

Results

Rock classification

Figure 4 shows the total alkali vs silica in a so called TAS-diagram (Le Maitre, 2005) that was constructed using the geochemical data to classify the rock type of the samples. All the samples plot in the sub-alkaline field and possess a dominant rhyolitic composition. It appears that sample 4A has a slightly higher alkali content than the rest of the samples (see appendix Table 1 and 2) and sample 4B which is the altered part of sample 4 has much higher alkali content possibly indicating a different style of alteration to the other altered samples. It is the only sample that is strongly Na-enriched during alteration and therefore the only one that should really be classified as “Na-alteration”. However as there is only one sample it is treated separately during the mass change investigation.

Table 1 lists the elements that are depleted and enriched in the altered samples (5B, 6, 7) compared to the least altered samples (1,2,3,5A). The definition of “depleted or enriched” used in this table is that the mean +/- the standard deviation of the altered and unaltered samples must not overlap. The table shows the loss of Mg and Fe, both chlorite forming minerals, as well as the loss off the REEs such as Yb, Tm, Lu etc.

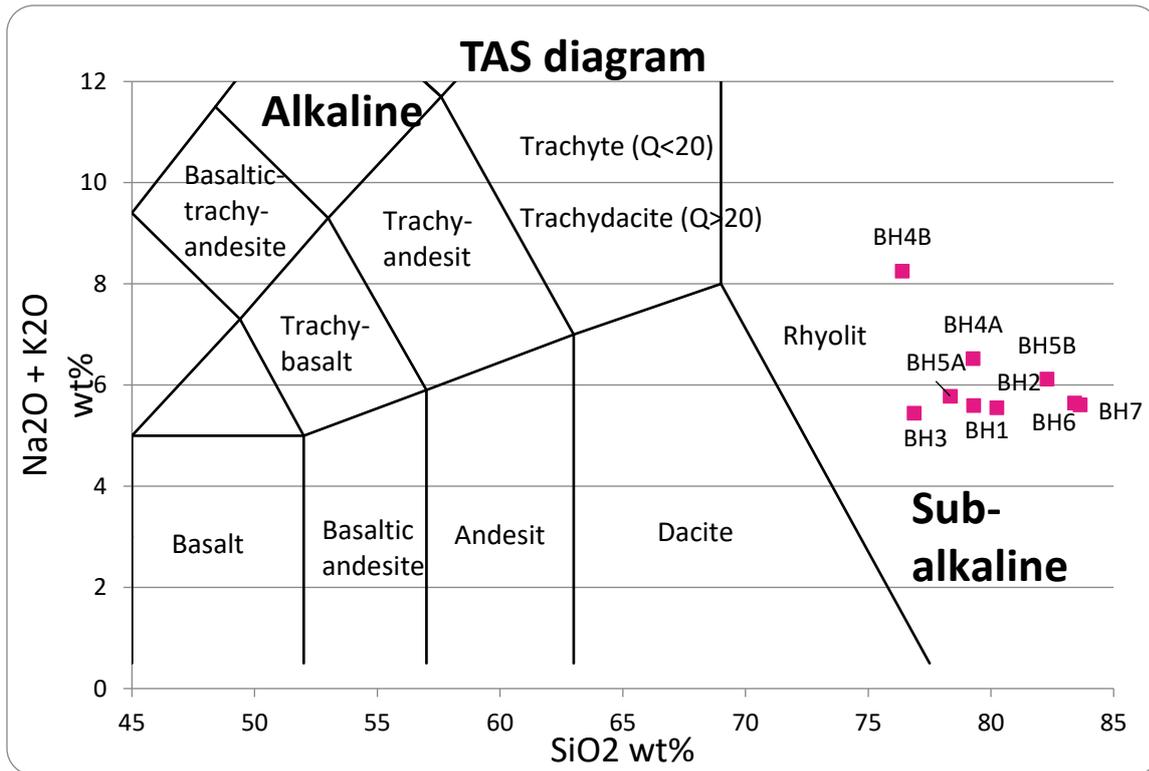


Figure 4. A TAS-diagram showing the dominant rhyolitic composition of the samples. Sample 4B exhibits a higher amount of Na compared to the rest of the samples.

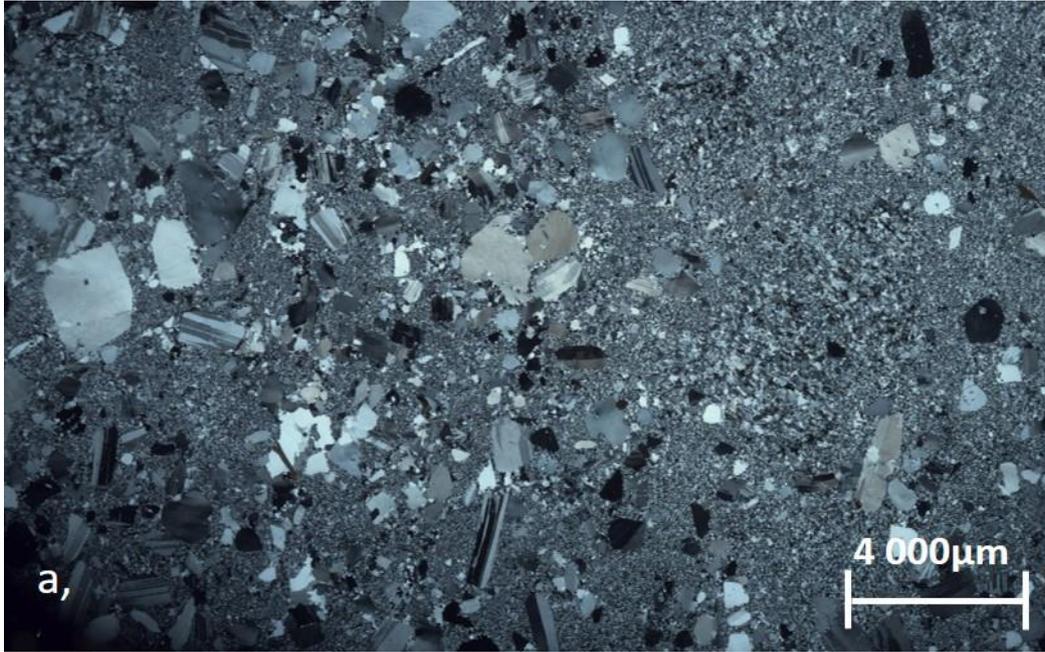
Elements enriched in altered samples					
SiO ₂	Na ₂ O	Cr ₂ O ₃	As	Bi	Ca
Cd	Cr	Ga	K	Pb	
Elements depleted in altered samples					
Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	LOI	Al
Co	Cs	Fe	Ni	Na	V
Li	Mg	Mn	Mo	Er	Zn
Sc	Sn	Lu	Tm	Yb	

Table 1.

Sample descriptions



Figure 5. An overview of the 9 samples that were made into thin sections.



