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Final report on rock type in the Alum Shale

Prepared for Total E&P

Niels H. Schovsbo, Kim H. Esbensen & Arne T. Nielsen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
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GEUS

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G E U S

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1. Introduction

This report collects the data interpretation and reporting made by GEUS to TOTAL E&P regarding rock types and core sampling. The work was made to Total E&P as part of a service contract. Raw data generated during the project are reported separately in the GEUS report 2014/xx. The data include hand-held XRF and XRD samples for the Albjära-1 and Sommerodde-1 wells.

The aim of the project was to be able to select the best zone for fracturing of the Alum Shale in the Vensyssel-1 planned to be drilled in 2015. For this purpose rock types in the Alum Shale will be definition based on a multi-proxy approach combining XRD data, XRF data, core description and petrophycial data with multivariate analysis of well and image logs.
The ability to predict rock types and lithological variation from wells logs was addressed by a description of the response of the resistivity, density and Gr logs. The possibility of prediction of rock strength was also addressed.

This report is structured according to the work plan agreed between Total E&P and GEUS.

Work Package 1:
1) Data inventory and review of Alum Shale related data including:

A. Data already acquired by Total
B. Data from GASH and Pau, Total
C. Additional data at GEUS
D. Possible New data to be measured during May 2014

2) Preparation of relevant core material for inspection, analytical work and sampling for laboratory tests

3) Formulation of detailed work frame for Work Package 2

Work Package 2:
Work package 2 aimed at defining and describing rock types in the Alum Shale. Current knowledge of variability includes but is not restricted to variation of: fabric types, occurrence of silty intercalations, carbonate concretions and fossils, pyrite, barite, and the TOC content.

Part of this work is to establishing the variation of mineral components expected to be reactive to fracturing fluids (e.g. carbonate, barite and pyrite) and its spatial relationship to preferred rock types (ultimate TOC rich and with brittle rock behaviour).

<u>The Appendix</u> of this report contains additional background material and common reference material.

2. Work Package 1

2.1. Data inventory

The wells available for the project and an overview of the available data and data sources relevant for definition and describing the lithological variation is presented in Table 1 and 2. The Alum Shale related research that this report is based upon was initiated by B. Buchardt, A.T. Nielsen and N.H. Schovsbo in the early 1990'thies (Buchardt et al. 1997). Following this work and subsequent drilling activities 7 scientific wells and more than 1500 geochemical samples have been measured.

The majority of the data have already been acquired by Total E&P as part of data acquisition from GEUS. Most of the XRF data are from unpublished data sources (Schovsbo 1995, 2001) and serves as background data for the project. In the Billegrav-2 core data on the sedimentology (Completion report 4) and fracture distribution (Completion report 5) has not been acquired by Total.

Bornholm wells

The Bornholm wells include the Sommerodde-1, Billegrav-2 and Skelbro-2 wells that were drilled within the last few years by GEUS. Data from the Skelbro-2 well are hosted within the GASH project available here because both Total and GEUS participated in the project. The GASH dataset include mineralogical analysis (XRD) and rock mechanical tests. For the Billegrav-2 well mineralogy and geotechnical (static and dynamic properties) data are also present. In the Sommerodde-1 well a very extensive logging suite was obtained including an image log that provides high resolution documentation of the lithological variation including fracture distribution. LIPS data from the Pau research centre is also available on part of the Skelbro-2 and Billegrav-2 cores.

Scania wells

The data available in these wells are TOC, sulphur, carbonate, major and trace elements and biostratigraphical/palaeoecological data (see Appendix C for logs). Mineralogy (XRD, clay types), sedimentology including fabric analysis and rock mechanics are either rudimentary done or lacking in these wells. Sedimentological logs have been made in the Albjära-1 wells (Appendix B).

The data collected was for the most parts from the thesis work of N.H. Schovsbo (1995, 2001) aimed at characterising the depositional environment by integration of trace elements and paleoecology of trilobites. Samples were picked to represent the average mud composition and macroscopic in-homogeneities (pyrite, calcite, barite) were avoided during sampling (Schovsbo 2001). The XRF analyses are thus very good for defining the general mud composition but care should be taken to use them as sole measure for the (in)-homogeneity of the shale itself.

Table 2-1: Overview of wells and data types.

Wells	Area	Status	well logs	Core	geomech. tests	Mineralogy	TOC, TS	Major elements	trace elements
Albjära-1	Scania	KU 1989, 1999	GR, res	yes	none	none	yes	Yes, few	only to 158 m
Fågeltofta-2	Scania	KU 1999	GR, res	yes	none	none	yes	none	yes, low resolution
Gislövshammar-2	Scania	KU 1992	GR, res	yes	none	none, only carbonate	yes	Yes, few	yes, high resolution
Sommerodde-1	Bornholm	GEUS 2012	full, incl Image files	yes	none	yes	yes	none	none
Billegrav-2	Bornholm	GEUS 2010	GR, res	yes	yes	yes	yes	yes, few	yes, few
Skelbro-2	Bornholm	GASH well 2010	GR, sonic res	yes not availabl e	yes	yes	yes	none	none
Terne-1	Kattegat	expo well 1985	full	none	none	yes	yes	yes, ICPMS	yes
Slagelse-1	Sjælland	expo well 1956	Gr	partly cored	none	yes	yes		none

Table 2-2: Overview of data sources.

Wells	Data in GEUS reports aquired by Total	From the GASH project	Pau (TOTAL) research	Other data sources (background)	Well log-stratigraphy
Albjära-1	log data and TOC data			XRF data included from Schovsbo (1995, 2001). Sedimentological log from Lauridsen 2000	Schovsbo and Nielsen unpublished
Fågeltofta-2	log data and TOC data			XRF data included from Schovsbo (1995, 2001)	Schovsbo and Nielsen unpublished
Gislövshammar-2	log data and TOC data			XRF data included from Schovsbo (1995, 2001)	Schovsbo and Nielsen unpublished
Sommerodde-1	Log data			Core analysis data provided by GEUS. Part of data is from Haugwitz unpublished	Schovsbo and Nielsen unpublished
Billegrav-2	Analysis of core plugs (completion report 3)		LIPS TOC Data	Data included from Completion report 1, 2, 4 and 5. These reports have not been acquired by Total	Schovsbo and Nielsen unpublished
Skelbro-2	logs, included in GASH	Log and core data	LIPS TOC Data		Schovsbo and Nielsen unpublished
Terne-1	All data				Schovsbo and Nielsen unpublished
Slagelse-1	All data				Schovsbo and Nielsen unpublished

2.2. Review of Alum Shale related data

The most comprehensive geological review of the Alum Shale and a compilation of Alum shale related maps are presented by Nielsen & Schovsbo (2013a, b). This report and the accompanied map database were both acquired by Total E&P. Reference to this report is thus made for the general description and only issues specific relevant for the purpose of this report is addressed below.

In Figure 2-1 an overview of the stratigraphy in the Alum Shale is presented and in Appendix A log derived stratigraphical breakdown of selected wells are presented.

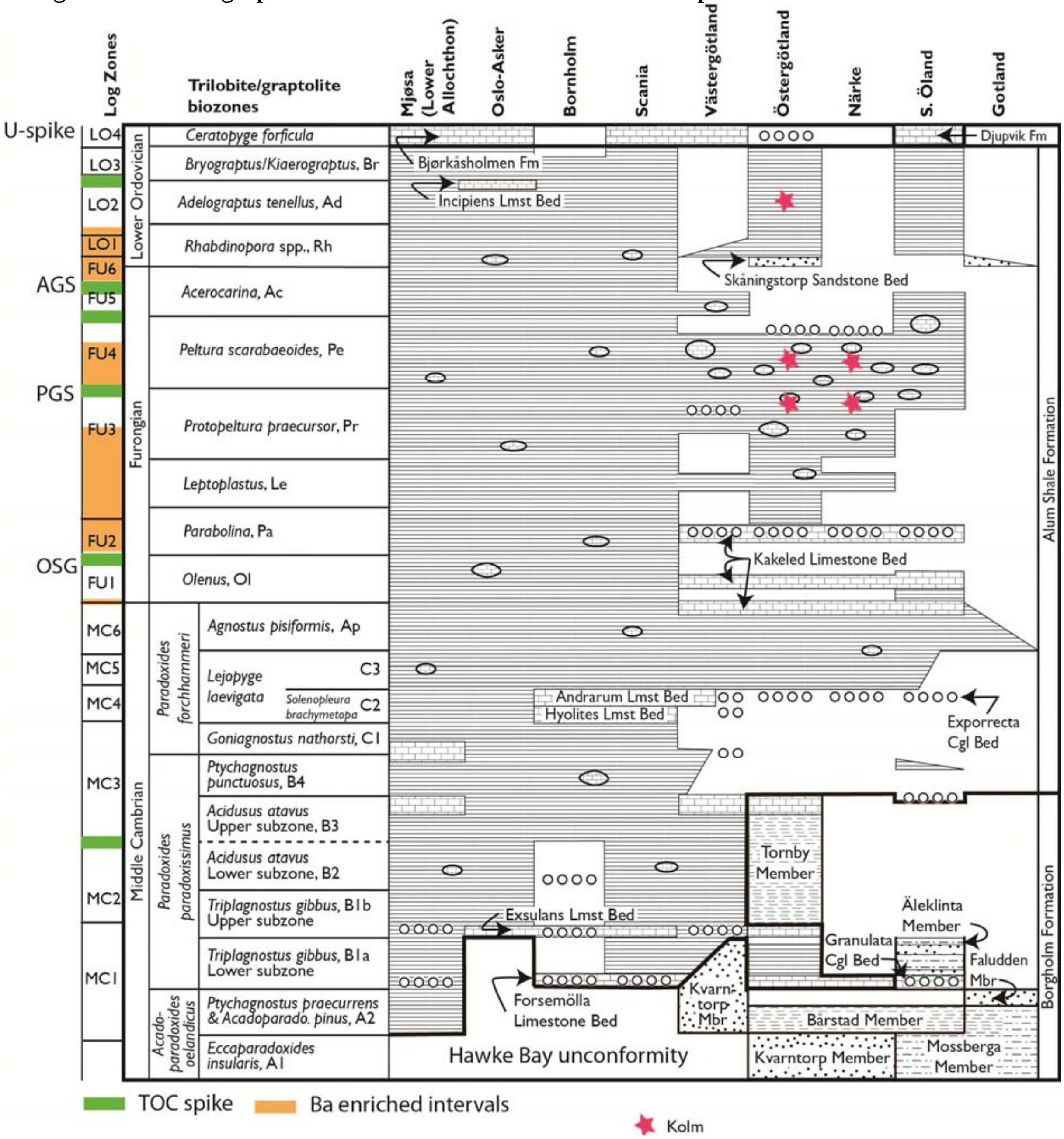

Figure 2-1: Stratigraphical overview of the Alum Shale Fm. OGS, PGS and AGS referees to Olenus Gamma ray spike, Peltura Gamma ray spike and Acerocare Gamma ray spike. Green lines indicate that the log zone boundary co-inside with a TOC maximum. Orange bar that elevated Ba values have been measured (see Geochemical logs in Appendix C). Red stars indicate the occurrence of Kolm nodules in Central Sweden (see Schovsbo 2002).

Best reservoir analogue for the Vensyssel-1

In terms of defining rock types, describing its variability and selecting samples for testing fracturing fluids then rock types that have the highest probability to be present in the Vensyssel-1 well should be selected preferentially.

The Vensyssel-1 well is planned to be drilled in Northern Jutland. Based on our current geological understanding of the Alum Shale it is expected that the new well will drill a relative deep-water setting within the former Alum Shale basin (Nielsen & Schovsbo 2013a). The closest off-set well is the Terne-1 well that drilled a 180 m thick Alum Shale.

In Figure 2-3 a correlation line of the main stratigraphical subdivisions of the Alum Shale (Middle Cambrians, Furongian and Lower Ordovician) extending approximately NW-SE is presented (see Figure 2-2 for location of the profile). The stratigraphical development along the profile is a general expansion of the Alum Shale toward NW and vise verse a condensation trend of the sections to the SE i.e. from Kattegat area towards Bornholm. In addition to a more expanded section in the Terne-1 well this well also drilled a rather thick Middle Cambrian section that appears more stratigraphically complete than the section in Scania and on Bornholm (Figure 2-3). A similarly expanded section as seen in the Terne-1 well is thus anticipated to be present in the Vensyssel-1 well.

Based on the correlation profile in Figure 2-3 it is clear that the best analogue for Vensyssel-1 well is the Terne-1 well. This well was, however, not cored and thus detailed sedimentological studies and geochemical profiling cannot be made in this well. Form Figure 2-3 is also evident that the log signature of the Alum Shale in the Terne-1 well can be tracked almost 1:1 to the Scanian wells (Albjära-1, Gislövshammar-2, Fågeltofta-2) and thus these wells seems to be the best reservoir analogs available for the Vensyssel-1 well.

The Bornholm wells (Sommerodde-1, Billegrav-2, Skelbro-2) are much more condensed than the Scania wells and thus these wells may not serve as the best analogie for Vensyssel-1. In these wells highly relevant data including wells logs exist, however, in order to use these data the effects of a condensated sedimentation on the shale composition and variability must be made. From a palaeo-geographical point of view the condensation of Bornholm is likely related to a more distal position on the Baltic Plate and perhaps a more sheltered from sediment source areas then the expanded section.

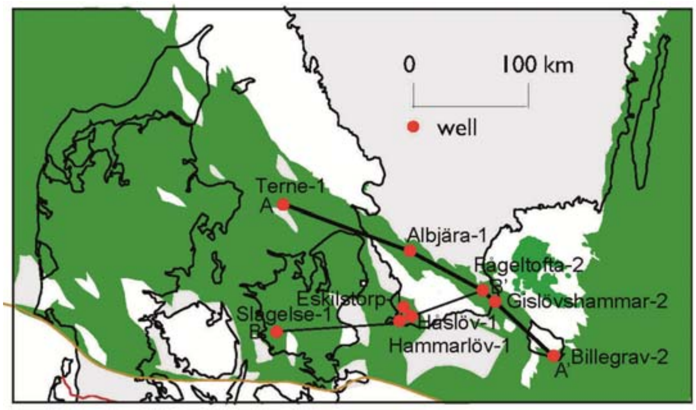

Figure 2-2: Wells used in the stratigraphical analysis. The Vensyssel-1 well is planned to be drilled in Northern Jutland with the Terne-1 well as closest off-set well.

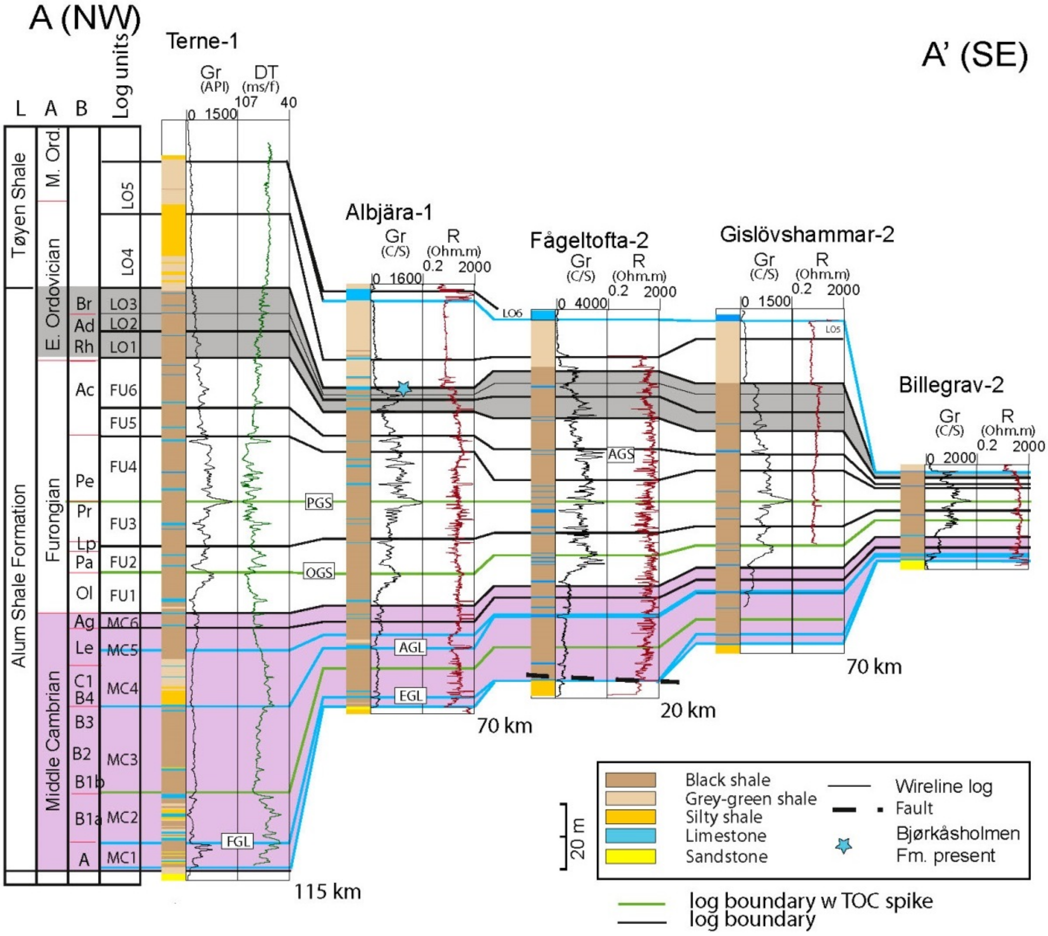

Figure 2-3: Correlation profile along line AA'(see Figure 2-1). For stratigraphical abbreviations see Figure 2-1.

Mineralogical data

Mineralogy (XRD) of the Alum Shale has been analysed on a limited number of samples from the Slagelse-1, Terne-1, Billegrav-2 and Skelbro-2 wells (Figure 2-4). A detailed study of the clay types has not been made. Lindgreen et al. (2000) studied the clay types and found that it was dominated by illite with varying low to no content of smectite in thermally mature Alum Shale samples. In addition to illite he found a NH4 rich variety –torbenite. In this clay type ammonia is fixed in the lattice and the clay-mineral is expected to behave in a similar manner as illite.

In a ternary diagrams carbonate, clay and Quartz+ Feldspar +Mica (QFM) the Alum Shale has between, 40-60% QFM, 40-60% clay and up to 40% carbonates. (It should be noted that without the differentiation in clay types part of the mica present is here plotted as clay and thus the amount of brittle GFM minerals maybe are underestimated.)

In Figure 2-4 the Schlumberger “sCore” classification diagram is shown. According to this classification the Alum Shale is a mixed “silica-rich argillaceous“ to “clay rich siliceous mudstone”. The more carbonate rich sample plot in the “mixed mudstone” part of the diagram.

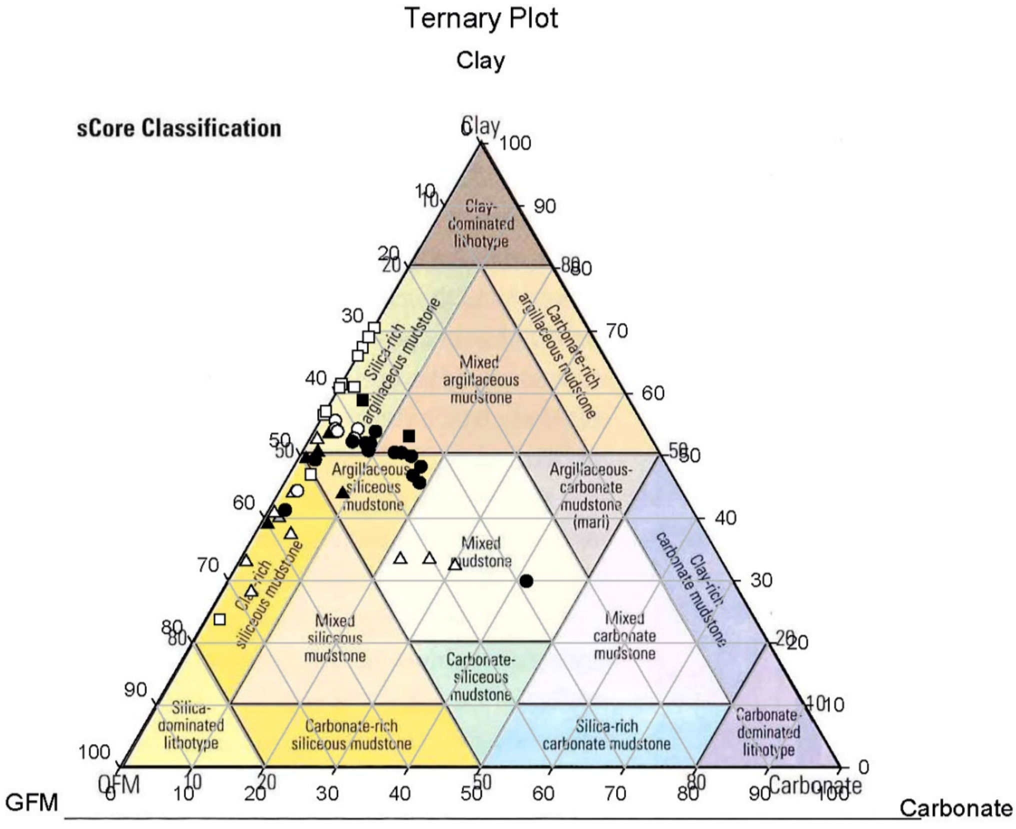

Figure 2-4: Mineralogical variation of Palaeozoic shale samples. sCore classification is from Glaser et al. (2013). Samples are from Billegrav-2 (10 samples), Terne-1 (30 samples), Slagelse-1 (2 samples). Colour: Black samples - Alum Shale, White - Ordovician and Silurian samples. Circles: Terne-1, Boxes: Slagelse-1; Triangles: Billegrav-2.

The mineralogy in the Terne-1 well has also been investigated by Total E&P on a similar suite of samples as analysed by GEUS. The mineralogical results are shown in Figure 2-5. Beside of quartz brittle minerals as albite and microcline are present. The carbonate phases consist of both dolomite and calcite. Sulphur phases include pyrite and barite. The clay types are chlorite and muscovite.

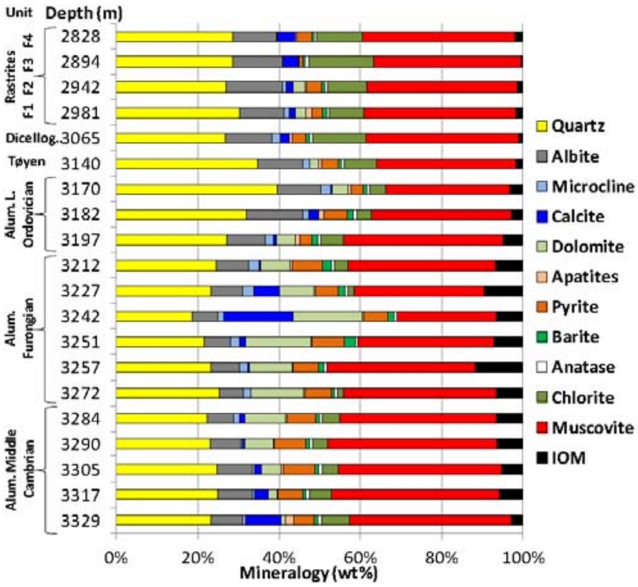

Figure 2-5: Mineralogical composition of 20 samples from Terne. Illustration from Total Memo dated the 8. August 2012.

Rock strength

Analysis of rock strength and static and dynamic properties of the Alum Shale has been made on a limited number of samples from the Billegrav-2 and Skelbro-2 wells. The Billegrav-2 well was analysis as part of the "Completion report 3" acquired by Total E&P. Analysis were made by the company GEO since GEUS does not have the analytical set-up required for preforming the experiments. The results are shown in Table 2-3 and Figure 2-6.

In Skelbro-2 rock mechanical tests were analysed as part of the GASH project by the GFZ team. The samples included a) Unconfined Compressive Strength (UCS) and b) Young's modulus (E, 15 tests), c) tensile strength (TS, 27 tests), and d) triaxial strength (20 tests) to determine the cohesion C and the coefficient of internal friction (μ).

Table 2-3: Overview of the sample program and test specimens in the Billegrav-2 core.

Formation	Acoustic velocity measurements		Unconfined compression test		Brazil tests	
	Plug samples	Test specimens	Plug samples	Test specimens	Plug samples	Test specimens
Rastrites	8	18	4	4	2	3
Lindegård	1	3	0	0	0	0
Dicellograptus	2	7	1	3	1	2
Alum	6	14	2	4	3	5
Total	17	42	7	11	6	10

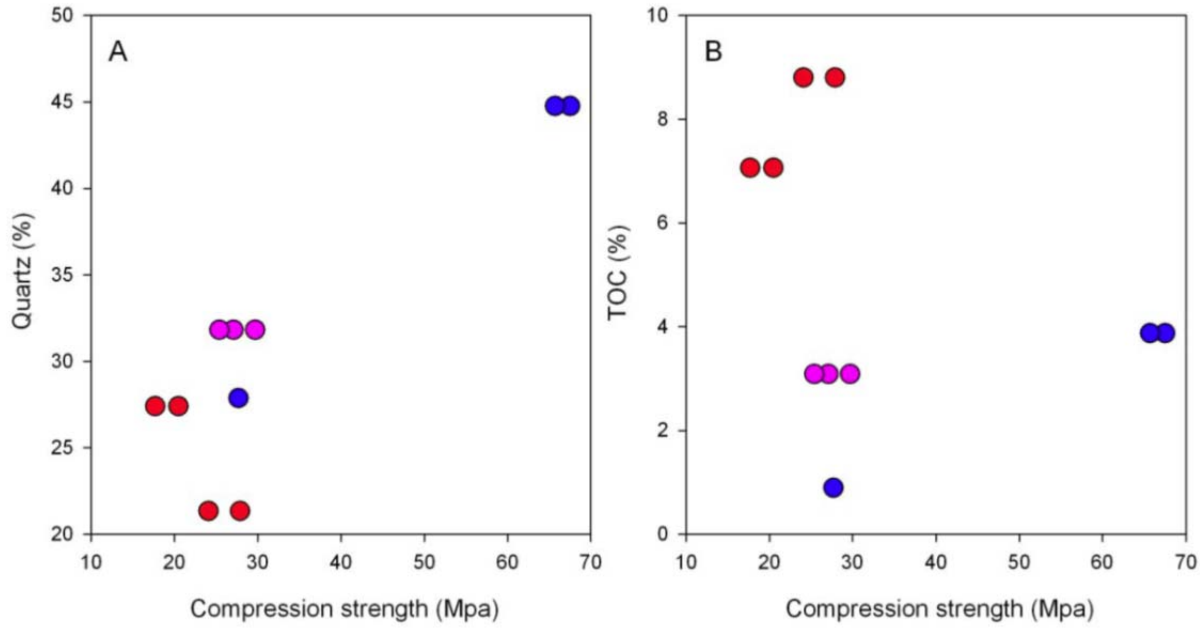

Figure 2-6: Relationship between compression strength and (A) quartz content and (B) TOC Content in The Billegrav-2 core. Legend: red: Alum Shale, pink: Dicellograptus Shale, green: Lindegård Fm., blue: Rastrites Shale.

