

Chemistry and mineralogy of shale oil mining waste at Kvarntorp

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Abstract

During World War II, the demand for liquid fuel increased rapidly and since export and import became difficult due to the war, the Swedish industry had to find another solution to this problem. As a result of this, Svenska Skifferolje AB was founded in 1941 and began to mine bituminous alum shale in Sweden and extract the oil. The alum shale was mined in open pits in Kvarntorp, Kumla and it was pyrolysed in large ovens. The shale was mined between 1942 and 1965 and the waste products were deposited nearby.

Kvarntorpshögen is a 100-meter-high pile with approximately 28 million tons of shale oil mining waste. The waste consists mostly of ash: burned alum shale with high amounts of for example Co, V, Cr, Zn, Cu, U, and Ba. Several of these heavy metals are so abundant there is a potential risk for the environmental and human health. Apart from containing high amounts of heavy metals, Kvarntorpshögen is also very hot. Within the burned ash, together with unburned alum shale, pyrite and kerogen are oxidizing, which is a heat generating process. Temperatures of up to 700°C have been measured only 15 m below the surface. The breakdown of pyrite is a likely source of metallic compounds detected in elevated concentrations in the ash.

Abstrakt

Under andra världskriget ökade förbrukningen av flytande bränslen och eftersom kriget hindrade export och import till och från Sverige blev man tvungen att hitta nya lösningar. Som följd av detta grundades Svenska Skifferolja AB år 1941 med målet att bryta bituminös alunskiffer och utvinna och använda dess olja. Alunskiffern bröts i stora dagbrott i Kvarntorp, Kumla och brändes i pyrolysugnar för att komma åt oljan. Mellan åren 1942 och 1965 bröts skiffern och restprodukterna efter ugnarna deponerades på Kvarntorpsängarna i närheten.

Idag utgör restprodukterna Kvarntorpshögen, en 100 m hög slagghög innehållandes uppskattningsvis 28 miljoner ton material. Materialet består mestadels av aska; bränd alunskiffer som innehåller höga halter av bland annat Co, V, Cr, Zn, Cu, U, och Ba. Flertalet av dessa metaller finns i såpass höga halter att det innebär en potentiell hälsofara för både miljö och människor. Förutom att Kvarntorpshögen innehåller höga halter av tungmetaller är den även varm då den brända askan, tillsammans med obränd alunskiffer, oxiderar pyrit och kerogen vilket är värmegenererande processer. Temperaturer upp emot 700°C har uppmätts endast 15 m under ytan. Nedbrytningen av pyrit är troligtvis källan till de förhöjda halterna av metaller i askan.

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Introduction

When World War II began in 1939, many important connections between Sweden and the rest of the world were cut off. Export and import became difficult and in some cases even impossible. The usage of liquid fuel in Sweden was relatively low during World War II. However, with increasing motorization on the roads, the escalating use of oil in ships and eventually the use of oil in houses and industries for heating, the demand for liquid fuels increased rapidly. When the imports could not be maintained any longer, industry had to find another solution to this problem (Schwartz, 1945).

Extracting oil from bituminous shales was not new technology. This material was the source of the first industrial-scale oil production and moved to the background during the 19th century when crude oil began its victory march. In the past, bituminous shales have been processed in several countries such as Scotland, France, Germany, North America and they are still being processed in Estonia (Schwartz, 1945).

Alum shale

Alum shale is a sedimentary, sulphide-bearing rock that was deposited in an anoxic environment on the seafloor around 500 million years ago. The alum shale can be bituminous and holds the largest fuel reserve in Sweden, representing approximately five billion tons of oil. The oil is in organic substances in the shale that are the remnants of dead plants and animals (Waldermarsson, 1991).

The sulphide content of shale is often related to the depositional environment. The stability of different sulphides in the rock is highly dependent on the metamorphic grade of the shale. For example, Jeng (1991) found that the unmetamorphosed shale in the Oslo Region contained pyrite (FeS_2) as the dominant iron sulphide, but in metamorphosed shale in other parts of Norway pyrrhotite (Fe_{1-x}S) was dominant.

Apart from the iron sulphide content, alum shale is also known to contain a number of heavy metals, such as Cd, Tl, As, and Ni. Notably, alum shale generally also holds high concentrations of U.

The content of toxic metals is a problem when dealing with waste materials from alum shale, especially in weathering conditions (Jeng, 1991). When alum shale weathers, sulphides are oxidized and sulphuric acid is released.

Bituminous shale occurs in Sweden at several locations (figure 1) but the amount of oil is generally too low for economic oil production. Shales with a sufficiently high content of oil (4%) can only be found in three areas; at Kinnekulle, in Närke, and in Östergötland. Bituminous shale occurs at two areas in Närke; the first at Kvarntorp, eight km east of Kumla, and the second west of Örebro (figure 2). The shales at Kvarntorp and Kumla are almost horizontally layered and the amount of oil is 5.5–6.5% and 4.8%, respectively. The thickness of the shale in these areas varies between 10 and 19 m and the total mineable amount was estimated to 1.5 billion tons of shale, which could give approximately 80 million tons of oil (Schwartz, 1945).

To meet the demand of oil, a public utility, Svenska Skifferolje AB, was constituted to start extracting oil from the alum shales in Sweden. Work started in 1941 after the decision to place the facility eight km east of Kumla, in Kvarntorp (Schwartz 1945).

Kvarntorp

Kvarntorp is today a small town situated in the municipality of Kumla in Örebro county in the middle of Sweden. Before the beginning of industrial development here in 1941, Kvarntorp was a farm about 90 ha in extent. A nearby stream provided water for the mill (Swedish: *kvarn*) that gave the area its name. Apart from agriculture, quarrying was an important livelihood in the area as early as the 17th century. Limestone and sandstone were for example used as building blocks for churches and other houses (Kumla kommun, länsstyrelsen i Örebro Län, 1979).

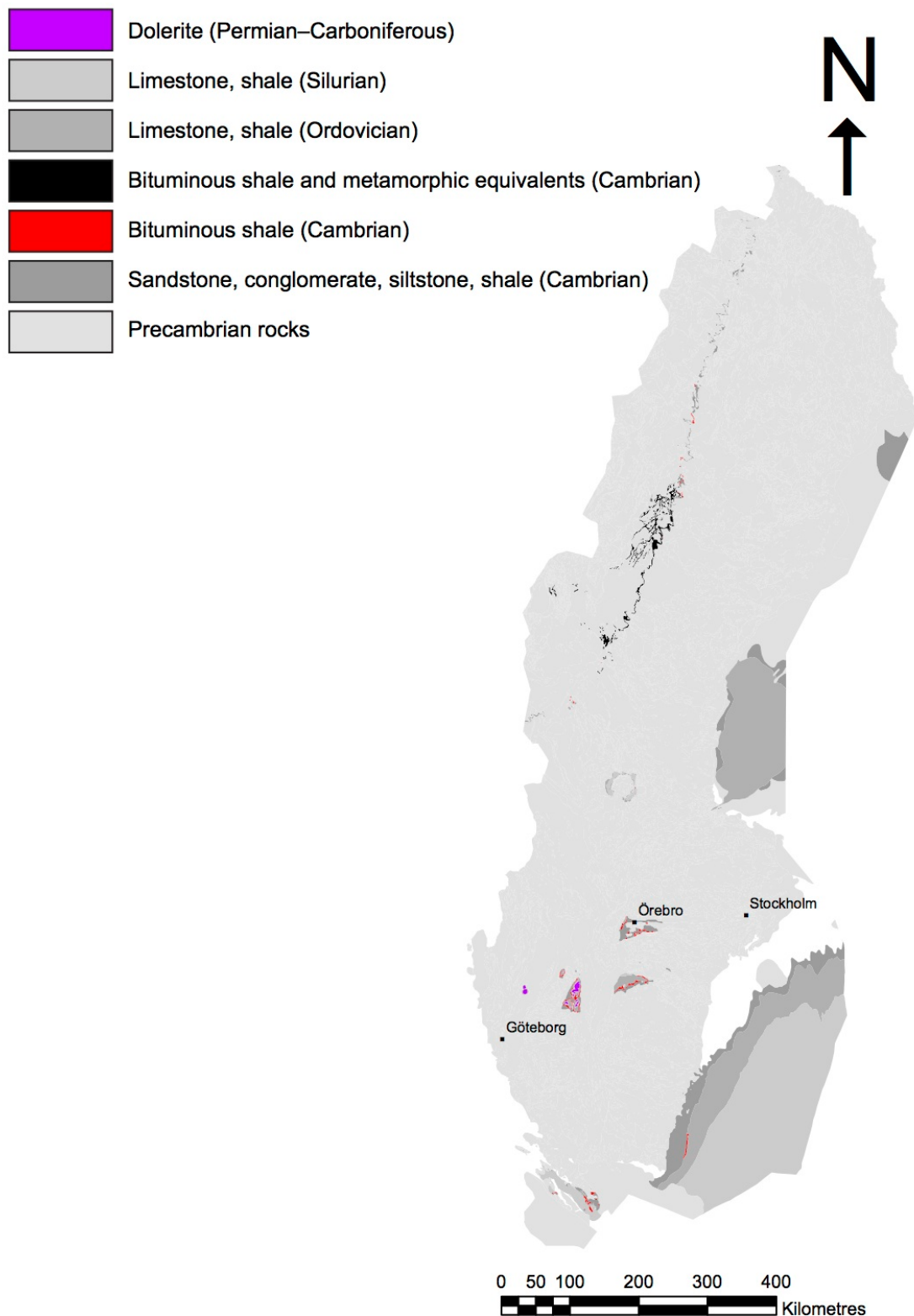


Figure 1. Map of Sweden showing the locations of Cambro-Silurian sedimentary rocks, including bituminous shales (© Sveriges geologiska undersökning).

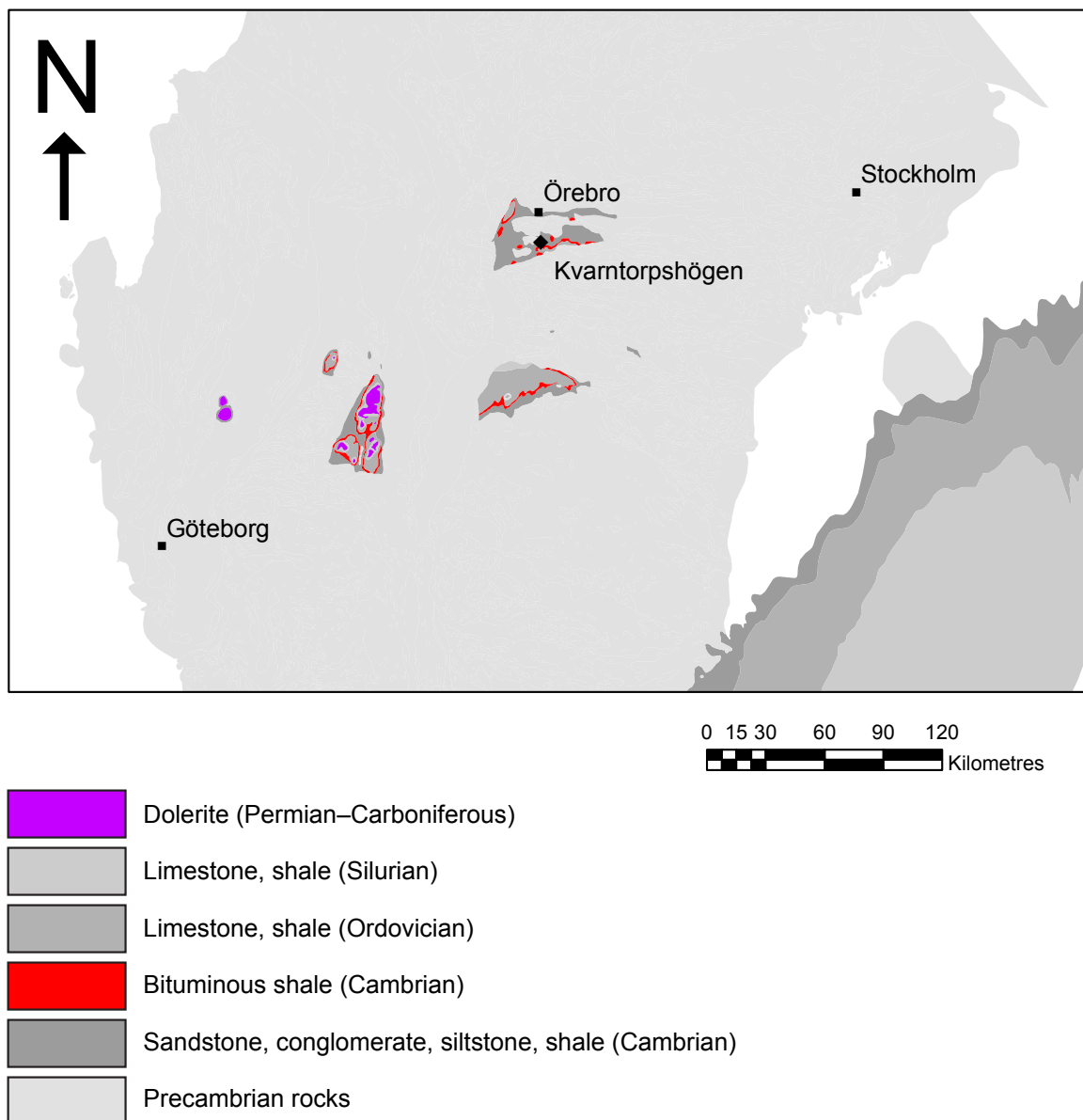


Figure 2. Detailed overview of Cambro-Silurian sedimentary rocks in Sweden showing the location of Kvarntorpshögen (© Sveriges geologiska undersökning).

The alum shale in this area is overlain by sediments and limestone, which had to be taken away before the shale could be mined in open pits (Holm, 2005).

A quantity of 1.3 million tons of alum shale had to be mined every year to meet the demands of shale oil production at Kvarntorp. The mined alum shale was transported by 8-ton trucks to the central crushing facilities near the open pits. The material passed a coarse crusher, a sorting step where anthraconite (bituminous limestone) was removed, and a finer crusher in which the material was crushed to a maximum size of 150 mm. Later, the material went through a second sorting step where it was divided into three grain sizes. The material larger than 30 mm was sent to the Channel- and the Hultman-Gustafson-ovens and the material between 30–5 mm was sent to the Bergh ovens. The smallest grain size, less than 5 mm, was discarded to avoid sintering in the ovens (Schwartz, 1945).

Bergh Oven

In the Bergh oven, crushed alum shale was deposited into the top of a vertical pipe with a diameter of 20 cm and a height of 200 cm. The pipe was heated from the outside and the by-product gas was led to a cooling system in which the heavy hydrocarbons were extracted to oil while the light hydrocarbons remained as gas. When the alum shale had gone through the pipe, then called "koks", air was introduced and the hot combustion gases burnt to heat the pipe. This made the oven self-sufficient with heat. When burned to ash, the remaining material was no longer of use (Schwartz, 1945).

Channel Oven

The crushed alum shale was loaded on carriages and run through long, horizontal cylindrical ovens. In this kind of oven, the koks was not burned but directly sent to waste, and secondary heat had to be applied (Schwartz, 1945).

Hultman-Gustafson

The Hultman-Gustafson was a Swedish modified Scottish oven. Vertical, cylindrical pipes with diameter of 70 cm and height of 800 cm were built together forming blocks of four pipes. The top part of the pipes was made of iron and the bottom part of heat-resistant ceramic material.

Crushed alum shale was put into the top part of the cylinders and the koks taken out at the bottom. The pipes were heated by burning gas outside the pipes (Schwartz, 1945).

Kvarntorpshögen

The waste material; the red ash from Bergh oven, the koks from the Channel- and Hultman-Gustafson-ovens and the crushed shale less than 5 mm ("stybb"), was put back into the open pits when done mining, but also deposited on Kvarntorpsängarna ("Meadows of Kvarntorp"). This wetland area had no economic interest for the company that mined the alum shale. Firstly, only trucks were used to transport the products onto the meadows, but later two cableways were installed and in 1950 one of the cableways was replaced by a conveyor belt. The decay products were deposited on the Meadows of Kvarntorp between 1942 and 1965. The "stybb" represented around 10–20% of the mined alum shale and the ashes represented about 75% (Holm, 2005).

Today, the waste material forms the Kvarntorpshögen, which is a small hill approximately 100 m higher than the surrounding landscape. It has a diameter of 700 m and its base area is estimated at 450,000 m². The material in Kvarntorpshögen is approximately 23 million tons of ash (burned alum shale), 3 million tons of stybb (crushed and sorted alum shale) and 2 million tons of koks. The koks is mainly situated in the bottom of the hill because during the period of oil production the ovens that produced koks were in some measure replaced by the Bergh oven that only produced ash (Holm, 2005).

When the waste material was deposited onto Kvarntorpshögen, the newly burned ash was very hot. It was deposited together with koks and stybb and with the access of oxygen, combustion processes by oxidation started in the near-surface material. When new material was deposited on top, some of the combustion processes stopped, but the new material could oxidize until newer material was deposited. Some of the oxidation processes are still ongoing today, even though extensive covering has been done by Kumla municipality in recent years. Local surface temperatures of up to 70°C have been noted and a maximum of 700°C was measured at a depth of just 15 m below the surface in 2004 (Holm, 2005).

Kvarntorpshögen is today used as a recreation area for people; there is a kiosk and an art exhibition on display at the top and during winter the local ski club uses one of the hillsides as ski slope.