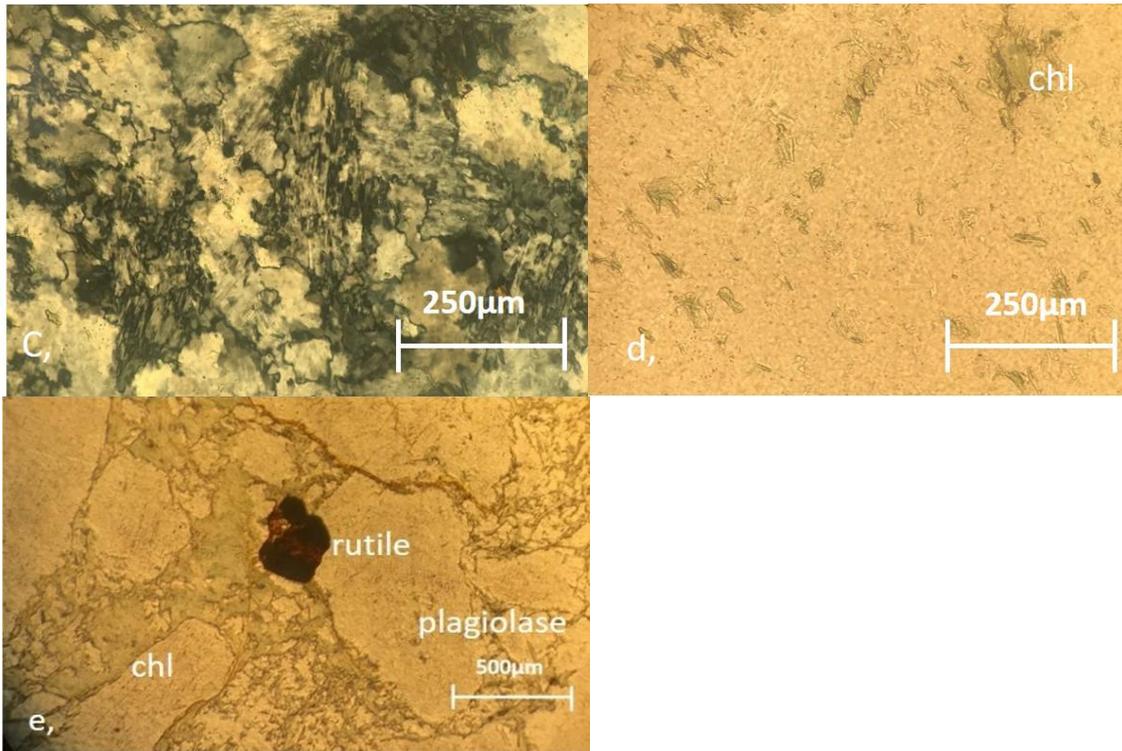


Figure. 6a, shows sample 1 in XPL the euhedral 0.5-1 mm euhedral plagioclase grains; **b**, shows sample 1 in PPL where the chlorite is visible; **c**, shows a slight close up, from sample 2, on the matrix where quartz and plagioclase cannot be told apart; **d**, shows the same as picture c however in PPL where the chlorite in the matrix is visible; **e**, is taken from sample 3 and shows the rutile and chlorite in the matrix.

Description of least altered samples (1, 2, 3, 4A, 5A):

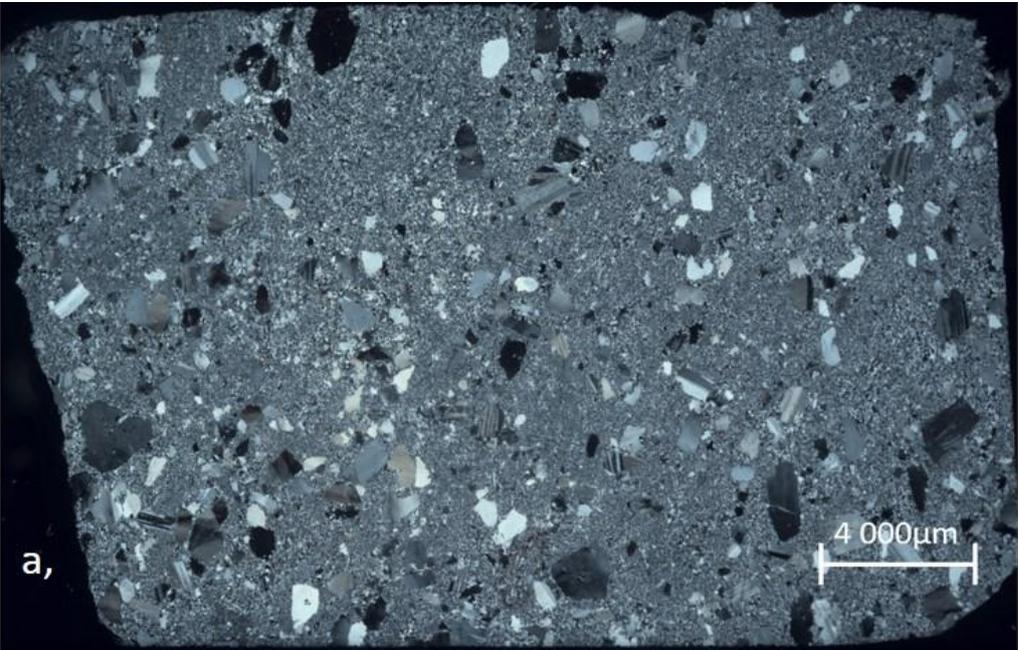
Mineralogy: chlorite (~20-25%), plagioclase, quartz, biotite, epidote, rutile, titanite, opaques

These samples show a porphyritic texture (figure 6a) where the euhedral plagioclase and quartz up to 0.5-1 mm, sometimes 2 mm, crystals set in a fine-grained matrix constituting quartz, chlorite and plagioclase. Fine-grained chlorite is enveloping the plagioclase porphyroblasts (figure 6b). Sub-grain development is apparent in both quartz and plagioclase phenocrysts. The matrix crystals show irregular interlocking grain boundaries. Some plagioclase porphyroblasts exhibit a poikilitic texture with inclusions of chlorite and epidote.

The sections are too fine-grained to estimate the mode (figure 6c and d), especially for epidote, rutile (figure 6e) and titanite, that are not very abundant and are fine-grained. Opaque minerals commonly sit in the chlorite around the edges of plagioclase phenocrysts are too fine grained to identify.

Some patches in the thin sections appear to have the form of a fine-grained fibrous mineral such as chlorite but they are now comprising quartz and feldspar. These textures contain chlorite in the least altered samples, but the chlorite is removed in the altered sample with only the texture

remaining. Sample 3 exhibits larger proportions of chlorite and biotite than 1 and 2 (see appendix page 25).



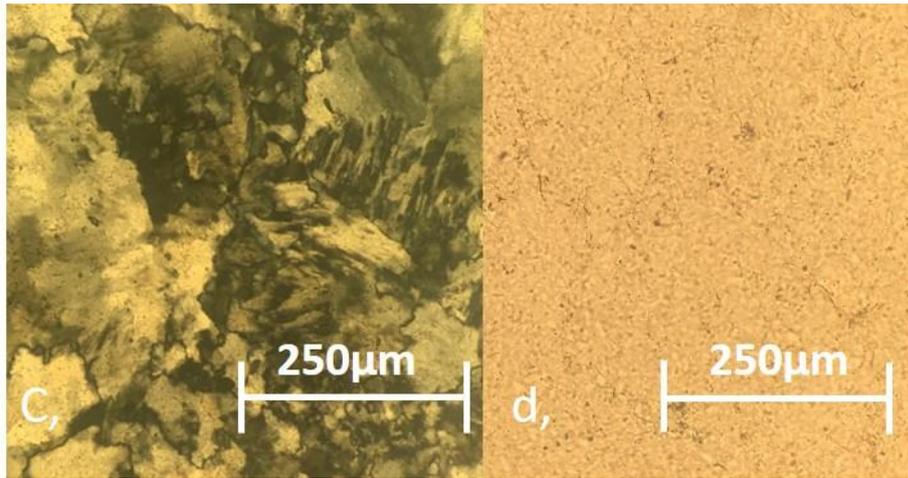


Figure 7a, shows the overview of sample 6, and an example of how an altered sample looked like in XPL; b, shows the overview of sample 6 in PPL exhibiting the almost no chlorite content; c shows the pseudomorph texture from sample 7 in PPL and d, shows the same texture in XPL which shows barely any chlorite.

Description of altered samples (4B, 5B, 6, 7):

Mineralogy: chlorite (<5%), plagioclase, quartz, titanite, epidote, biotite, opaque minerals

The texture suggests that the secondary alteration mostly affected the fine grained matrix because the euhedral porphyroblasts, 0.5-1 mm, sometimes even 2 mm, and the sub-grain developments are seemingly unaffected (figure 7a). Opaque minerals, titanite and epidote are sparse in these samples, but the clearest difference is the decrease in chlorite content (figure 7b). There is no rutile apparent in the altered samples. The matrix is almost fully composed of a fine-grained fibrous textured quartz and plagioclase that may be pseudomorphed chlorite (7c). Chlorite is rare in the altered samples indicating the breakdown of chlorite is one of the clearest mineral reactions during the alteration (figure 7d).

Differences between the least altered and altered:

The mineral textures (and reaction textures) indicate that the “unaltered” sample isn’t fully unaltered however, there’s an apparent difference in the altered and least altered samples in terms of the amount of alteration textures in the matrix. The plagioclase porphyroblasts seem unaffected since their abundance and form hasn’t changed.

The altered samples are strongly depleted in chlorite and also appear poorer in opaque minerals. The chlorite went from being a large part in the matrix in the least altered samples to be a small, barely component in the altered ones. Rutile was only observed in the least altered samples.