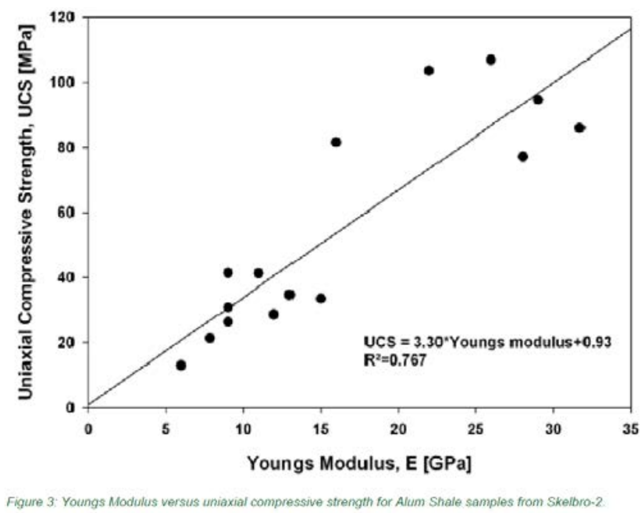

Figure 2-7: Summary of test results from the Skelbro-2 well. From GASH final report 2012.

TOC distribution

The TOC content in the Alum Shale is very high with average levels of 9% in Scania (Figure 2-8). In Table 2-4 a stratigraphical breakdown of the TOC variation is presented. In the table the most TOC enriched biozone are shown in green (TOC>10%) and orange (TOC 8-10%). These zones all occur within the Furongian.

A slightly lower TOC content is measured in the Terne-1 well compared with the Albjära-1 well. This may reflect the higher maturity in Terne-1 but can also reflect that the analysis in the Terne-1 well is based on cuttings whereas the analysis in the Albjära-1 well is made on core material.

The cm-scale variability in the TOC content has been investigated by researchers in Pau by means of the LIPS apparatus (Figure 2-9). The data shows a long term variation similar to previous studies (Schovsbo 2001) but revealed a hitherto unknown variability in TOC.

XRF profiles in Billegrav-2 can be compared directly to TOC measurements to see if same variability is present in other data sets.

Table 2-4: Stratigraphical breakdown of the TOC variation in the Alum Shale in the Terne-1 and Albjära-1 well. From Schovsbo (2012).

Formation/age	**Terne-1**					**Albjära-1**				
	Thick, m	**Avg TOC**	**STD TOC**	**Max TOC**	**Min TOC**	**Thick. m**	**Avg TOC**	**STD TOC**	**Max TOC**	**Min TOC**
Alum Shale:	180,0	6,4	2,6	13,7	1,8	97,8	8,2	3,2	15,3	0,5
Tremadoc	34,1	4,1	1,2	6,3	2,4	7,0	6,2	2,6	11,8	0,7
Bryograptus	13,4	3,0	0,6	3,8	2,4	3,0	4,4	2,0	7,1	0,7
Adelograptus	16,6	5,0	0,8	6,3	3,8	2,0	5,4	2,4	11,8	0,7
Rhapdinopora	4,4	5,4				2,5	6,5	2,3	11,8	1,7
Furongian	64,5	9,0	1,9	13,7	6,5	58,7	10,1	2,2	15,3	4,9
Acerocare	12,6	8,2	1,8	10,7	6,6	12,6	10,2	2,1	14,3	7,3
Peltura scarabaeoides	14,6	10,9	2,0	13,7	9,2	13,5	10,6	2,0	15,3	7,3
Peltura minor	5,4	10,2	0,0	10,3	10,2	4,1	11,5	1,7	14,3	8,8
Protopeltura praecursor	4,4	7,5				4,8	11,5	1,6	14,6	8,7
Leptoplastus	2,1	7,6				2,5	10,4	1,1	11,5	8,7
Parabolina spinulosa	10,1	7,3	0,8	7,9	6,5	9,0	7,8	1,2	10,0	5,4
Olenus	15,2	8,8	1,8	11,1	7,0	12,2	10,2	2,4	14,9	4,9
Mid Cambrian	79,7	5,2	1,5	7,2	1,8	32,0	5,3	2,1	10,4	0,5
Agnostus pisiformis	5,7	7,1	0,2	7,2	6,9	4,5	7,2	1,2	10,4	4,9
Paradoxides forchhammeri	28,4	5,7	1,0	6,8	4,2	9,8	5,9	2,4	8,4	0,7
Paradoxides paradoxissimus	51,2	5,0	1,5	6,8	1,8	17,7	4,4	1,6	7,4	0,5

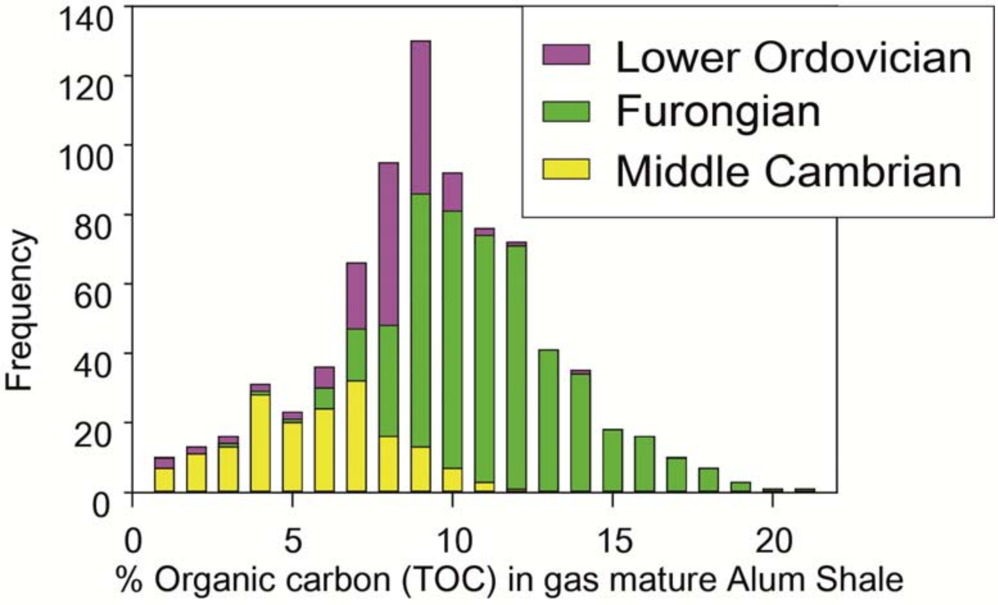

Figure 2-8: TOC distribution in Alum Shale from Scania. Additional histograms of the TOC distributions are shown in Appendix D.

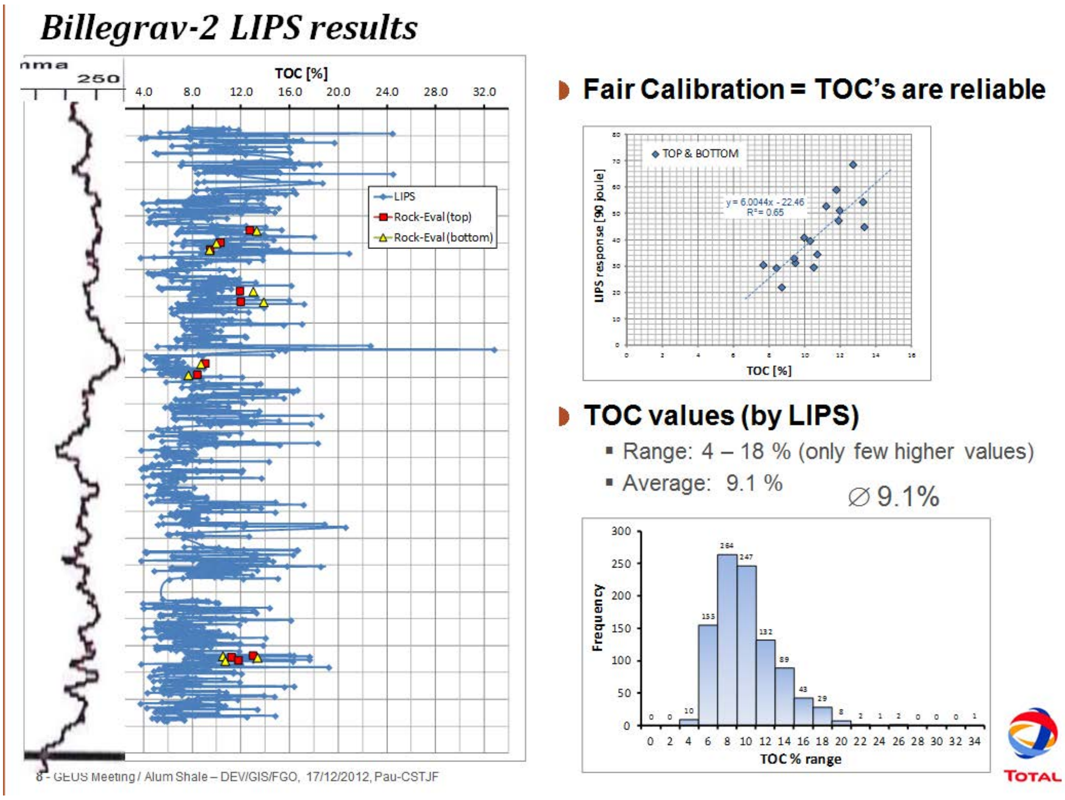

Figure 2-9: Analysis of the cm-scale variability of TOC in the Billegrav-2 core. Slide from presentation by TOTAL to GEUS in December 2012.

Sulfur distribution

In the Alum Shale practically all sulfur is present as pyrite (Fe2S) with barite (BaSO4) as a minor component. Pyrite occur either as disseminated –framboidals form of as macroscopic form. Macroscopic forms range in type from pseudomorphs after barite, impregnation of fossils to cm thick layers and nodules. The sulfur content generally tracks the TOC variation and highest content occur in the Furongian (see geochemical logs presented in Appendix C).

Pyrite is a semi-conductive mineral and has a high specific gravity. Thick pyrite layers can thus be seen as conductive peaks on the resistivity log (Figure 2-13). Spikes on the density log are also diagnostics to pyrite but also barite and carbonate may cause elevated density readings and is thus not diagnostic.

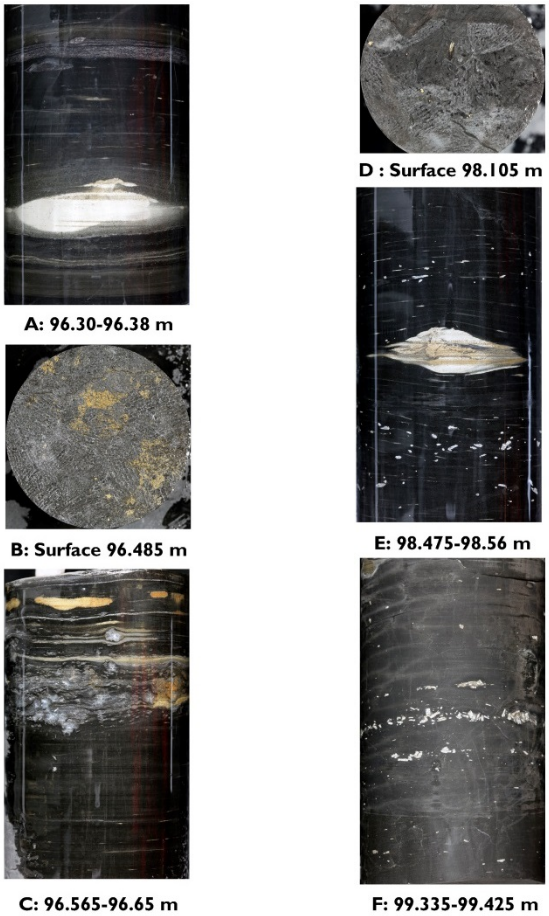

Figure 2-10: Examples of macroscopic pyrite in the Alum Shale. The pictures are all 5.5 cm wide and approximately 15-20 cm high. Pyrite also occur microscopically –disseminated- in the shale. Pictures are from the Billgrav-2 well (Nielsen & Schovsbo 2012 Completion Report 4).

Barium/Barite distribution

The concentration of barium typical around 1000 ppm in the Alum shale. Very high barium concentrations occur, however, in specific zones where several % have been measured (see geochemical wells logs in Appendix C). The mineral barite ($BaSO_4$) is commonly detected in XRD analysis of the Alum Shale and it is assumed that all Ba measured is hosted in this mineral which also can be seen macroscopic (Figure 2-8). Ba-rich feldspars are also a possible host for some of the measured Ba.

The reason why barite accumulated in the sediment is unclear. It is assumed that it is a biologically mediated precipitate that settled together with organic matter. The minute barite crystals becomes unstable during early digenesis and barium either migrates out of the sediment or is captured and precipitated as larger stable crystals within suitable micro environments in the sediment.

In the Alum Shale high Ba concentrations mostly occur in the Furongian and Lower Ordovician parts of the formation. Judging from the geochemical profiles in Appendix C barium enrichment seems to be linked to specific intervals. It appears that high Ba concentrations preferentially occur in the shale above zones with peaks in TOC occur (see summary Figure 2-1).

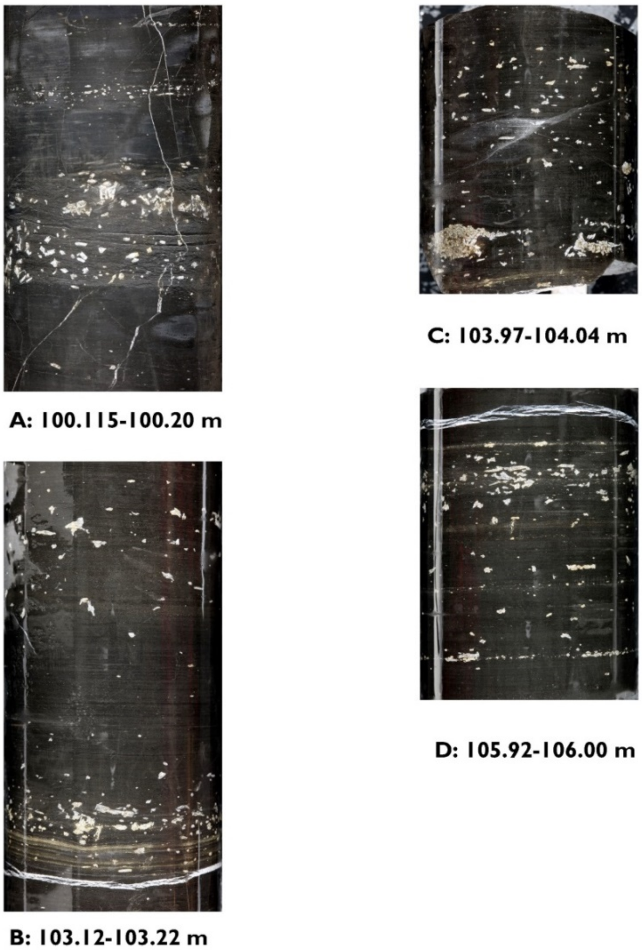

Figure 2-11: Core photos form the Billegrav-2 well showing different modes of distribution of barite crystals. Pictures are 5.5 cm wide and approximately 15 cm high. From Nielsen & Schovsbo (2012 – The Billegrav-2 Completion Report 4). Scanning with XRF device of cores would enable a detailed documentation of the occurrence.

One possible method to achieve a detailed occurrence of barite is from analysis of the Sommerodde-1 core image file (Figure 2-9). Here the relationship between barite occurrence and log response can also be examined.

High resolution profiles of Ba can be obtained from XRF scanning of the core. The Ba-log can be compared with other log suites and the precise log patterns can be obtained. Barite has a very high specific gravity and is expected to give characteristic spikes on the density log.

Pyrite is also very good imaged on CT scanning (Figure 2-17).

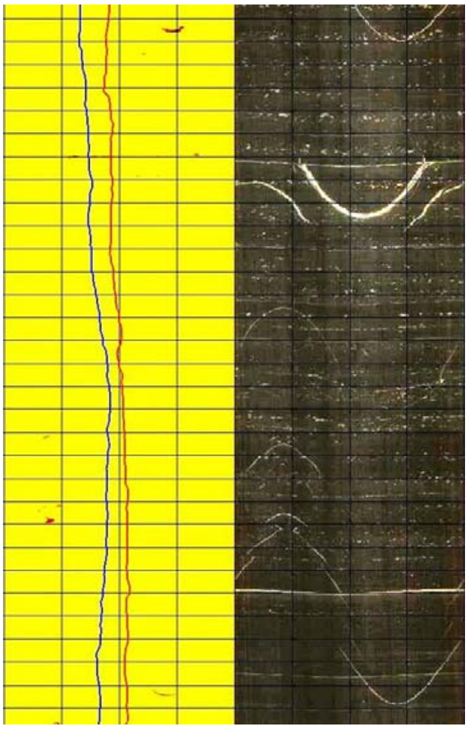

Figure 2-12: Example of well log image from Sommerodde-1 (226.8-228.4 m). Barite crystals occurs in a >1m thick intervals around 227.6 m. The occurrence is reflected in slightly higher Density readings (blue curve). The core picture is an unfolded 360o picture of the 5.7 cm wide borehole. Note the calcite-healed fractures.

Carbonate

Calcite, dolomite and siderite have been detected in the XRD data. In the Alum Shale two types of facies occur. A platform facies characterized by high abundance of calcite concretions and primary carbonate beds and a deep-water facies characterized by low abundance of carbonate beds (Figure 2-1). The Alum Shale in Kattegat, Scania and on Bornholm is a deep water type and relative low abundance of carbonate is expected.

The carbonate content in the shale itself range between 1-10 %. Diagenetic formed carbonate concretions between dm to m in thickness occur in the formation. These beds typical has >70% carbonate. (See geochemical logs in Appendix C but note that the carbonate beds generally have been avoided in sampling and it occurrence is thus not documented in the geochemical profiles). Carbonate also occur in fractures and vein filling cement.

The occurrence of carbonate concretions have been documented in most of the wells also because of the distinct log signature (e.g. Figure 2-13, 2-16 and Appendix A). However, carbonate rich parts of the shales have generally not been documents. These enriched parts are typical due to high fossil abundance. XRF profiles can quantify this distribution.

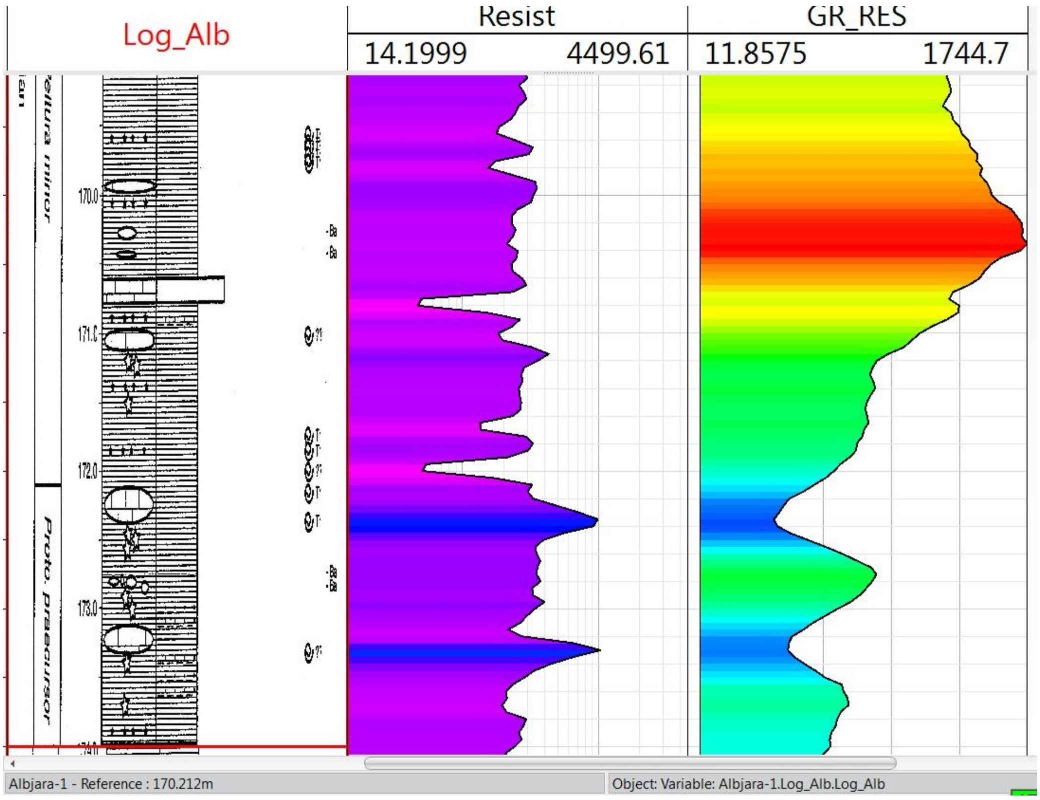

Figure 2-13: Part of the sedimentological log from the Albjära-1 well (169-174 m) showing the Furongian *Peltura* Zone. Resistivity and Gr logs are shown to the right. Carbonate beds are seen as high resistive log spikes. Low resistive log spikes appear associated with pyrite rich beds. (Sedimentological logs is presented in Appendix B).

The source for the carbonate in the concretions and cement is both from dissoleved carbonate shells, typical trilobites, and from biological mediated bicarbonate produced from the degradation of organic carbon (Buchardt & Nielsen 1985).

In the Alum Shale fossils are dominated by trilobites that now is preserved either as imprints or with the original calcite shell preserved. The trilobite types that occur are specially adapted to low oxyygen environments and may occur in very high aboundances in specific zones in the shale (Figure 2-15).

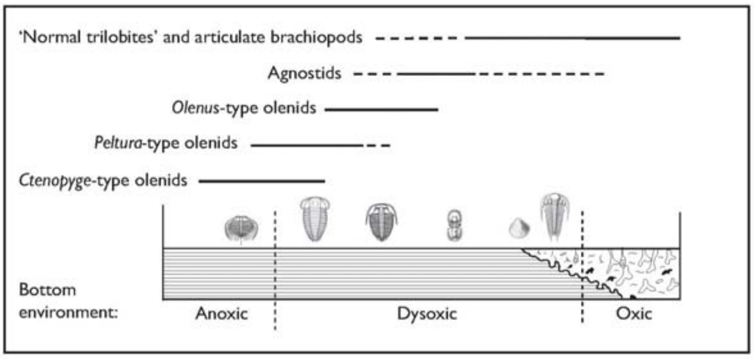

Figure 2-14: The trilobite faunae in the Alum Shale were highly specializes to the bottom water environment and when favorable conditions occur they occur in high abundance in the shale. Carbonate concretions may form in such zones due to dissolution of shells and re-precipitated. From Schovsbo (2001).

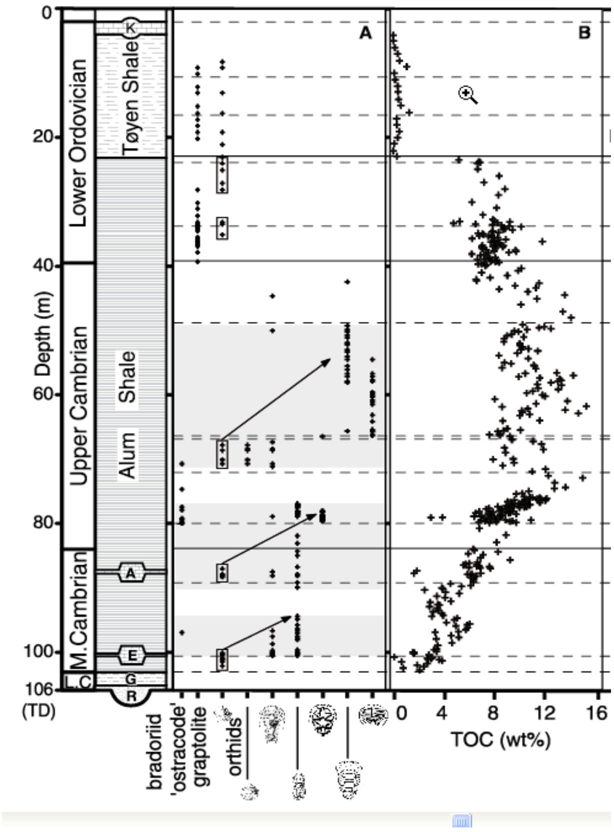

Figure 2-15: Occurrence of fossils in the Alum Shale from the Gislövshammar-2 core. From Schovsbo (2001).

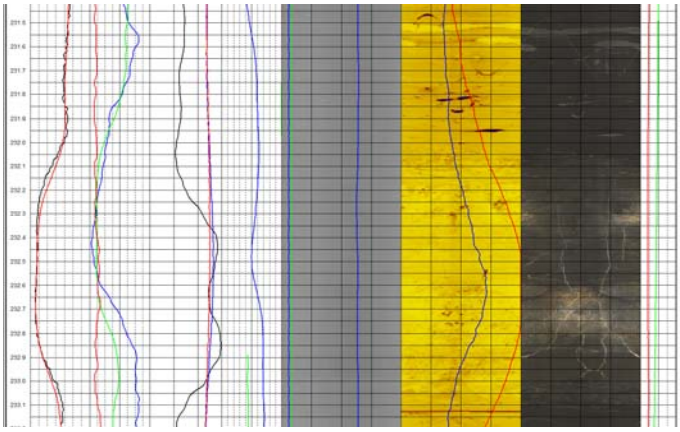

Figure 2-16: Example of a well panel from the Sommerodde-1. Limestone bed @ 232.7 m can be seen on the image log and the impact on the logs (low GR, high Resistivity, density).