Previous work

In 2003, SWECO VIAK started an extensive study of Kvarntorpshögen on behalf of the Geological Survey of Sweden (Holm, 2005). The aims of their study was to answer the following questions:

- To what extent does the present situation represent a risk of contamination spreading by groundwater from the dump?
- To what extent is there a risk of future pollution spreading when Kvarntorpshögen cools?

Their study concluded that there is a very large amount of environmentally hazardous substances of primarily heavy metals. The investigations indicate that the situation is serious or very serious regarding metals such as Ni, Tl, Cd, Mo, As, Hg, and V. The risks comprise spreading of heavy metals to surrounding ground- and surface water, risk of human health for visitors who are exposed to the pollution, and the areas that are still hot. Another risk worth considering is some small collapses of surfaces that have occurred, also in recent years.

SWECO VIAK also concluded (in Holm, 2005) that the determining factor for an increased risk of the spreading of contaminants in the future is the reduction of temperature. The temperature reduction can lead to an increased amount of groundwater formation, which in turn can lead to more leaching, material transport and an increase of the reaction rates in the oxidation processes.

Research questions

The aim of this study is to get a fuller picture of how the various types of material on Kvarntorpshögen differ from each other.

My research questions are as follows:

- Are there systematic geochemical, mineralogical, and physical differences between the different kinds of burned and unburned alum shale at Kvarntorpshögen?
- Is the composition of the material at Kvarntorpshögen a potential environmental hazard? Does the material for instance contain high concentrations of lead, zinc, uranium or arsenic, etc.?
- Can the metal concentrations be connected to primary or secondary processes?
- Is the material at Kvarntorpshögen a potential source of raw materials or energy?

Methods

Sampling

At the beginning of November 2012 fourteen samples of just above 1 kg (table 1) were collected; ten on Kvarntorpshögen and four samples of the natural alum shale in the nearby area (figure 3 and 4).

Table 1. List and description of samples and their sampling locations. Sampling locations are plotted in figures 3 and 4.

Sample	X	Y	Location	Color	Material	Sample depth (m)	T°: sample depth	T°: surface
LC12-01	6556014	1468230	Kvarntorpshögen	Red	Ash	0.4	1.1	2.9
LC12-02	6555911	1468268	Kvarntorpshögen	Red	Ash	0.7	4.0	4.0
LC12-03	6556410	1468362	Kvarntorpshögen	Red	Ash	0	4.0	4.0
LC12-04	6556410	1468362	Kvarntorpshögen	Red	Ash	0	4.0	4.0
LC12-05	6555840	1468358	Kvarntorpshögen	Grey	Stybb	0.60	4.4	4.4
LC12-06	6555811	1468212	Kvarntorpshögen	Grey	Stybb	0	5.0	5.0
LC12-07	6555811	1468212	Kvarntorpshögen	Grey	Stybb	0.50	5.0	5.0
LC12-08	6555872	1468461	Kvarntorpshögen	Grey	Stybb	0.60	5.3	5.3
LC12-09	6555953	1468611	Kvarntorpshögen	Black	Other	0	7.0	5.5
LC12-10	6555953	1468611	Kvarntorpshögen	Pink	Other	0	5.5	5.5
LC12-11	6555670	1469617	Outcrop	Black	Shale	-	-	-
LC12-12	6555670	1469617	Outcrop	Black	Shale	-	-	-
LC12-13	6555461	1470184	Near Lake	Black	Shale	-	-	-
LC12-14	6555473	1470209	Near Lake	Black	Shale	-	-	-

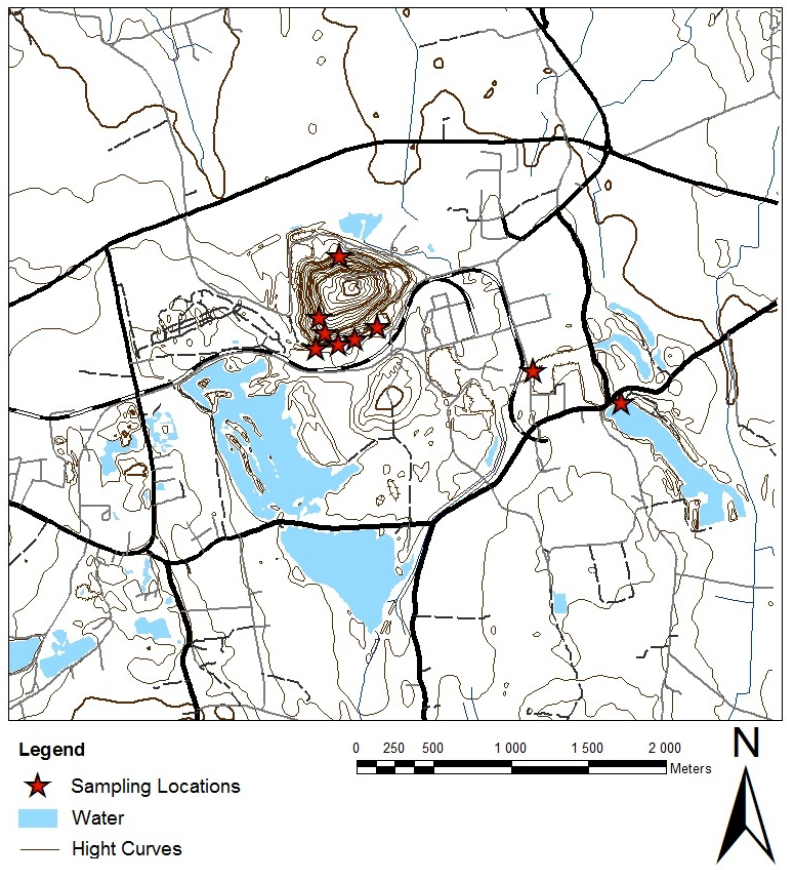


Figure 3. All fourteen sampling locations. The three largest lakes are water-filled open pits.

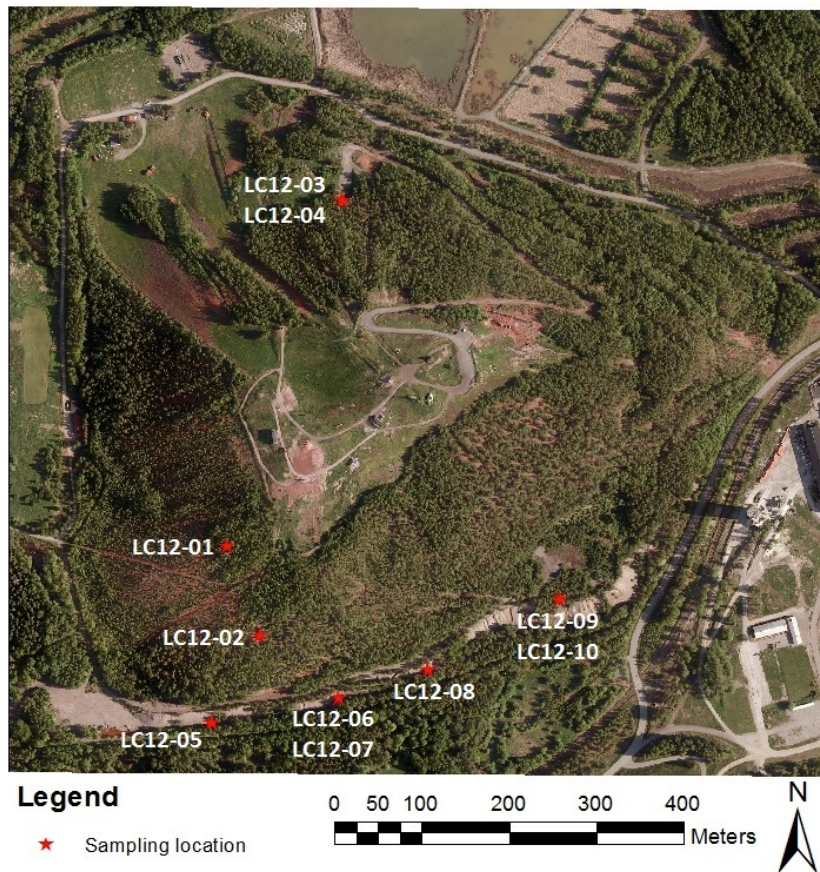


Figure 4: Close up map over the ten sampling locations at Kvarntorpshögen.

The displayed and sampled alum shale (figure 5.A) in the area is heavily weathered. The shale is black on fresh surfaces but there is precipitation of sulphur seen on several locations. Anthraconite, which is a bituminous limestone, occurs in the shale. Of the ten samples taken on Kvarntorpsshögen, four are described as ash (figure 5.B), four as stybb (figure 5.C) and two are undefined samples and are hence called "other" (figure 5.D) The ash is the residual product from the Bergh ovens and is crushed, pyrolysed shale. The ash is reddish in color and has a grain size of 5–30 mm. The stybb is the material that was removed from the process to avoid sintering in the ovens. It is the material that has a grain size less than 5 mm after the crushing of the alum shale. The stybb is grey to brown in color.

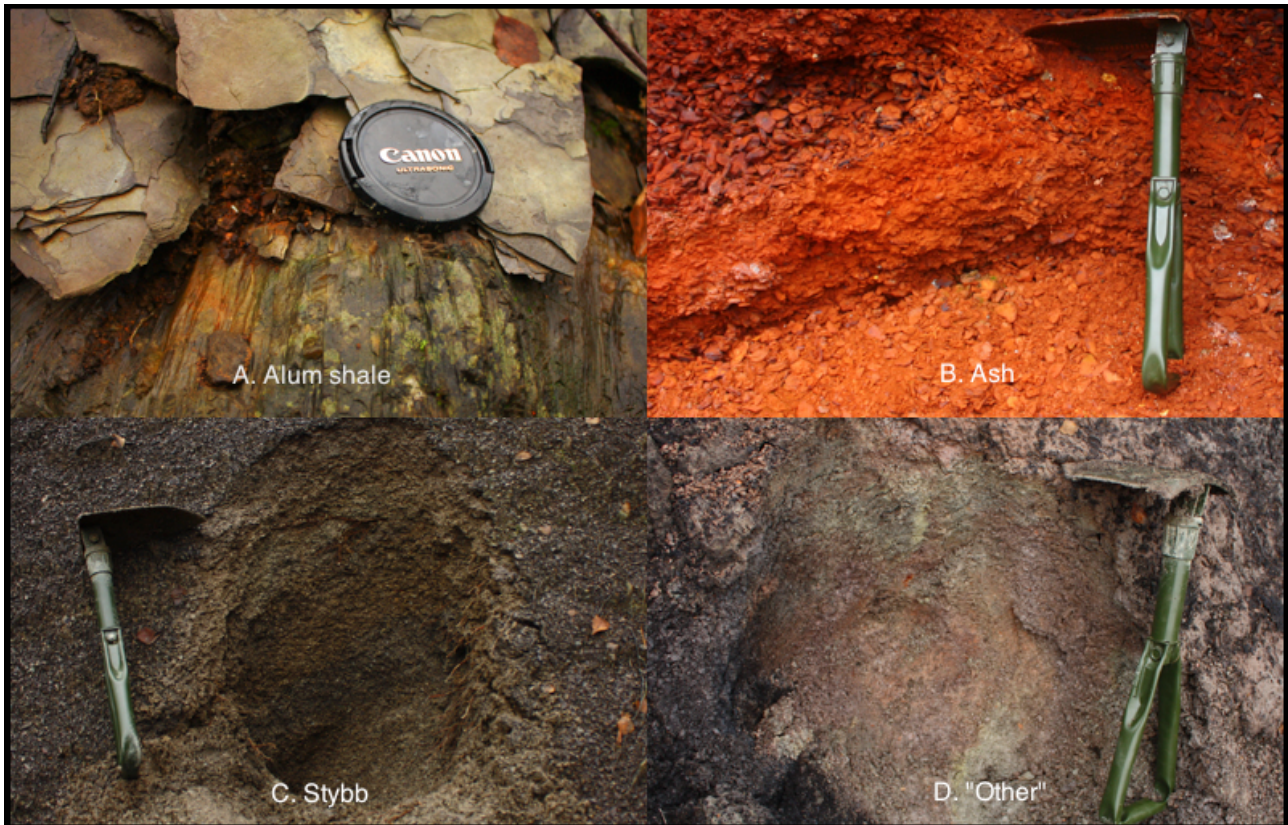


Figure 5. Sample pictures. A. Alum shale. B. Ash. C. Stybb. D. Undefined samples, called "other". The shovel is 0,4m long.

Chemical analyses

All fourteen samples were dried in an oven over night at 105°C. They were split into smaller sizes, using a splitter, and about one third of the total sample was finely crushed using a Cr-steel disk mill.

To achieve really fine grain sizes, 5 g of each milled samples was put into a silicon nitride swing mill and wet milled with ethanol, to avoid clumping. After this, the sample and the mill were put into an oven to dry for 30 minutes at 80°C. When dry, the sample was recovered from the mill and put into a plastic beaker.

To remove adsorbed moisture, about 1 g of each sample, accurately weighed, was put into an oven at 110°C for 30 minutes, cooled in a desiccator and weighed again. Then it was ignited at 960°C for 20 minutes, which drives off crystalline water and CO₂, which makes it easier to melt and oxidizes all iron to Fe₂O₃. The samples were cooled in a desiccator and weighed again, to calculate loss on ignition.

About 0.1 gram of the ignited sample was put into carbon coated molybdenum „boats” for fusion to glass in an argon overpressure. It was fused for 5–10 seconds, or until the sample was entirely melted as seen through a gold-coated window. Some samples did not melt at the first attempt, but

when re-ignited at 960°C for 40 minutes, they melted well. The glass was then cut into pieces and mounted in two epoxy pucks, which was set overnight and put into an oven at 40° C for three hours for further hardening. The puck was sanded down until all samples were well exposed and polished until all scratches were small.

Major elements by SEM-EDS

The puck was cleaned and carbon coated before the analyses in a Scanning Electron Microscope (SEM). Because the glass might have been contaminated by the molybdenum boats, the results for molybdenum are not presented. Each sample glass was analyzed three times with the EDS detector and an average was calculated for each sample. The live time for each analysis was 100 seconds, using a 20 kV voltage and 3.5 nA sample current.

Minor elements by LA-ICP-MS

After the analysis in the SEM, the carbon coating was removed from the pucks. The pucks were mounted on a holder and put into an Inductively Coupled Plasma Mass Spectrometer (ICP-MS). Each sample was ablated with the ultraviolet laser (213 nm Nd:YAG), analysed three times and a mean value was calculated for each sample.

Leaching analysis by ICP-MS

According to the leaching procedure that was used, 1 g of milled sample was mixed with 20 ml of HNO₃ and put into a Duran bottle in an autoclave at 120°C for 20 minutes. When done, the sample mixture was transferred into test tubes and put into a centrifuge for three minutes, allowing the remaining powder to sink to the bottom. Only the liquid was transferred to new test tubes and diluted 50 times with HNO₃ for analysis in the ICP-MS.

Major elements by pXRF

The milled sample from the Cr-steel disk mill was also analyzed using a handheld X-Ray fluorescence device with Mining Plus software settings. Each sample was analyzed three times; 60 seconds for each analysis. A mean value for each sample was calculated.

Mineralogy

XRD

A couple of grams of milled sample was put into a holder in a X-ray Diffractometer (XRD). In this device an incident beam of X-rays hits the sample and the crystals of the mineral grains in the sample diffract the beam in a characteristic way, creating a diffractogram for each sample.

The diffractogram from the XRD was opened in a program called EVA, which analyses the diffractogram and suggests what mineral they might reflect. The diffractogram was then evaluated in TOPAZ, which calculates the volume percent of each mineral put into the system. A value of Goodness of Fit (GOF) is given for each sample, telling how well the diffractograms of the chosen minerals agree with that of the analyzed sample. If the value of GOF is 1, the diffractogram matches and all the minerals are found. If <1, some minerals might be missing, or mistaken for another mineral.

The calculated volume percent of each mineral was recalculated into weight percent, using literature values for composition and density. This gives a rough estimate of the theoretical chemical composition and can be compared with the whole-rock analysis for a quality control of the XRD analyses.

MINSQ

Whole-rock data (Table 2) were processed by the MINSQ spreadsheet (Herrmann & Berry, 2002), which utilizes the *Solver* function of Microsoft Excel. 1.5 wt.% S was added manually to the whole-rock data, because sulphur was not analyzed by the SEM-EDS due to the ignition and glass-making process. This value was estimated as representative from XRF analyses of material that was not ignited.

The MINSQ spreadsheet uses a least squares approach to match calculated mineral compositions with the whole-rock analysis. The minerals that were used for this calculation are quartz, calcite, kaolinite, K-feldspar, jarosite, albite, muscovite, and some sulphides (Table 8, Figure 25). When the program was run with pyrite included in the list, MINSQ calculated all sulphur as pyrite instead of jarosite, which gave unrealistic results. Thus pyrite was removed from the calculation.

Results

Major elements by SEM-EDS

The whole-rock analyses are seen in table 2. Loss on Ignition (LOI) was calculated on all fourteen samples and shows great variation (figure 6). The shale and the stybb have a LOI of 30–35 wt.% while the ash is only at 1–5 wt.%.

The analyses by the SEM-EDS show that the amount of iron is significantly higher in the ash than in the stybb and the shale (Figure 7). The iron content varies between 4–9 wt.% in the shale and stybb and goes up to 12–15,5 wt.% in the ash. Contents of silica and aluminium is similar in all samples (Figure 8 and 9).

Table 2. Showing whole-rock analyses (SEM) in weight percent (wt.%) including Loss on Ignition. Sulphur and uranium are excluded, because they were not detected by this method.