Geochemical and mineralogical changes

Figure 8 is an isocon diagram which plots the average concentrations of the least altered samples along the x axis and altered samples along the y axis. Each chemical element is labelled on the diagram and their compositions are scaled to fit between 0 and 100. The diagram shows clear depletion of REEs and in the elements related to chlorite such as Mg. These elements plot below the isocon indicating they're much lower in concentration in the altered samples. There is no systematic depletion of the base metals as they plot both above, below and close to the isocon.

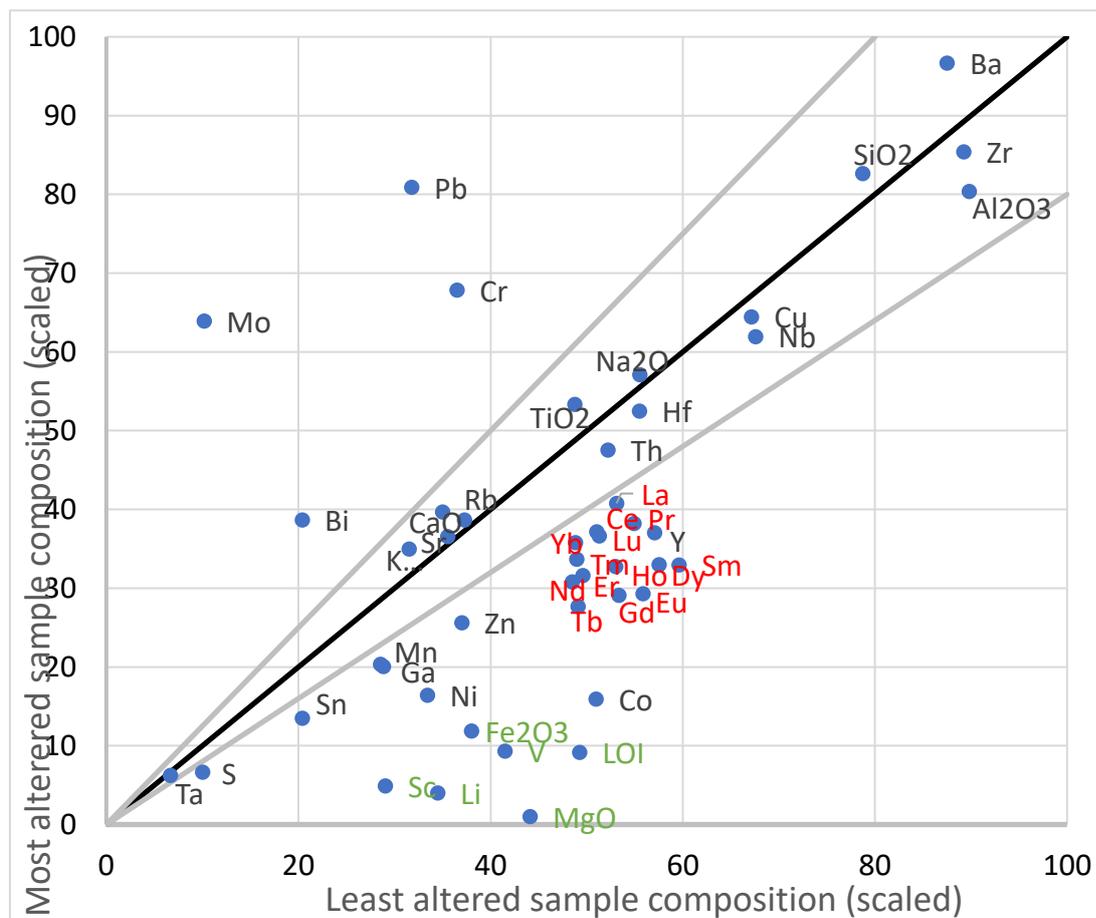


Figure 8. Isocon showing the enriched and depleted elements in the altered samples compared to the least altered. The REEs are marked in red, chlorite forming minerals in green and the base metals black.

Figure 9 is a similar isocon diagram but plotted to show the least altered part of the sample, 4a versus the altered part, 4b. This diagram shows some interesting differences compared to figure 8. Na is enriched plotting above the isocon indicating about 20% enrichment. Al and Ba also appear enriched whereas similar to figure 8, the chlorite forming components Fe, Mg, loss on ignition (LOI) etc are depleted. The alteration appears to fractionate the REEs. The light REEs

have been depleted such as La, Ce, Sm etc are depleted while the heavy REEs Lu, Yb, Ho etc plot on the isocon indicating they have not been mobilised. Also, Cu, Zn, Co and Ni are depleted.

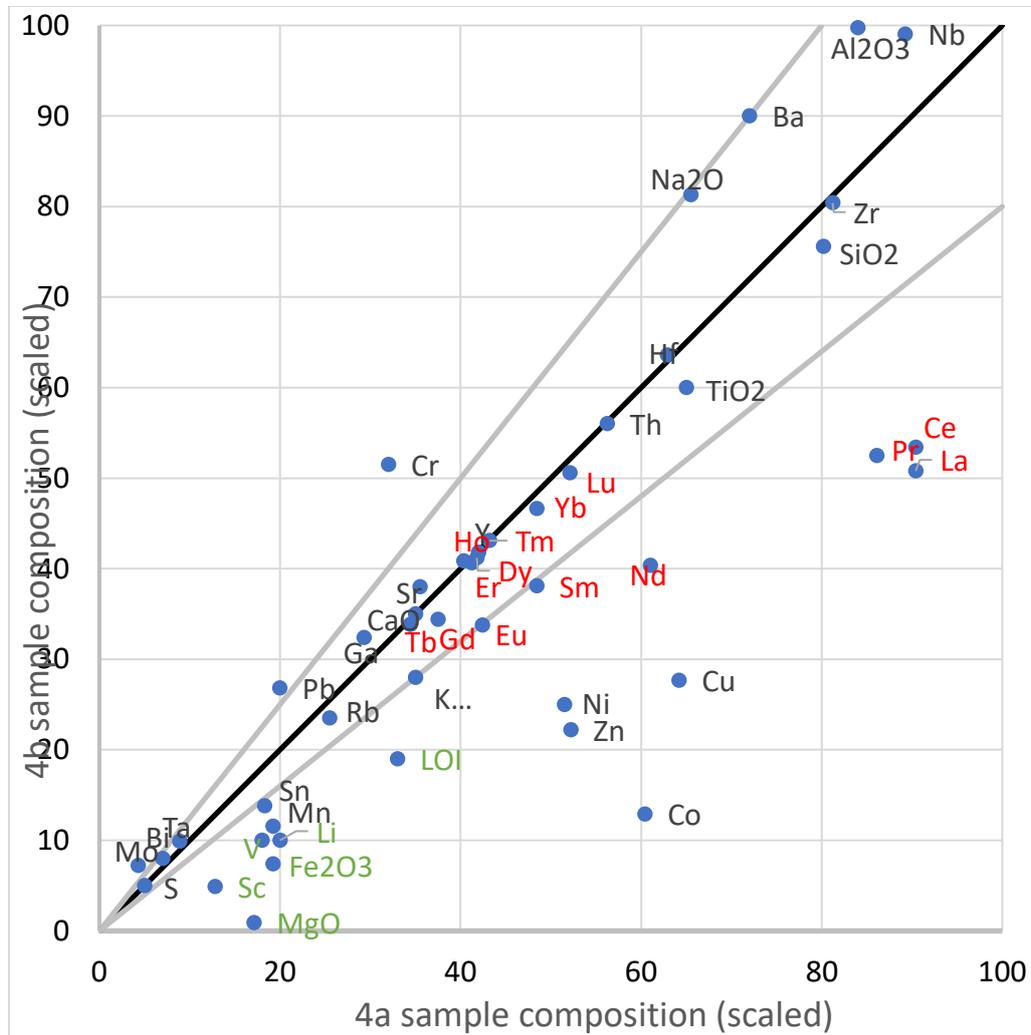


Figure 9. Isocon of sample 4b plotted against 4a.

Discussion

Element mobility during alteration

An isocon diagram is a method that is applied to detect changes in mass concentration of elements during metasomatism. The diagram is constructed by drawing a line from the origin through the “immobile” elements whose concentration should not have changed during alteration. Choice of which immobile element is used to define the isocon is difficult and varies between different styles of alteration. Commonly high field strength elements such as Zr, Ti,

Hf and Th are used (Grant 1986). All of these elements plot on or near the line on both isocons in figures 8 and 9. Elements that plot along or close to this line are similar in concentration in both the altered and least altered samples, indicating they are immobile during the alteration. In this study we have defined samples plotting within 20% addition or depletion (shown by the light grey lines on the isocon diagrams) to be immobile. If the elements plot above the isocon it means they've been enriched in the altered samples and if they plot below, they've been depleted. This method was used as an attempt to figure out which elements were mobilised during the alteration process.