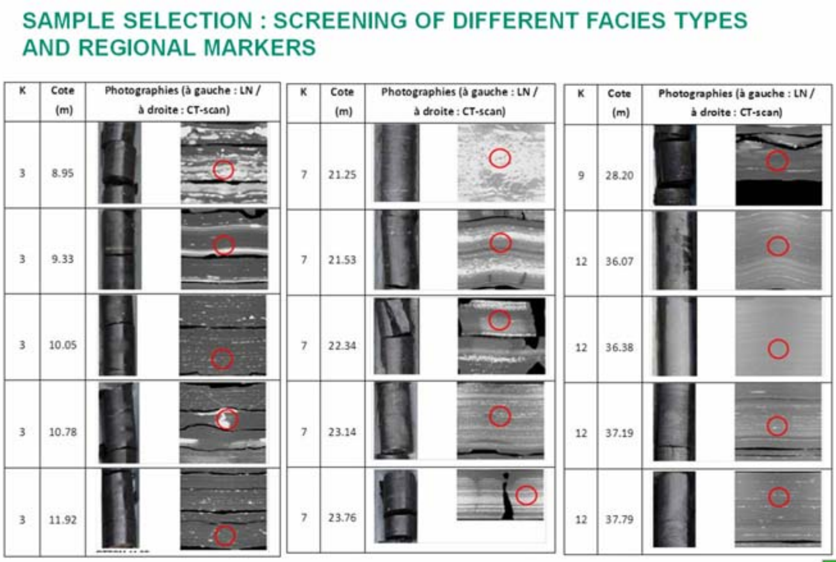

Figure 2-17. Example of CT scanning of Alum Shale samples. From presentation by Total E&P to GEUS.

Silt and sandy intercalations

The Alum shale was deposited below storm wave base. Intercalations of silt beds occur in the Alum Shale notably in the Middle Cambrian (Figure 2-18) and in the Lower Ordovician part of the formation. Silt beds in the Furongian are generally lacking. A detailed documentation has not been made of silt streaks in the Scanian wells. A sequence stratigraphical model of the formation has been presented by Nielsen & Schovsbo (2013) but no predictions on silty occurrences were made.

2.3. Preparation of relevant core material

In May and June 2014 cores from the Albjära-1, Gislövshammar-2, Fågeltofta-2, Sommerodde-2 and Billegrav-2 will be available for analysis and description. Evaluation of preservation state of the cores will be made together with TOTAL representatives in order to identify the cores that could are suitable for laboratory testing of fracturing fluids (Figure 2-18, 2-19).

In general terms the sulphur rich shale parts of the Scania wells (drilled between 1989-1999) now already begins to show signs of weathering and thus not all parts of the cores are equally suitable for testing (Figure 2-18, 2-19).

Figure 2-18: Example of core box from Gislövshammar-2. Depth 89-93 m, Middle Cambrian. Excellent preservation state. Note silt streaks and carbonate concretion.

Figure 2-19: Example of core preservation from the Gislövshammar core. Box level 54 m, Furongian Peltura zone. Pyrite rich intervals are covered with the “pyrite plague” – a white “silver” layer. The high pyrite shales in the Furongian are much more reactive to the humidity than the Middle Cambrian shales.

2.4. Formulation of a detailed work frame for Work Package 2

The work plan of the has been discussed and planned on a project meetin on the 30. April. From the review of existing Alum Shale data it was clear that the shale is not homogeneous but that in-homogeneities exist on many different scales ranging from mm - 10 of m scale.

In-homogeneities

The general level of observation is that of a log-scale i.e. on a 15 cm basis. In this project in-homogeneities occurring on a cm-scale are have importance. As the porpose for describing inhomogeneties is related to fracture progradation defining lateral continuing in-homogeneities has high priority since these may act as fracture barriers.

Barite and pyrite and to certain extent carbonate concretions is evaluated to be of local formation with little lateral extension. These will not pose as fracture barriers.
Lateral extensive carbonate beds such as the Exsulans and Andrarum lmst (marked with blue line in figure 2-2) are will on the other hand be likely fracture barriers. Beds with high fossil content may also give a strong anisotropy to the fabric that may be regional extensive. Local difference in preservation of shell may on the other hand reduce the lateral extent of such shell beds.

An overview table of possible in-homogeneities, their mode of distribution and mineralogy will be made as part of WP2.

Rock mechanics
It is clear which to include rock mechanical testing. Contact by GEUS to 3rd partner on Brinell test.

In order to achieve the goals in Work Package 2 the work has to be highly structured and an overview of the sampling program is presented in Table 2-5. In Work Package 2 the following milestones has to be meet:

1. **Criteria for rock type definitions made by 15/5-2014**
2. **Sampling of Rock types made by 21/5 -2014**
3. **Variability analysis of rock types made by 1/6-2014**
4. **Potential zones for stimulation made by 16/6-2014**
5. **Predictive model (PLS) made by 16/6-2014**

Table 2-5: Identified (expected and possible) project data.

	WP 1	WP2								WP3
Wells	Suitable for rock type definitions	XRF scanning	Spectral core scanning and Density	XRD	Sedimentological work	Variogram descriptions	Image log analysis	PCA -rock types	PLS predictions of Rock types	Suitable for test
Albjära-1	yes	to be made	no	Possible	log available	to be made on logs and xrf	no		no	yes
Fågeltofta-2	yes	to be made	no	Possible	to be made	to be made on logs and xrf	no	to be made	no	yes
Gislövshammar-2	yes	to be made	no	Possible	to be made	to be made on logs and xrf	no	to be made	no	yes
Sommerodde-1	yes	to be made	yes, to be made	Possible	made from image log	to be made on logs and xrf	to be made	to be made	Learning set	yes
Billegrav-2	yes	no	yes		log available		no		no	yes
Skelbro-2	no	no	yes		no		no		no	not available
Terne-1	yes	no	none		no		no		to be made	only cuttings
Slagelse-1	no	no	none		not relevant		no		no	yes, core quality?

Work initiated 1th May:

PCA analysis of existing XRF data - completed 15 May

In order to be able to define rock types a solid understanding has to be made on the critical components in the Alum Shale. There exist data to perform this analysis on and it is suggested to be based on a statistical analysis of the existing XRF data. From this the element variation associated with detrital components will be addresses and the association to TOC, S, TOC and Ba will be addressed. This will be made with Principal component analysis (PCA) tool. The outcome will be a PCA characterization of the wells. Any effects of a condensated sedimentation on the shale on Bornholm compared to Scania will be addressed.

Issue 1: We do not have large data sets that link XRF with XRD data on a robust manner.
Issue 2: We do not have a data set that links rock strength data to either XRD or XRF in a robust manner.

XRF scanning of selected rock sections – completed 15 May

In order to detail the geochemical variation scanning of relevant sections will be made. We expect a total number of analyses to be around 700. Pending on the sampling spacing it will be about 35 m of section that can be characterized by this technique.
Objectives:

1) To compare the XRF scanning with log responses of: resistivity, density and Gr.
2) To detail the rock types variation identified in the PCA analysis
3) To establish detail profiles of Barite, Pyrite and Carbonate rich in selected intervals since these mineral phases are expected to be reactive to fracturing fluids and thus may exclude certain portion of the shale

Sedimentological logs of the Gislövshammar and Fågeltofta-2 wells completed 1th June

Sedimentological descriptions of selected section in the Gislövshammar-2 and Fågeltofta-2 wells. The sections to be logged depend of the analysis of potential rock types. The logging will create data that allow for the analysis of rock type variability. A total of 40 m of section is expected to be logged.

Additional analytical possibilities

1. Spectral gamma ray scanning and density scanning of relevant sections in the Sommerodde-1. Part of this core has been scanned (Haugwitz unpublished) and existing data may be sufficient for the needed analysis
2. XRD analysis of selected samples from the Albjära-1, Gislövshammar-2, Fågeltofta-2 wells.
3. CT-Scanning of selected intervals

Work initiated on the 15 May completed 16th June.

1. **Variability analysis of rock types in selected zones made by 1/6-2014**
2. **Potential zones for stimulation made by 16/6-2014**
3. **Predictive model (PLS) made by 16/6-2014**

Analysis of shale variability in the Alum Shale will be made from statistical analyses of well logs and XRF data and image data.

Variograms of selected well logs, XRF data and TOC measurements
Image analysis of Sommerodde-1: Log of pyrite, carbonate and Ba occurrences

Predictive models of rock type will be made based on relationships between rock components, image logs and well logs. The possibility that rock types may have predictable rock strengths will also be addressed.

3. Work package 2

3.1. Rock Types in the Alum Shale and Preliminary PCA results and Image anlysis

Rock Types in the Alum Shale

Report of WP 2 activities, Copenhagen, 15/5-2014

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Reservoir geologist

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Klima-,Energi- og Bygningsministeriet

Work Package 1 -30/4

- 1) Data inventory and review of Alum Shale related data including:
- Data already acquired by Total
- Data from GASH and Pau, Total
- Additional data at GEUS
- New data to be measured during May 2014
- 2) Preparation of relevant core material for inspection, analytical work and sampling for laboratory tests
- 3) Formulation of detailed work frame for Work Package 2

Agenda for meeting 14/5

Progress on Work package 2 (work in progress):

- Sedimentology description of identified facies in the Alum Shale
- Characterisation of shale in the Albjära-1 core by XRF
- Mineralogical analysis
- PCA analysis on XRF data from Albjära-1
- Image analysis of the Sommerodde-1

Core workshop: Albjära-1

-Lunch-

- Review of the core measurements in the Billegrav-2
- The Sommerodde-1 Vp and Vs log

Presentation by GEO on new geo-mechanical test (13:00)

Criteria for rock type definitions with respect to geo-mechanical data

Aims of the data collection within WP2

- Focus on the Albjära-1 well, which is the nearest cored off-set well to Vensyssel-1:
  - 30 XRD samples send to analysis
  - 600 XRF measurements by hand held apparatus
  - Sedimentological description and facies typing

Aims of the data interpretation within WP2

- Facies types, rock types and variability in the Albjära-1 well

- Analysis of Bornholm wells (Billegrav, Skelbro and Sommerodde) where rock mechanical data exist

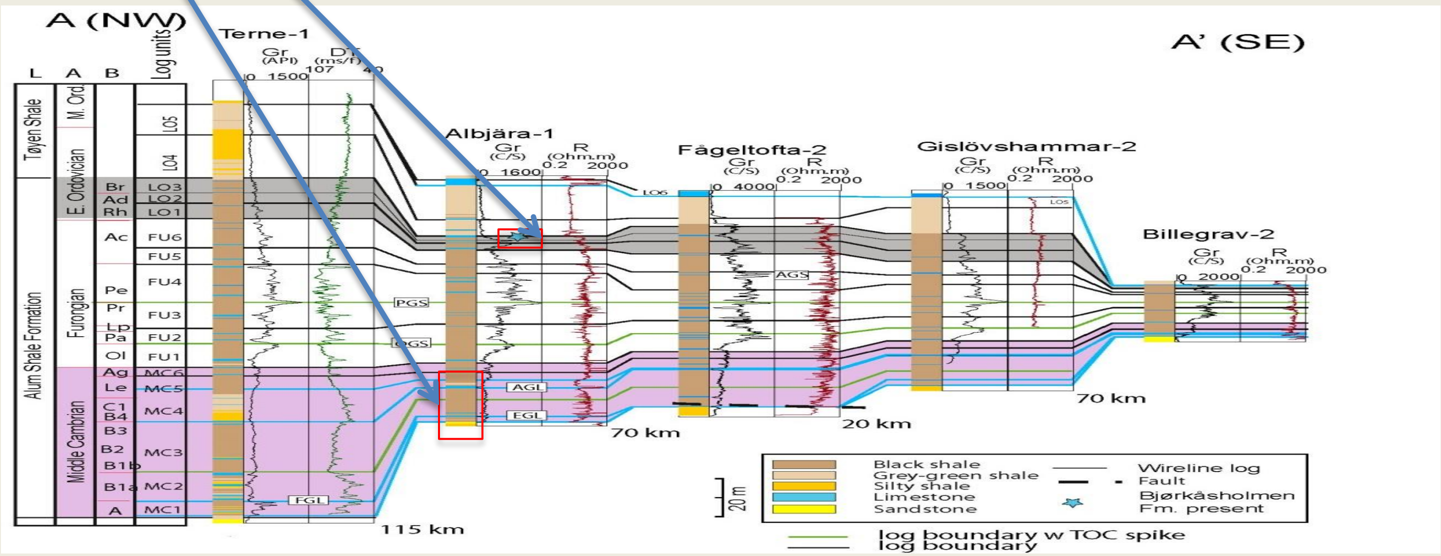
Facies types in the Albjära

Alum Shale Fm contains 4 facies:

Alum Shale type 4: thin laterally *persisten*t bioclastic limestones:

- The Middle Cambrian (Andrarum Lmst and Exsulans Lmst)
- Lower Ordovician and in the top of the Formation (Bjørkåsholmen Fm.)

Limestone concretions that does not form lateral persistent layers occur in the shale also they are mostly less than a few dm thick, but may rarely be up to 2 m long and 1 m thick. Occur mostly in top M. Cambrian to Furongian

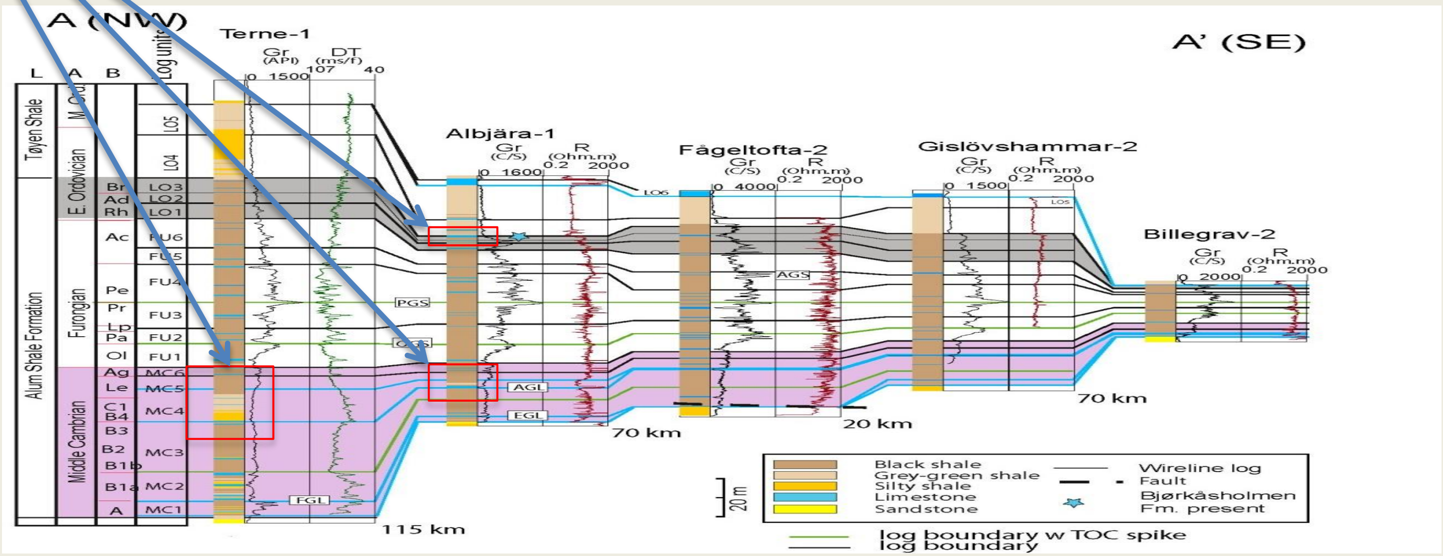


- Example of primary limestone bed

- Lateral continuous – a likely fracture barrier

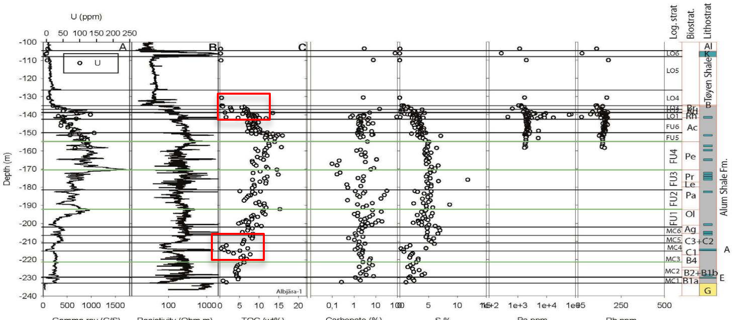
Facies types in the Albjära

- **Alum Shale Type 2:** Low TOC type
- Colour banded shale comprising blackish shale alternating with bands of dark grey shale. The individual bands are from 1-5 cm thick. No limestone concretions seen in the Albjära core. This rock type occurs primarily above the Andrarum Limestone and in the top most part of the core. A few scattered pyrite concretions seen in this rock type but overall pyrite is uncommon and apparently no disseminated pyrite occurs (macroscopic inspection). This interval is much more expanded in the Terne-1 well (above the Andrarum Lmst) judging from log interpretation.



- Low TOC type Alum Shale. Occur in the Albjära-1 in the M. Cambrian an in the topmost par of the Fm.

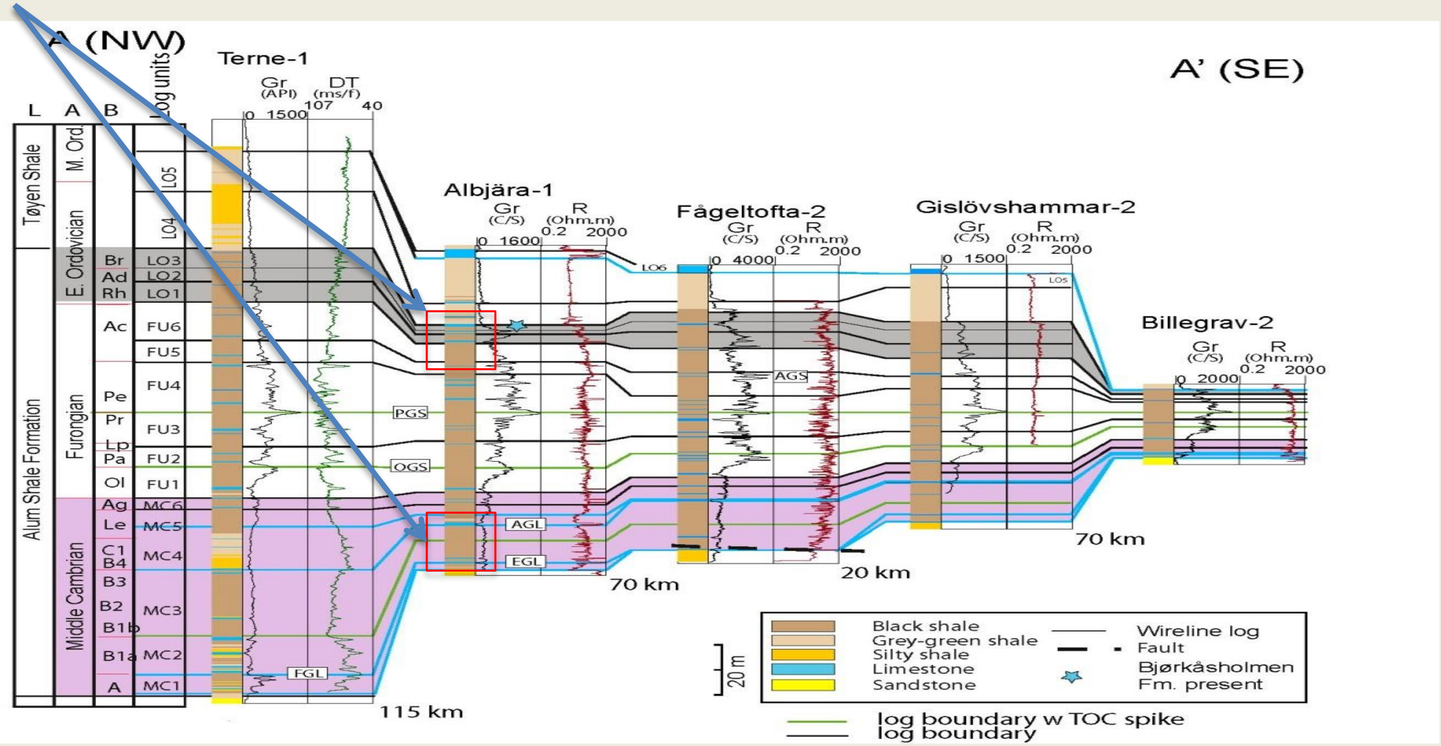
- Occur also in the Terne-1 (from log-correlation)



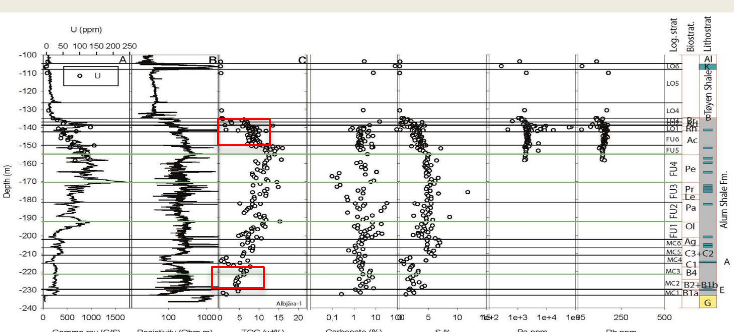
Facies types in the Albjära

Alum Shale Type 3: Homogeneous, medium TOC rich and with low pyrite

– Homogenous to laminated Alum Shale with relatively rare macroscopic pyrite and low content of dissiminated pyrite. Sporadic very thin laminae of pyrite (?concentrated dissiminated) may occur. Scattered concretions. TOC content moderate. This type of Alum Shale characterizes the Middle Cambrian interval and in the Lower Ordovician

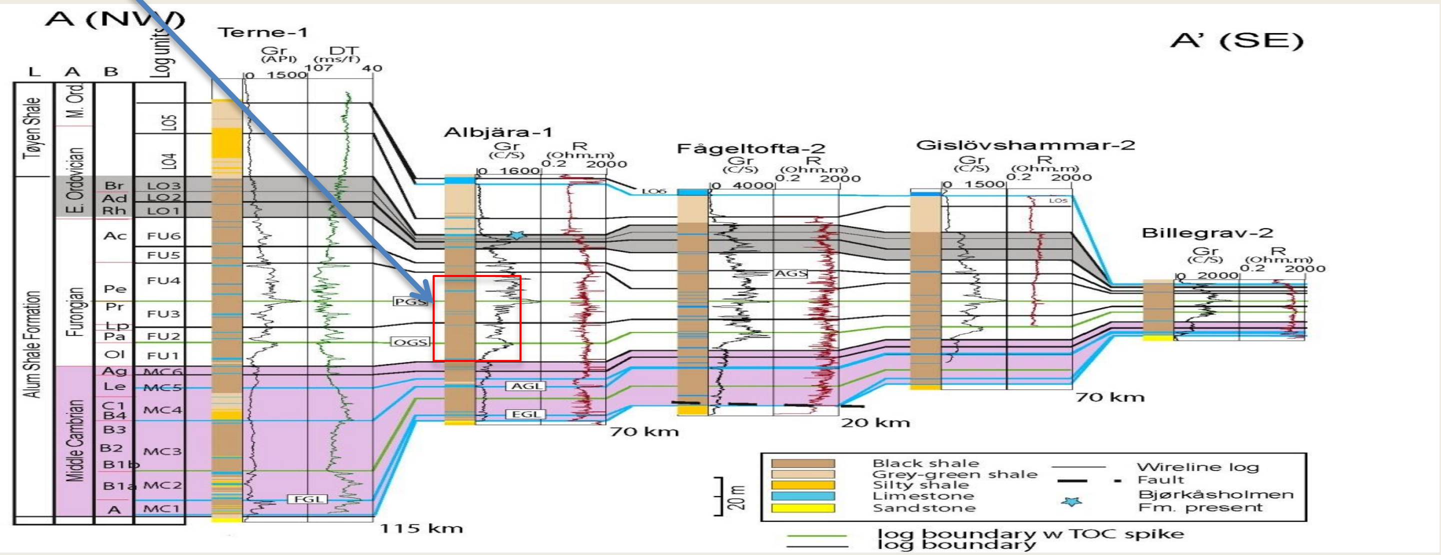


- Homogeneous Alum Shale. Medium TOC and S content

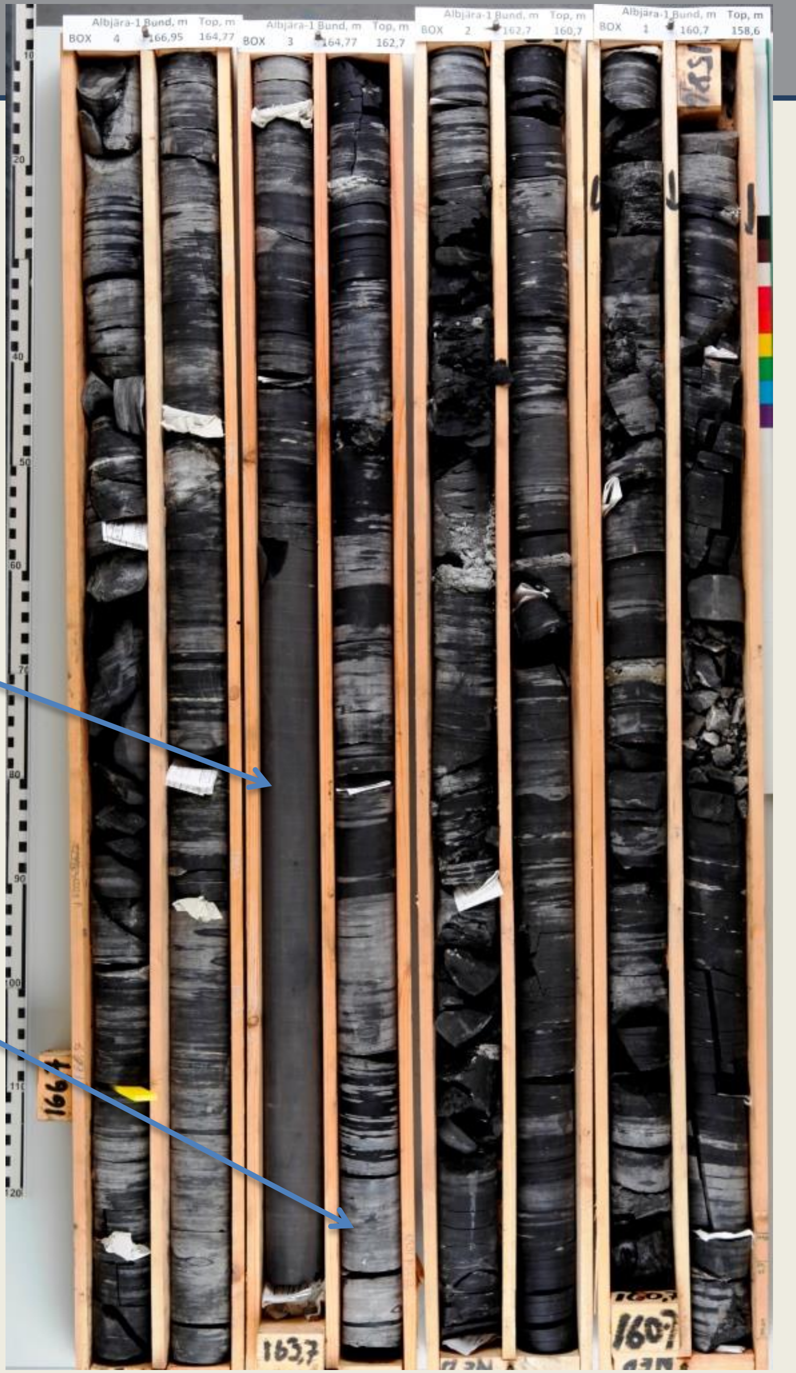


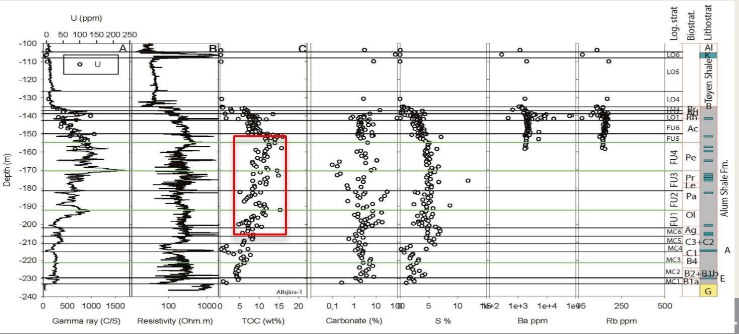
Facies types in the Albjära

- **Alum Shale Type 4:** Heterogeneous high TOC, high pyrite and concretions
- Blackish, laminated, often highly pyritic (dissiminated) shale with scattered limestone nodules. Here and there is seen comparatively large pyrite nodules (i.e. up to some 5 cm diameter), but dissiminated pyrite dominates. Overall high TOC content. This rock type starts in the pisiformis Zone at around 209-210 m and characterizes the rest of the entire Furongian and lower Tremadocian (Note: as this is written only the core up to 158 m has been inspected).