	LC12-01	LC12-02	LC12-3	LC12-4	LC12-5	LC12-06	LC12-07
	Ash	Ash	Ash	Ash	Stybb	Stybb	Stybb
Na ₂ O	0,22	0,14	0,21	0,30	0,28	0,20	0,23
MgO	0,91	0,19	0,57	1,29	0,56	0,66	0,61
Al ₂ O ₃	16,04	14,44	16,41	16,09	9,64	11,71	10,91
SiO ₂	56,92	57,85	59,91	58,97	40,21	46,67	41,95
P ₂ O ₅	0,08	0,05	0,03	0,08	0,01	0,00	0,00
K ₂ O	4,41	4,12	4,56	5,24	3,62	4,04	3,72
CaO	3,76	2,57	2,70	4,05	3,48	0,24	2,61
TiO ₂	0,88	0,99	0,95	0,93	0,62	0,73	0,68
V ₂ O ₅	0,13	0,11	0,13	0,14	0,09	0,09	0,09
MnO	0,08	0,01	0,01	0,04	0,00	0,00	0,01
Fe ₂ O ₃	11,85	14,60	12,45	11,86	8,00	3,11	6,30
NiO	0,02	0,01	0,01	0,04	0,01	0,01	0,00
LOI%	4,71	4,96	2,09	0,97	33,49	32,55	32,92
TOTAL %	100,008369	100,026344	100,013965	100,025724	100,02	100,017603	100,026828
	LC12-08	LC12-09	LC12-10	LC12-11	LC12-12	LC12-13	LC12-14
	Stybb	Other	Other	Shale	Shale	Shale	Shale
Na ₂ O	0,27	0,14	0,27	0,24	0,25	0,19	0,24
MgO	0,58	0,50	0,65	0,67	0,70	0,67	0,70
Al ₂ O ₃	10,60	8,96	12,62	10,81	10,68	10,25	10,18
SiO ₂	43,10	36,75	53,96	47,68	48,54	44,29	43,54
P ₂ O ₅	0,00	0,00	0,03	0,00	0,00	0,00	0,00
K ₂ O	3,69	3,25	4,66	4,33	4,57	3,84	4,18
CaO	3,20	0,50	3,47	0,31	0,10	0,64	0,71
TiO ₂	0,67	0,66	0,85	0,66	0,74	0,61	0,62
V ₂ O ₅	0,10	0,07	0,08	0,08	0,09	0,09	0,08
MnO	0,02	0,01	0,01	0,00	0,01	0,02	0,01
Fe ₂ O ₃	5,87	2,65	12,05	3,62	3,04	5,18	4,49
NiO	0,00	0,00	0,00	0,01	0,00	0,00	0,01
LOI%	31,93	46,53	11,37	31,61	31,30	34,25	35,25
TOTAL %	100,03	100,02	100,01	100,02	100,02	100,03	100,01

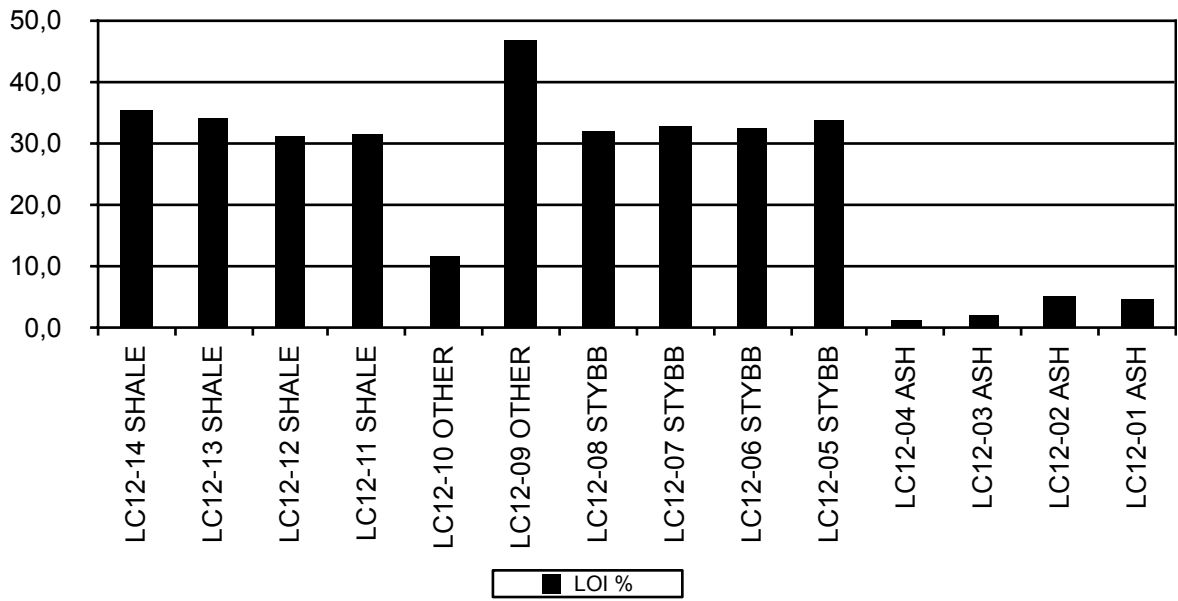


Figure 6. Loss on ignition (LOI) from table 2.

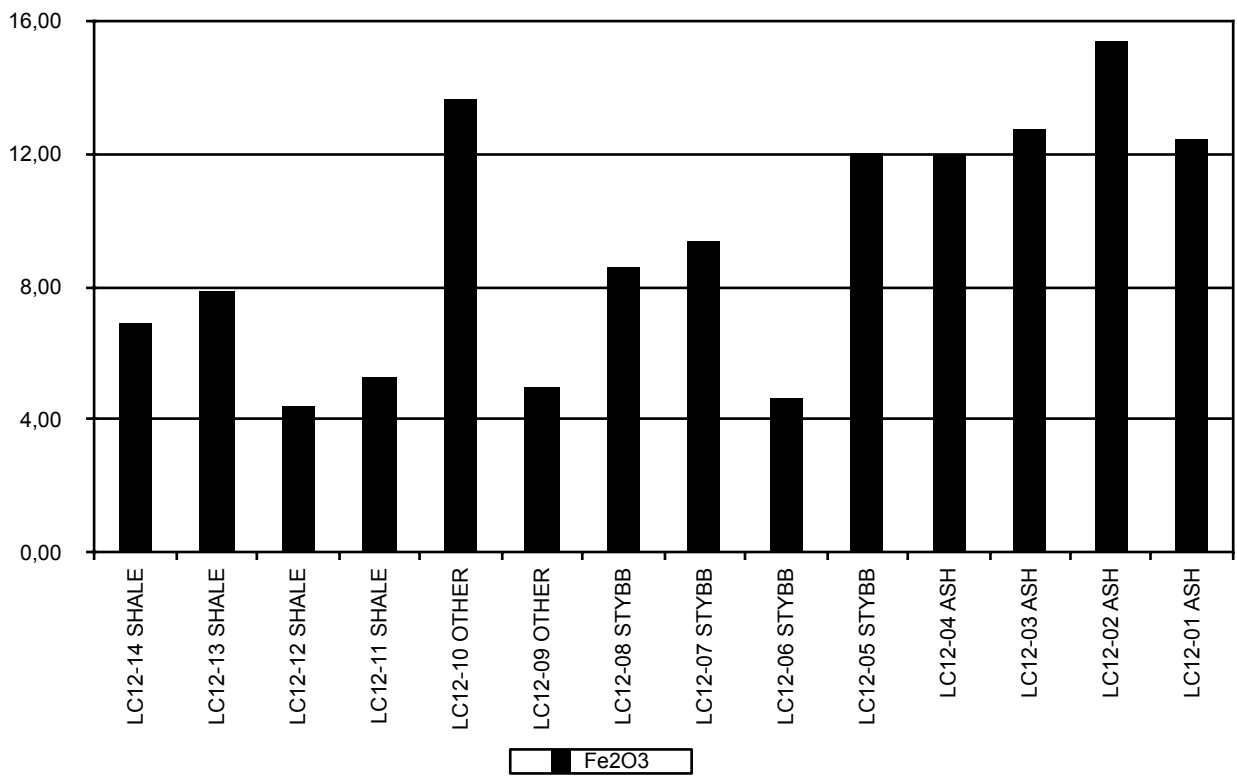


Figure 7. Iron content in percent (%) from table 2, but recalculated without Loss On Ignition.

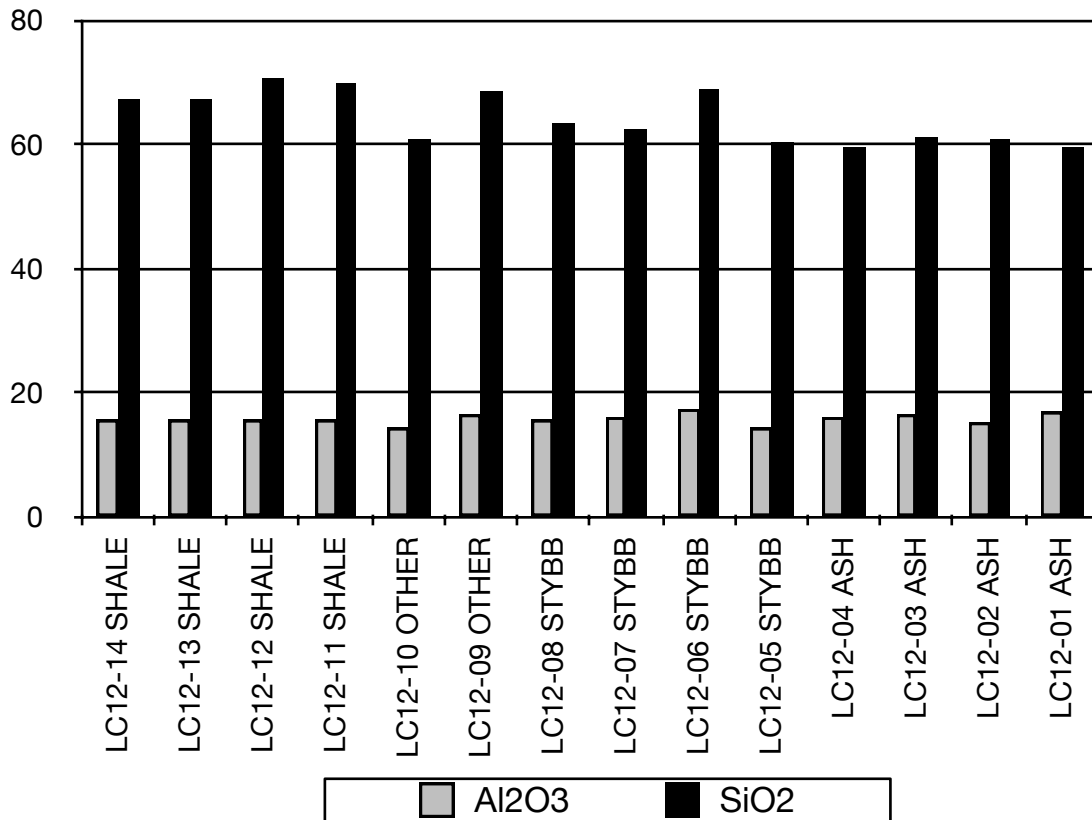


Figure 8. Aluminum content in red, and silica content in black, from table 2 but without loss on ignition. All values in percent (%).

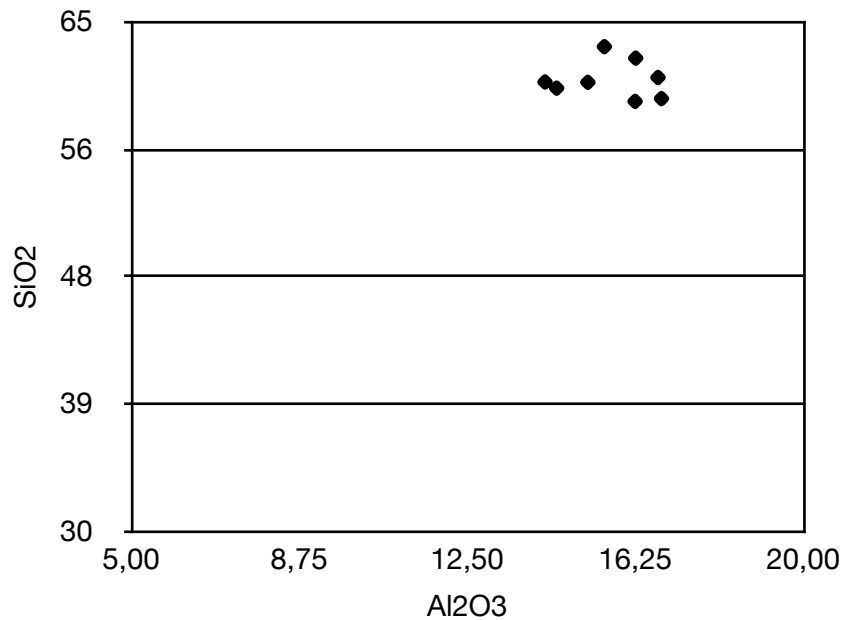


Figure 9. Aluminum on X plotted against silica on Y. All values in percent (%). Data from whole rock analyses, without loss on ignition.

Minor and trace elements by LA-ICP-MS

The results from the LA-ICP-MS are shown in the table 3. Some data from table 3 are plotted in the following figures (figures 10–16) and compared with KM and MKM values. KM stands for "sensitive land use" and MKM for "less sensitive land use" and are guidelines developed by the Swedish Environmental Protection Agency (Naturvårdsverket, 2009). The land use controls the type of activities in the area and the demands for protection of the environment. Different types of activities gives different environmental demands. The general guidelines are considering four parameters: people visiting the area, the areal environment, groundwater, and surface water.

Table 3. Result from LA-ICP-MS in ppm. Elements not included: Ni, As, Mo, Cd, Hg, Tl, due to unreliable analyses.

	LC12-01	LC12-02	LC12-03	LC12-04	LC12-05	LC12-06	LC12-07
Elements	ASH	ASH	ASH	ASH	STYBB	STYBB	STYBB
Si	270828	257151	420171	280434	285652	363068	304117
P	686	795	1037	956	451	422	366
Ca	28588	19297	28588	29303	37164	2573	27873
Sc	16	7	23	17	13	16	14
Ti	4952	5454	7853	5163	5105	7517	5884
V	675	650	1221	737	723	988	801
Cr	121	144	143	103	83	107	90
Mn	474	26	159	334	61	85	70
Co	36	19	33	34	3	3	2
Cu	231	214	297	209	45	55	50
Zn	322	90	246	116	35	33	32
Rb	268	209	254	174	169	410	356
Sr	109	64	143	103	143	98	130
Zr	196	190	273	181	178	257	223
Nb	20	22	31	20	20	33	24
Cs	18	18	17	11	11	28	25
Ba	674	691	967	646	643	1012	881
Hf	5	4	7	5	5	6	5
Ta	1	1	2	1	1	2	2
Pb	29	47	39	13	52	34	34
Th	30	21	26	18	12	24	17
U	330	97	263	216	60	103	79
	LC12-08	LC12-09	LC12-10	LC12-11	LC12-12	LC12-13	LC12-14
Elements	STYBB	OTHER	OTHER	SHALE	SHALE	SHALE	SHALE
Si	373911	483560	317260	390866	472169	405283	402992
P31	1035	1355	602	415	675	1278	949
Ca	33591	7147	28588	3288	1072	7147	7862
Sc	15	18	12	15	16	16	15
Ti	8339	11983	6048	6879	8552	7455	7958
V	926	1119	580	861	1029	1077	812
Cr	51	59	70	73	82	61	52
Mn	107	98	72	79	108	212	141
Co	5	3	4	3	3	24	10

Cu	45	55	82	37	45	140	53
Zn	56	53	31	30	38	534	259
Rb	549	703	337	428	575	489	531
Sr	245	165	114	160	146	163	200
Zr	407	437	279	261	234	306	399
Nb	40	61	26	29	37	35	37
Cs	38	42	23	27	37	31	34
Ba	1459	1942	937	933	1181	1111	1183
Hf	9	10	6	6	6	7	10
Ta	3	4	2	2	2	2	3
Pb	63	32	41	22	29	22	25
Th	46	32	33	23	24	46	43
U	128	169	58	144	267	362	229

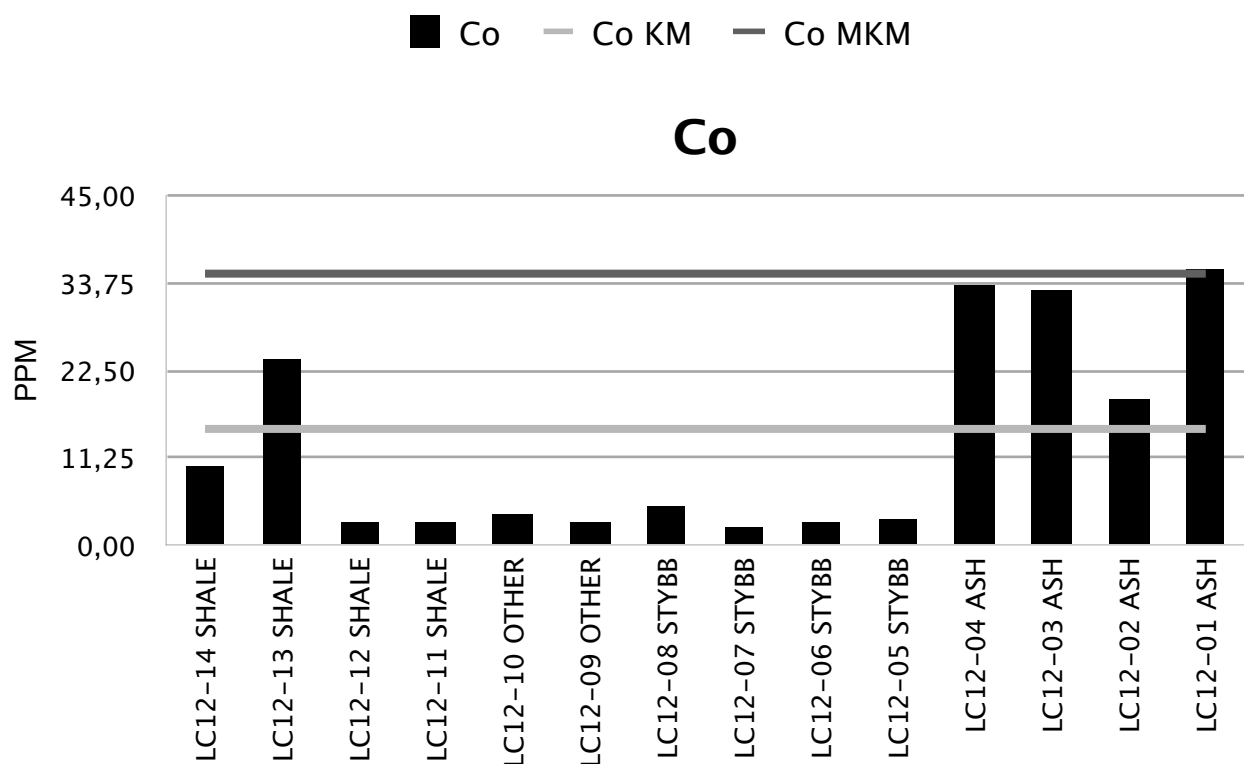


Figure 10. ICP-MS laser results in PPM for cobalt. Values for KM (sensitive ground use) in light grey and MKM (less sensitive ground use) in dark grey (Naturvårdsverket, 2009).