Figure 8 shows the isocon of the averaged altered samples plotted against the averaged least altered samples and Figure 9 shows the isocon for sample 4A plotted against 4B. In both isocon diagrams the elements related to the mineral chlorite such as Mg, Fe, water (as shown by the loss on ignition value – LOI) as well Sc, V, Li that are common trace elements in chlorite are depleted. These chemical changes are confirmed by the thin section observations in which a substantial decrease in chlorite could be observed during alteration. The least altered samples contain around 20% chlorite, while the altered samples contain less than 5%. The other clear chemical change is the depletion in the REEs. Figure 8 showing the isocon for the averaged altered and least altered samples shows all REEs plotting below the isocon. Figure 9 shows some fractionation of the REEs with the immobile HREEs plotting on the isocon, and the MREEs and LREES being progressively depleted. The mineralogical control on REE mobility is not known as identification of REE bearing minerals (e.g. allanite, monazite, xenotime) in the petrographic microscope was not possible.

Base metals are not systematically mobilised in the main group of samples shown in figure 8. However, in sample 4B which shows the clearest trend of Na-alteration, the base metals Cu Zn and Co are depleted. Lagerblad and Gorbachev (1985) indicated that it was primarily this style of alteration in which the base metals were depleted. However, the list of elements showing depletion in that study (Fe, K, Mn, Rb, Ba, Cu, Zn and Pb; Lagerblad and Gorbatschev 1985) is not entirely consistent with the elements observed to be mobile in sample 4B in this study. For example, Pb is not depleted in any of the altered samples in this study. The alteration observed in our suite of samples would not have produced metal enrichments in the altering fluid as was predicted in the hypothesis. The main alteration excluding sample 4B does not show the Na-alteration that was expected. This hydrothermal alteration has basically resulted in the removal of chlorite and the REEs and some few base metals.

Implications for ore deposits in Bergslagen

The isocon for sample 4B also shows a depletion in base metals such as Cu, Zn, Co and Ni. It also shows a depletion in K compared to the isocon for the rest of the samples. This sample shows the type of alteration described in Lagerblad and Gorbachev (1985) that has been suggested to produce base metal enrichments in the altering hydrothermal fluids. Interestingly this sample and also those others investigated in this study show clear REE mobility. It is possible therefore that the base metal rich brines produced during Na alteration may have also been enriched in REE's. This would be an alternative fluid and metal source for some of the REE enriched mineral deposits in the Bergslagen district.

Conclusions

The project aims were to evaluate which chemical elements are mobilised during the alteration at Björnhället, Bergslagen and constrain the main mineral changes during alteration and attempt to link this to the geochemical mobility. The main geochemical changes are depletions in elements associated to chlorite (Fe, Mg, water, Sc, V, Li) and depletion in the REEs. The mineralogical changes observed in thin section confirm the depletion of chlorite but the mineral hosts for the REEs were not identified. The main style of alteration did not show any Na-depletion and therefore the alteration shouldn't be called Na-alteration. Sample 4B, showed a different alteration pattern than the rest of the altered samples with a substantial increase in Na and depletions in elements related to chlorite, base metals and HREEs. This sample resembles the Na enriched samples of Lagerblad and Gorbatshev (1985). This alteration pattern of sample 4B seems to have generated those metal rich fluids. Unfortunately, this is the only sample that behaves this way and to make sure of this statement more samples would be needed to be investigated.

Suggestions for a further study of more samples collected at this area is advised to see how the leaching and to what extent the hydrothermal alteration stripped these samples, like sample 4, of their base metal components.

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Appendix

Table with the TAS-diagram geochemical data.

Samples	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	Cr ₂ O ₃	TiO ₂	LOI	Total
	%	%	%	%	%	%	%	%	%	%	%
1	77.8	10.75	1.71	0.07	1.25	5.45	0.04	0.002	0.08	0.96	98.12
2	80.9	10.85	1.58	0.04	0.99	5.56	0.04	0.002	0.09	0.76	100.83
3	77.9	11.85	2.43	0.03	2.2	5.49	0.03	0.002	0.09	1.32	101.35
4A	80.2	12	0.96	0.05	0.57	6.55	0.05	0.002	0.13	0.66	101.18
4B	75.6	14.25	0.37	0.05	0.03	8.13	0.04	0.002	0.12	0.38	98.97
5A	78.3	11.45	1.88	0.06	1.44	5.71	0.07	0.003	0.13	0.9	99.95
5B	81.6	10.6	0.55	0.06	0.03	6.01	0.06	0.006	0.12	0.12	99.17
6	83.4	9.89	0.63	0.06	0.05	5.6	0.05	0.003	0.1	0.2	99.99
7	82.9	9.65	0.6	0.05	0.02	5.52	0.04	0.003	0.1	0.23	99.12

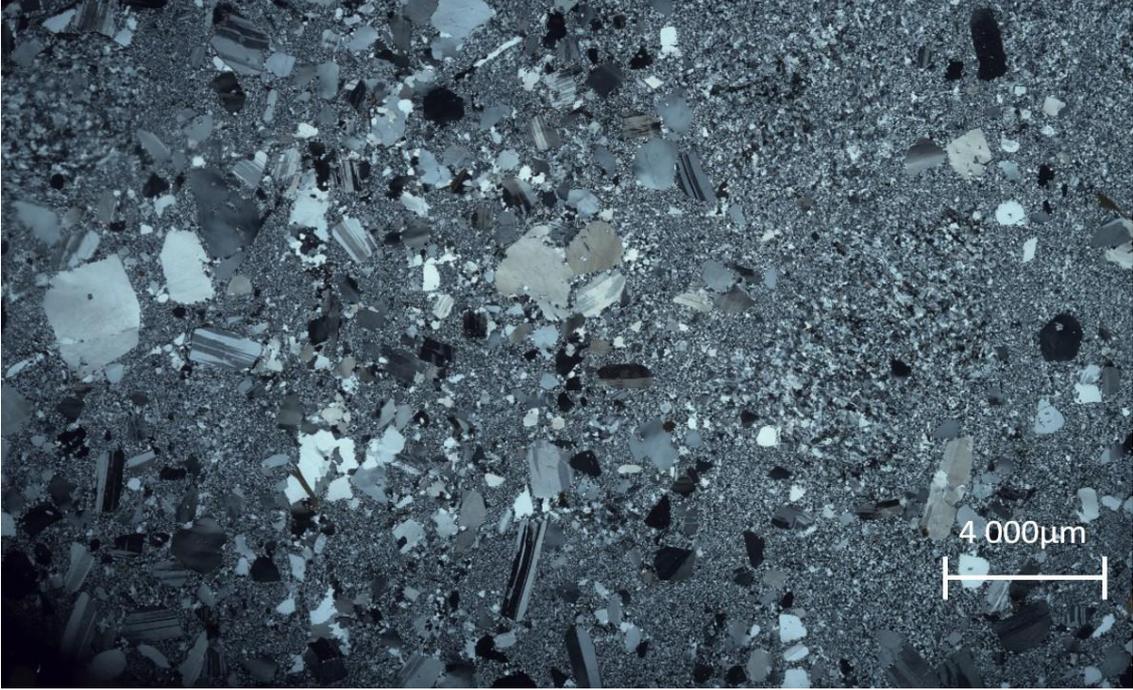
Table 1.

The table with normalised data used for the TAS construction.