- High TOC type, high sulphur and with carbonate concentrations
- The pyrite in the Albjära-1 core is weathered and particulate S rich intervals are white coloured.





Sedimentology status

- 4 main facies types have been defined based on core descriptions
  - Primary limestone
  - Low TOC shale
  - Homogeneous medium TOC shale
  - Heterogeneous high TOC shale

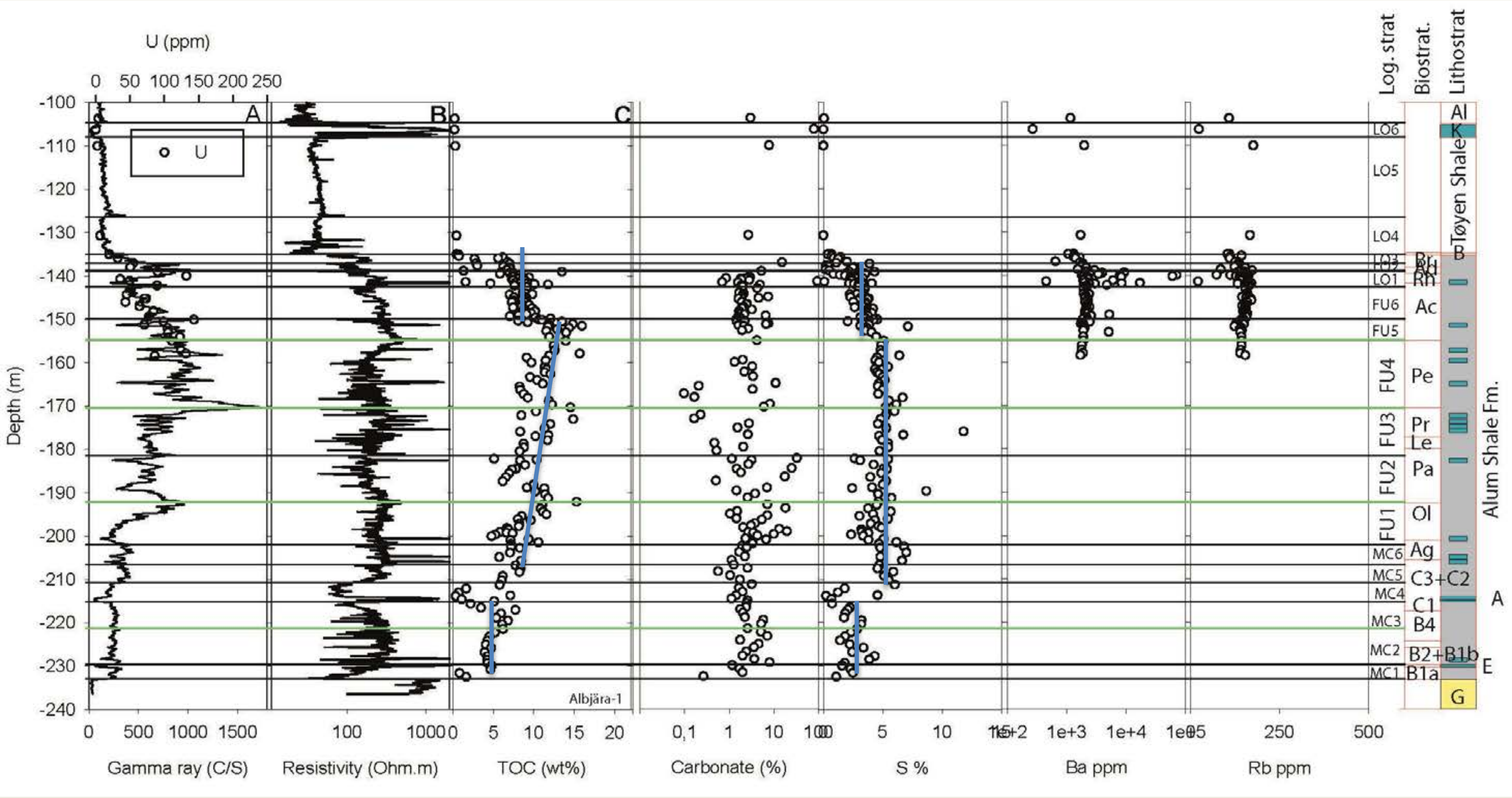
- Logging of the shale facies and concretions (pyrite, barite and carbonate) is in progress.

The logging will be made in stratigraphical frame and “flag-curves” for lithological properties will be made

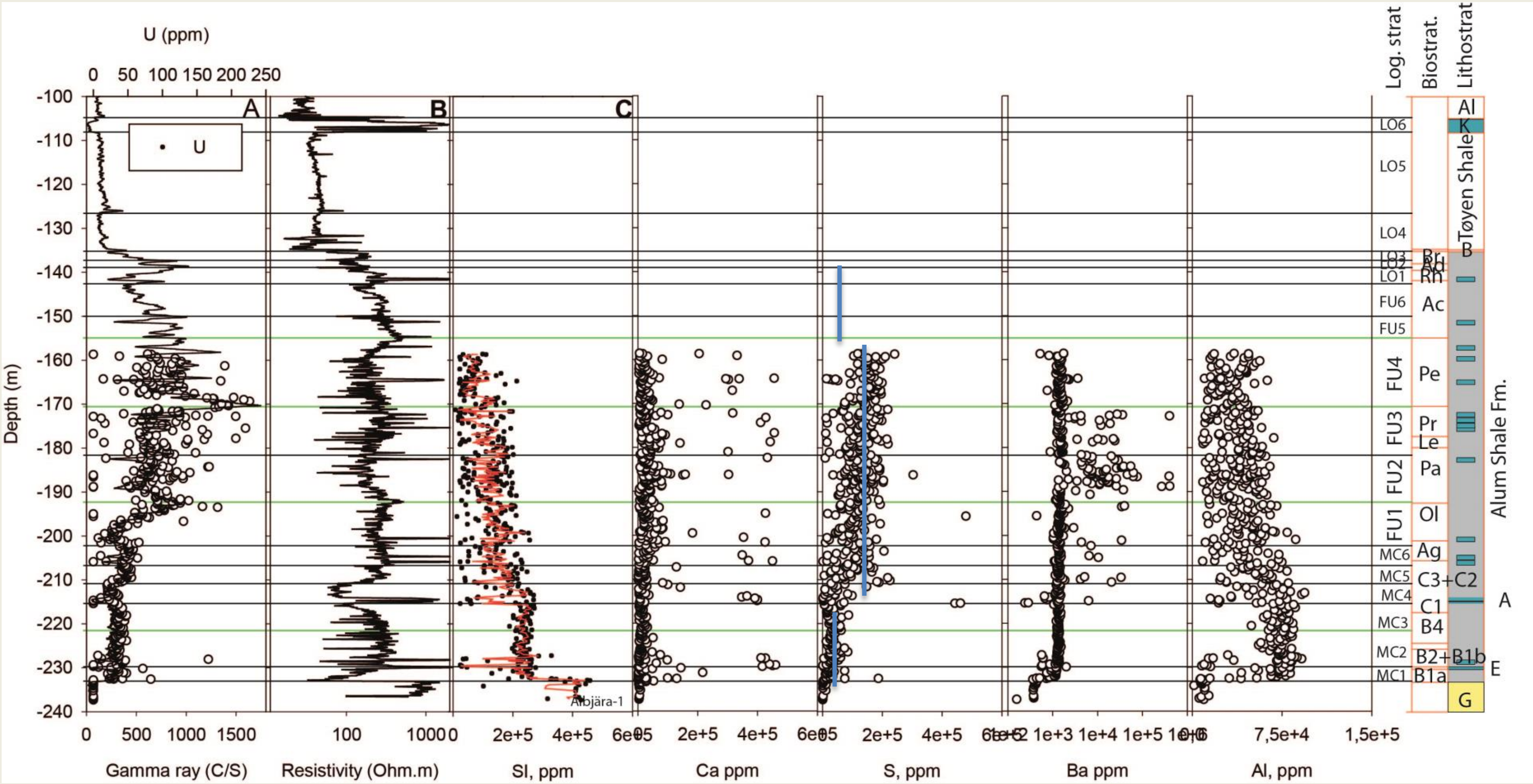
XRF status

- Lower 80 m (158-238 m) of the core analysed (432 measurements)
- Upper part (135-158 m) expected completed by the 19/5
- XRF profiles will be made in selected intervals in Sommerodde-1 and integrated with image analysis
- XRF will be made on XRD samples to make a "statistical bridge"

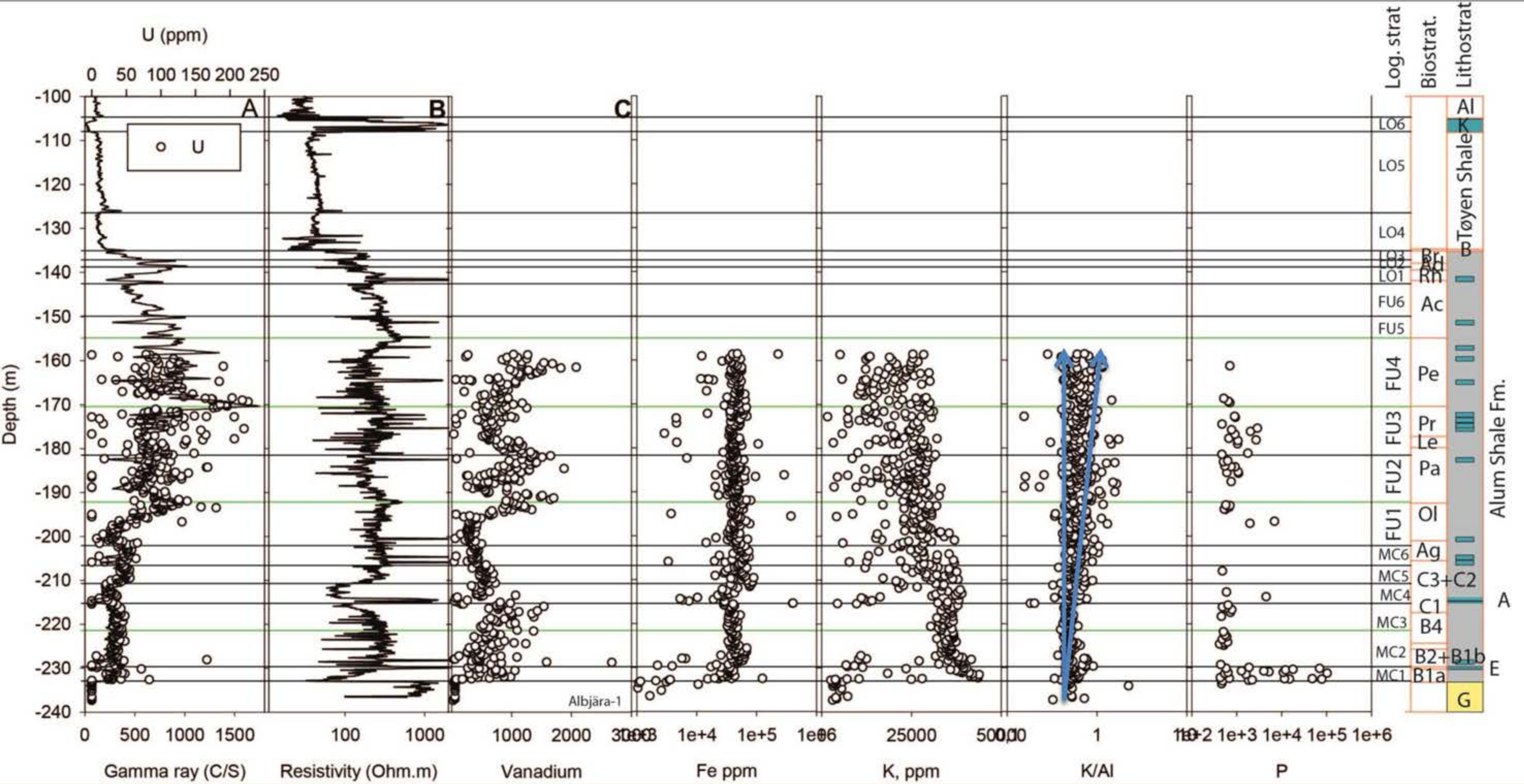
Albjära-1 core data



Albjära-1 core XRF data



- Uranium measurements alike the GR log
- Step-wise decrease in Si, Al due to addition of non siliciclastic. Very low Si, Al content in concretions


U (ppm)
0 50 100 150 200 250
Depth (m)
U
A
B
C
Albjära-1
Gamma ray (C/S)
Resistivity (Ohm.m)
Vanadium
Fe ppm
K, ppm
K/Al
P
Log. strat
Biostrat.
Lithostrat
LO6
LO5
LO4
LO3
LO2
LO1
FU6
FU5
FU4
FU3
FU2
FU1
MC6
MC5
MC4
MC3
MC2
MC1
Al
K
Tøyen Shale
B
Pr
Ad
Rh
Ac
Pe
Pr
Le
Pa
Ol
Ag
C3+C2
C1
B4
B2+B1b
B1a
G
Alum Shale Fm.
A
E

XRF summary

- The main facies types defined from sedimentological description can be identified also in the XRF data

- Further PCA analysis of XRF data will refine the facies types and form the backbone for the rock type definition

GEUS

Preliminary PCA results

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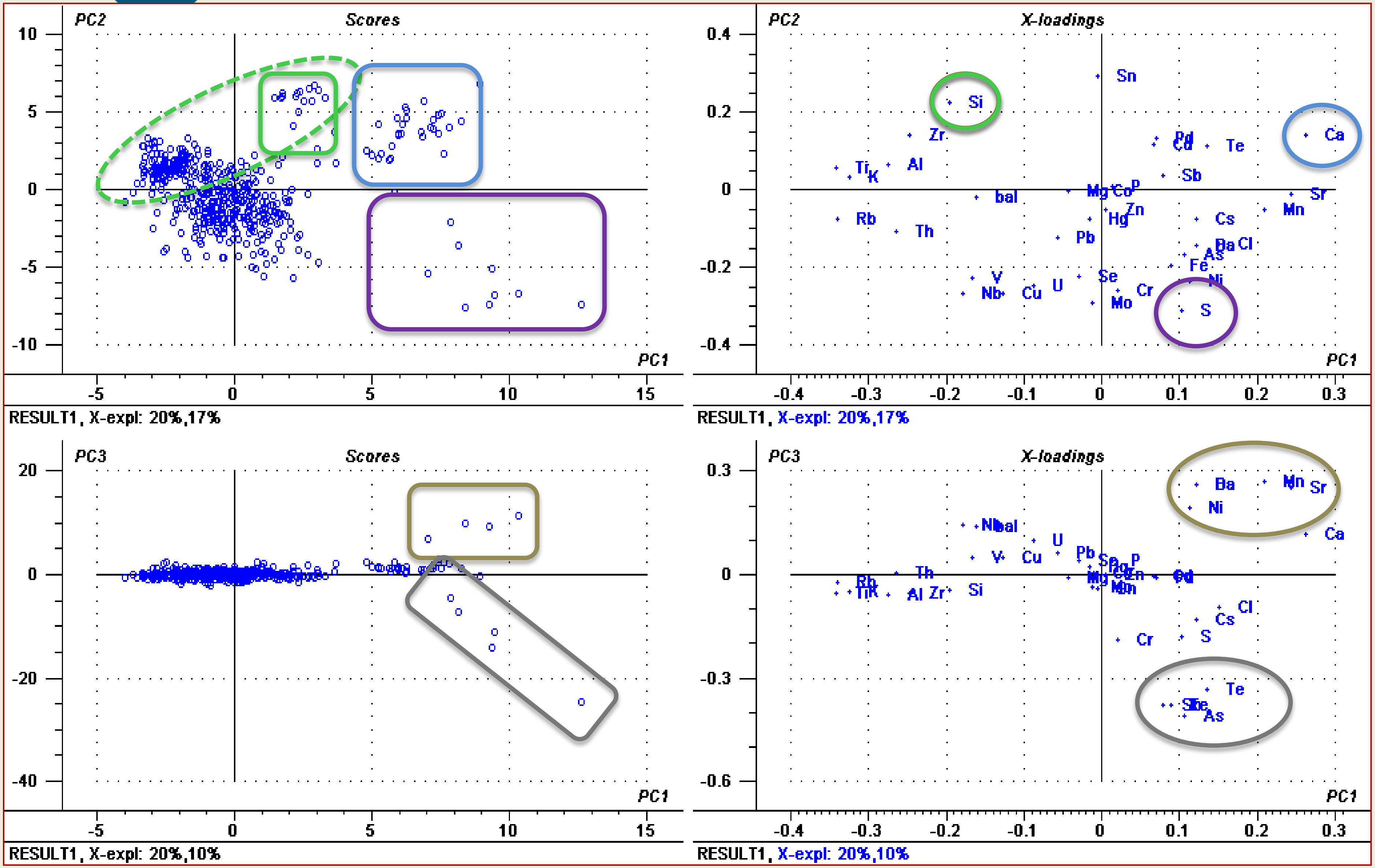
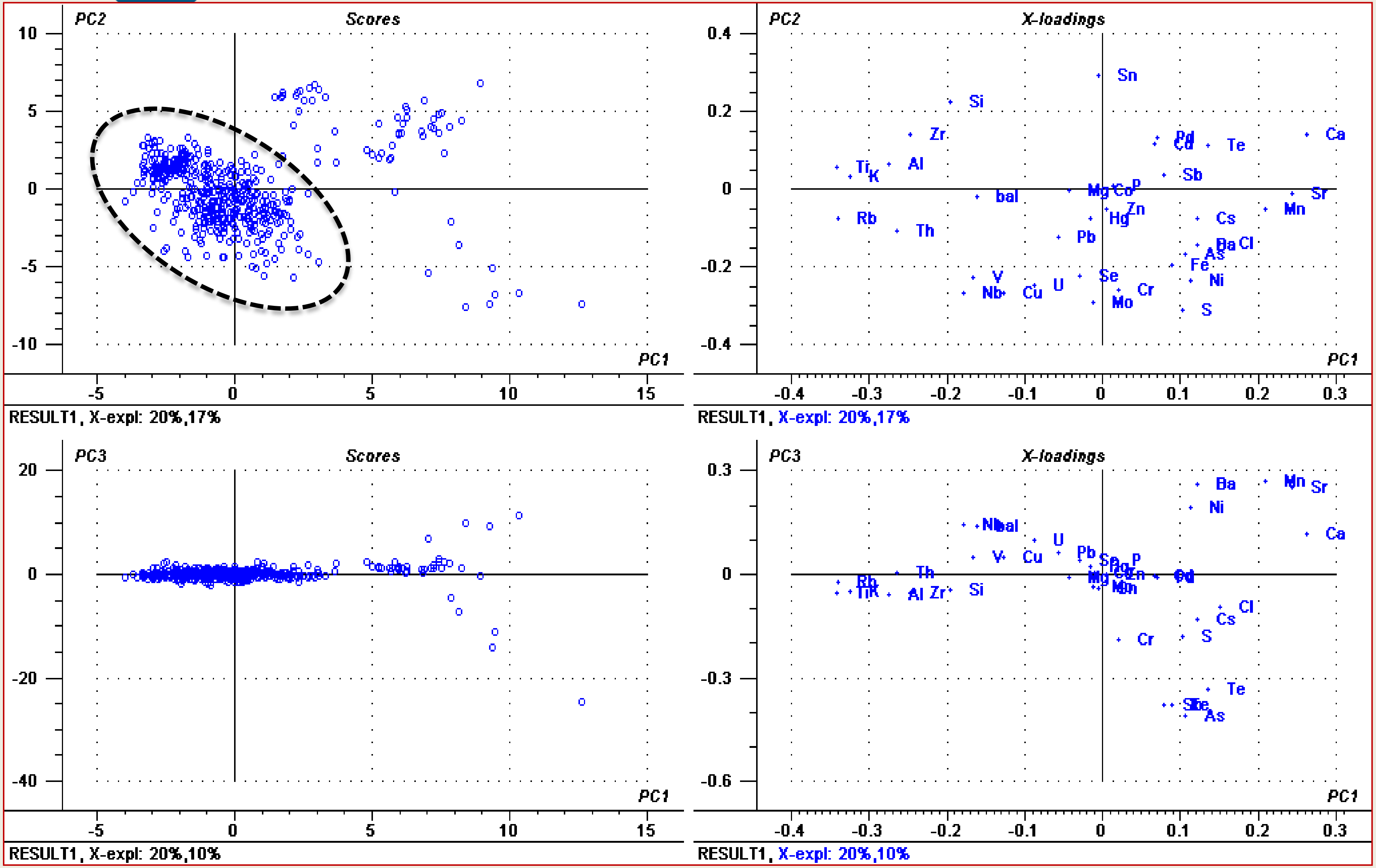
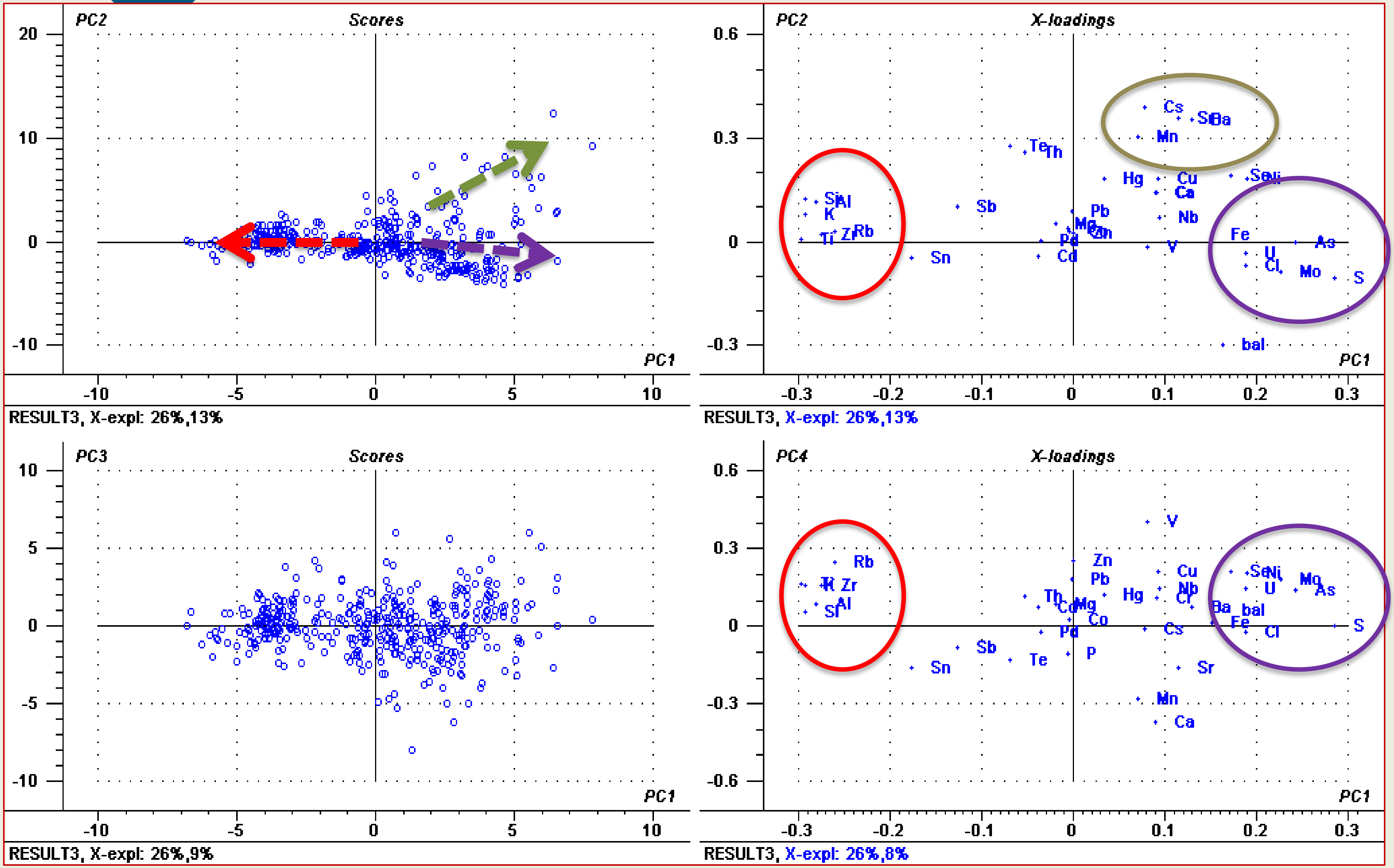
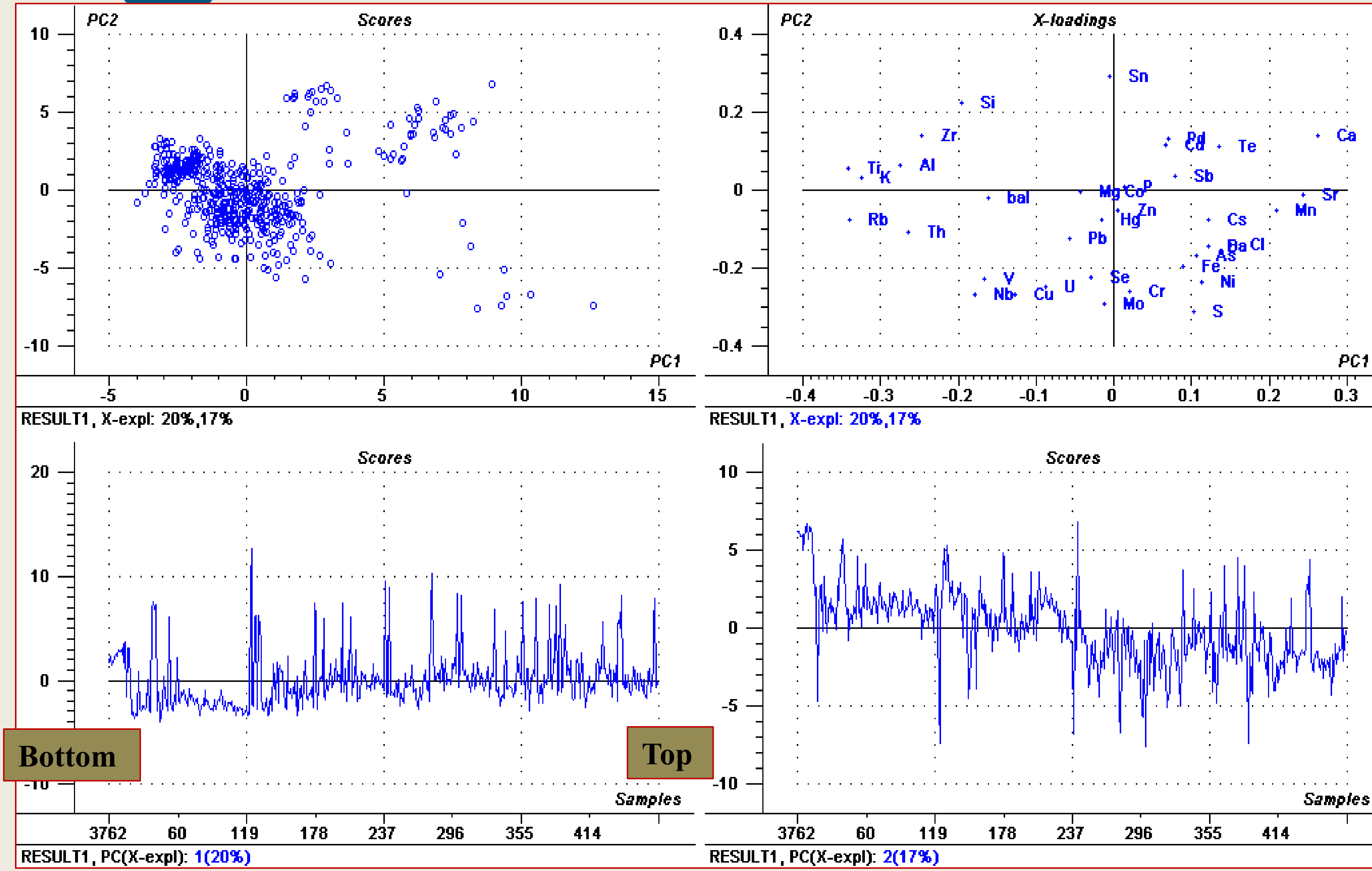
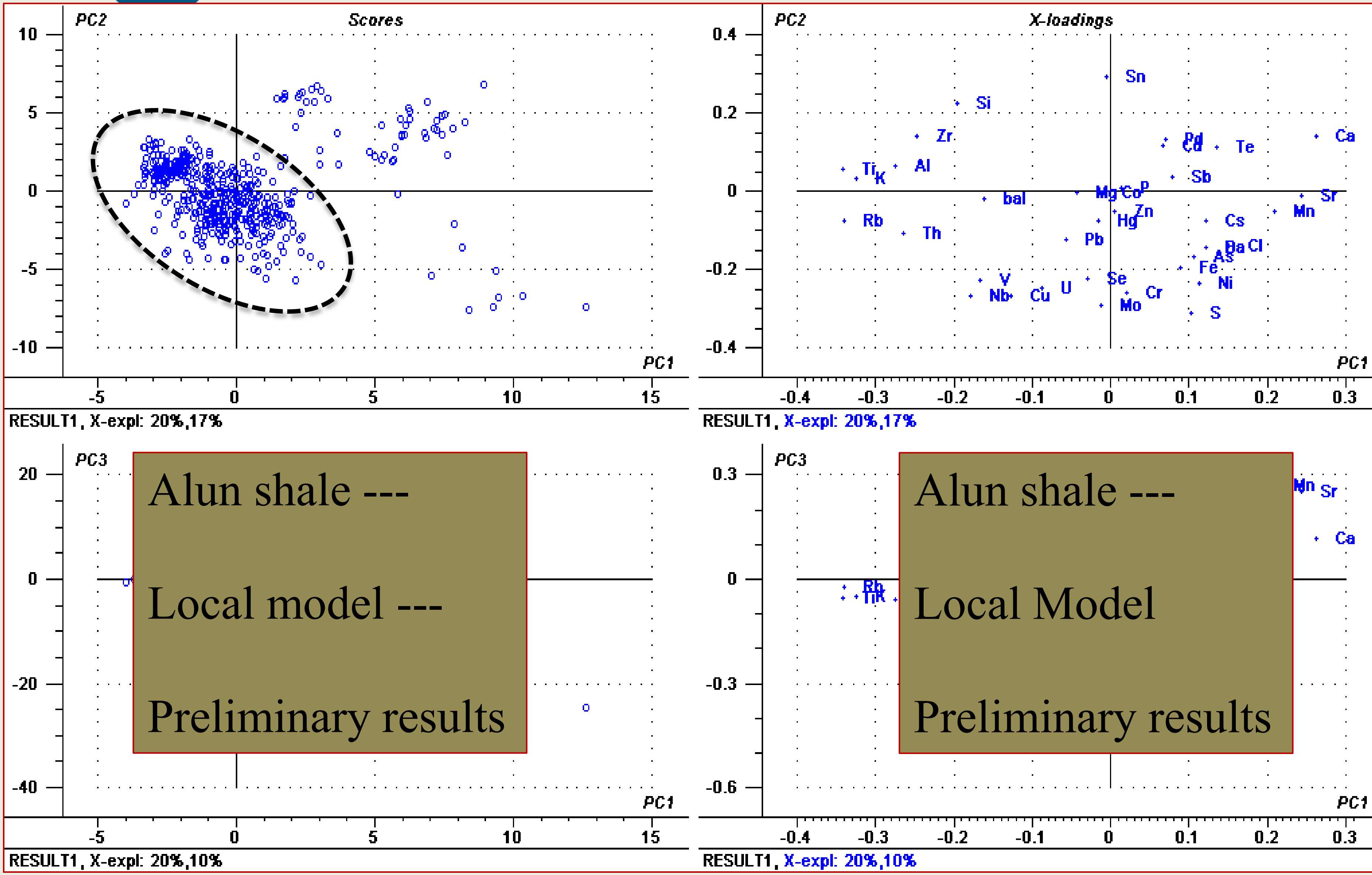