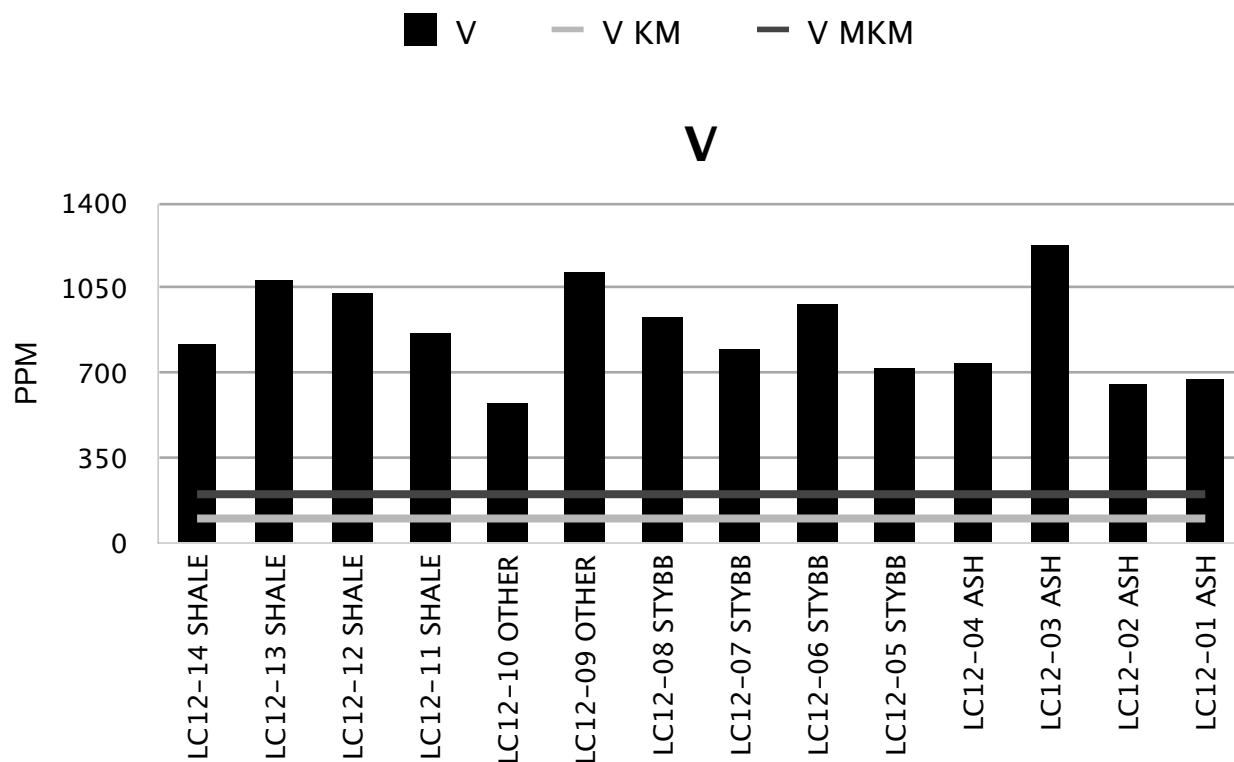


Figure 11. ICP-MS laser results for vanadium. Values for KM (sensitive ground use) in light grey and MKM (less sensitive ground use) in dark grey (Naturvårdsverket, 2009).

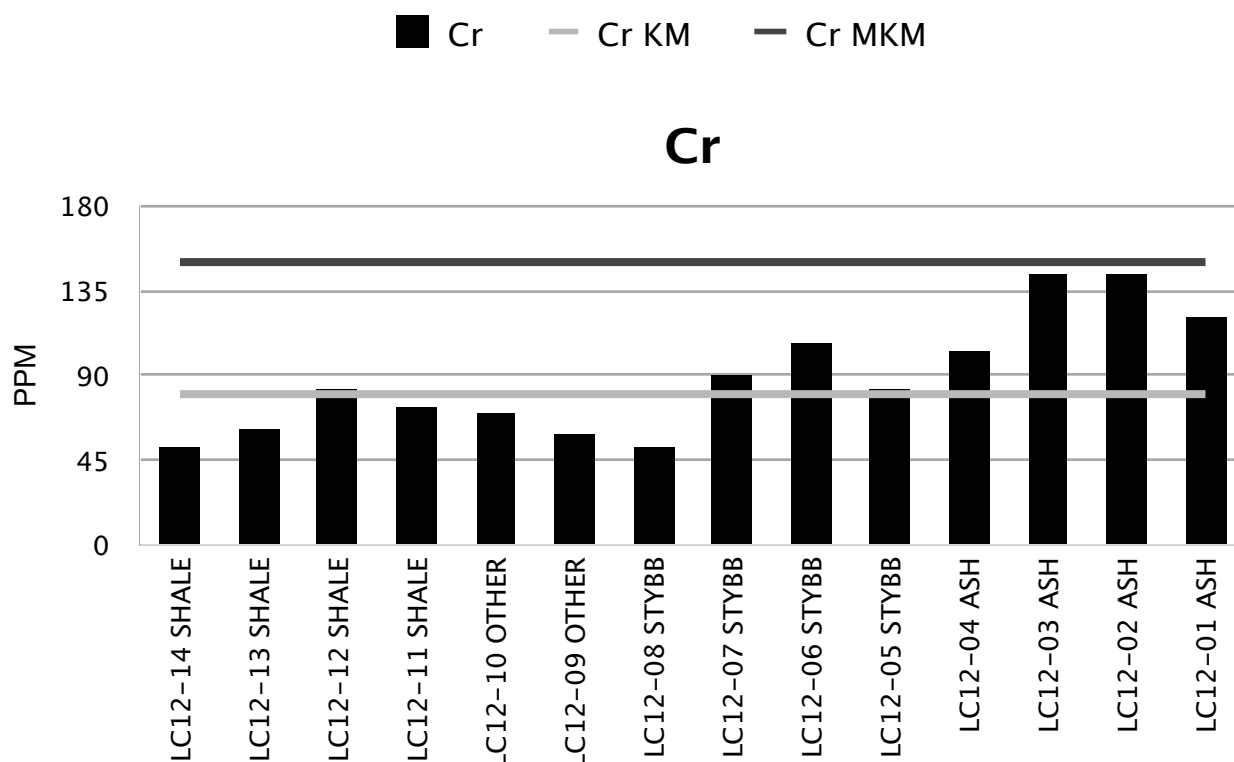


Figure 12. ICP-MS laser results for chromium. Values for KM (sensitive ground use) in light grey and MKM (less sensitive ground use) in dark grey (Naturvårdsverket, 2009).

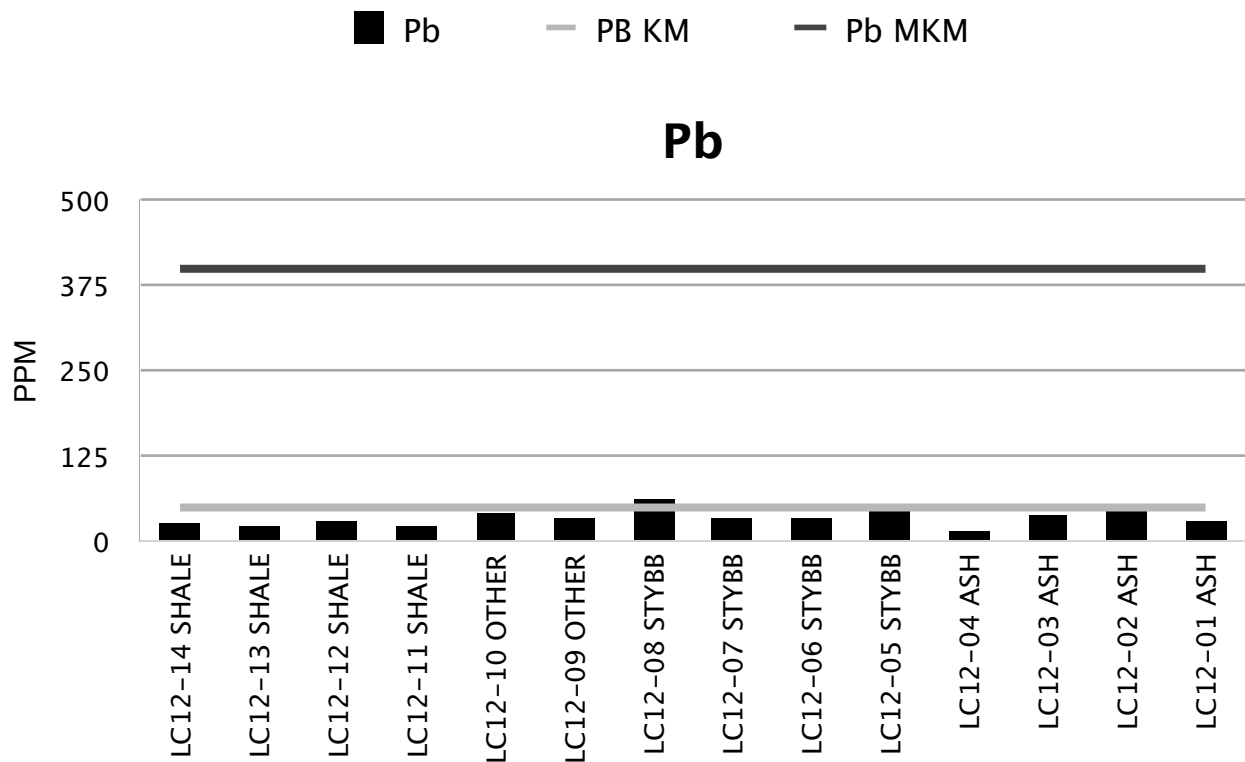


Figure 13. ICP-MS laser results for lead. Values for KM (sensitive ground use) in light grey and MKM (less sensitive ground use) in dark grey (Naturvårdsverket, 2009).

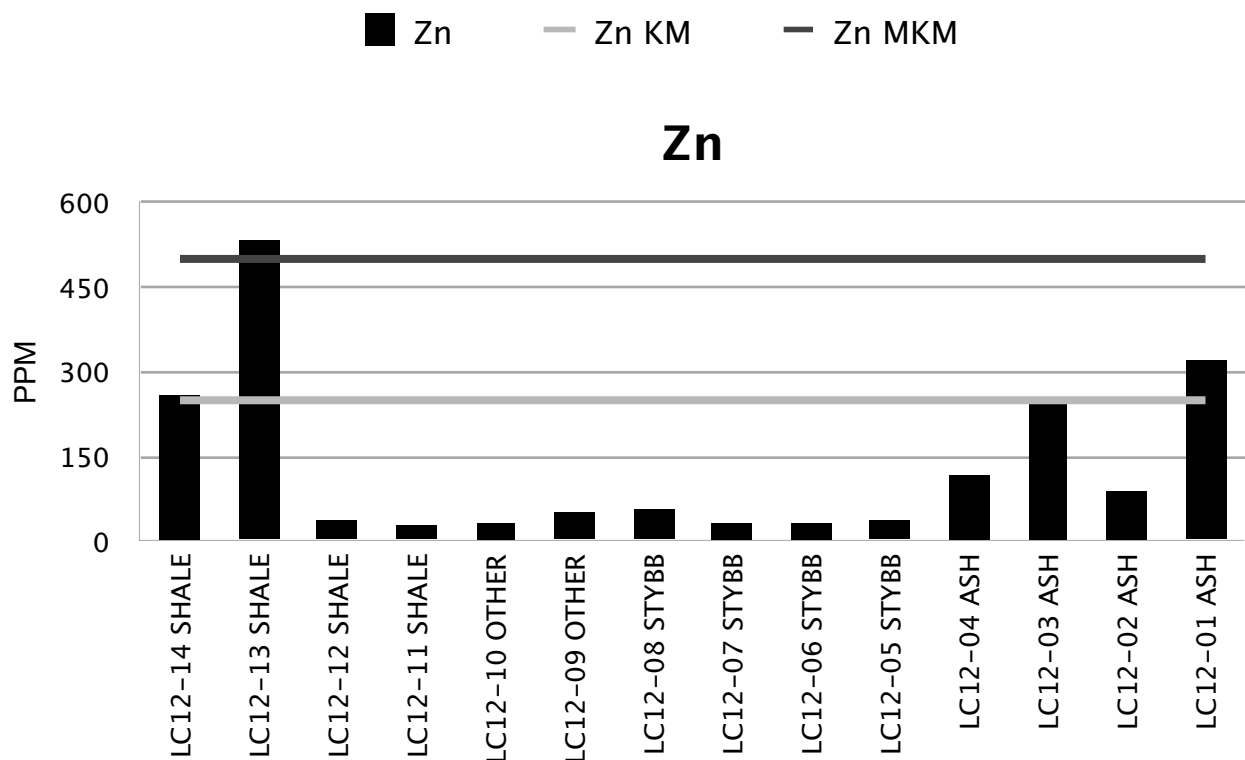


Figure 14. ICP-MS laser results for zinc. Values for KM (sensitive ground use) in light grey and MKM (less sensitive ground use) in dark grey (Naturvårdsverket, 2009).

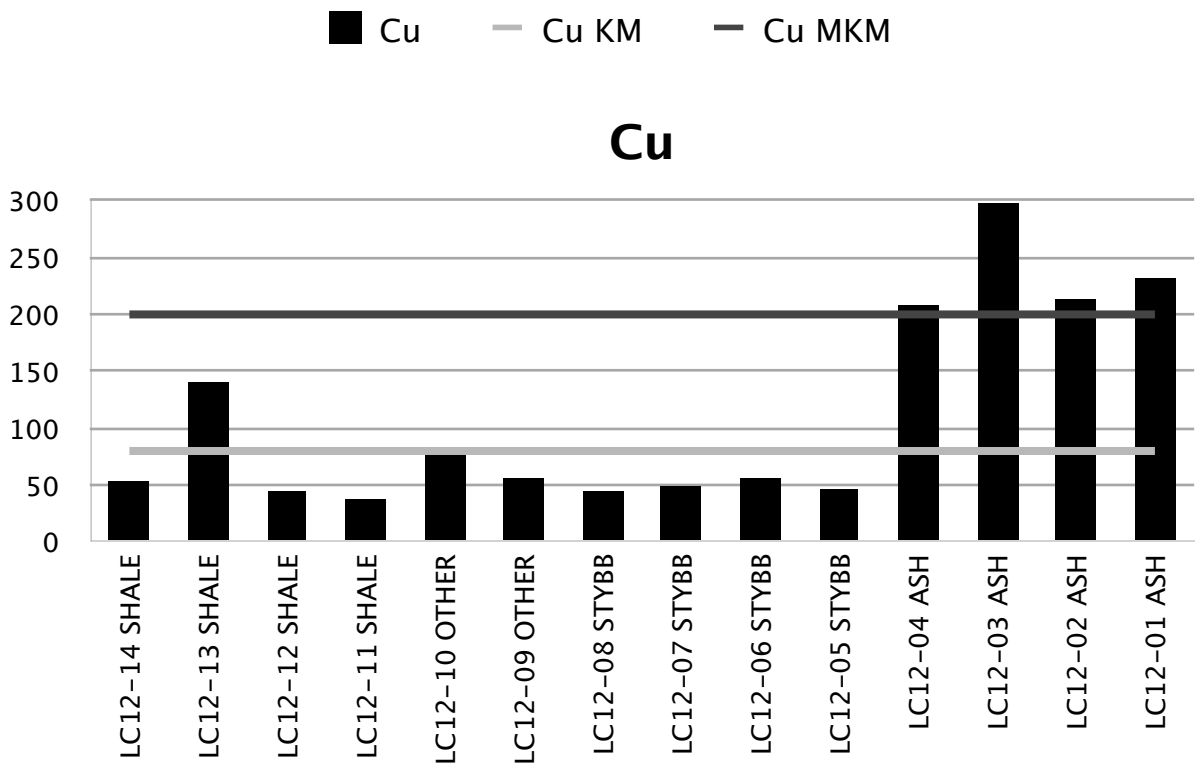


Figure 15. ICP-MS laser results for copper. Values for KM (sensitive ground use) in light grey and MKM (less sensitive ground use) in dark grey (Naturvårdsverket, 2009).