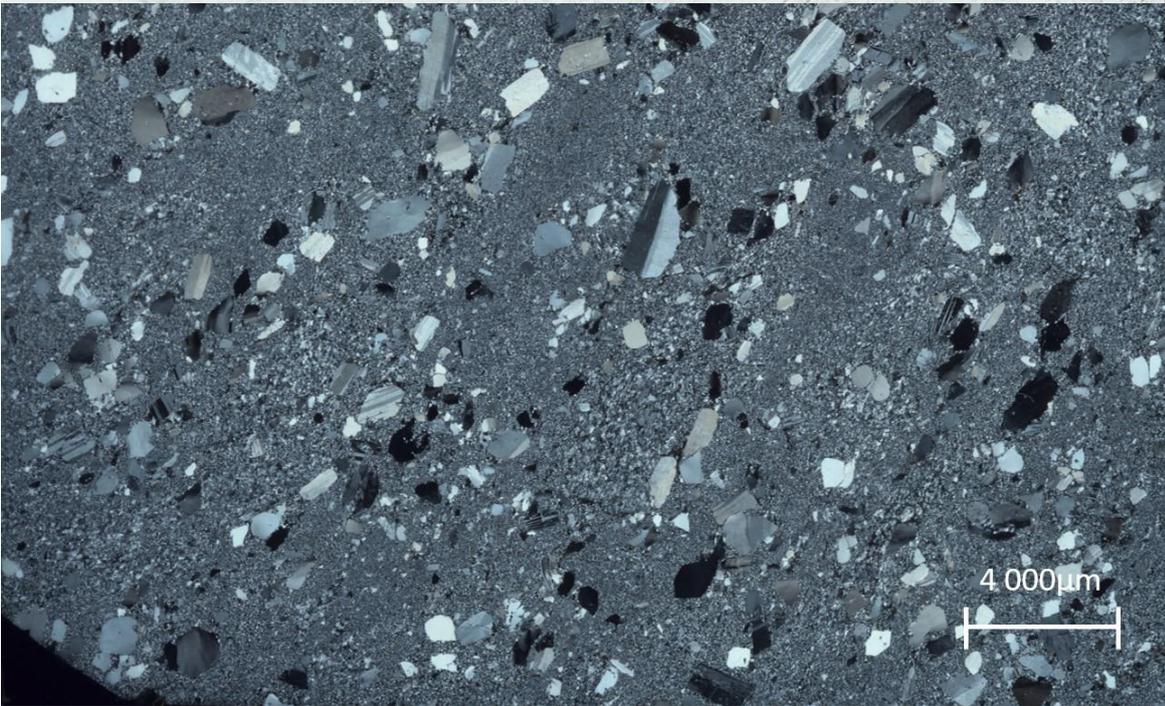
Samples	SiO₂	Al₂O₃	Fe₂O₃	CaO	MgO	Na₂O	K₂O	Cr₂O₃	TiO₂	LOI	Total	Na+K
	%	%	%	%	%	%	%	%	%	%	%	%
1	79.29	10.96	1.74	0.07	1.27	5.55	0.04	0.00	0.08	0.98	99.99	5.60
2	80.23	10.76	1.57	0.04	0.98	5.51	0.04	0.00	0.09	0.75	99.98	5.55
3	76.86	11.69	2.40	0.03	2.17	5.42	0.03	0.00	0.09	1.30	99.99	5.45
4A	79.26	11.86	0.95	0.05	0.56	6.47	0.05	0.00	0.13	0.65	99.99	6.52
4B	76.39	14.40	0.37	0.05	0.03	8.21	0.04	0.00	0.12	0.38	100.00	8.26
5A	78.34	11.46	1.88	0.06	1.44	5.71	0.07	0.00	0.13	0.90	99.99	5.78
5B	82.28	10.69	0.55	0.06	0.03	6.06	0.06	0.01	0.12	0.12	99.99	6.12
6	83.41	9.89	0.63	0.06	0.05	5.60	0.05	0.00	0.10	0.20	99.99	5.65
7	83.64	9.74	0.61	0.05	0.02	5.57	0.04	0.00	0.10	0.23	99.99	5.61

Table 2.