PC2
Scores
PC1
RESULT1, X-expl: 20%,17%
PC2
X-loadings
Sn
Si
Zr
Ti
K
Al
Pd
Cd
Te
Ca
Sb
bal
Mg
Co
P
Sr
Mn
Rb
Th
Hg
Zn
Cs
Pb
Ba
Cl
As
Fe
V
Se
Ni
Nb
Cu
U
Cr
Mo
S
PC1
RESULT1, X-expl: 20%,17%
PC3
Scores
PC1
RESULT1, X-expl: 20%,10%
PC3
X-loadings
Ba
Mn
Sr
Ni
Ca
Nb
bal
U
V
Cu
Pb
Th
Rb
Ti
K
Al
Zr
Si
Cl
Cs
S
Cr
Te
As
PC1
RESULT1, X-expl: 20%,10%

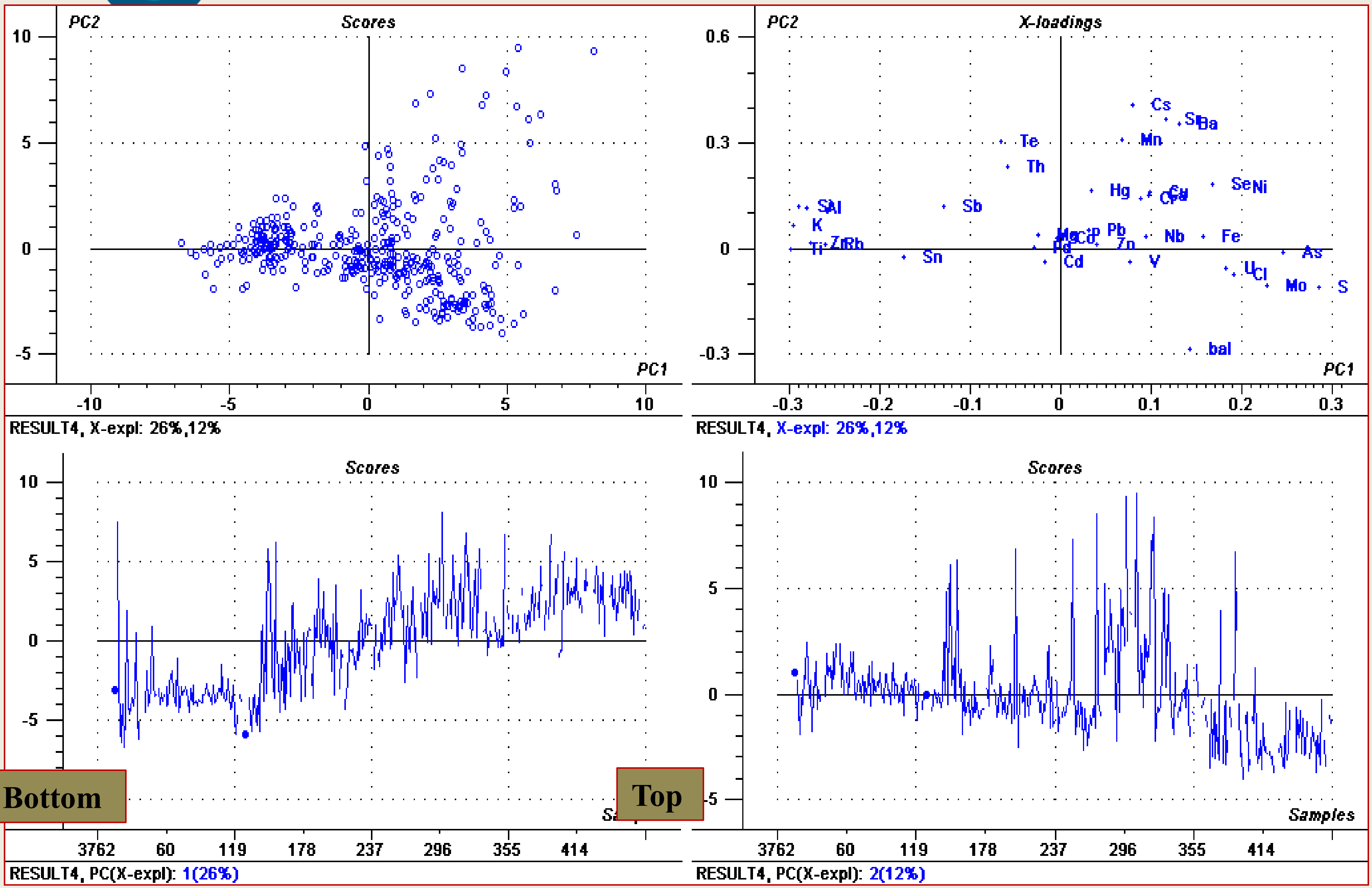

PC2
Scores
PC1
RESULT1, X-expl: 20%,17%
PC2
X-loadings
Sn
Si
Zr
Ca
Pd
Cd
Te
Ti
K
Al
Sb
bal
Mg
Co
P
Sr
Mn
Rb
Th
Hg
Zn
Cs
Pb
Ba
Cl
As
Fe
V
Se
Ni
Nb
Cu
U
Cr
Mo
S
PC1
RESULT1, X-expl: 20%,17%
PC3
Scores
PC1
RESULT1, X-expl: 20%,10%
PC3
X-loadings
Ba
Mn
Sr
Ni
Ca
U
Cu
Pb
Th
Si
Cr
Te
As
PC1
RESULT1, X-expl: 20%,10%

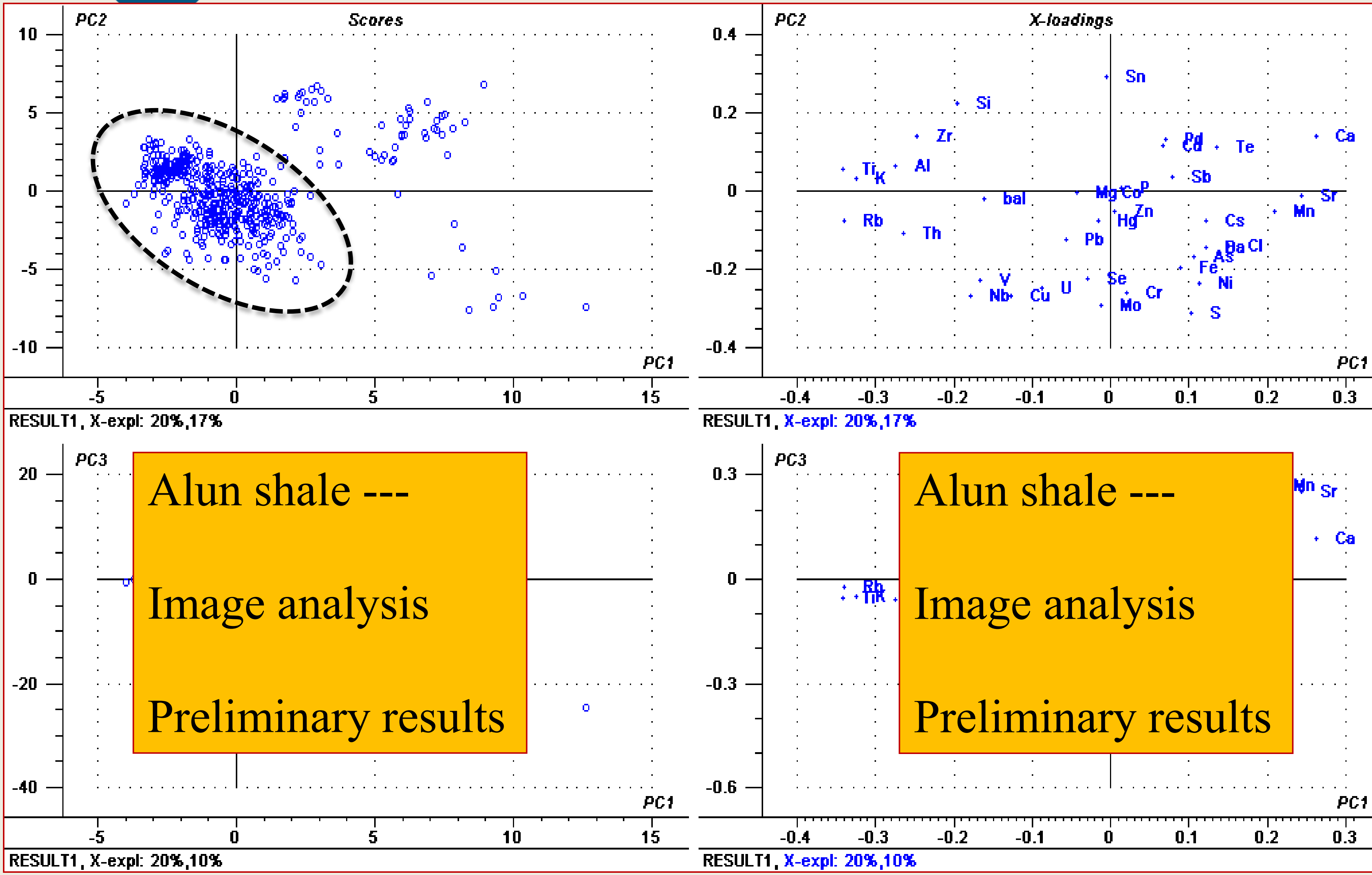

PC2
Scores
PC1
RESULT3, X-expl: 26%,13%
PC2
X-loadings
Cs
Sr
Ba
Mn
Te
Th
Hg
Cu
Ca
Se
Ni
Si
Al
K
Sb
Pb
Nb
Ti
Zr
Rb
Mg
Zn
Fe
As
Pd
Cd
V
U
Sn
Cl
Mo
S
bal
PC1
RESULT3, X-expl: 26%,13%
PC3
Scores
PC1
RESULT3, X-expl: 26%,9%
PC4
X-loadings
V
Rb
Zn
Cu
Se
Ni
Mo
Pb
Nb
As
Zr
Th
Hg
U
Cr
Ba
bal
Al
Cd
Mg
Si
Co
Fe
Cs
S
Pd
Cl
Sb
P
Te
Sn
Sr
Mn
Ca
PC1
RESULT3, X-expl: 26%,8%


PC2
Scores
PC1
10
5
0
-5
-10
-5
0
5
10
15
RESULT1, X-expl: 20%,17%
PC2
X-loadings
PC1
0.4
0.2
0
-0.2
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
Sn
Si
Zr
Ti
K
Al
Rb
Th
bal
Mg
Co
P
Pd
Cd
Te
Ca
Sb
Sr
Mn
Hg
Zn
Cs
Pb
Ba
Cl
As
Fe
Ni
V
Nb
Cu
U
Se
Cr
Mo
S
RESULT1, X-expl: 20%,17%
Scores
20
10
0
Samples
3762
60
119
178
237
296
355
414
Bottom
Top
RESULT1, PC(X-expl): 1(20%)
Scores
10
5
0
-5
-10
Samples
3762
60
119
178
237
296
355
414
RESULT1, PC(X-expl): 2(17%)



PC2
Scores
PC1
RESULT1, X-expl: 20%,17%
PC2
X-loadings
Sn
Si
Zr
Ti
K
Al
Rb
Th
bal
Mg
Co
P
Hg
Zn
Pb
V
Nb
Cu
U
Se
Mo
Cr
Pd
Cd
Te
Ca
Sb
Sr
Mn
Cs
Ba
Cl
As
Fe
Ni
S
PC1
RESULT1, X-expl: 20%,17%
PC3
PC1
RESULT1, X-expl: 20%,10%
PC3
Mn
Sr
Ca
Rb
TiK
PC1
RESULT1, X-expl: 20%,10%
Alun shale ---
Local model ---
Preliminary results
Alun shale ---
Local Model
Preliminary results


PC2
Scores
PC1
RESULT4, X-expl: 26%,12%
PC2
X-loadings
Cs
Sr
Ba
Te
Mn
Th
Hg
Cu
Cr
Ga
Se
Ni
Si
Al
Sb
K
Ti
Zr
Rb
Sn
Mo
Co
P
Pb
Zn
Pd
Cd
Nb
Fe
V
As
U
Cl
Mo
S
bal
PC1
RESULT4, X-expl: 26%,12%
Scores
RESULT4, PC(X-expl): 1(26%)
Scores
Samples
RESULT4, PC(X-expl): 2(12%)
Bottom
Top



Alun shale ---

Image analysis

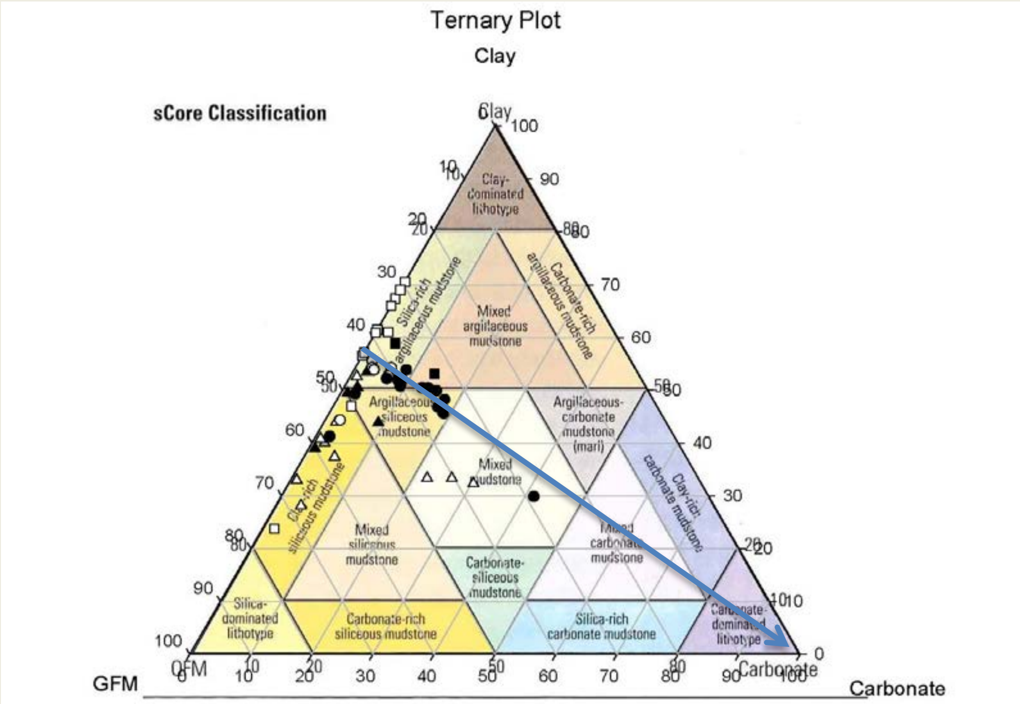
Preliminary results

Alun shale ---

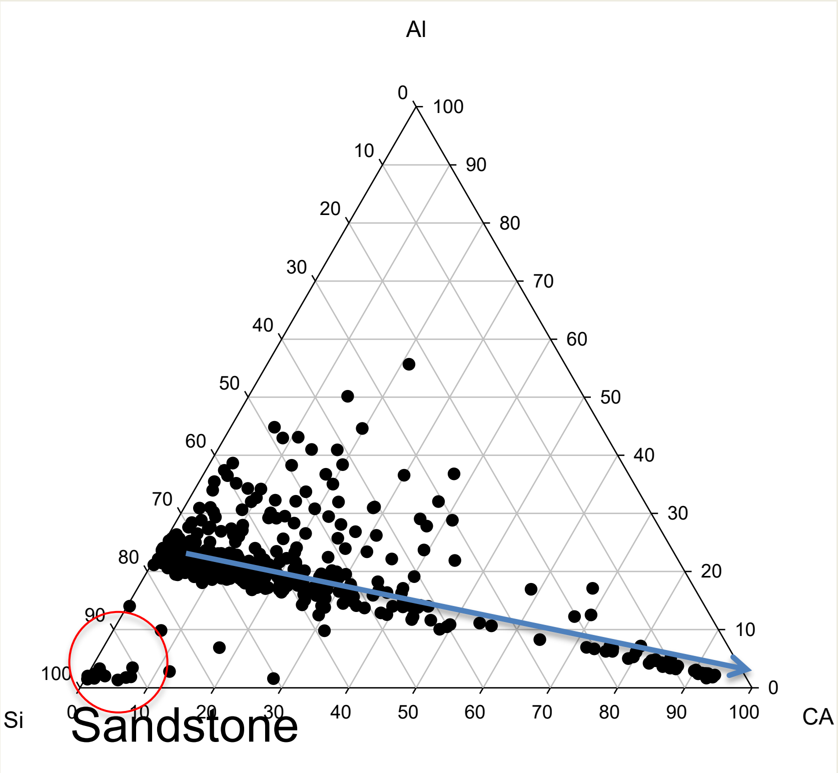
Image analysis

Preliminary results

Mineralogi



XRD analysis from Terne-1, Billegrav-2, Slagelse-1. Black symbol: Alum Shale



XRF data Albjära-1. Blue Arrow indicate expected dilution of siliciclastic with carbonate