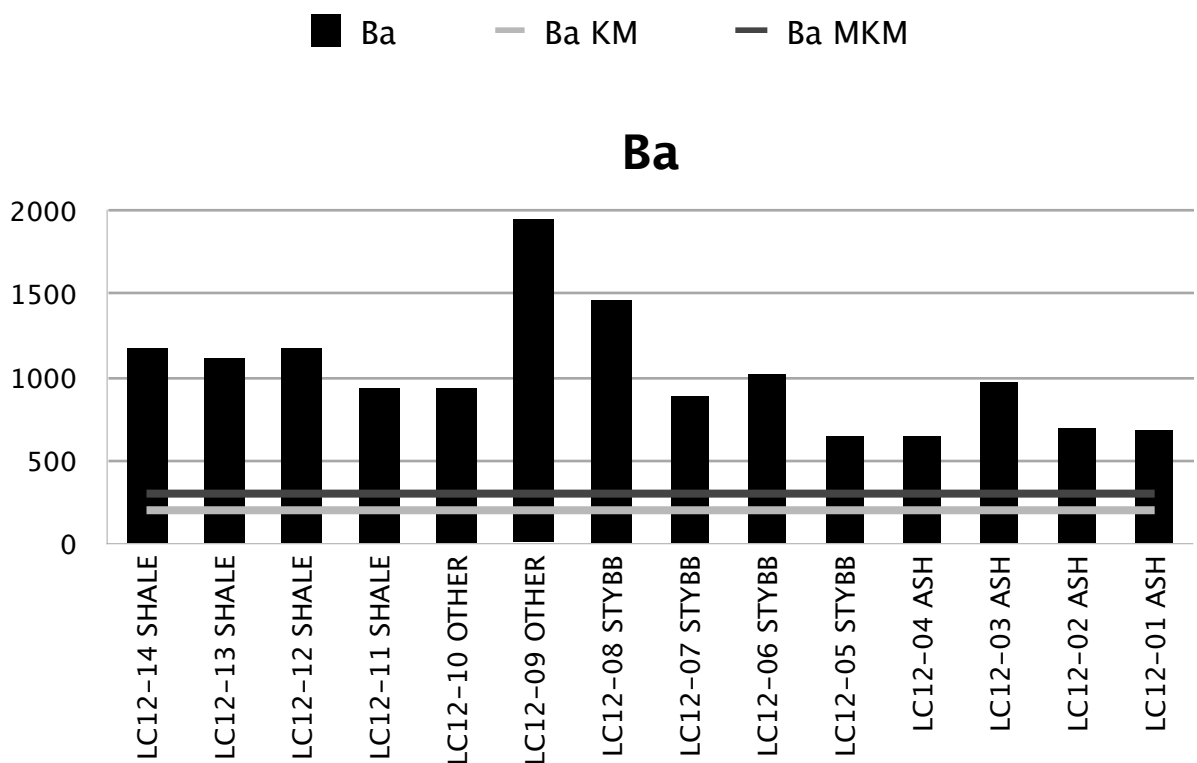


Figure 16. ICP-MS laser results for barium. Values for KM (sensitive ground use) in light grey and MKM (less sensitive ground use) in dark grey (Naturvårdsverket, 2009).

Leaching analysis by ICP-MS

The following table (table 4) displays the results from the leaching analysis by the ICP-MS in ppm. Values for uranium and mercury are plotted in figures 17 and 18.

Table 4. Results from leaching by ICP-MS, in ppm.

	LC12-14	LC12-13	LC12-12	LC12-11	LC12-8	LC12-7	LC12-6	LC12-5	LC12-4	LC12-3	LC12-2	LC12-1
	Shale	Shale	Shale	Shale	Stybb	Stybb	Stybb	Stybb	Ash	Ash	Ash	Ash
Na	136	112	145	287	393	493	218	640	397	287	259	288
Mg	1677	1289	1312	1040	712	748	801	518	1379	710	165	1794
Al	8330	10025	8379	8305	6719	6423	7460	5030	7250	7776	5105	23603
K	6180	5575	6253	6760	5974	5617	5340	6190	2897	4338	7958	9356
Ca	5445	4868	308	2185	24694	19643	1535	23635	29295	20082	19057	28113
Sc	2	3	2	2	2	2	2	1	2	3	1	6
Ti	904	867	935	857	582	561	486	450	1484	1323	4678	1737
V	240	299	262	258	217	229	237	178	38	200	171	369
Cr	18	23	17	18	17	13	17	12	18	16	13	35
Mn	55	105	21	18	27	14	15	10	117	56	8	397
Fe	31950	38740	20177	24295	44000	44398	19500	53850	7180	9168	31849	38392
Co	6	15	1	1	3	1	1	1	3	4	1	35
Ni	52	120	18	23	20	12	13	11	16	22	9	199
Cu	40	113	21	26	37	28	30	25	25	64	20	133
Zn	174	463	9	62	22	12	8	15	14	35	39	340
As	48	60	37	36	41	43	32	38	3	34	38	86
Se	0	0	0	0	0	0	0	0	0	0	0	0
Y	13	14	8	7	8	5	5	7	21	47	6	72
Mo	173	194	170	180	126	139	77	117	121	316	102	94
Cd	2	5	0	0	0	0	0	0	3	1	0	5
In	2	2	2	2	2	2	2	2	2	2	2	2
Ce	42	47	29	28	46	28	29	39	60	88	29	88
Re	2	2	2	2	2	2	2	2	2	2	2	2
Hg	17785	16700	19707	19025	18520	19648	22395	15215	549	409	434	415
Tl	9	9	13	10	12	12	4	9	1	2	3	6
Pb	28	89	20	56	32	32	28	33	7	24	33	21
Th	605	718	454	472	590	377	432	430	461	718	520	679
U	59	125	78	44	23	21	24	15	29	38	12	26

U

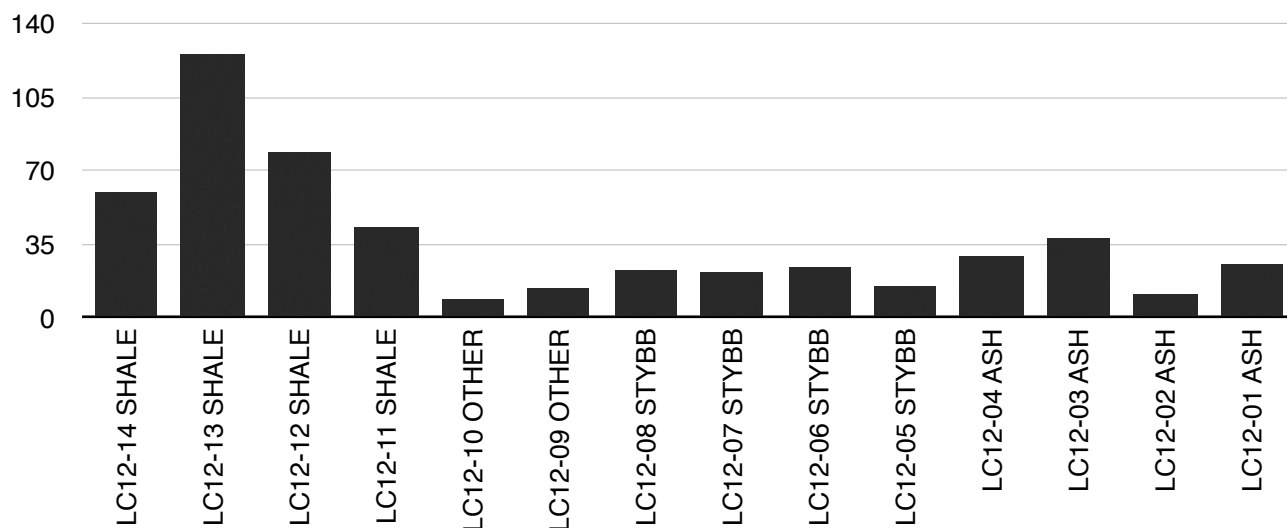


Figure 17: ICP-MS leaching results for Uranium, in PPM.

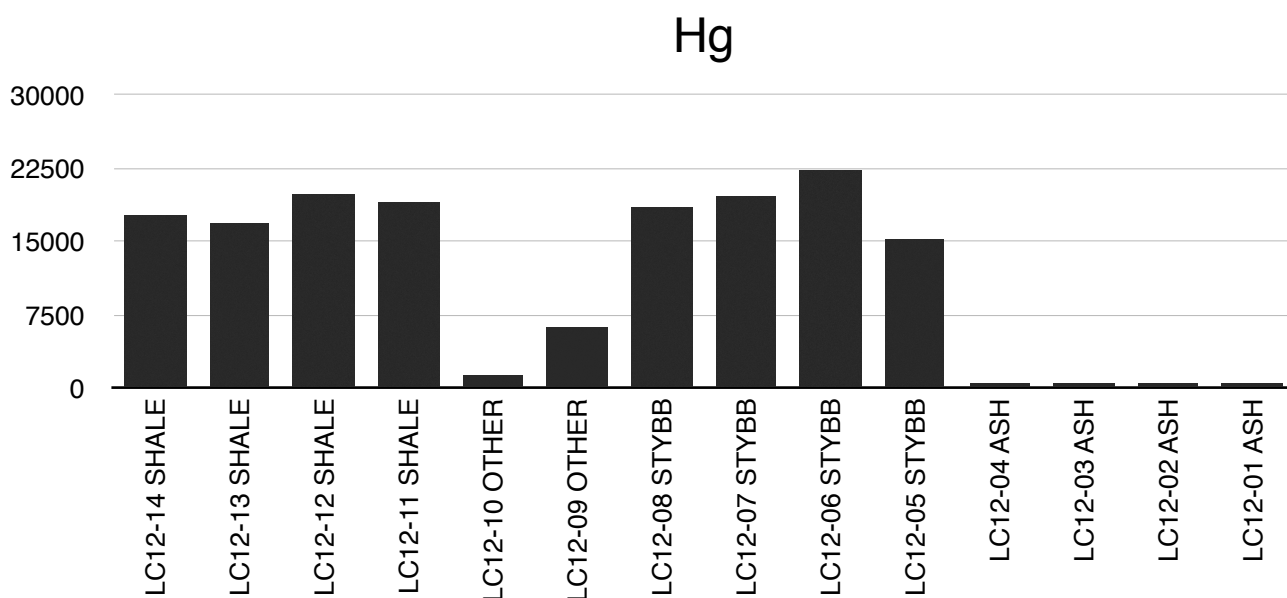


Figure 18: ICP-MS leaching results for Mercury, in PPM.

Major elements by XRF

XRF measurements (table 5) show somewhat similar result as the analyses from the Whole-rock analysis by SEM-EDS (table 2). The iron content (figure 19) is higher in the ash than in the stybb and shale. The aluminium and silica are here slightly higher in the ash than in the stybb and shale (figure 20). The analysis by the XRF also shows that the amount of light elements (LE) decreases in the ash. The amount of LE in the shale and stybb varies between 750,000–800,000 ppm and decreases to around 680,000 ppm (figure 21). The XRF results also show a similar trend for copper, arsenic, nickel, zirconium, cadmium, and vanadium (figure 22 & 23).

Table 5. Showing results from portable XRF analyses in ppm. Elements on the left, samples on top. LE stands for Light Elements, which are all chemical elements lighter than aluminium.

	LC12-01	LC12-02	LC12-03	LC12-04	LC12-05	LC12-06	LC12-07
Elements	ASH	ASH	ASH	ASH	STYBB	STYBB	STYBB
Al	31300	21533	24000	22433	9900	18800	15500
Si	136000	135667	140833	133600	69367	113100	89900
P	433	313	410	406	222	0	0
S	13302	17483	11005	12294	30784	11485	27906
K	30950	28728	31738	35562	21425	30150	26254
Ca	21533	15684	16435	26883	22504	695	18311
Ti	3127	3637	3512	3375	2189	2949	2554
V	823	640	817	816	445	572	590
Cr	161	103	134	123	111	106	96
Mn	484	0	155	368	0	83	85
Fe	85841	98096	82204	80190	52608	21686	43016
Co	487	573	453	441	393	195	0
Ni	242	103	153	193	32	29	0
Cu	212	152	201	203	31	32	33
Zn	387	62	163	101	0	0	0
As	104	113	74	0	33	27	44
Zr	166	157	171	175	101	106	113
Ag	195	188	196	213	165	121	135
Cd	259	245	230	284	212	159	182
Sn	229	252	230	298	220	149	188
Sb	374	351	320	402	320	209	269

Pb	55	52	46	18	43	35	39
Bi	34	29	34	32	0	18	0
LE	673300	675700	686133	681433	789233	799433	774800
	LC12-08	LC12-09	LC12-10	LC12-11	LC12-12	LC12-13	LC12-14
Elements	STYBB	OTHER	OTHER	SHALE	SHALE	SHALE	SHALE
Al	16533	13133	16767	18633	18533	16833	16100
Si	97600	90533	111900	118333	123867	103600	101333
P	259	0	0	0	172	302,7	217
S	29673	23221	23172	12227	13502	28536	21611
K	24878	22988	31323	31372	35027	28461	28382
Ca	22139	2683	18376	990	0	4147	4192
Ti	2493	2235	3014	2492	2835	2407	2270
V	630	491	588	551	562	578	452
Cr	110	92	100	87	80	91	104
Mn	85	56	89	73	80	120	100
Fe	41113	17891	85796	23240	22324	33686	27714
Co	0	0	434	0	0	251	0
Ni	38	21	43	33	36	105	46
Cu	44	22	106	26	25	86	33
Zn	0	0	0	0	0	246	93
As	33	0	93	29	33	44	34
Zr	117	69	158	97	119	97	102
Ag	151	104	183	133	132	140	132
Cd	206	125	264	181	175	207	178
Sn	222	107	274	171	174	204	161
Sb	302	161	385	233	262	277	228
Pb	41	34	69	37	32	30	27
Bi	20	0	28	17	18	20	20
LE	763300	826100	706933	790933	782033	779567	796433

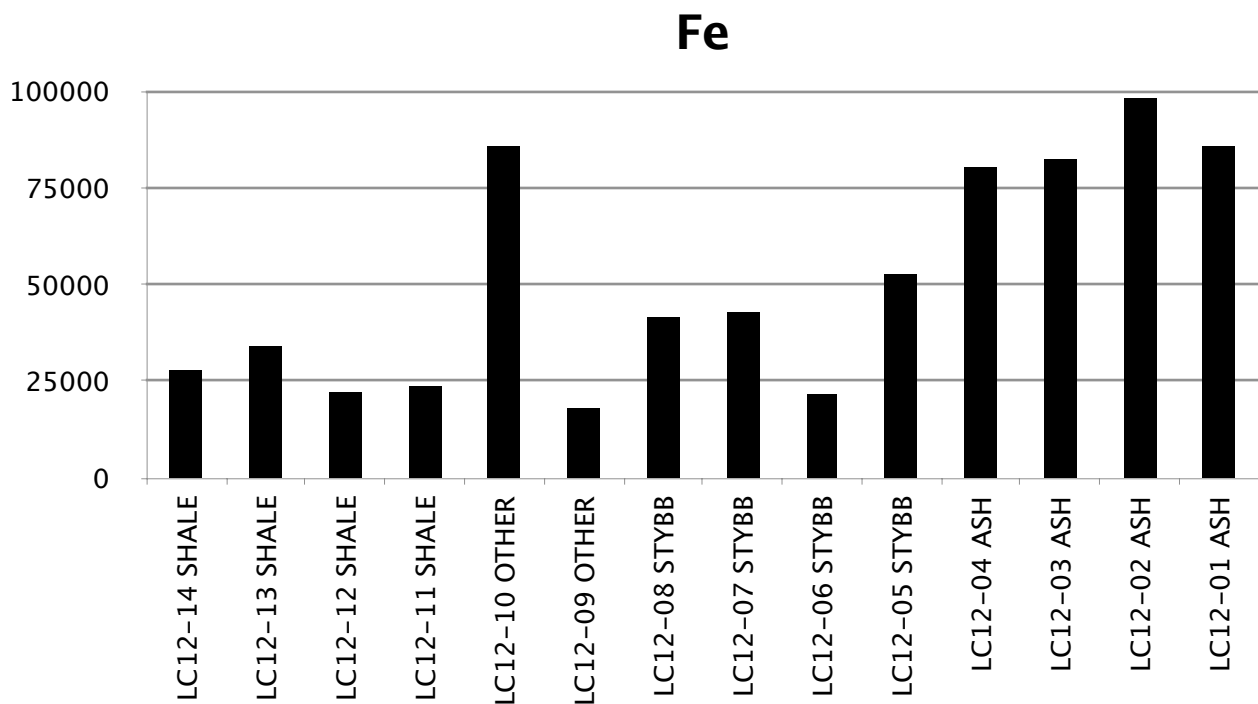


Figure 19. Iron in ppm, from XRF analyses.