Thin section scans
Sample 1 in PPL and XPL



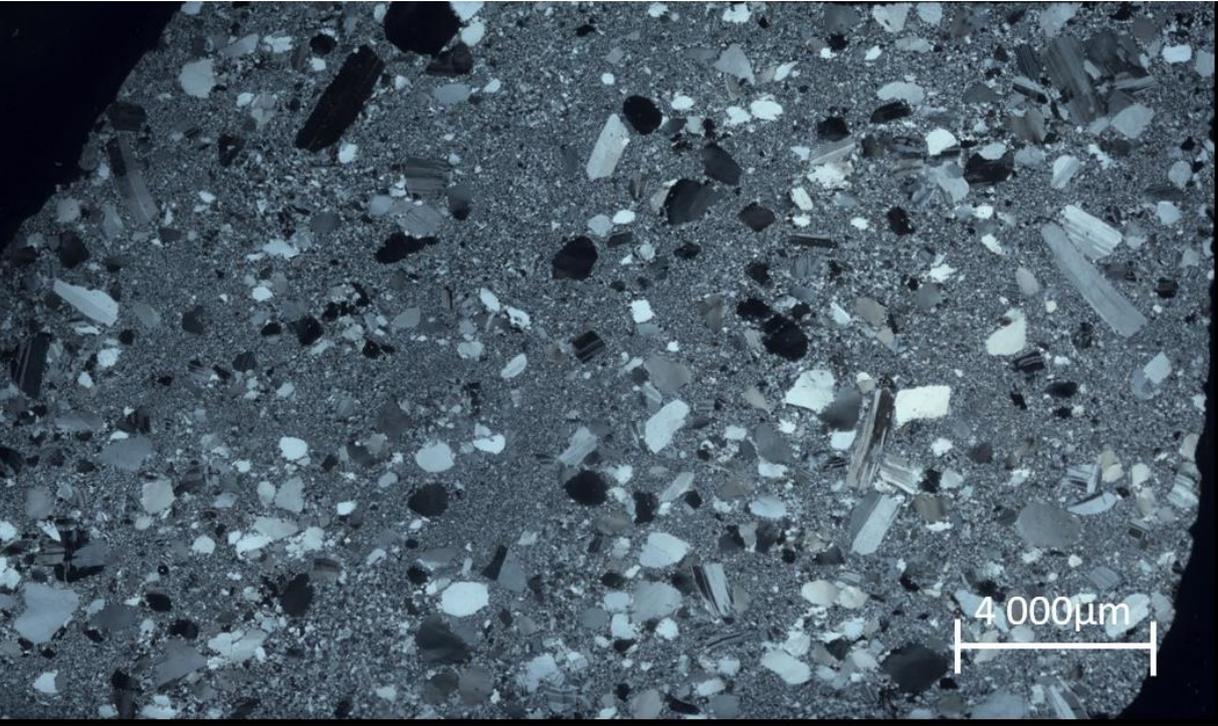
Sample 2 in PPL and XPL



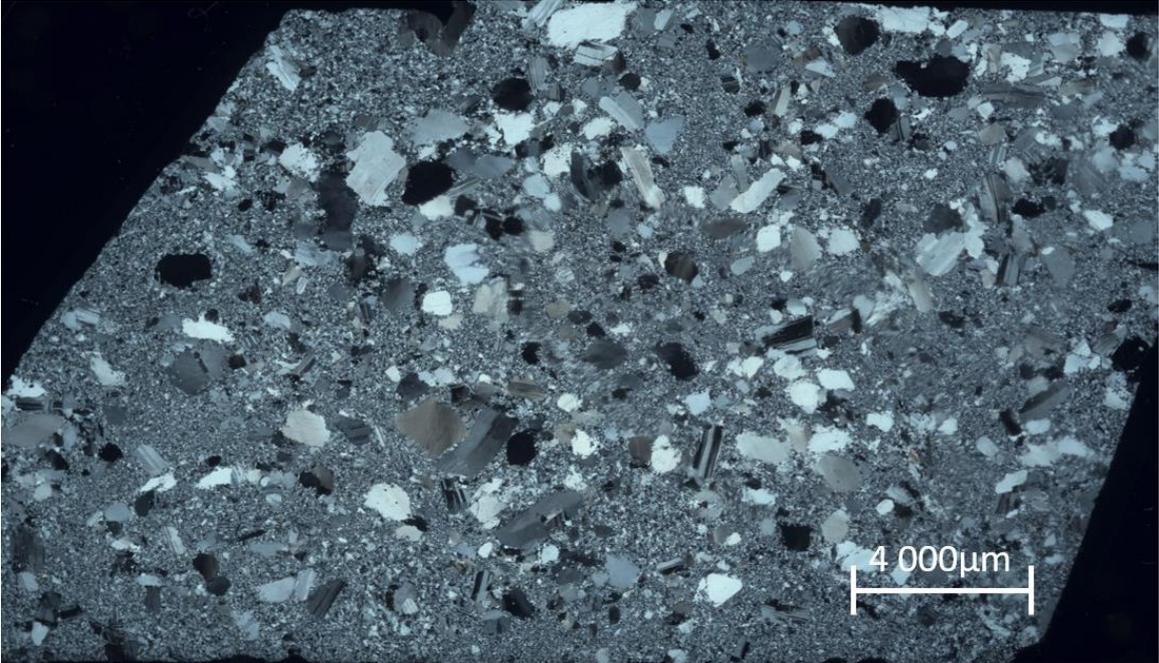
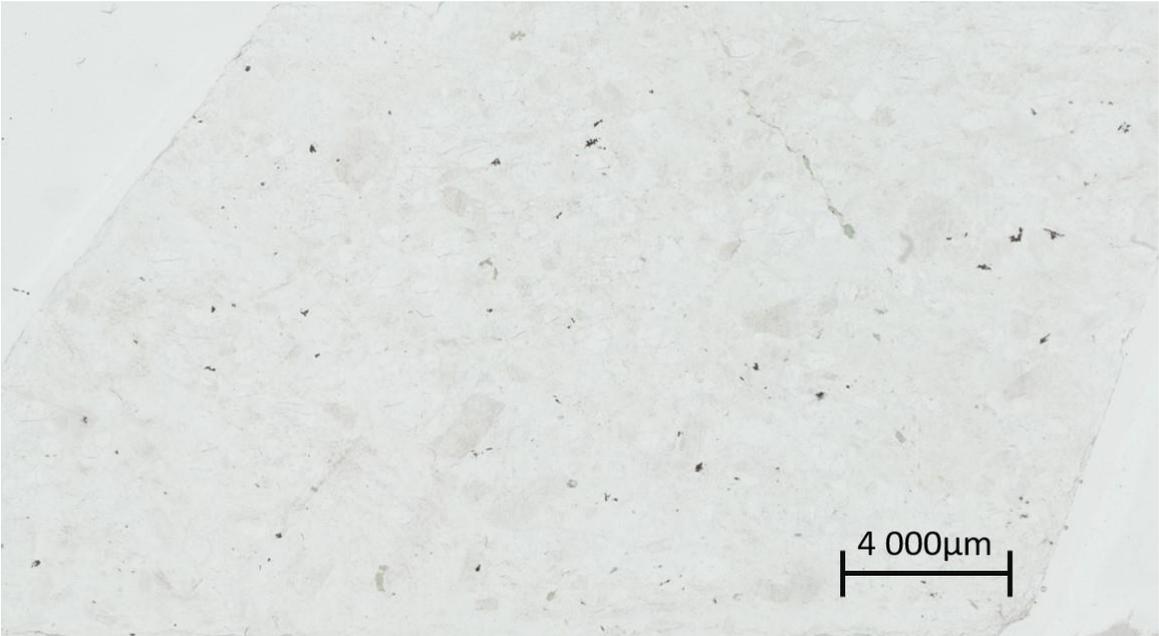
Sample 3 in PPL and XPL