Mineralogy

- 40 samples send to analysis for XRD. XRF will be obtained for same sample to provide as a learning set.
- Link to TOC, TS will be made by measuring sample aliquots

Image analysis of Sommerodde-1

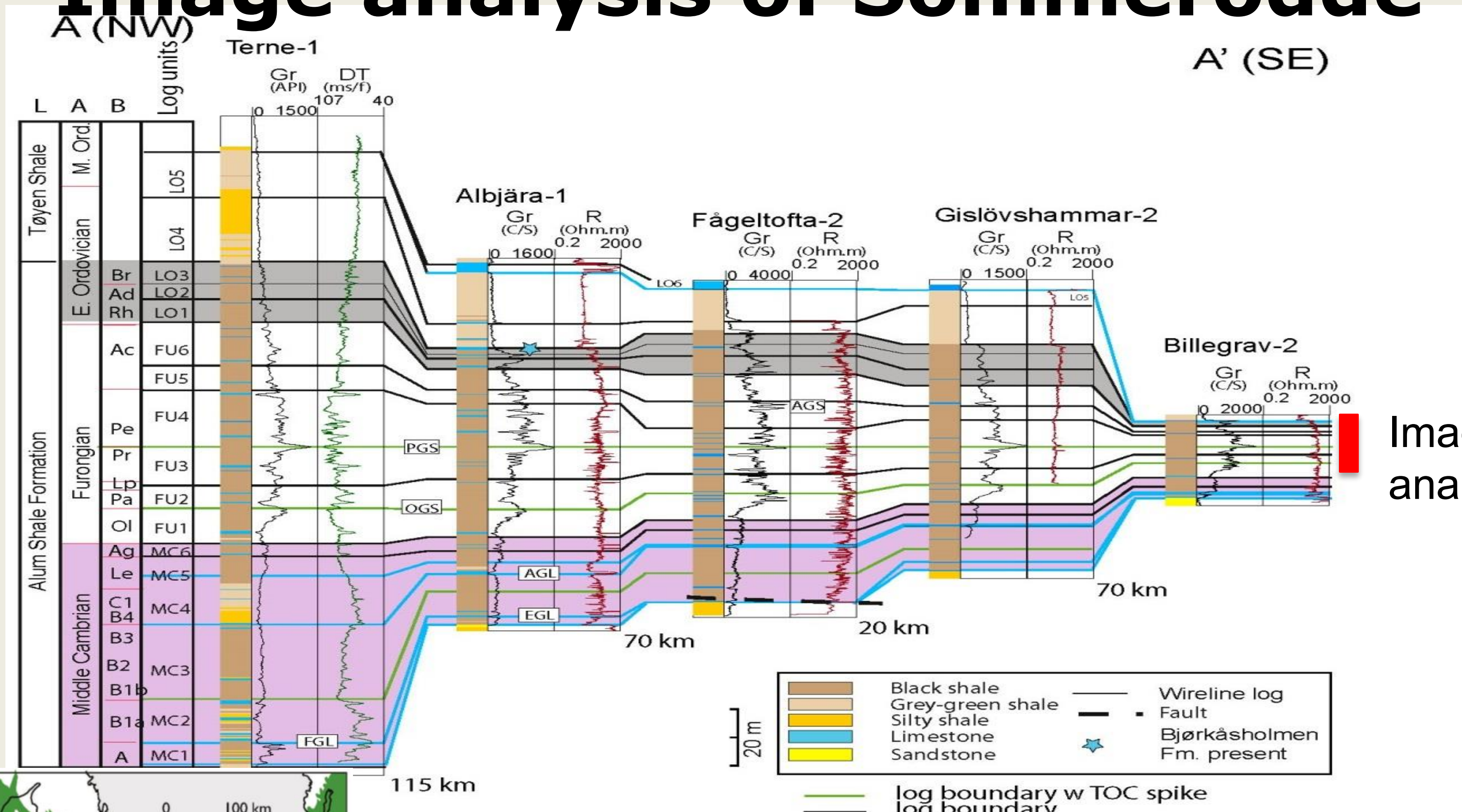


Image analysis

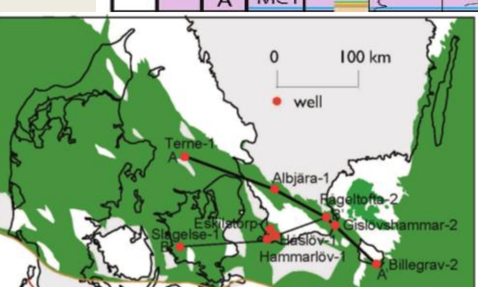
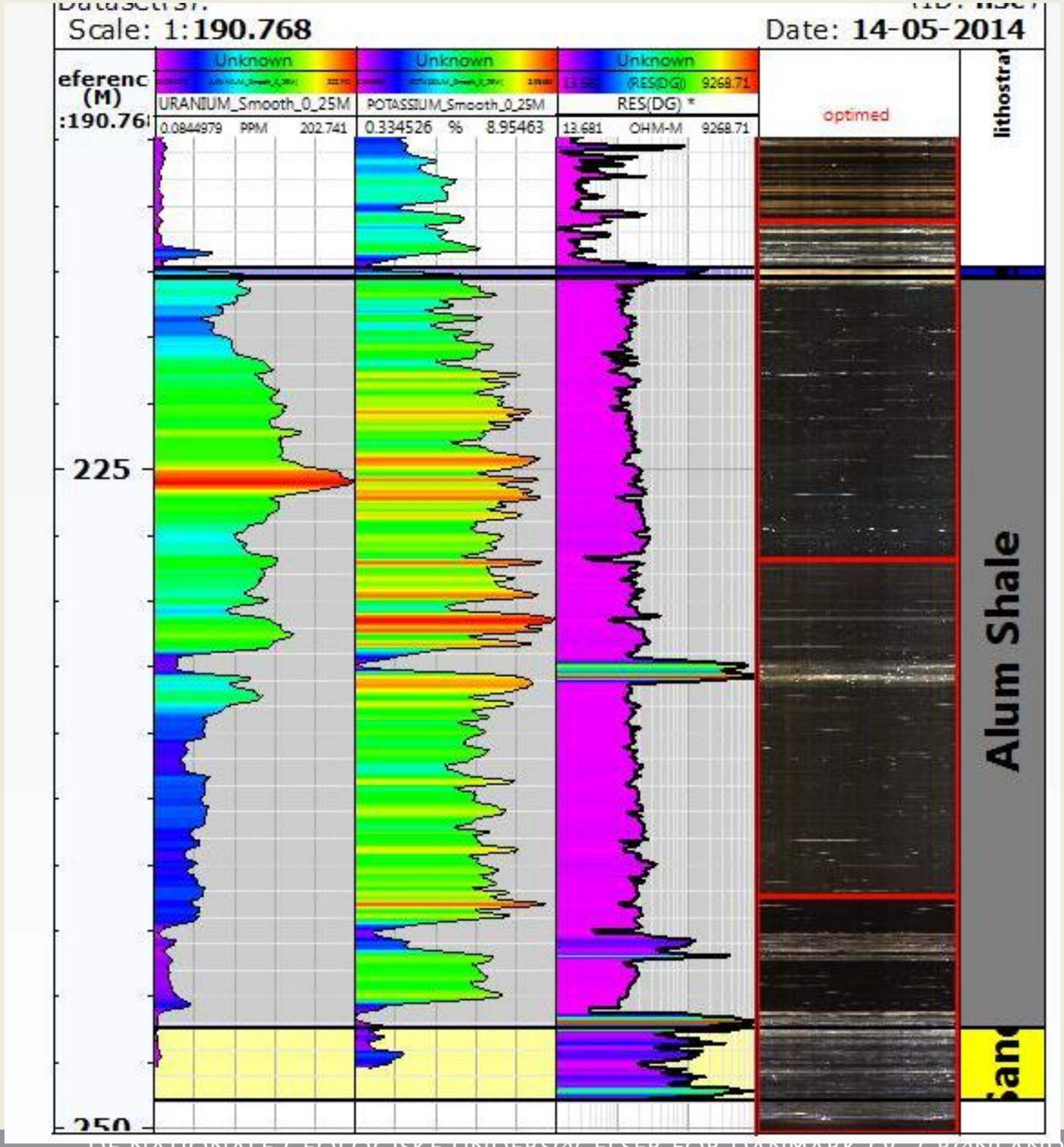


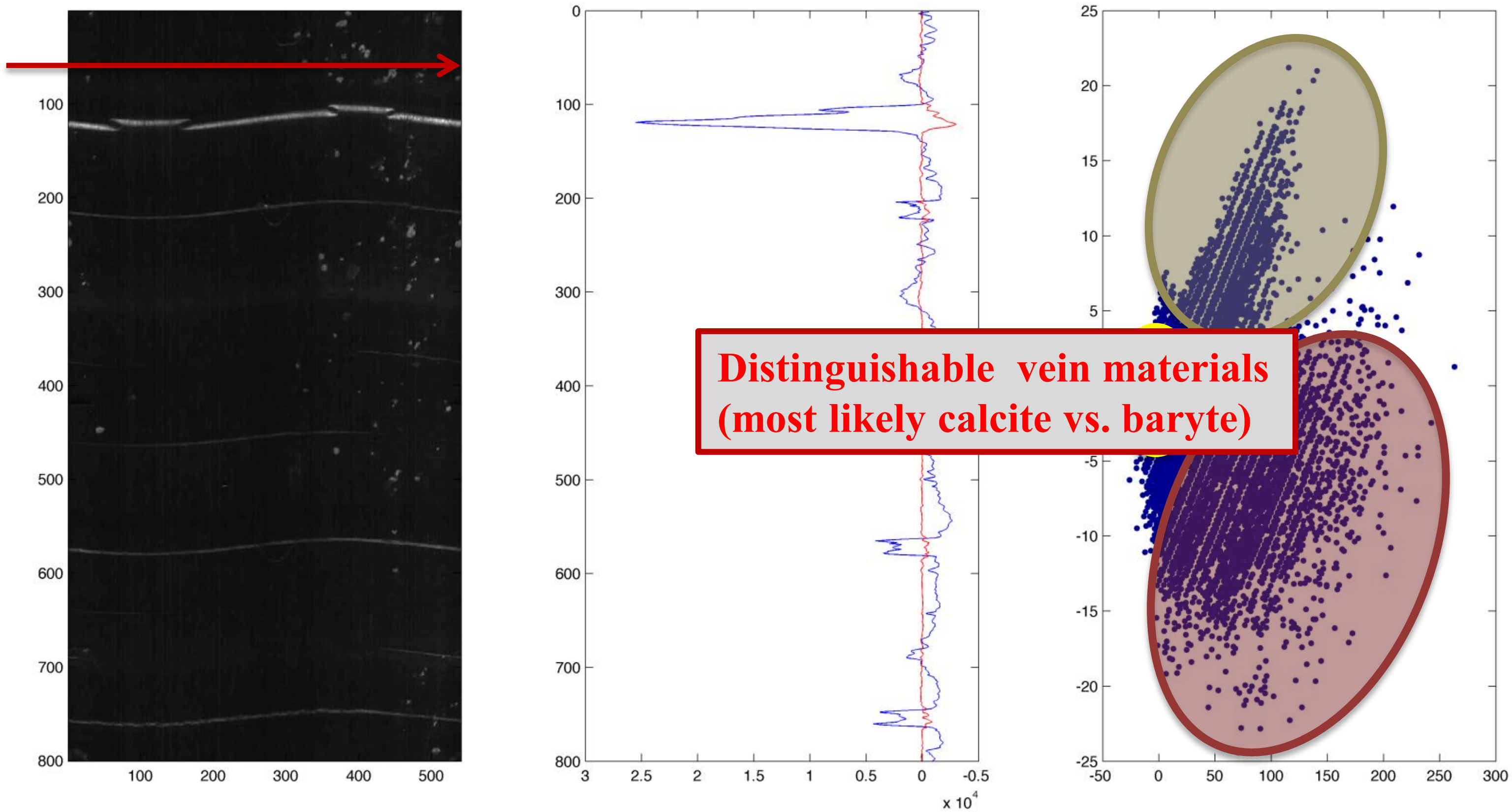
Image analysis – Sommerodde-1



GEUS

t_1 – score: R/G/B image log
t_2 – score: R/G/B image log

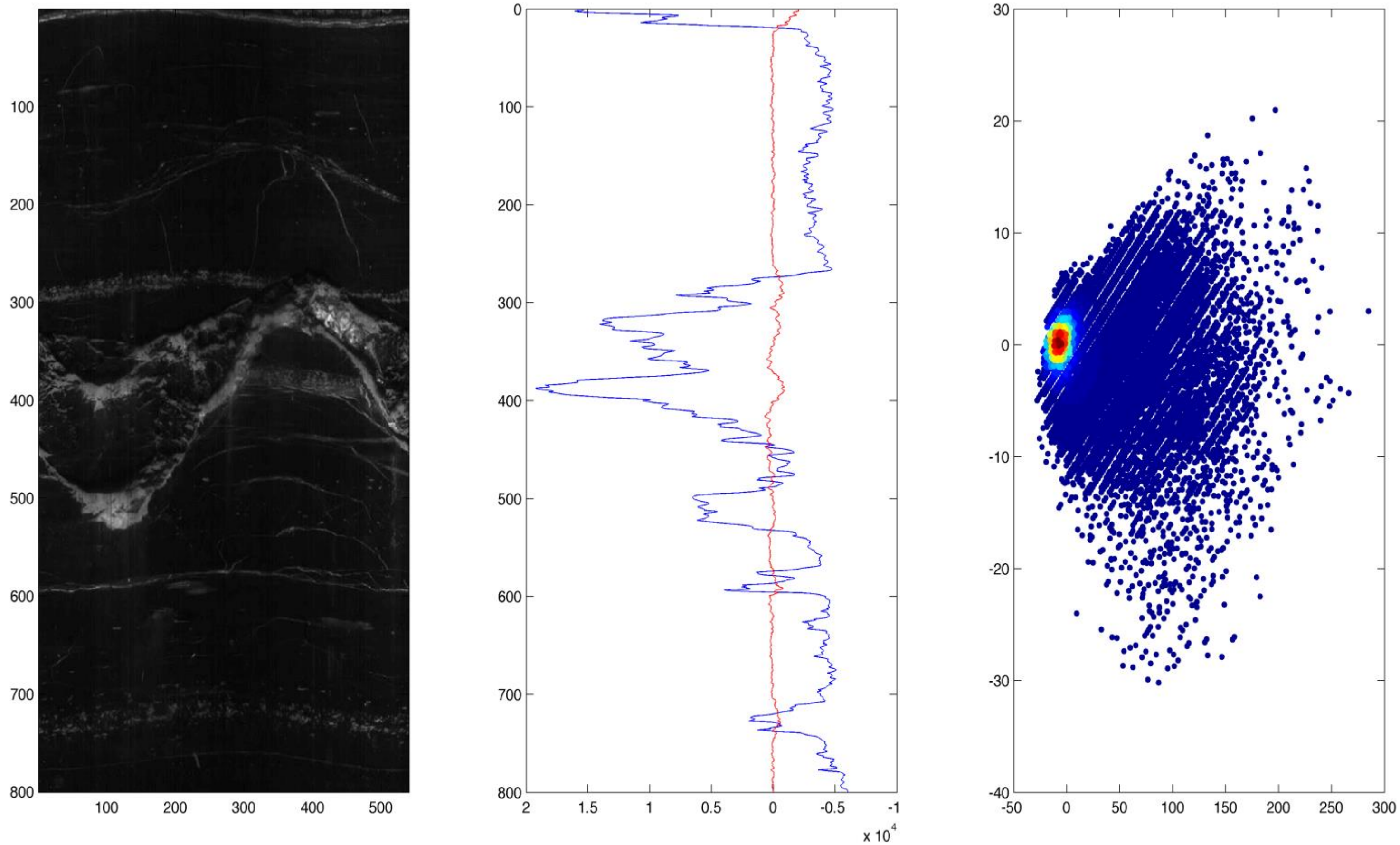
Cumulative score sum / row-for-row …



Distinguishable vein materials (most likely calcite vs. baryte)

GEUS

t_1 – score: R/G/B image log
t_2 – score: R/G/B image log



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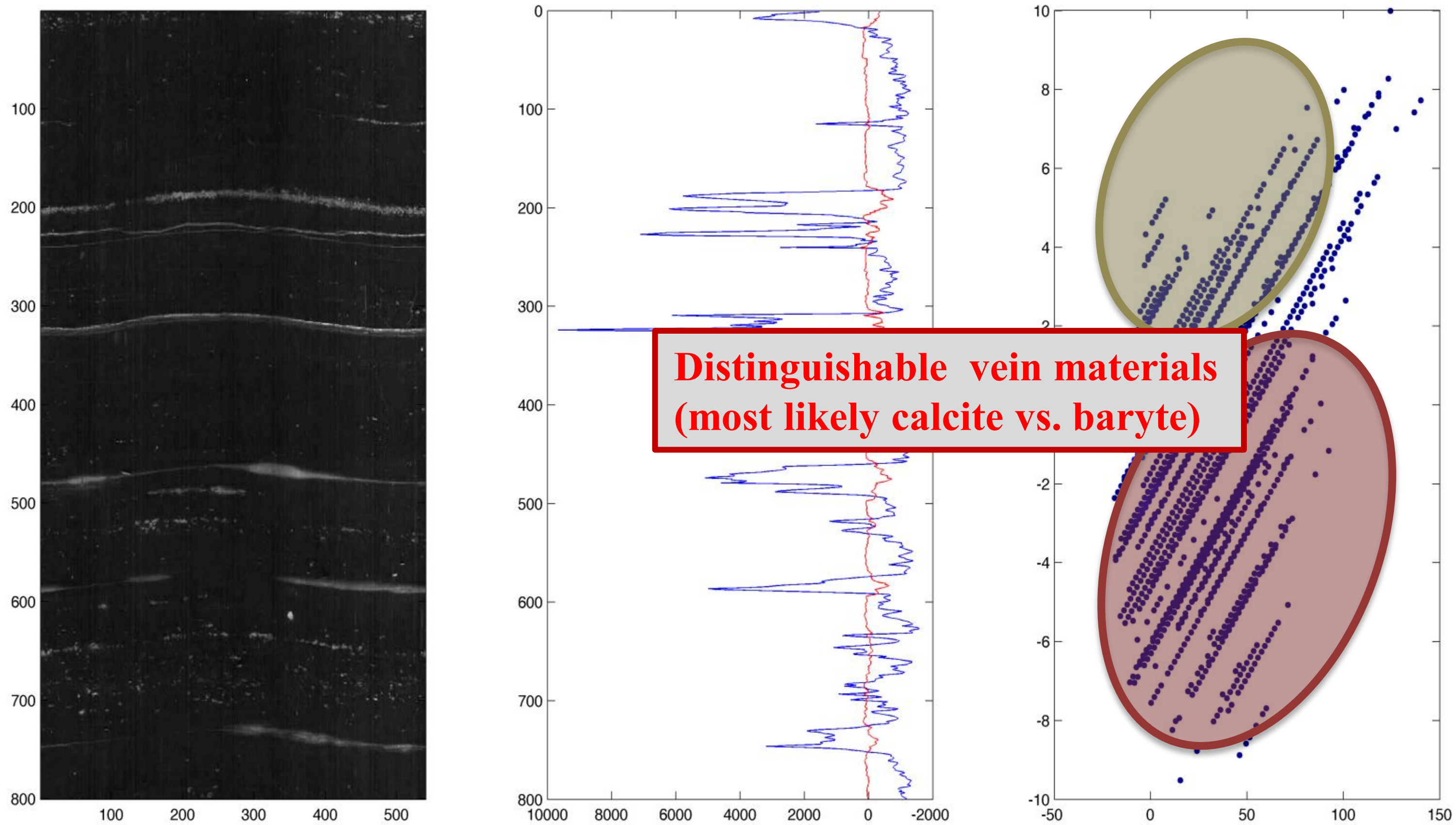

Distinguishable vein materials (most likely calcite vs. baryte)

GEUS

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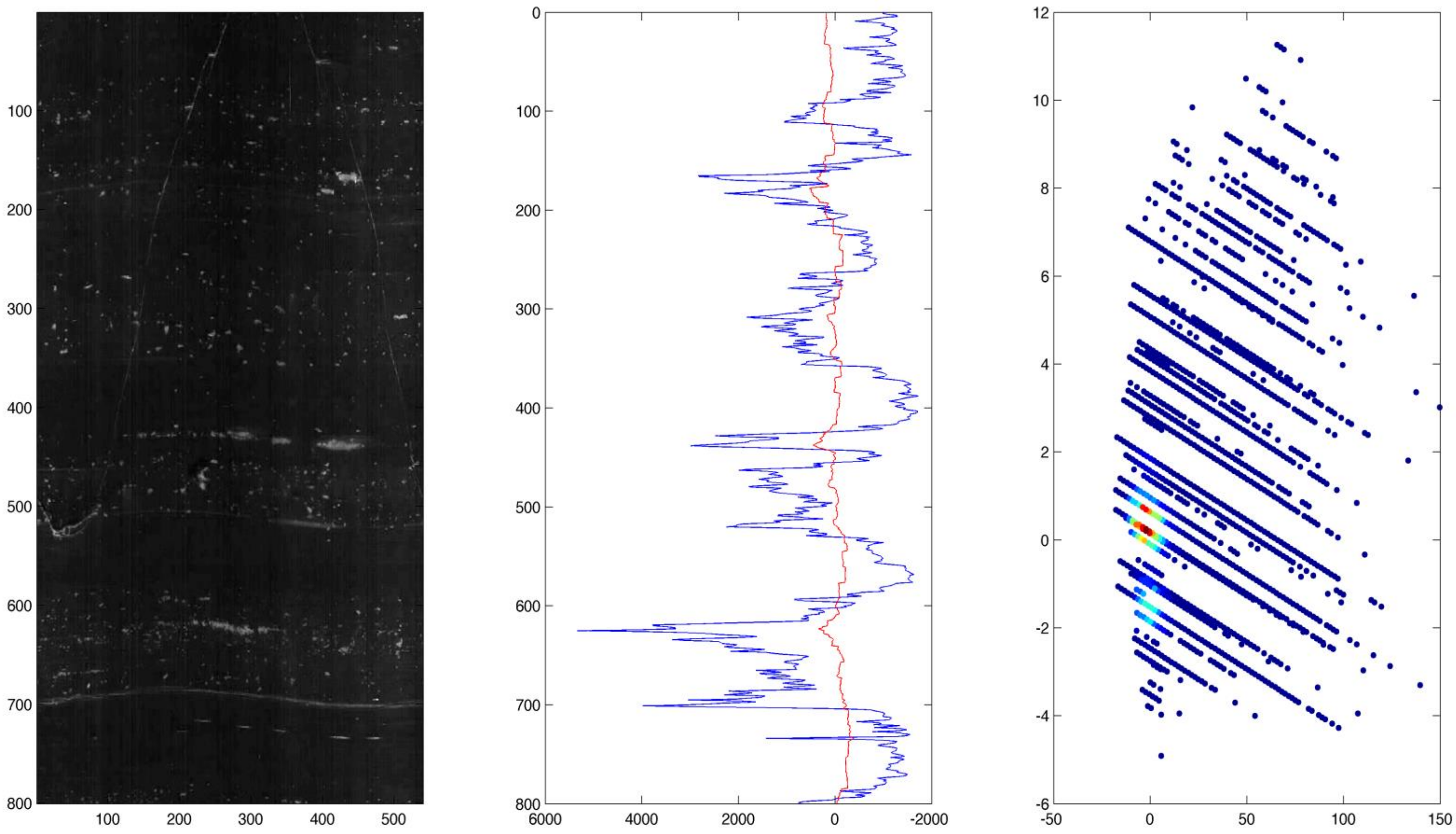
t_2 – score: R/G/B image log