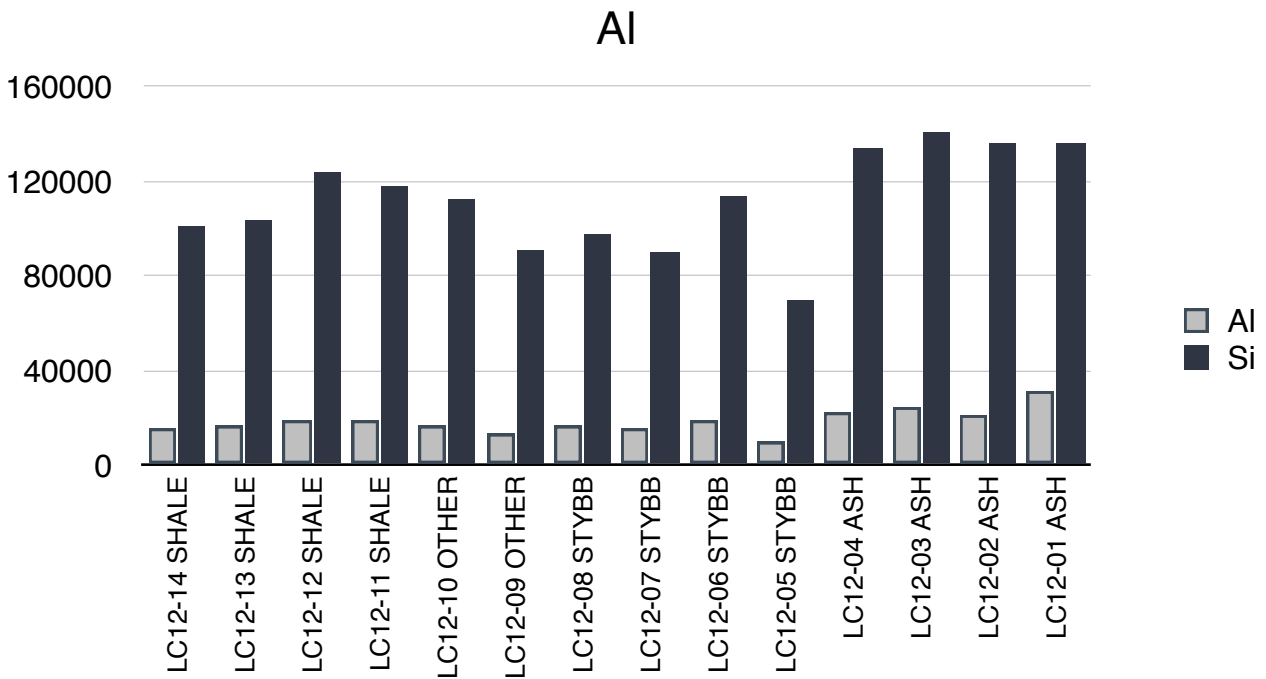


Figure 20. Aluminium and silica in ppm, from XRF analyses.

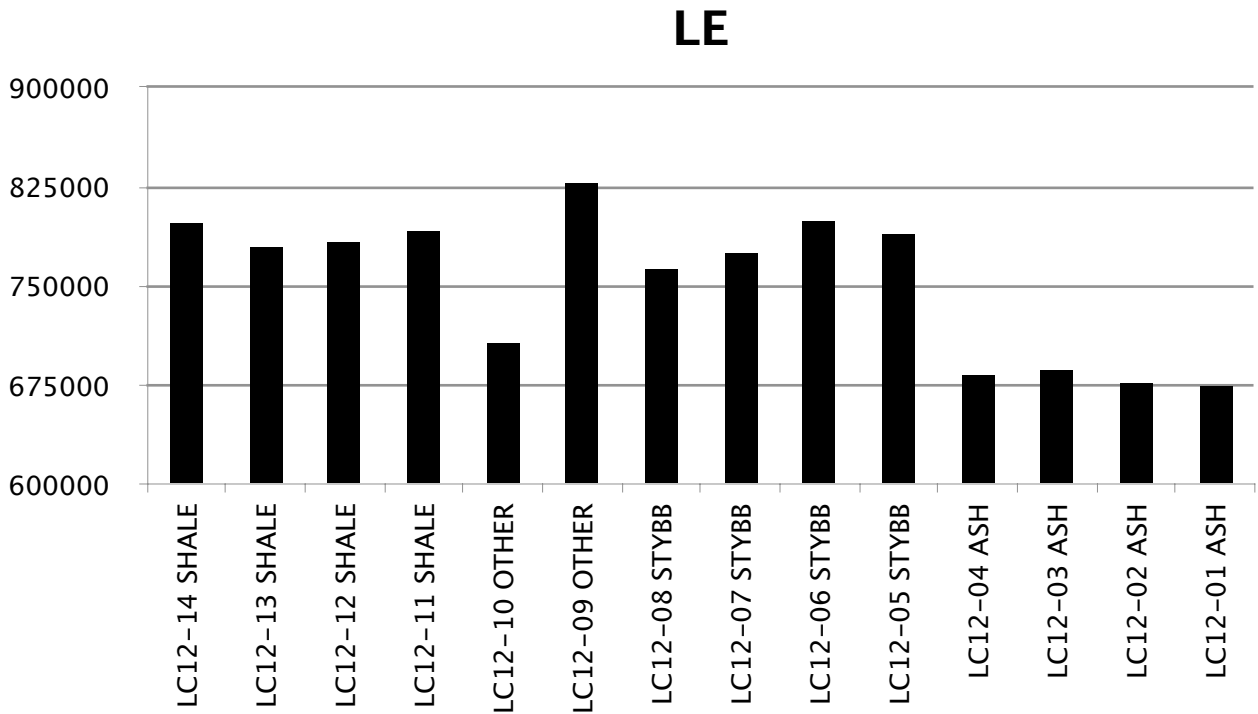


Figure 21. Light elements (LE) in ppm, from XRF analyses. Light elements means lighter than aluminum, thus elements that the XRF cannot detect.

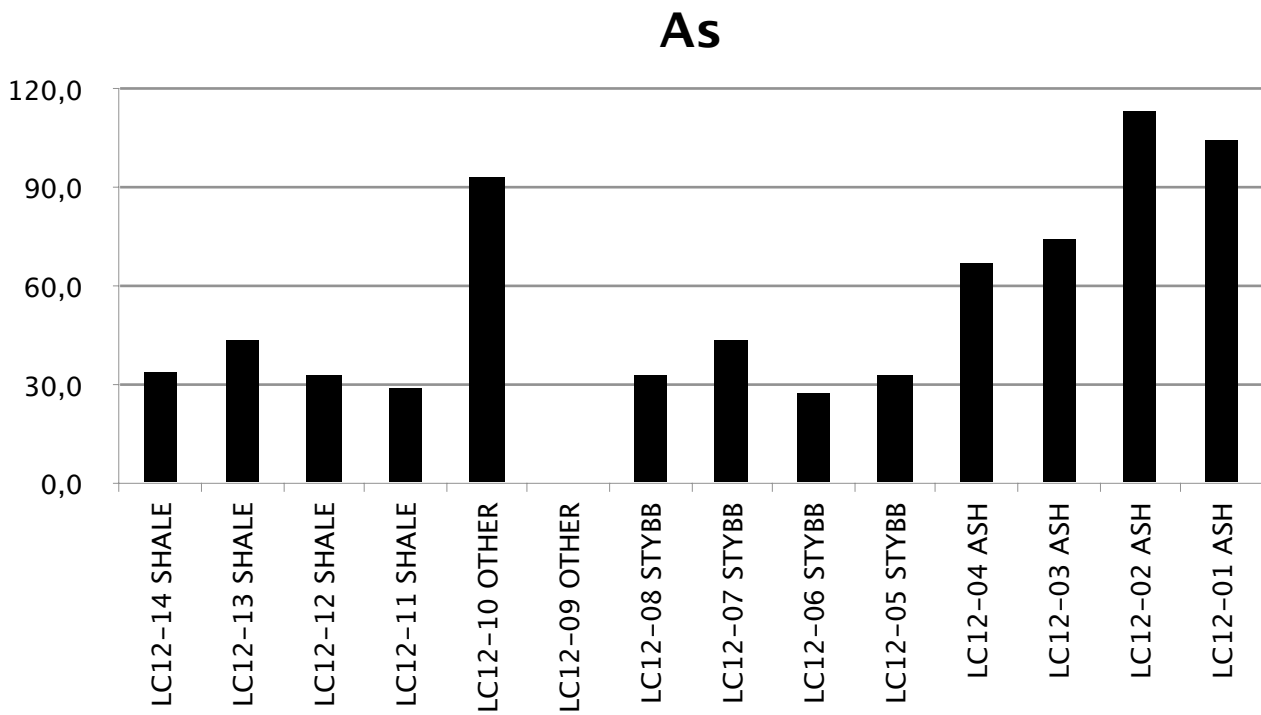


Figure 22. Arsenic (As) in ppm, from XRF analyses.

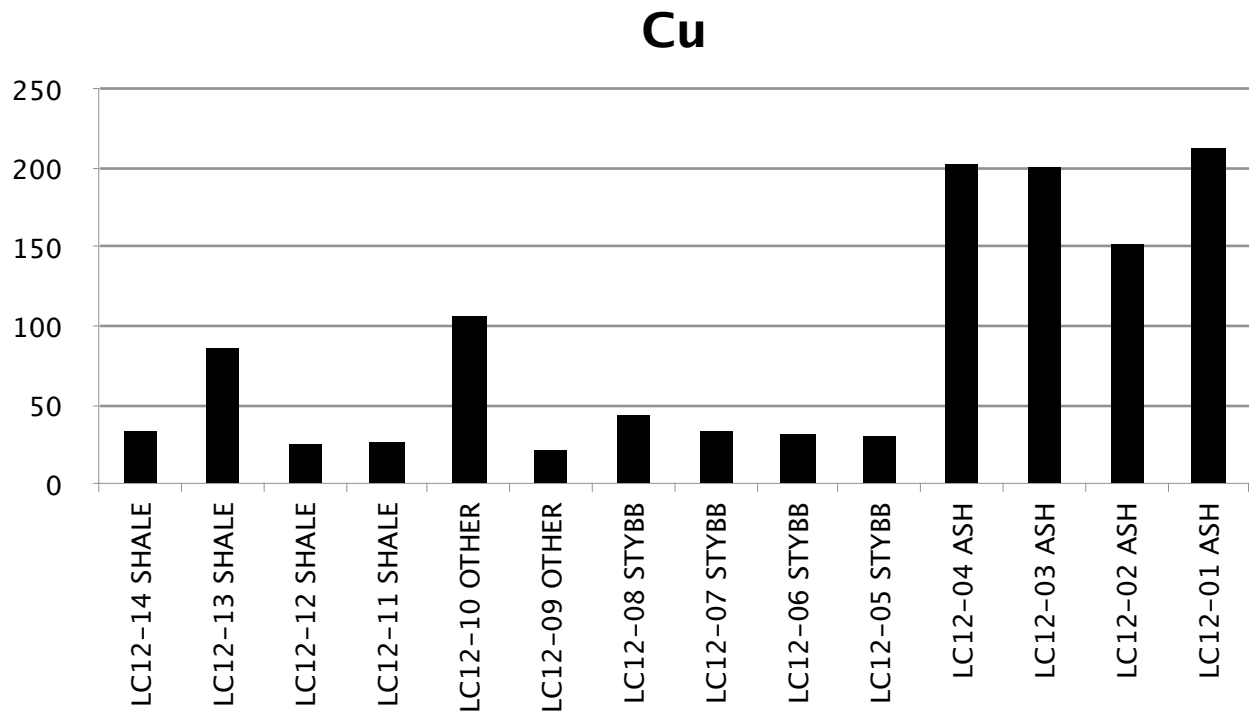


Figure 23. Copper (Cu) in ppm, from XRF analyses. Note the significant amount of copper in the ashes; around 200 ppm, which corresponds well to the analyses of copper by the ICP-MS (Figure 15).

In the following three figures (Figure 24, 25, and 26), some comparisons between the data from the XRF with the whole-rock data from the SEM are presented in weight percent element. The whole-rock data used are not corrected for the loss on ignition since the XRF analyses were performed on non-ignited samples and include light elements in the bulk.

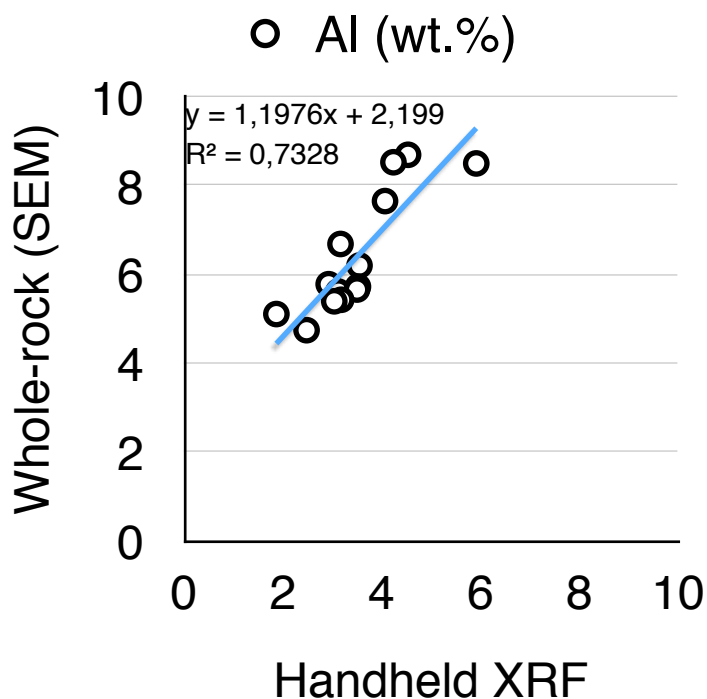


Figure 24. Comparison of Al for whole-rock data on y-axis and data from the XRF och x-axis.

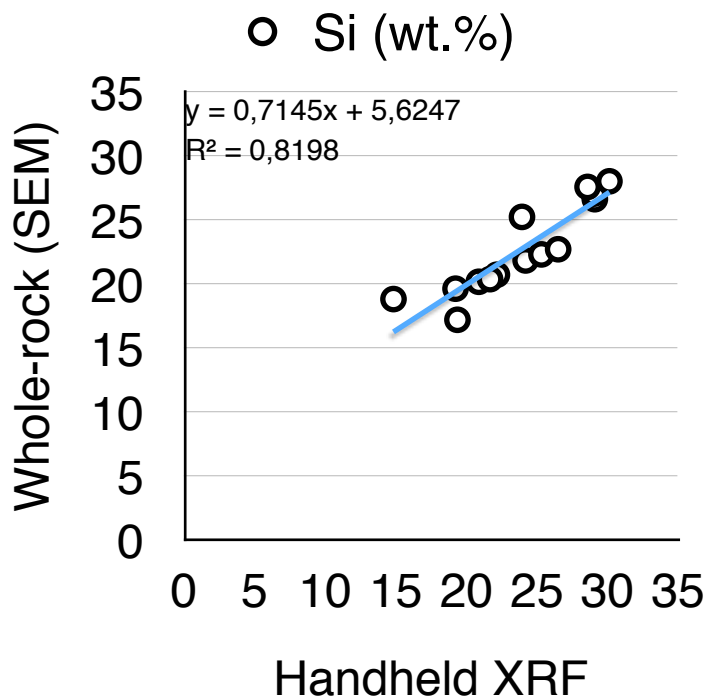


Figure 25. Comparison of Si for whole-rock data on y-axis and data from the XRF och x-axis.

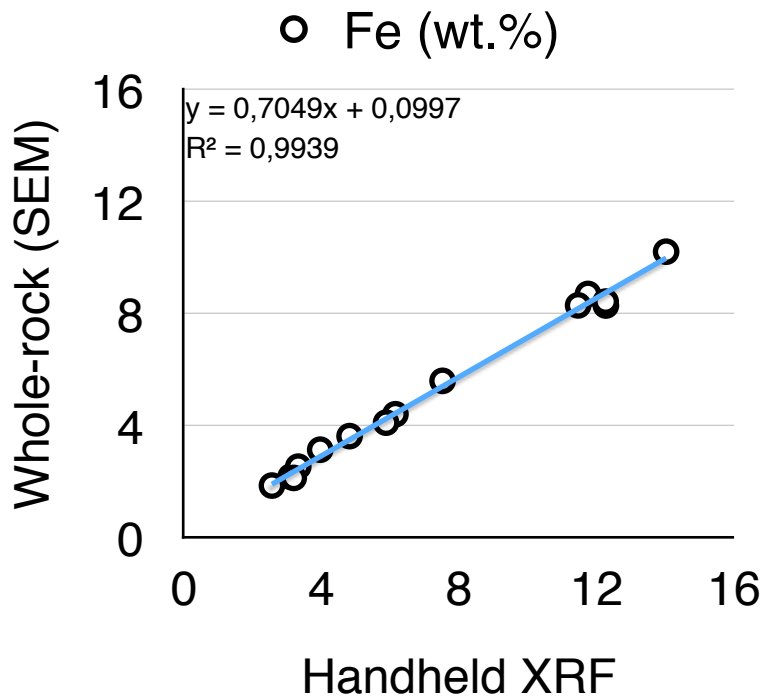


Figure 26. Comparison of Fe for whole-rock data on y-axis and data from the XRF och x-axis.

Mineralogy by XRD

The XRD analyses are presented in table 6 and 7. Only eight samples were analysed with this method; the ash samples and the "other" samples were excluded. In figure 24, a comparison of silica is plotted, between whole-rock analyses and XRD analysis, to try to validate the data from the XRD.

Table 6. Analyses from XRD, interpreted by the software EVA and TOPAZ. Values in percent, except GOF which stands for Goodness of Fit, which is a value indicating the correctness of the values in the table. The closer to 1, the better the result. The amount of each element is shown in table 7.