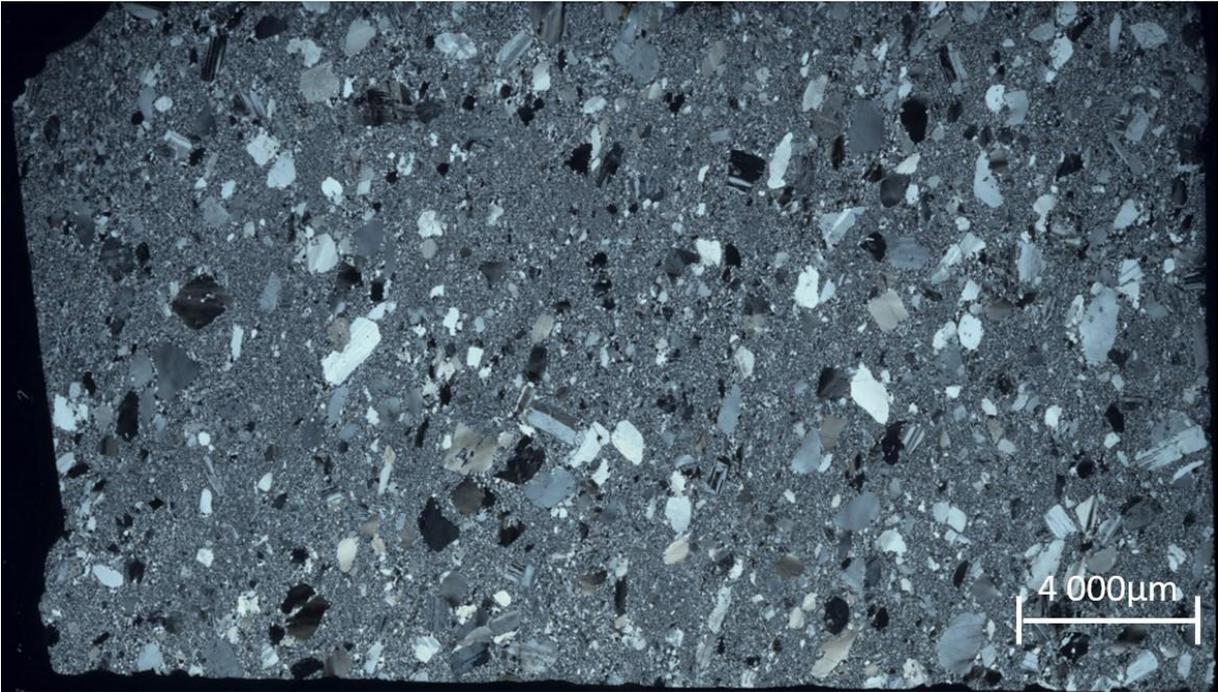
Sample 4A in PPL and XPL



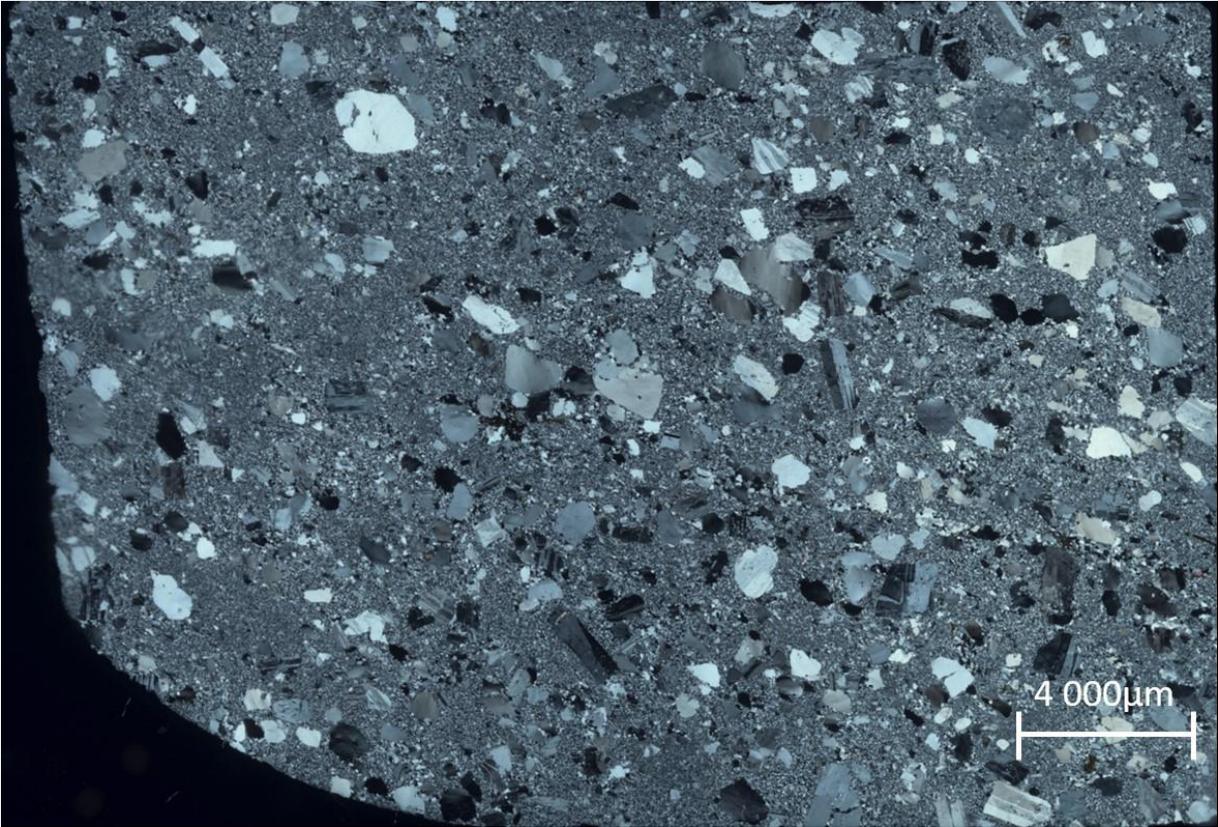
Sample 4B in PPL and XPL



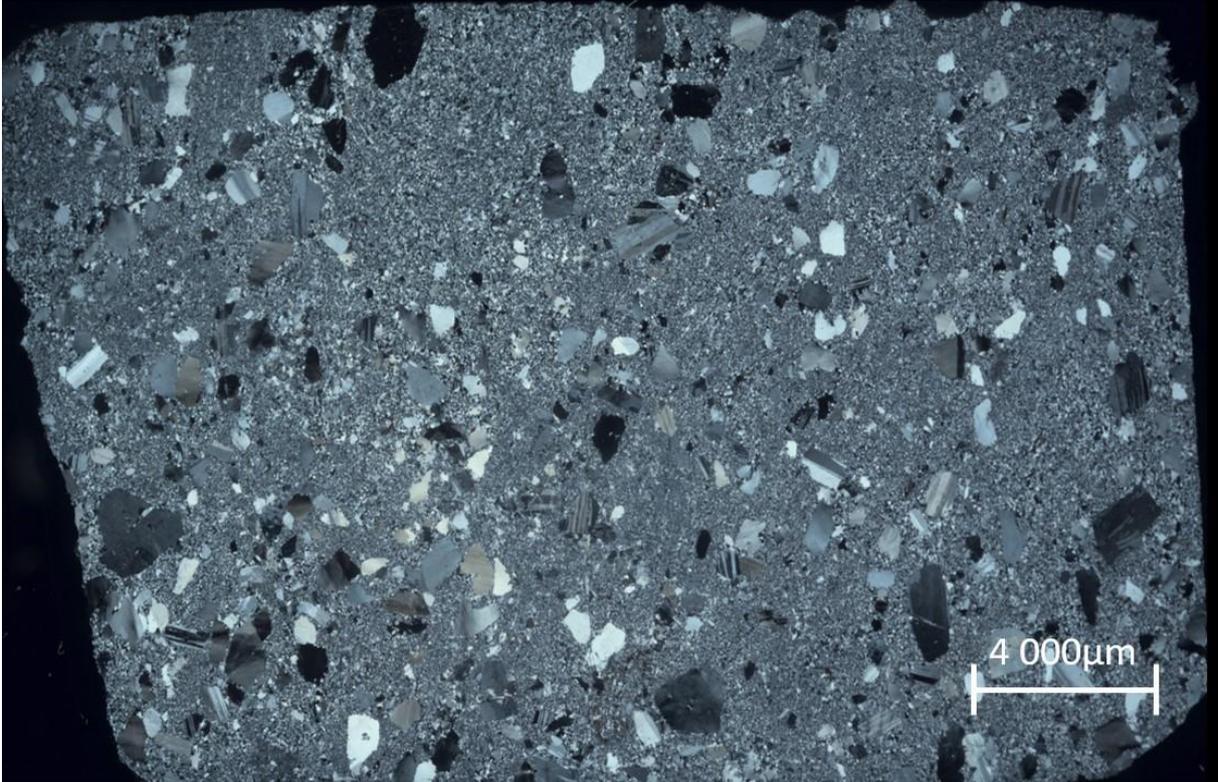
Sample 5A in PPL and XPL



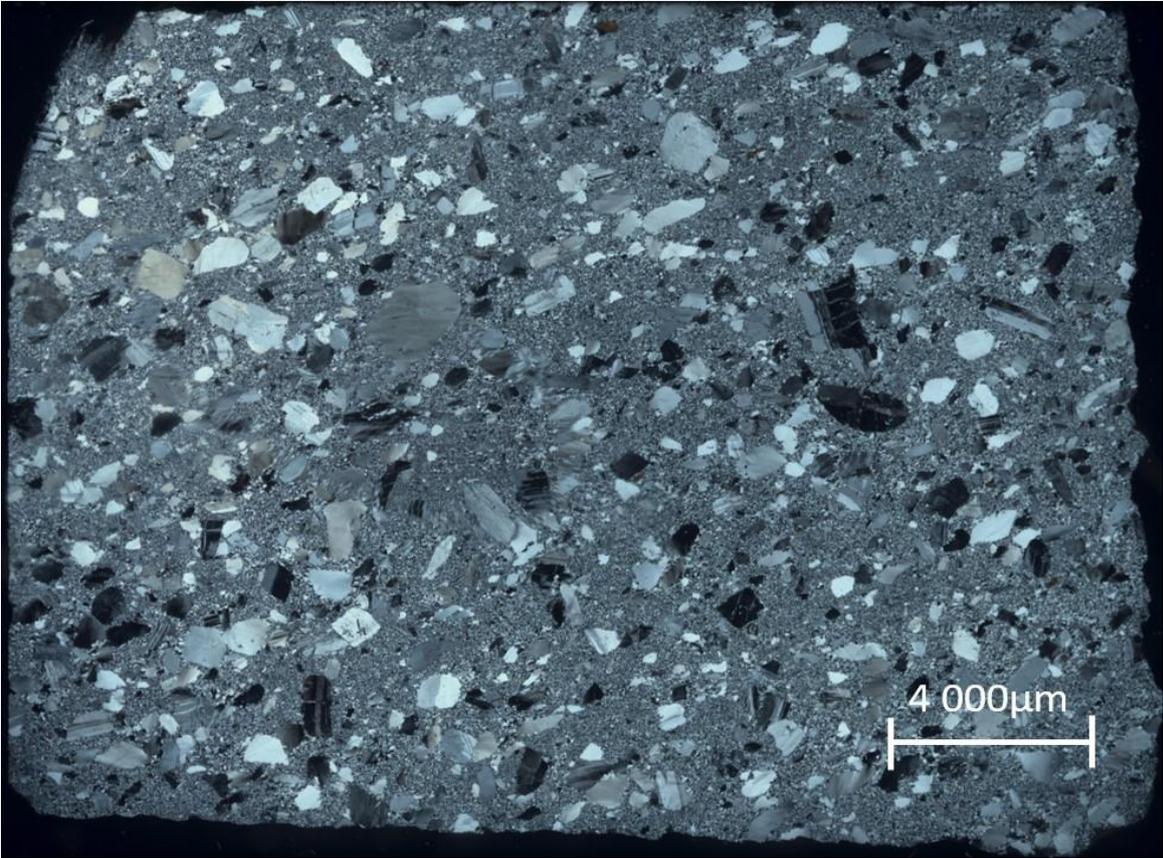
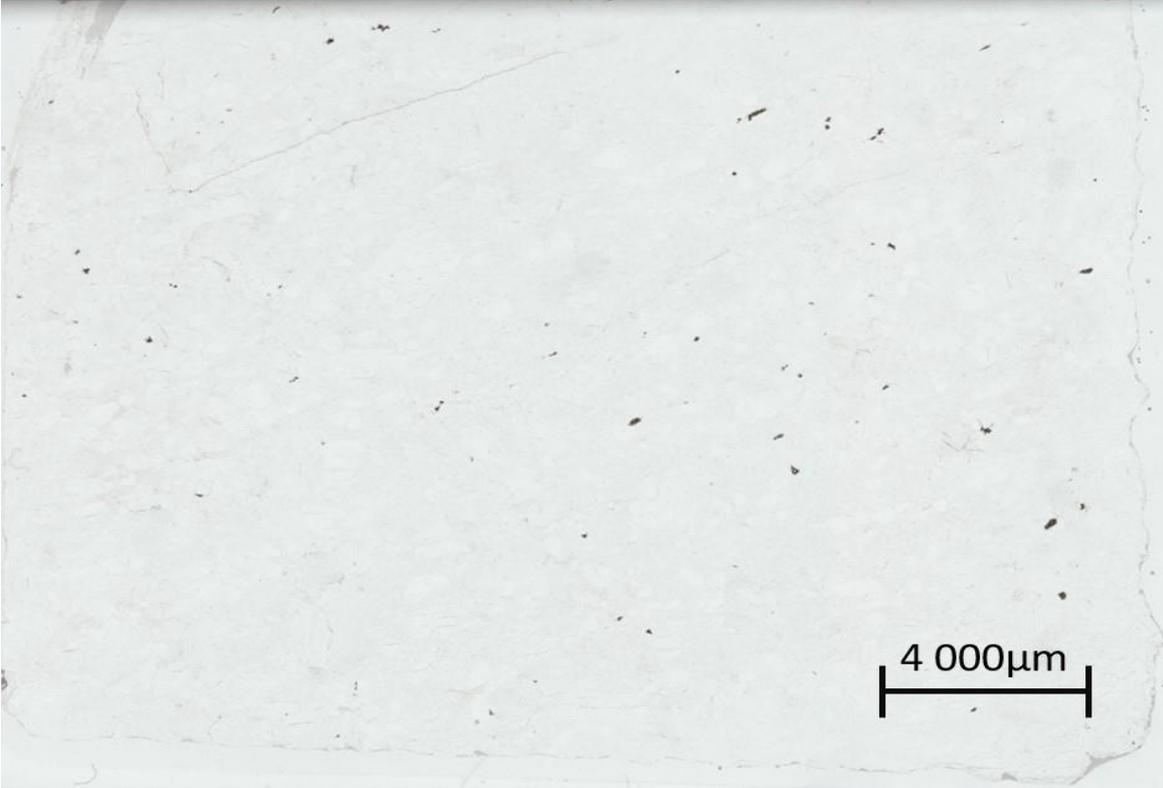
Sample 5B in PPL and XPL