	LC12-05	LC12-06	LC12-07	LC12-08	LC12-11	LC12-12	LC12-13	LC12-14
	STYBB	STYBB	STYBB	STYBB	SHALE	SHALE	SHALE	SHALE
Quartz	24,3	27,7	26,5	27,4	32,1	29,9	27,8	24,7
Kaolinite	11,0	15,1	12,0	10,4	12,1	10,7	11,7	12,6
Jarosite	19,5	10,7	15,3	14,6	8,1	11,2	8,2	12,0
Muscovite	23,1	26,6	26,2	23,8	24,9	23,4	24,6	24,0
Orthoclase	20,0	19,9	18,5	22,1	22,7	24,8	24,6	26,7
Halite	2,1		1,4	1,6				
Pyrite							3,2	
TOTAL	100	100	100	100	100	100	100	100
GOF	1,30	1,36	1,28	1,34	1,31	1,31	1,34	1,33

Table 7: Analyses from XRD for each element used in the software EVA and TOPAZ. In percent (%), calculated from the minerals in table 6.

	LC12-05	LC12-06	LC12-07	LC12-08	LC12-11	LC12-12	LC12-13	LC12-14
	STYBB	STYBB	STYBB	STYBB	SHALE	SHALE	SHALE	SHALE
Na	0,7	0,0	0,5	0,5	0,0	0,0	0,0	0,0
Al	9,1	10,7	9,8	9,3	10,0	9,6	10,3	10,3
Si	24,6	27,7	26,0	26,7	29,6	28,6	28,9	27,3
S	2,7	1,4	2,1	2,0	1,1	1,5	1,1	1,6
K	5,1	5,5	5,2	5,5	5,7	5,8	6,1	6,1
Fe	6,9	3,8	5,4	5,2	2,9	4,0	3,0	4,3
O	49,2	50,4	49,6	49,4	50,3	50,1	50,0	49,9
H	0,7	0,6	0,6	0,6	0,5	0,5	0,5	0,5
Cl	1,1	0,0	0,7	0,8	0,0	0,0	0,0	0,0
TOTAL	100	100	100	100	100	100	100	100

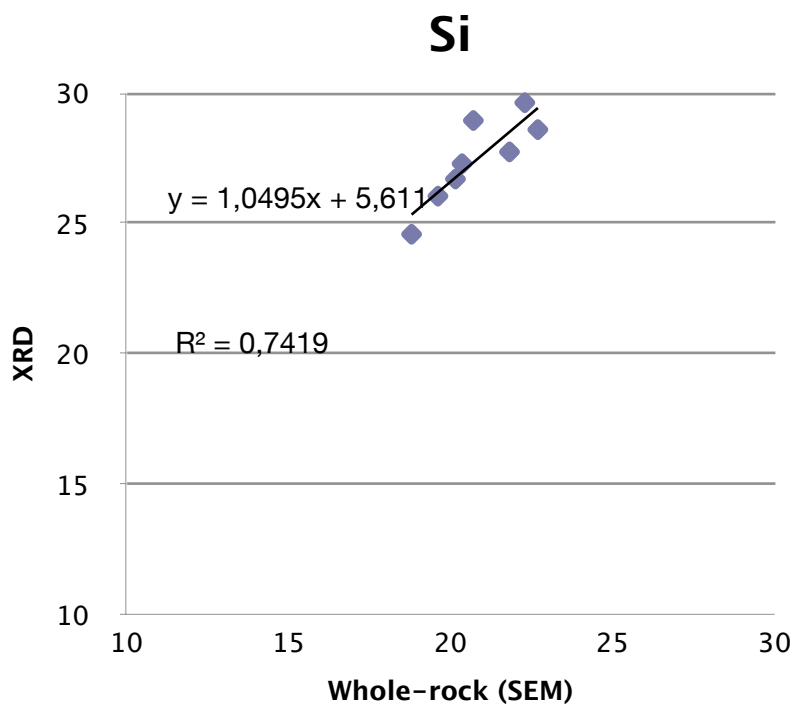


Figure 27. Comparison of silica between whole-rock analyses and XRD analysis. Loss on ignition is included in the whole-rock data.

Mineralogy by MINSQ

In table 8, data from the MINSQ spreadsheet (Herrmann & Berry, 2002) is presented and it is plotted in figure 28.

Table 8. Calculated mineral modes calculated using MINSQ spreadsheet (Herrmann & Berry, 2002) based on whole-rock data (table 2).

		Quartz	K-feldspar	Albite	Muscovite	Calcite	Kaolinite	Jarosite	Sulphide	TOTAL	Residual SSQ
LC12-01	Ash	35,7	0,0	0,0	20,5	2,4	22,5	18,9	0,0	100,0	15,6
LC12-02	Ash	39,8	0,0	0,0	12,3	0,5	23,5	23,8	0,0	100,0	20,3
LC12-03	Ash	38,6	0,0	0,0	19,8	0,4	22,6	18,6	0,0	100,0	21,0
LC12-04	Ash	36,9	0,0	0,0	28,0	2,0	16,0	17,1	0,0	100,0	22,9
LC12-05	Stybb	26,1	0,0	0,0	19,9	3,8	9,8	15,0	0,0	74,6	5,3
LC12-06	Stybb	28,4	0,0	0,0	31,9	0,3	6,2	3,5	1,3	71,6	1,3
LC12-07	Stybb	25,9	0,0	0,0	23,2	2,8	10,6	11,4	0,1	74,1	3,2
LC12-08	Stybb	26,1	3,7	0,8	18,2	3,5	11,4	10,8	0,2	74,7	4,5
LC12-09	Other	19,9	9,9	1,1	10,6	0,6	9,8	4,0	1,2	57,1	1,1
LC12-10	Other	34,9	0,0	2,1	23,3	3,7	13,6	22,4	0,0	100,0	7,5
LC12-11	Shale	29,4	0,0	1,9	33,8	0,3	1,6	4,5	1,1	72,6	1,0
LC12-12	Shale	27,3	11,6	2,1	19,5	0,1	6,4	4,2	1,2	72,4	1,1
LC12-13	Shale	27,5	1,2	1,6	24,7	0,7	6,5	8,7	0,5	71,4	0,7
LC12-14	Shale	25,3	4,7	2,0	23,8	0,8	5,2	7,2	0,7	69,7	0,8

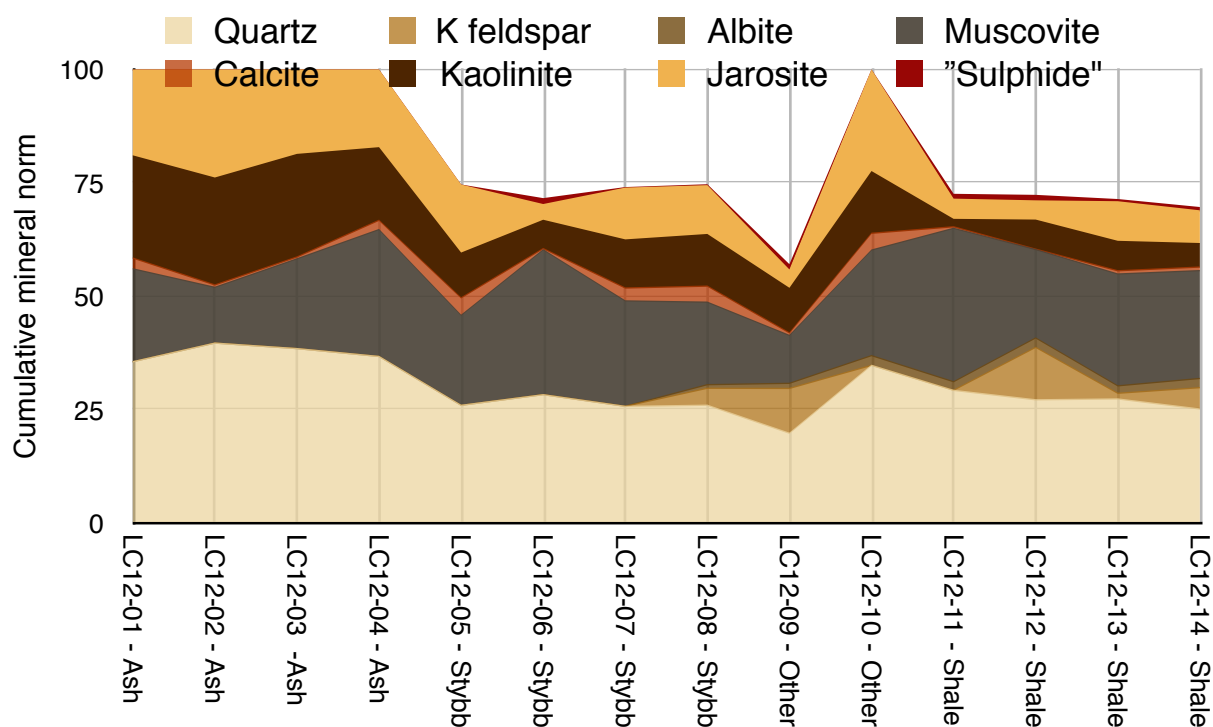


Figure 28. Calculated mineral modes from table 8, based on whole-rock data.

Discussion

Geochemical and mineralogical variations

My data show that the unprocessed alum shale in the area is very similar both mineralogically and geochemically to the stybb (unburned shale) at Kvarntorpshögen. The shale varies a little between the two sampling sites and the variations in the stybb lie within those variations.

The ash (burned shale) varies slightly in composition compared to the stybb and the shale. The whole-rock analyses show that the amounts of iron is significantly higher in the ash (Figure 7) and this trend is also seen in the XRF-analysis (Figure 19). The increased amounts of iron in the samples is probably due to the pyrolysis process during which the shale is burned (Falk *et al.*, 2005).

The ash, stybb, and shale have similar amounts of silica and aluminium in the whole-rock analyses (Figure 8), but in the XRF analyses the ash has slightly higher concentrations of these elements (Figure 20). The XRF analyses include light elements whereas the whole-rock analyses were normalized to remove loss on ignition. Light elements that are present in the sediment as volatile molecules, such as hydrocarbons and sulphur, are removed and thus the relative part of the heavier elements increases. This is evident in the respective samples' loss on ignition (Table 2, Figure 6). Probably for the same reason the XRF analyses of unburned samples show higher contents of "light elements" (Table 5, Figure 21).

Cobalt and zinc have higher concentrations in the ash, however, the natural shale shows a great variation in these metals, too (Figures 10 & 14). Both the data obtained by the LA-ICP-MS and the XRF point out a higher amount of copper in the ashes (Figures 15 & 23). Both methods give amounts of approximately 200 ppm, compared to 40 ppm in the shale and stybb.

In Figures 24, 25, and 26 results from whole-rock analyses and the XRF are compared. Amounts of iron and aluminium are variable and do not show a very good correspondence, but the amount of silica is similar in both methods.

The differences in mineralogy are investigated by the XRD and its software, and by the MINSQ spreadsheet (Herrmann & Berry, 2002), which calculates normative mineral modes from whole-rock data. Only the stybb and the shale were analysed by XRD and the results do not show a significant difference in composition between the two (Table 6). Minerals present in all samples are quartz, kaolinite, jarosite (a sulphate mineral with formula $KFe^{3+}_3(OH)_6(SO_4)_2$), muscovite, and orthoclase. Halite was found in three out of four stybb samples, and pyrite was detected in one of the shales.

The MINSQ results suggest that there is no K-feldspar or albite in the ash. There is more kaolinite in the ash, due to the higher amount of alumina in the whole-rock data, and there are also slightly jarosite in the ash. The high value for residual SSQ (sums of squares) of the ashes indicates that the calculated mode does not match the whole-rock data well enough, indicating that there is at least one mineral missing. Presumably this is a secondary mineral that was produced by breakdown of one or more minerals in the shale during the pyrolysis. As no XRD analyses were performed on the ash, I can only speculate which mineral it might be, but the high alumina content of the ash would lead me to think it is likely a clay mineral.

Comparison between results from XRD and normative mineralogy (Figure 27, 28) shows that they both give the same order of magnitude for most minerals. However, had I not known that the samples contain a secondary mineral after pyrite (jarosite), then the MINSQ quantification would have been significantly different. The applicability of the normative calculation is thus highly dependent on previous knowledge about mineralogy or the complexity of the sample.

In Holm (2005) previous data on the material at Kvarntorpshögen from 1952 and 1965 are shown. These data are comparable with my whole-rock analyses and show a good correlation both for ash and for stybb (Figures 29 & 30).

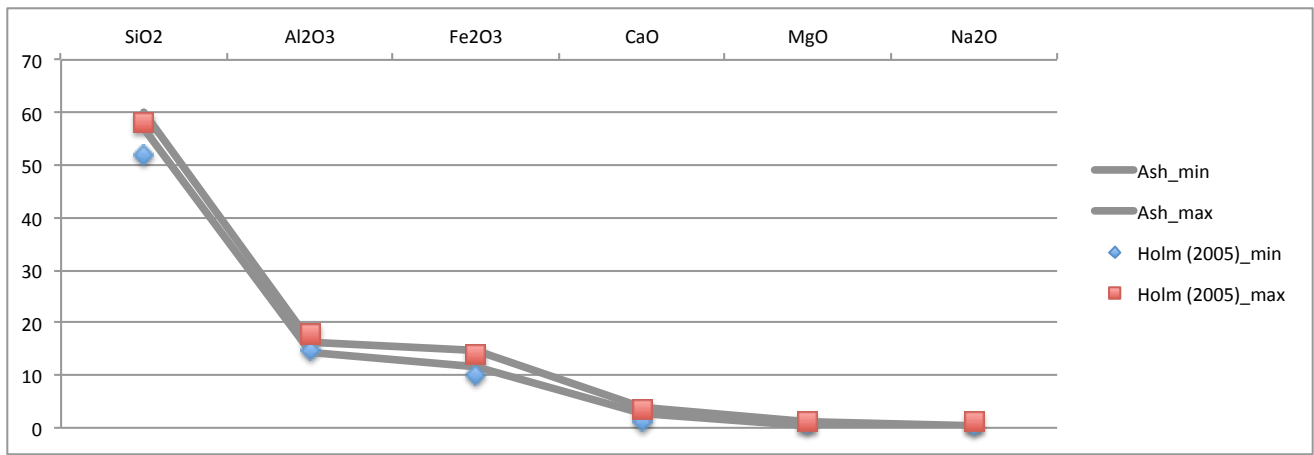


Figure 29. Comparison between ash from my whole rock analyses (table 2) and from Holm (2005). The grey lines are the range of data from my four ash-samples, the blue dots are Holms min values and the red dots are his max values.

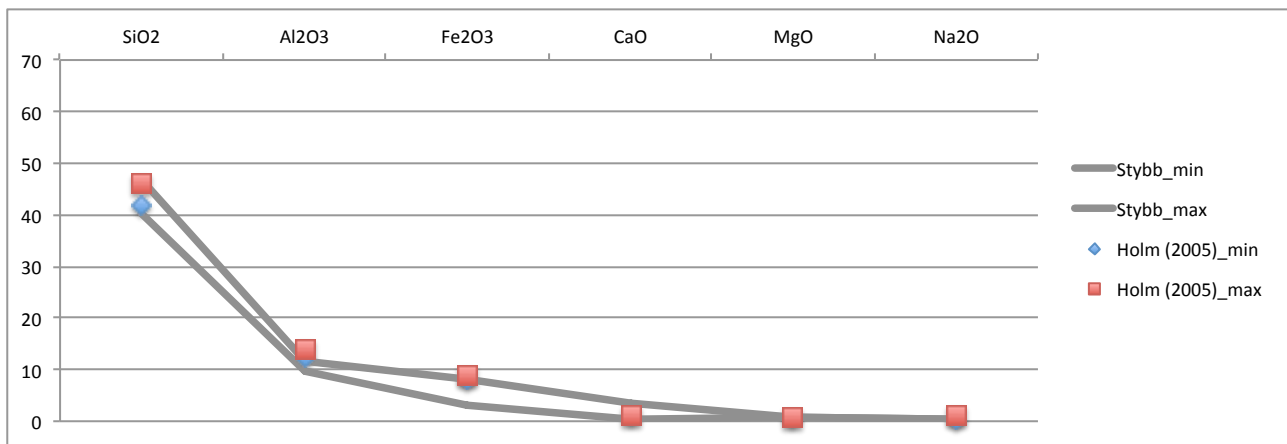


Figure 30. Comparison between stybb from my whole rock analyses (table 2) and from Holm (2005). The grey lines are the range of data from my four stybb-samples, the blue dots are Holms min values and the red dots are his max values.

Environmental aspects

A similar problem such as in Kvarntorp, exist in Degerhamn on southern Öland, Sweden (Falk *et al.*, 2005). Here, alum shale was mined and used to make alum ($KAl(SO_4)_2 \cdot 12H_2O$). As in Kvarntorp, the alum shale was burned and extensive waste material of ash remained. Both the exposed alum shale and the waste material leaks heavy metals into Kalmarsund and contributes to the environmental problems in the Baltic Sea. This problem was discovered in the beginning of the 21st century when investigations showed very high amounts of cadmium in the municipal sewage treatment plant in Degerhamn and in the seaweed off the coast. The amounts of heavy metals that leaks into Kalmarsund every year is estimated to be around 60 kilograms of As, Ba, Cd, Mo, U, and V. It leaks into Kalmarsund by surface water and groundwater and it all comes as a result of the mining and burning of the alum shale in the Degerhamn area (Falk *et al.*, 2005). In the future, this could be a likely scenario for Kvarntorp area as well. When the interior of the pile cools, the amount of water runoff will be greater and thus carry more heavy metals out to the water systems in the area.

According to Naturvårdsverket (2009), there are different guidelines and standard values for contaminated ground depending on what it is supposed to be used for. The standard values indicate the level of contamination in the soil below which the risk of negative effects on people, the

environment or natural resources is normally acceptable. The standard values are divided into two groups; sensitive ground use (KM) and less sensitive ground use (MKM).

The sensitive ground use is where the quality of the soil should not limit the choice of ground use. All kinds of people (adults, children, and elders) can reside permanently within the area during a lifetime.

The less sensitive ground use is where the quality of the soil limits the choice of ground use, for example offices, industrial sites, and roads. The exposed people (adults, children, and elders) are supposed to reside in the area temporarily.

According to these guidelines, Kvarntorpshögen belongs to the second group; less sensitive ground use (MKM). There are no people living here permanently, but there are all kinds of people visiting the area temporarily; skiing, walking, running, picnicking, visiting the art exhibition, etc.

Co, V, Cr, Zn, Cu, and Ba are heavy metals that are high above the MKM values, or just under, and they are all a potential threat to human and environmental health. Vanadium and barium are the highest ones. Both vanadium (Figure 11) and barium (Figure 16) occur naturally in alum shale and other sedimentary formations but can in high concentrations pose a threat to human health.

All of the samples was leached using HNO³ and the results from the ICP-MS leaching (Table 4) do not show the same distinctive differences between the ash and the shale as for example iron does by other methods. These leaching tests might not be absolutely reliable, due to a lack of data to compare with. I judge them to be equally (un)reliable and relative internal comparisons should be okay.

In a HNO³ leaching test on alum shale from Mount Billingen, Sweden, performed by Allard *et al* (1991) a significant amount of leaching was seen on PO₄, Al, Fe, K, Mg, V, Cr, U, Mn, Ni, Zn, and Cd. In the same leaching test, elements that were not leached are SiO₂, C, S, CO₃, K, Ca, Ti, Na, Mo, Cu, As, Pb, and Sb. Allard *et al* (1991) also mentions that in all leaching tests with HNO³, Fe together with other heavy metals would be solubilized, thus this would be applicable on the samples from Kvarntorp as well.

There is an interesting pattern for the concentrations of leached uranium and mercury (Figures 17 & 18), which show the same pattern seen in the other methods (different amount in the shale compared to the ash). The concentrations of leached uranium and mercury are high, too, and both of these elements are known to be a risk for human health. Since the absolute quality of these leaching tests is questionable, I recommend that a thorough leaching survey has to be performed.

Primary or secondary?

Alum shale, in general, are known to contain a relatively high amount of different heavy metals due to the origin of the shales. Some are related to the sulphide phase of the shale, and others may be connected both to the sulphide and the clastic phase. During weathering sulphuric acid is produced and acts as a weathering agent for silicates which contributes to the secondary processes in the shale (Jeng and Bergseth, 2009).

Since there are some metals, in the samples from Kvarntorpshögen, that occur in significantly and systematically higher amounts in the ash than in the stybb and shale, these concentrations are connected to secondary processes. The higher amounts can be due to contamination during pyrolysis of the shale or due to weathering of the shale after it was burned. In the second scenario, which is more likely, there are various alternatives, too. Pyrolysis could have broken down some minerals in the shale, which then weathered more easily and released metals. Alternatively, heat and sulphuric acid produced by oxidation of kerogen and sulphides released metals, which were dissolved in the acid thus making them more mobile (Andersson *et al*, 1983).

Other elements that occur in high concentrations seem unaffected by the pyrolysis, such as uranium and vanadium. These high concentrations are related to the primary deposition of the alum shale in anoxic conditions.

Raw materials and energy

There are a few metals that are present in high enough concentrations in Kvarntorpshögen that it could be a potential resource for these. This is mainly regarding uranium, which shows concentrations of 58–362 ppm in both the unprocessed and processed material. Alum shale has been prospected widely for uranium in Sweden. Sweden has one of the world's largest uranium reserves, mainly as low-grade mineralization in the voluminous alum shale. If a company like Aura Energy Ltd. would start mining alum shale in Jämtland, they would build a processing plant that is designed for alum shale. A potential solution to remediate the environmentally hazardous Kvarntorpshögen would be to extract its metals (U, V, Ni, etc.). Remediation is normally a very costly process but extracting metals from the material could make it economically favorable or at least cover a part of the cost. There was a refinery in the Billingen mountain, Sweden, in 1965, for processing U from low-grade alum shale. It was designed for a yearly production of 120 ton U which corresponds to 800,000 ton of alum shale. This was however only operating for a couple of years and shut down for economical reasons, but surely, some inspiration could be taken from that method (Allard *et al*, 1991).

The exothermic oxidation of sulphides and kerogen is causing Kvarntorpshögen to "burn" inside. Temperatures up to 700°C have been measured locally under the surface (Holm, 2005). The potential exists to harness this heat, either for producing electricity or hot water.

Conclusions

There are systematic differences in chemical and mineral content of different materials at Kvarntorpshögen. The stybb (unburned shale) shows great similarity with unprocessed shale. Ash (burned shale), however, shows some differences compared to the shale, mainly by its lower content of volatile compounds and higher Cu, Zn, Co, and Fe content.

The differences between stybb and ash can be connected to secondary processes, either directly connected to pyrolysis or as an after effect of pyrolysis and weathering.

Some elements lie significantly above regulated values for less sensitive ground use (MKM), as defined by Naturvårdsverket (2009). Co, V, Cr, Zn, Cu, and Ba are present at levels that could pose a threat to human health in case of permanent residence.

Relatively high contents of U could make Kvarntorpshögen a potential resource, together with other elements such as V and Ni. Mining Kvarntorpshögen as a secondary resource could be a possible solution to remediate this environmental hazard, which normally is a costly process.

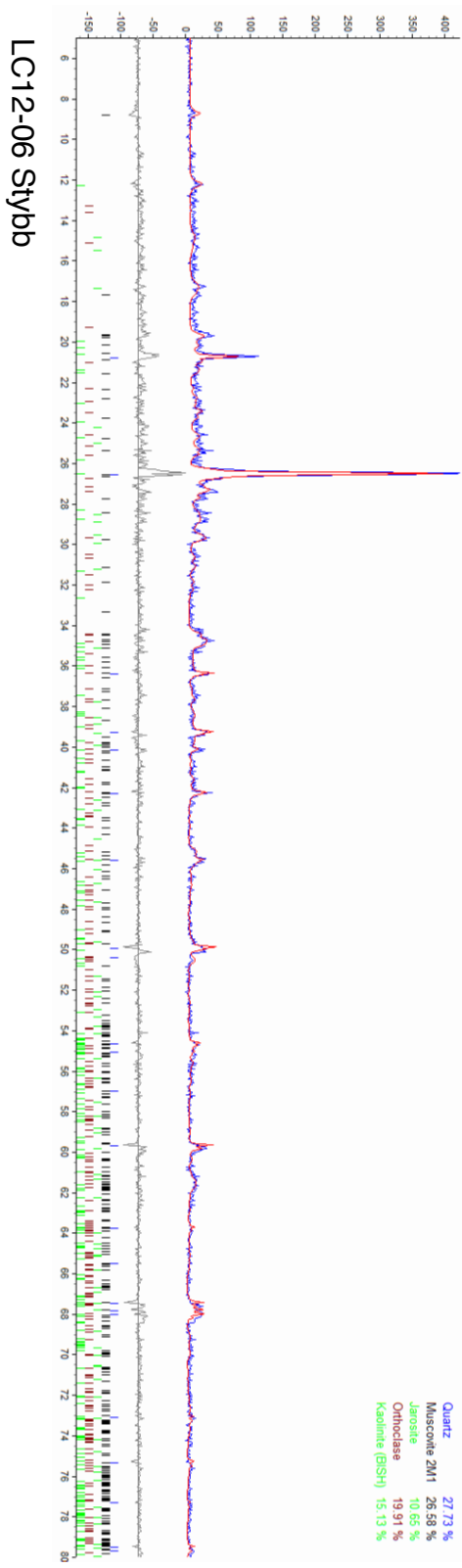
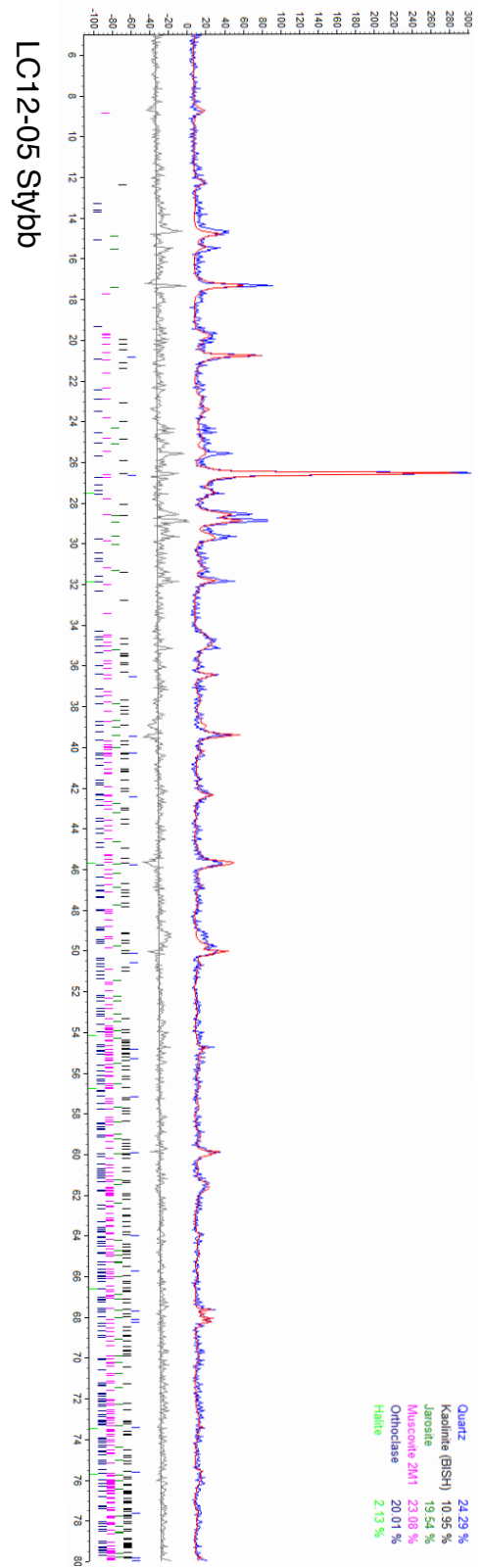
Acknowledgements

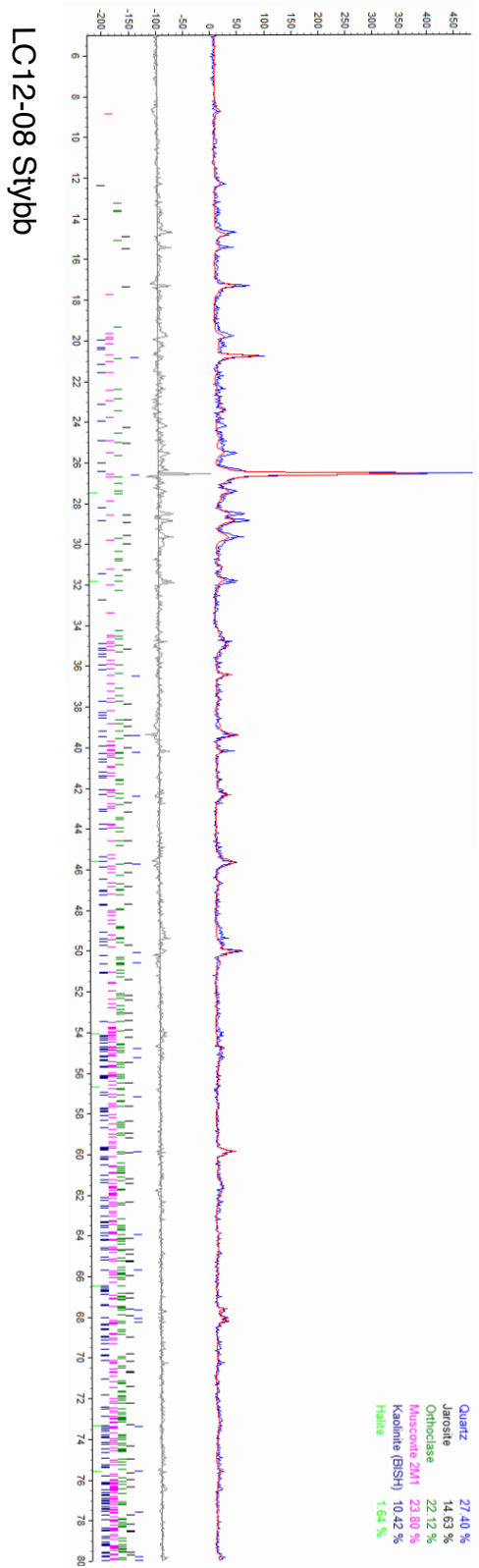
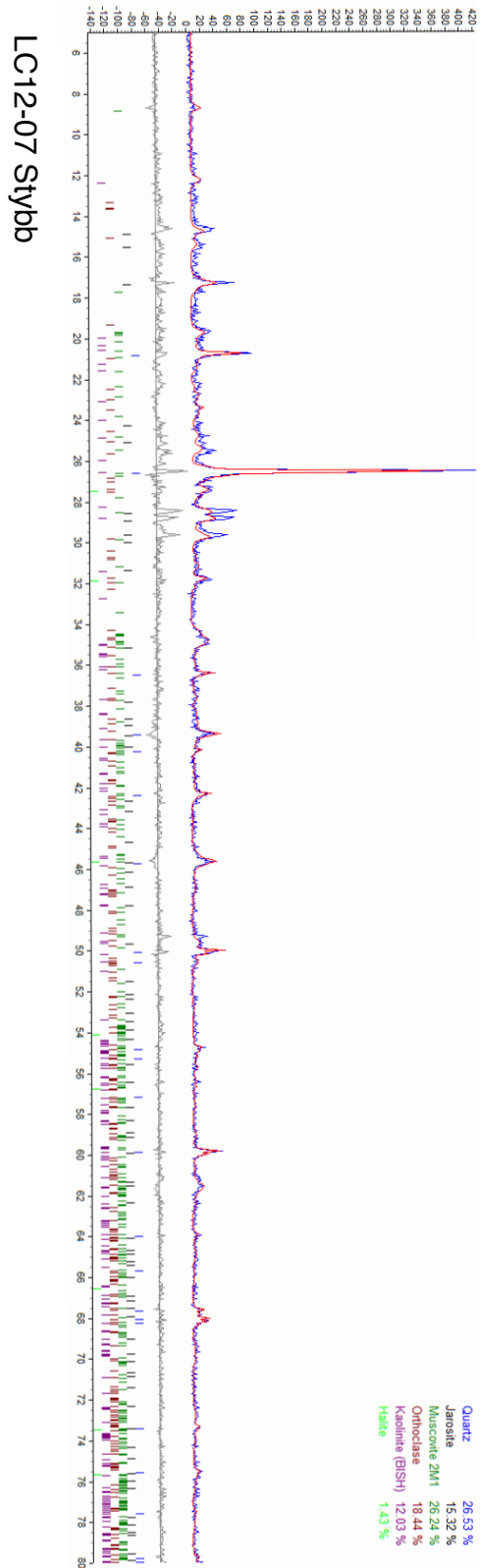
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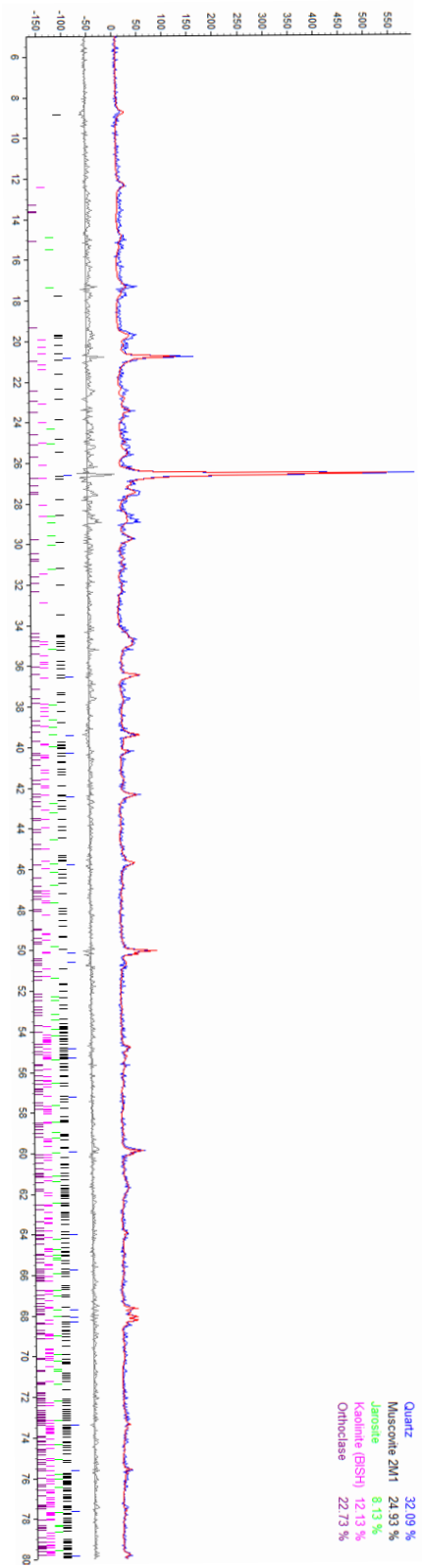
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Appendix





LC12-11 Shale



LC12-12 Shale