Sample 6 in PPL and XPL



Sample 7 in PPL and XPL



ALS geochemical data

These following four tables represent the ALS geochemical data

SAMPLE	Pass75sum	SiO2	Al2O3	Fe2O3	CaO	MgO	Na2O	K2O	Cr2O3	TiO2	MnO	P2O5	SrO	BaO	LOI	Total
DESCRIPTION	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
1	90	77.8	10.75	1.71	0.07	1.25	5.45	0.04	0.002	0.08	0.01	<0.01	<0.01	<0.01	0.96	98.12
2		80.9	10.85	1.58	0.04	0.99	5.56	0.04	0.002	0.09	0.01	0.01	<0.01	<0.01	0.76	100.83
3		77.9	11.85	2.43	0.03	2.2	5.49	0.03	0.002	0.09	0.01	<0.01	<0.01	<0.01	1.32	101.35
4a		80.2	12	0.96	0.05	0.57	6.55	0.05	0.002	0.13	0.01	<0.01	<0.01	<0.01	0.66	101.18
4b		75.6	14.25	0.37	0.05	0.03	8.13	0.04	0.002	0.12	<0.01	<0.01	<0.01	<0.01	0.38	98.97
5a		78.3	11.45	1.88	0.06	1.44	5.71	0.07	0.003	0.13	0.01	<0.01	<0.01	<0.01	0.9	99.95
5b		81.6	10.6	0.55	0.06	0.03	6.01	0.06	0.006	0.12	0.01	<0.01	<0.01	<0.01	0.12	99.17
6		83.4	9.89	0.63	0.06	0.05	5.6	0.05	0.003	0.1	0.01	<0.01	<0.01	<0.01	0.2	99.99
7		82.9	9.65	0.6	0.05	0.02	5.52	0.04	0.003	0.1	0.01	<0.01	<0.01	<0.01	0.23	99.12

Table 3.

SAMPLE	Ag	Al	As	Ba	Be	Bi	Ca	Cd	Ce	Co	Cr	Cs	Cu	Fe	Ga	Ge
DESCRIPTION	ppm	%	ppm	ppm	ppm	ppm	%	ppm	ppm	ppm	ppm	ppm	ppm	%	ppm	ppm
1	0.049	5.48	0.3	9	1.65	0.032	0.04	0.037	11.95	1.91	8	0.03	15.75	1.21	14.05	0.08
2	0.024	5.19	0.47	8	5.59	0.043	0.03	0.015	21.9	2.52	5.5	0.02	15.7	1.1	14.6	0.09
3	0.014	5.65	0.42	7	1.67	0.024	0.03	0.007	13.9	1.715	6.7	0.04	18.3	1.59	14.2	0.06
4a	0.022	5.11	0.26	8	0.77	0.014	0.03	0.027	22.6	0.604	6.4	0.02	21.4	0.61	14.65	0.07
4b	0.017	5.27	0.28	10	0.95	0.016	0.04	0.021	13.35	0.129	10.3	0.02	9.22	0.21	16.2	0.06
5a	0.062	5.48	0.41	11	0.72	0.064	0.04	0.028	3.55	4.05	9	0.04	17.4	1.23	14.8	0.05
5b	0.05	4.42	0.31	8	0.64	0.037	0.04	0.031	7.33	0.324	11.7	0.02	23.1	0.31	10.15	<0.05
6	0.057	4.29	1.33	10	2.27	0.108	0.04	0.037	17.7	1.86	15.3	0.02	14.85	0.49	10.1	0.07
7	0.071	4.61	0.24	11	0.69	0.087	0.04	0.025	2.44	0.205	13.7	0.02	10.4	0.35	9.87	0.05

Table 4.

SAMPLE	Hf	In	K	La	Li	Mg	Mn	Mo	Na	Nb	Ni	P	Pb	Rb	Re	S
DESCRIPTION	ppm	ppm	%	ppm	ppm	%	ppm	ppm	%	ppm	ppm	%	ppm	ppm	ppm	%
1	4.97	0.01	0.04	5.78	1.4	0.72	48.2	0.58	4.09	8.22	1.06	0.001	5.25	0.72	<0.002	0.01
2	5.61	0.009	0.04	8.42	0.9	0.56	45.3	0.42	4.16	10.75	2.06	0.002	3.64	0.67	0.002	0.04
3	5.34	0.012	0.03	5.38	2.1	1.22	67	0.55	3.92	9.78	1.57	0.002	3.46	0.52	<0.002	0.01
4a	6.29	<0.005	0.04	11.3	1	0.32	38.4	0.43	4.82	12.75	1.03	0.002	2.85	0.51	0.002	0.01
4b	6.36	<0.005	0.04	6.35	0.5	0.02	23.1	0.72	6	14.15	0.5	0.002	3.83	0.47	0.002	0.01
5a	6.27	0.012	0.06	1.665	2.5	0.82	67.6	2.52	4.24	9.87	1.99	0.002	5.81	1.07	0.002	0.02
5b	5.16	<0.005	0.04	3.47	0.2	0.02	33.4	4.89	4.48	6.72	0.8	0.001	10.1	0.67	0.002	0.01
6	5.28	<0.005	0.04	7.7	0.2	0.03	49.8	10.8	4.14	12.65	1	0.003	19.1	0.74	<0.002	0.02
7	5.31	0.006	0.05	1.065	0.2	0.02	39	3.49	4.09	7.18	0.66	0.001	5.47	0.91	<0.002	0.01

Table 5.

SAMPLE	Sb	Sc	Se	Sn	Sr	Ta	Te	Th	Ti	Tl	U	V	W	Y	Zn	Zr
DESCRIPTION	ppm	ppm	%	ppm	ppm	ppm	ppm	ppm	ppm	ppm						
1	0.22	2.57	<0.2	0.51	8.13	0.57	<0.04	9.84	0.031	0.005	3.04	0.7	0.889	22.5	14.2	159.5
2	0.19	3.25	0.4	0.64	5.75	0.73	<0.04	11	0.039	<0.004	3.52	2.5	1.115	47.9	14.9	178.5
3	0.29	3.32	0.3	0.94	6.98	0.66	<0.04	9.88	0.032	<0.004	2.87	1.8	1.825	23.7	19.9	170
4a	0.21	1.28	0.2	0.61	7.1	0.89	<0.04	11.25	0.059	0.004	3.86	0.9	2.3	21	17.4	203
4b	0.24	0.49	0.2	0.46	7.6	0.99	<0.04	11.2	0.062	<0.004	4.66	0.5	2.6	20.9	7.4	201
5a	0.22	2.47	0.3	0.63	7.56	0.71	<0.04	11.05	0.06	0.028	4.66	3.3	1.615	20	25	206
5b	0.22	0.49	0.2	0.5	7.09	0.5	0.04	8.76	0.048	0.02	3.23	0.4	1.125	14.15	16.8	172
6	0.23	0.53	0.5	0.34	7.14	0.82	0.09	11.15	0.049	0.015	4.14	0.6	1.32	27.1	12.9	169
7	0.19	0.45	0.3	0.51	7.71	0.55	0.06	8.61	0.047	0.022	3.1	0.4	1.475	14.35	8.7	171.5

Table 6.