GEUS

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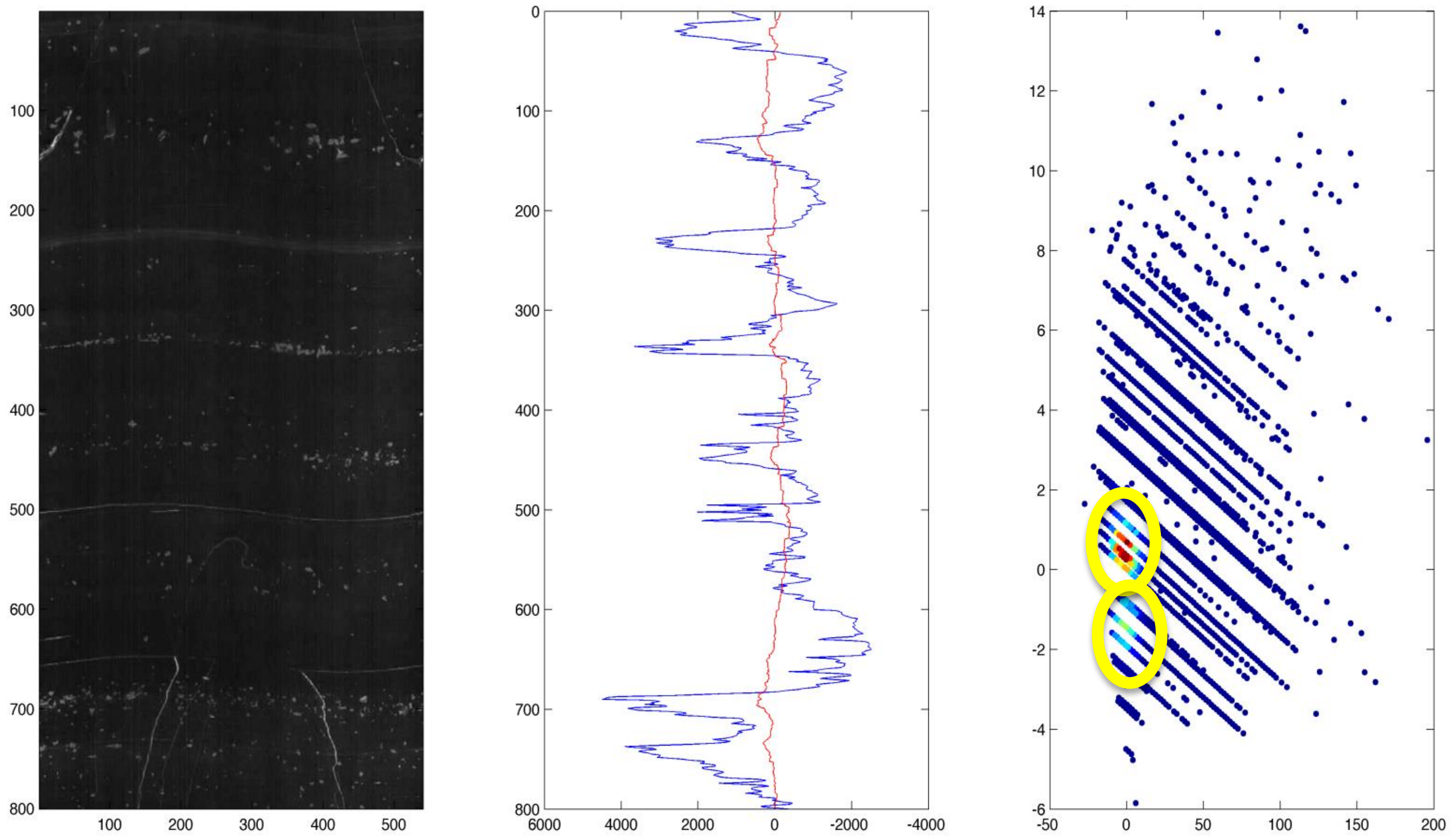
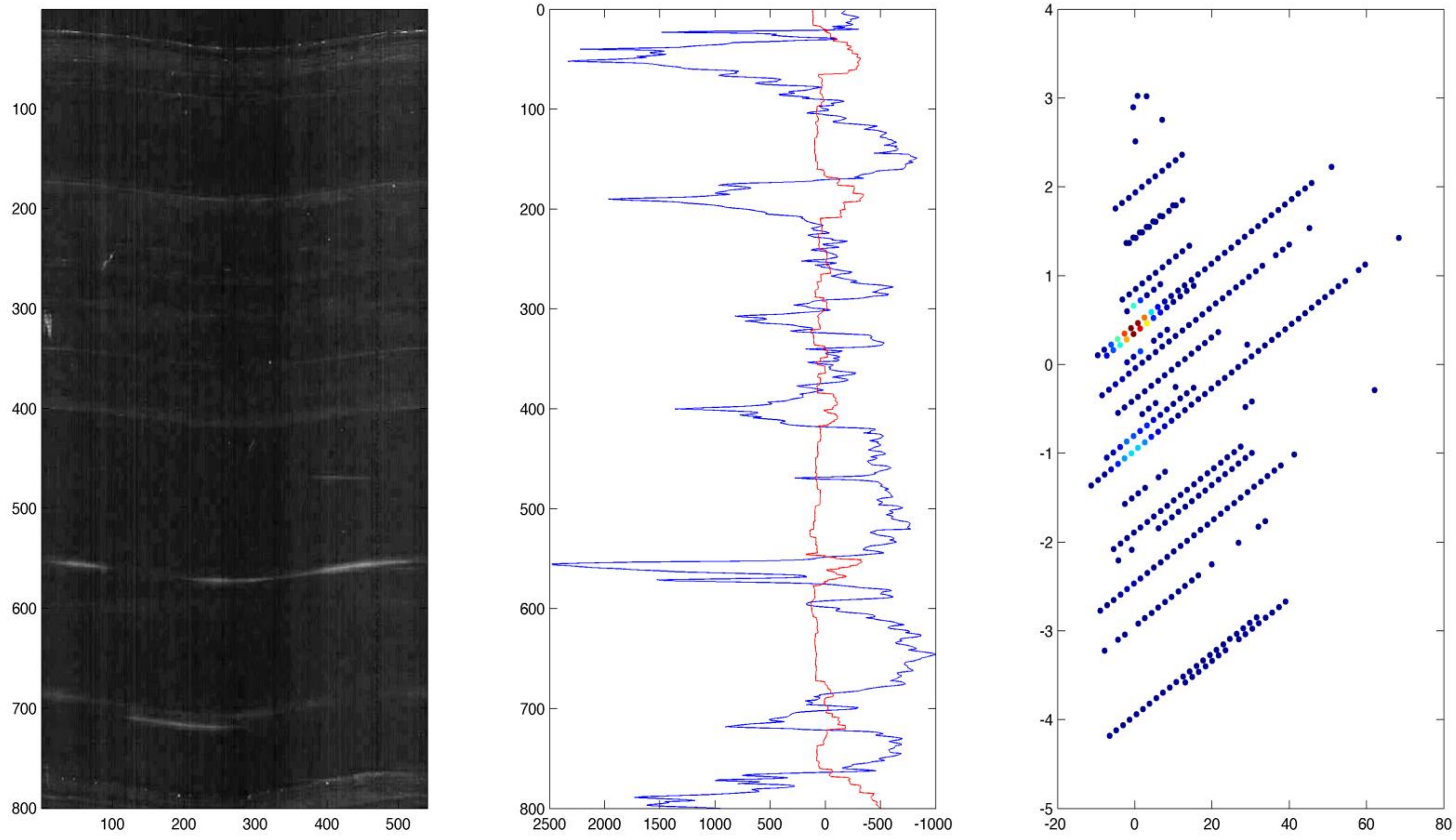
t_2 – score: R/G/B image log



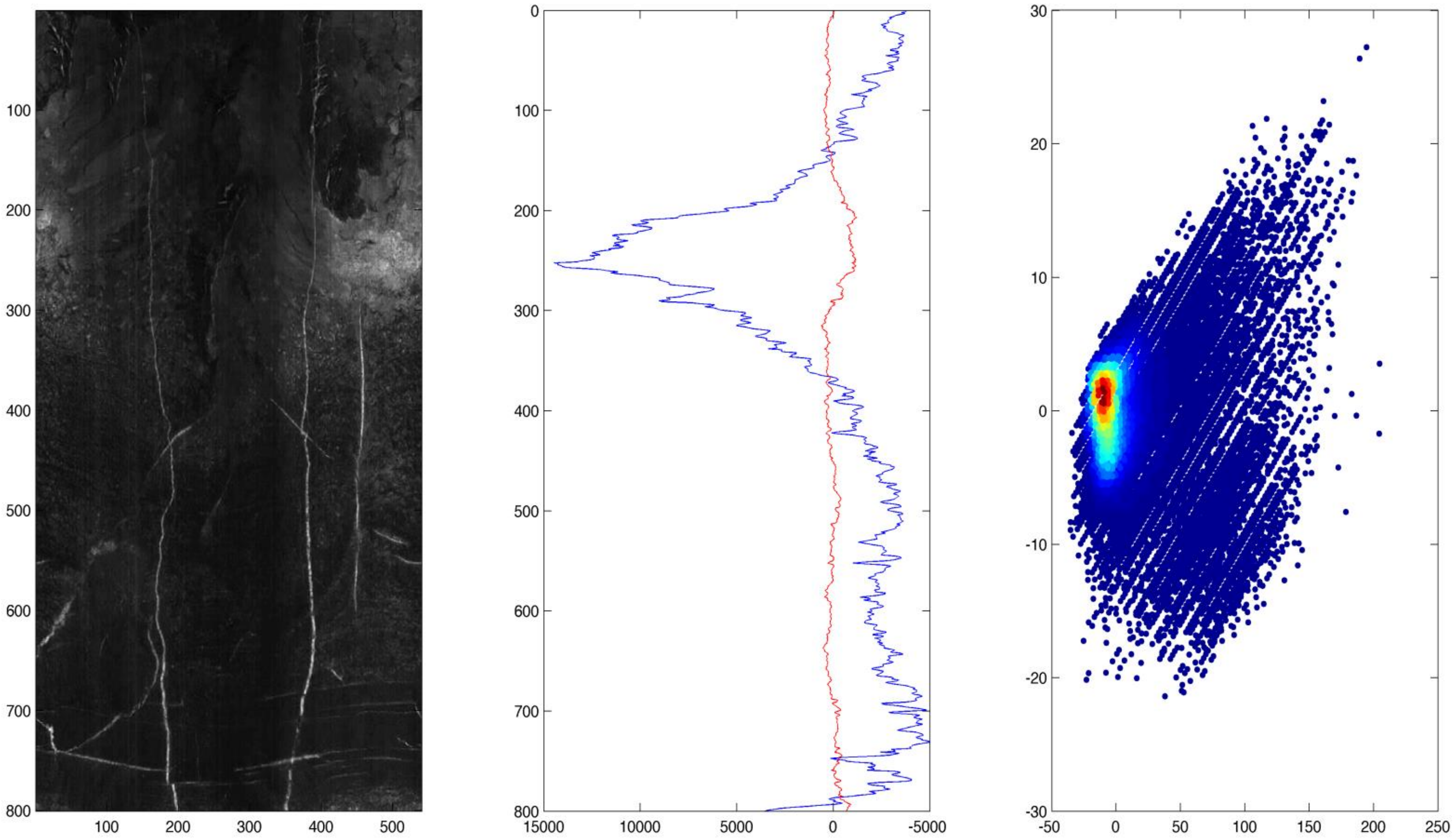
GEUS

t_1 – score: R/G/B image log
t_2 – score: R/G/B image log

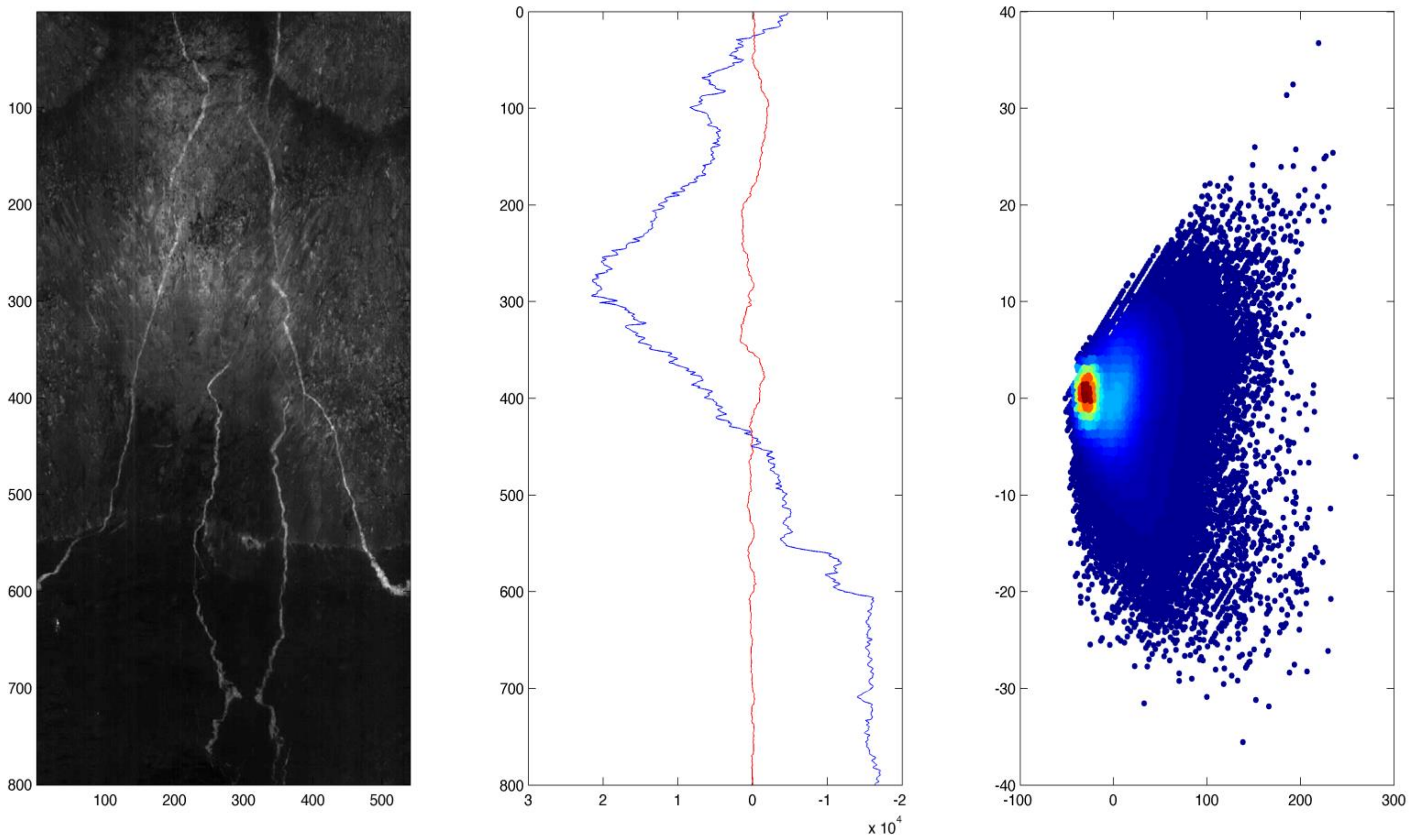


GEUS

t_1 – score: R/G/B image log
t_2 – score: R/G/B image log



t_1 – score: R/G/B image log
t_2 – score: R/G/B image log



Core measurements in the Billegrav-2

Rock strength

Formation	Acoustic velocity measurements		Unconfined compression test		Brazil tests	
	Plug samples	Test specimens	Plug samples	Test specimens	Plug samples	Test specimens
Rastrites	8	18	4	4	2	3
Lindegård	1	3	0	0	0	0
Dicellograptus	2	7	1	3	1	2
Alum	6	14	2	4	3	5
Total	17	42	7	11	6	10

Rock strength analysis made in the Billegrav-2 (GEUS) (above)
and Skelbro-2 (GASH).

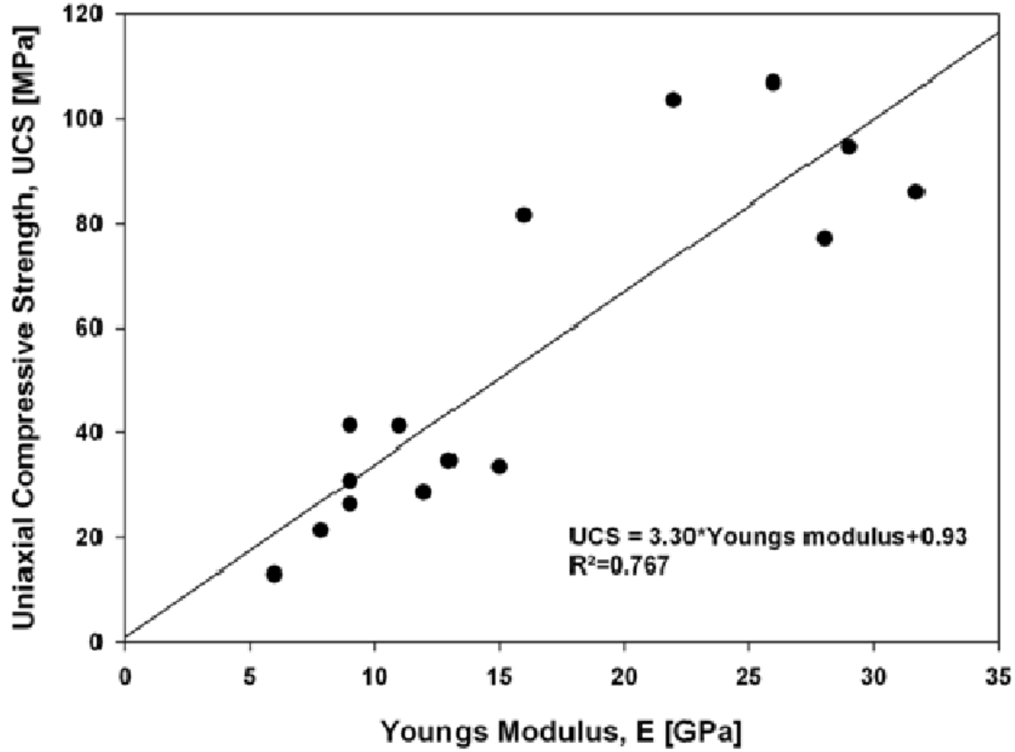


Figure 3: Youngs Modulus versus uniaxial compressive strength for Alum Shale samples from Skelbro-2.

Rock Strength measurements in the Skelbro-2 well, GASH data. All samples are the Alum Shale. High values probably reflect carbonate rich samples (un-clear from text)

Core Measurements in the Billegrav-2

Lab no	Depth	Formation	ρ bulk	Moisture	σt	σt	σc	E	V
	m		g/cm3	%	MPa	PSI	MPa	MPa	MPa
4A	19.87	Rastrites	2.48	3.2			67.5	10129	0.29
4B	19.87	Rastrites	2.48	2.8			65.7	9874	0.14
5	23.18	Rastrites	2.5	2.5	2.63	381			
9A	41.02	Rastrites	2.61	2			19.2	6170	0.08
9B	41.2	Rastrites	2.6	1.9			27.7	5847	0.22
10A	42.74	Rastrites	2.57	2.4	2.75	399			
10B	42.74	Rastrites	2.57	2.5	6.19	898			
17A	76.82	Dicellograptus	2.51	2.8			27.1	5144	0.06
17B	76.85	Dicellograptus	2.49	2.9			25.4	7090	0.09
17C	76.85	Dicellograptus	2.47	2.8			29.7	3183	
19A	86.68	Dicellograptus	2.63	1.5	(11.47)	(1663)			
19B	86.68	Dicellograptus	2.59	1.7	4.69	680			
21A	96.76	Alum	2.45	2.6	4.32	626			
21B	96.76	Alum	2.47	2.6	3.37	489			
22C	98.81	Alum	2.46	2.6			17.7	5324	0.24
22A	98.86	Alum	2.49	2.7			20.5	4588	0.2
24A	102.93	Alum	2.47	3.3	2.35	341			
24B	102.93	Alum	2.56	3.2	4.46	647			
27	113.35	Alum	2.51	2.7	3.52	511			
28A	115.67	Alum	2.68	2.5			24.1	5757	0.14
28B	115.67	Alum	2.61	2.4			27.9	6402	0.21

Rock strength analysis made in the Billegrav-2 by GEO. Static young's modulus range between 4.5 – 6.4 GPa

- 4 samples measured

Horizontal:

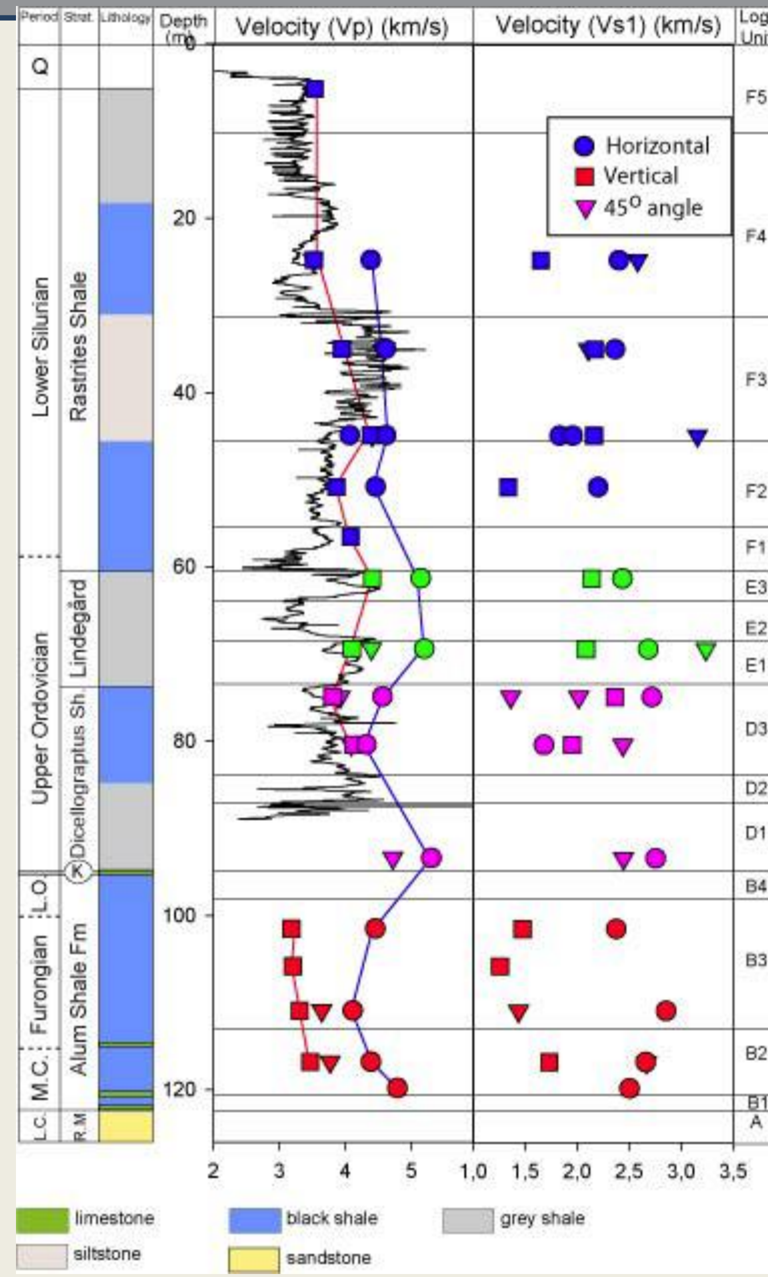
Vp: 4 – 5 km/s

Vs: 2.5 - 3.0 km/s

Vertical:

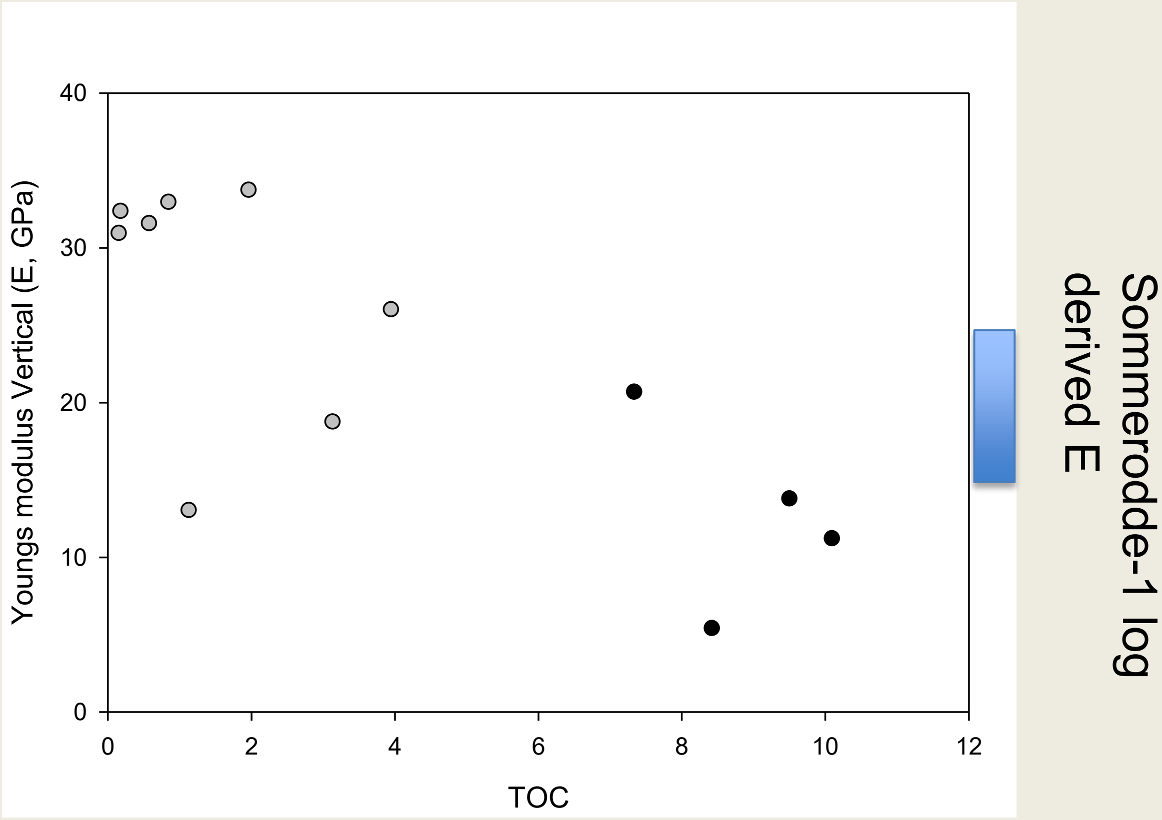
Vp: 3 - 4 km/s

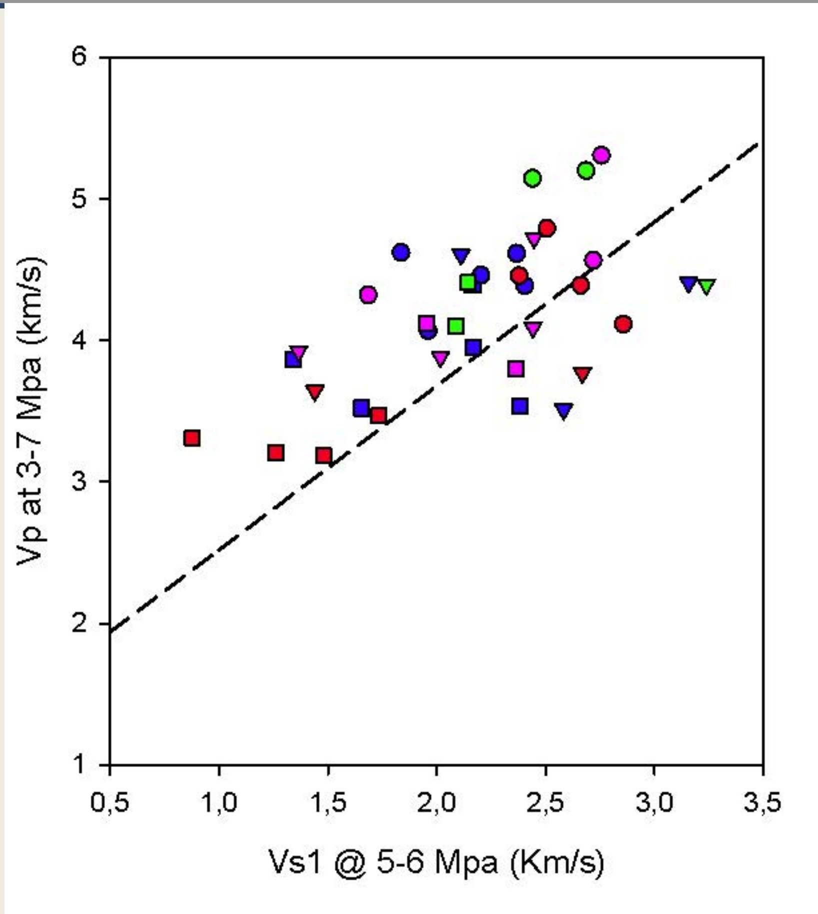
Vs: 1.2-1.7 km/s



- Calculated E from vertical measurements show a dependence to het TOC content

- Black: Alum Shale
- Grey: non Alum Shale

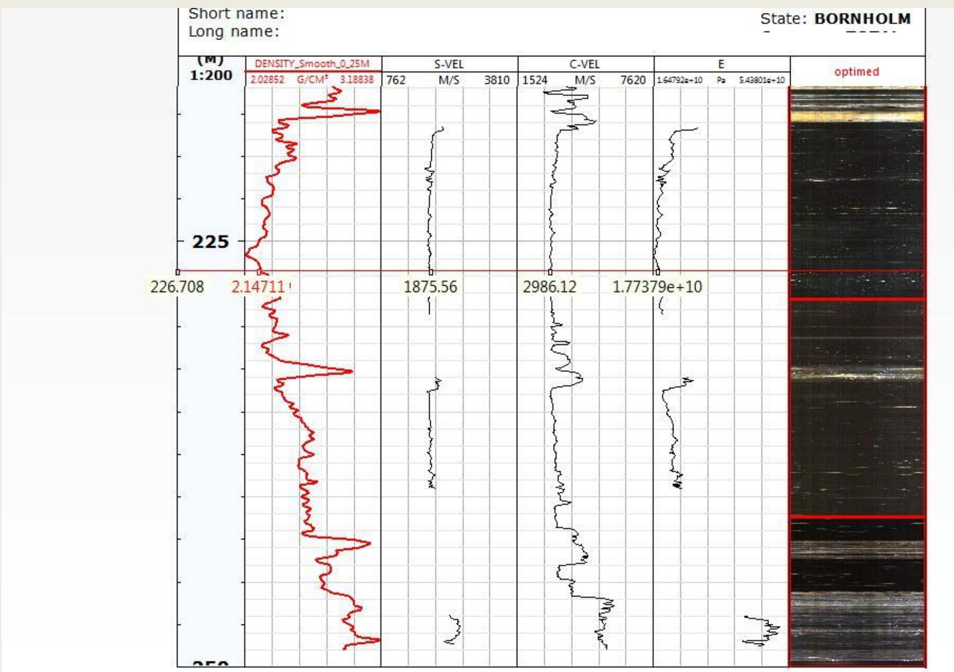


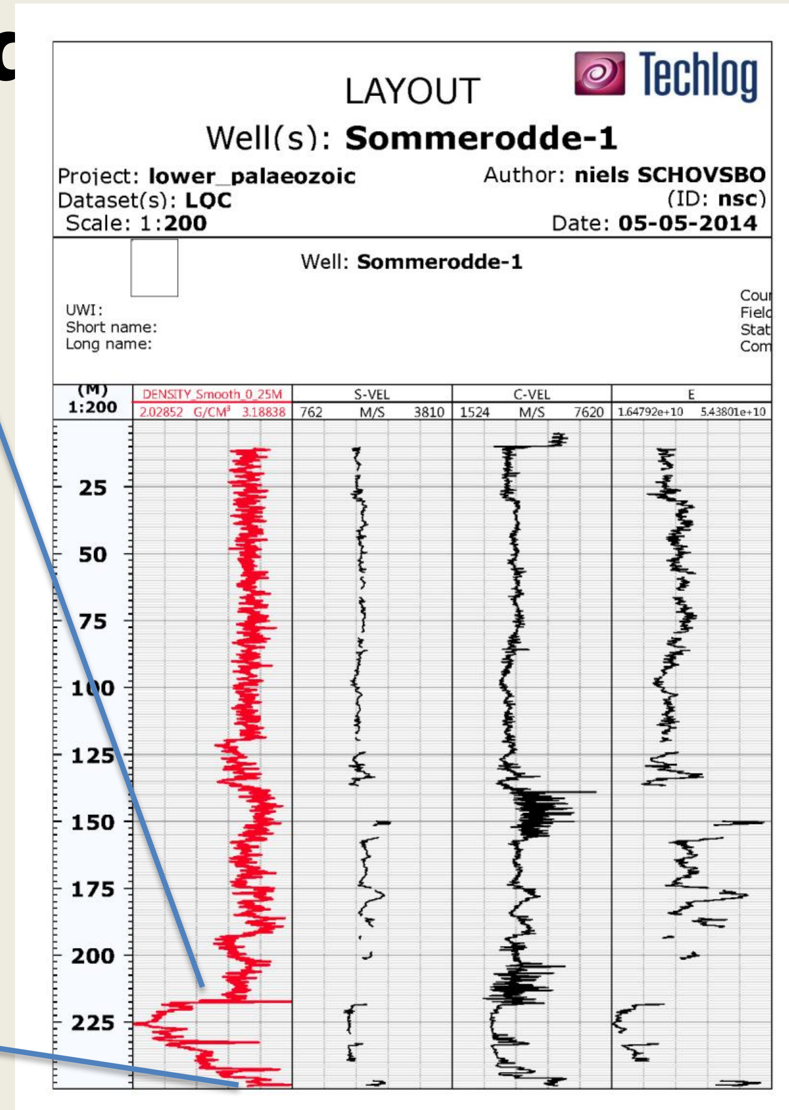


Relationship between core plug measurements of VP and Vs1. Legend: shape of symbols: circles: horizontal to bedding, squares: vertical to bedding, triangles: 45o angle to bedding. Colours: red: Alum Shale, pink: Dicellograptus Shale, green: Lindegård Fm., blue: Rastrites Shale. The mud-rock line (Vp=1.16Vs +136) is shown with broken line for reference (Castagna et al. 1985).

Vp and Vs measurements Sommerod

- Log calculated E range between 17-24 GPa
- Vp, Vs has same trend as core measurements in the Billegrav-2





Rock strengths

- Rock strength data exist on Bornholm where a condensed variety of the "Alum Shale type 4" heterogeneous TOC rich shale exist
- This type is expected to be the least brittle of all Alum Shale rock types.
- Validation that the shale in Albjära has similar strength is needed.

Criteria for rock type definitions

- Step 1: PCA on the following parameters (Logs, Mineralogy, age,…) we should be able to determine 4 or 5 rock types.
  - Data collection (XRF, XRD) near complete
- Step 2: Review the variance of each rock type and associate the Geo-mechanics parameters (Dynamic Young, Poisson ratio, Recalc UCS..)
  - Review and analysis in Sommerodde near complete
- Step 3: Brinell test on each rock type, to associate some ‘strength’ value of the rock
  - To be sampled
- Step 4: Triax analysis for each rock type, we should be able to validate some kind of relationship between the brinell, the Dynamic E, and the static E
  - To be sampled

Milestones

- Criteria for rock type definitions made by 15/5-2014
- Sampling of Rock types made by 21/5 -2014
- Variability analysis of rock types made by 1/6-2014
  - Flag-curves or variograms?
- Potential zones for stimulation made by 16/6-2014
- Predictive model (PLS) made by 16/6-2014

3.2. Sampling of rock types in the Furongian for frac. fluid testing

GEUS

Rock Types in the Alum Shale

Sampling of rock types in the Furongian for frac. fluid testing
version 0, 20/5-2014

Niels H. Schovsbo, Kim Esbensen & Arne T Nielsen

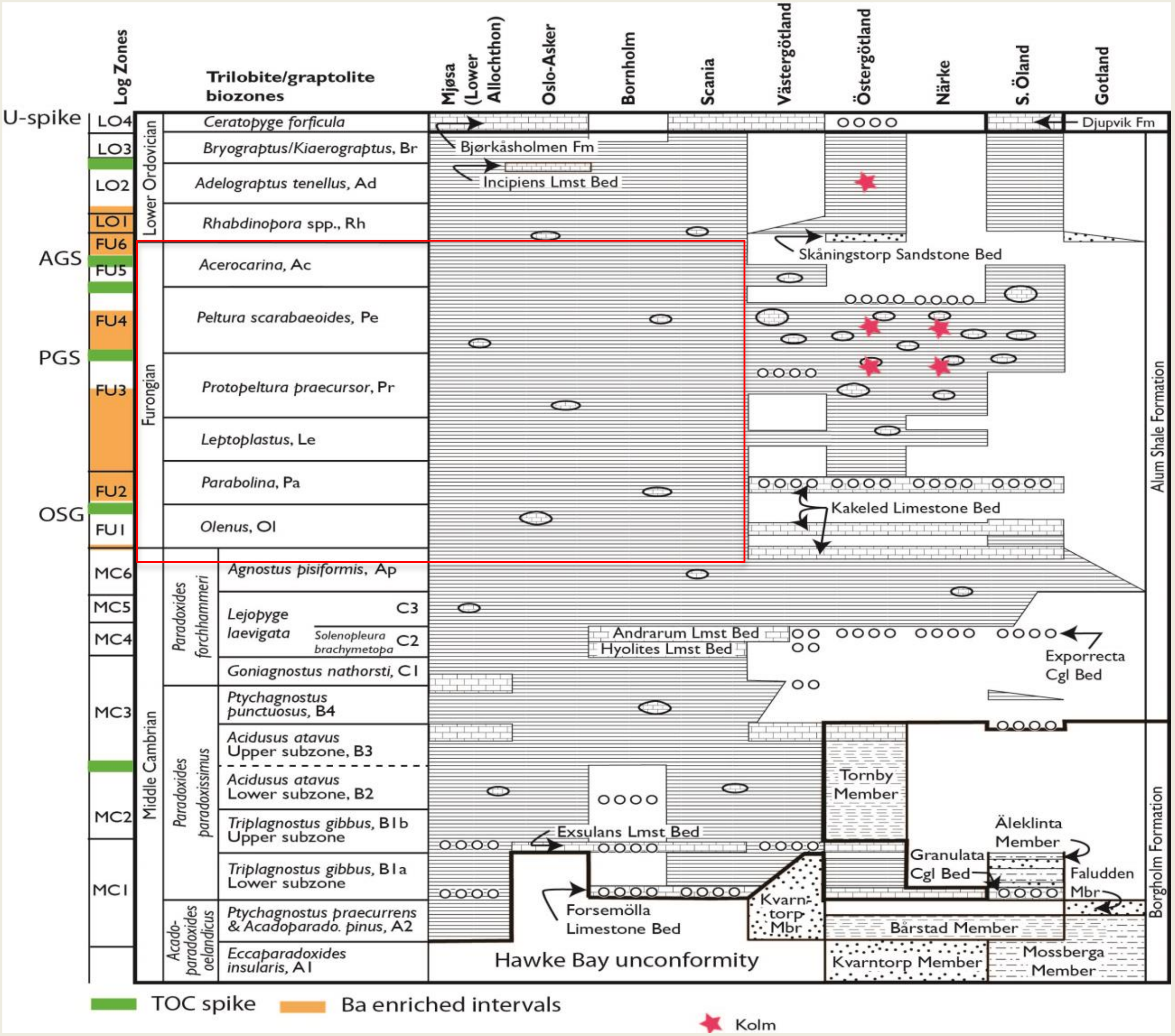
De Nationale Geologiske Undersøgelser for Danmark og Grønland
Klima-,Energi- og Bygningsministeriet

The Furongian holds the highest TOC content on average.

Formation/age	Terne-1					Albjära-1				
	Thick, m	Avg TOC	STD TOC	Max TOC	Min TOC	Thick. m	Avg TOC	STD TOC	Max TOC	Min TOC
Alum Shale:	180,0	6,4	2,6	13,7	1,8	97,8	8,2	3,2	15,3	0,5
Tremadoc	34,1	4,1	1,2	6,3	2,4	7,0	6,2	2,6	11,8	0,7
Bryograptus	13,4	3,0	0,6	3,8	2,4	3,0	4,4	2,0	7,1	0,7
Adelograptus	16,6	5,0	0,8	6,3	3,8	2,0	5,4	2,4	11,8	0,7
Rhapdinopora	4,4	5,4				2,5	6,5	2,3	11,8	1,7
Furongian	64,5	9,0	1,9	13,7	6,5	58,7	10,1	2,2	15,3	4,9
Acerocare	12,6	8,2	1,8	10,7	6,6	12,6	10,2	2,1	14,3	7,3
Peltura scarabaeoides	14,6	10,9	2,0	13,7	9,2	13,5	10,6	2,0	15,3	7,3
Peltura minor	5,4	10,2	0,0	10,3	10,2	4,1	11,5	1,7	14,3	8,8
Protopeltura praecursor	4,4	7,5				4,8	11,5	1,6	14,6	8,7
Leptoplastus	2,1	7,6				2,5	10,4	1,1	11,5	8,7
Parabolina spinulosa	10,1	7,3	0,8	7,9	6,5	9,0	7,8	1,2	10,0	5,4
Olenus	15,2	8,8	1,8	11,1	7,0	12,2	10,2	2,4	14,9	4,9
Mid Cambrian	79,7	5,2	1,5	7,2	1,8	32,0	5,3	2,1	10,4	0,5
Agnostus pisiformis	5,7	7,1	0,2	7,2	6,9	4,5	7,2	1,2	10,4	4,9
Paradoxides forchhammeri	28,4	5,7	1,0	6,8	4,2	9,8	5,9	2,4	8,4	0,7
Paradoxides paradoxissimus	51,2	5,0	1,5	6,8	1,8	17,7	4,4	1,6	7,4	0,5

Green: TOC >10%, orange TOC 8-10%

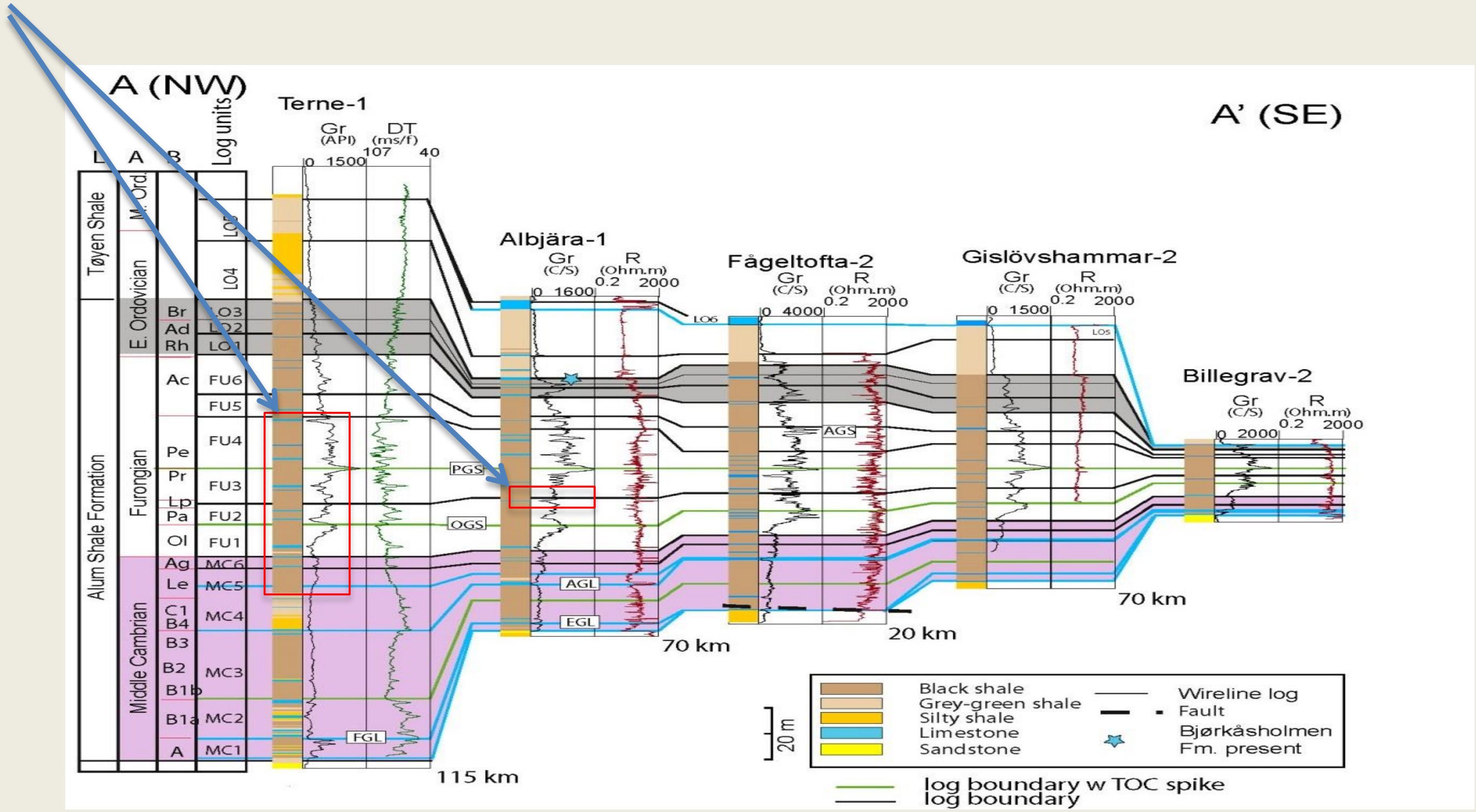
Stratigraphy



Shale with few concentrations (Ba, Ca, FeS) expected

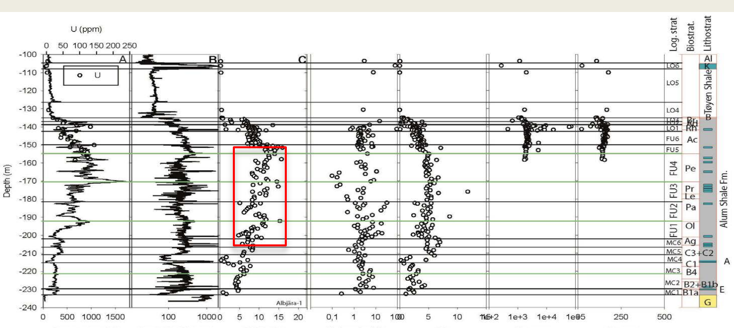
Furongian – most likely zone to fracture in

- If the fracture initiation Zone is to be at least 40 m from top and base then the Furongian will the most likely spot

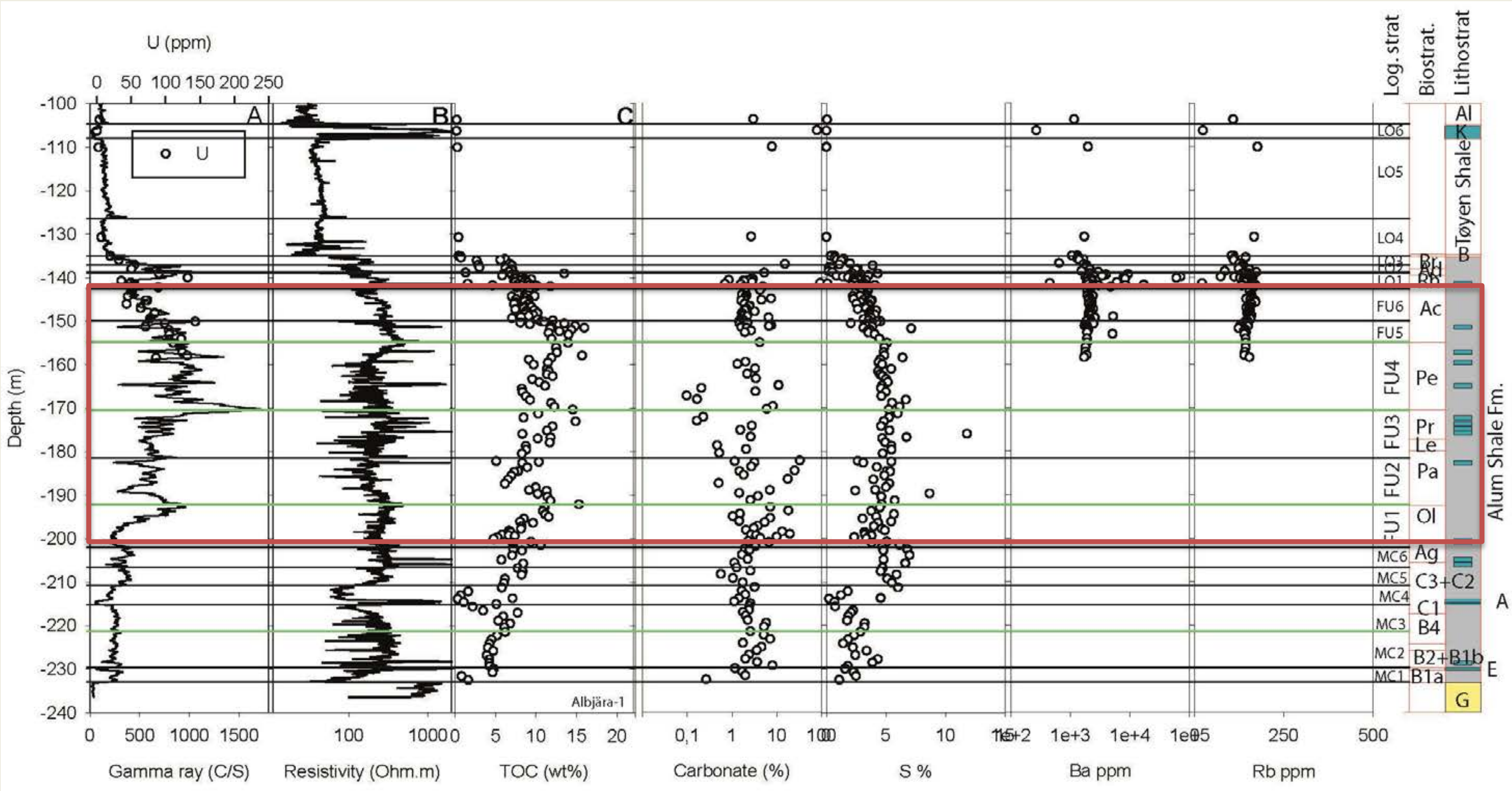


Facies in Furongian

- High TOC type, high sulphur and with carbonate concentrations
- The pyrite in the Albjära-1 core is weathered and particulate S rich intervals are white coloured.

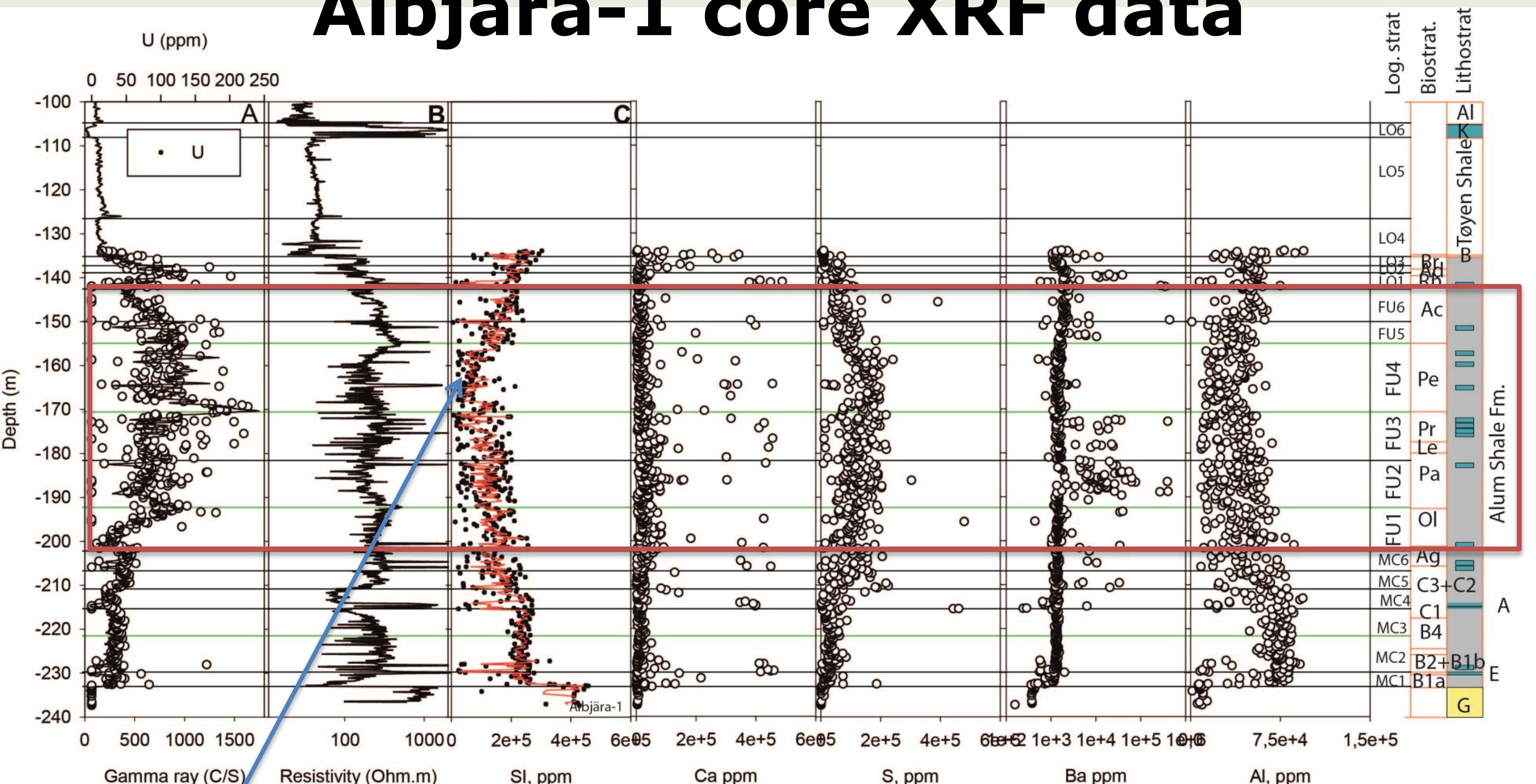


Albjära-1 core data

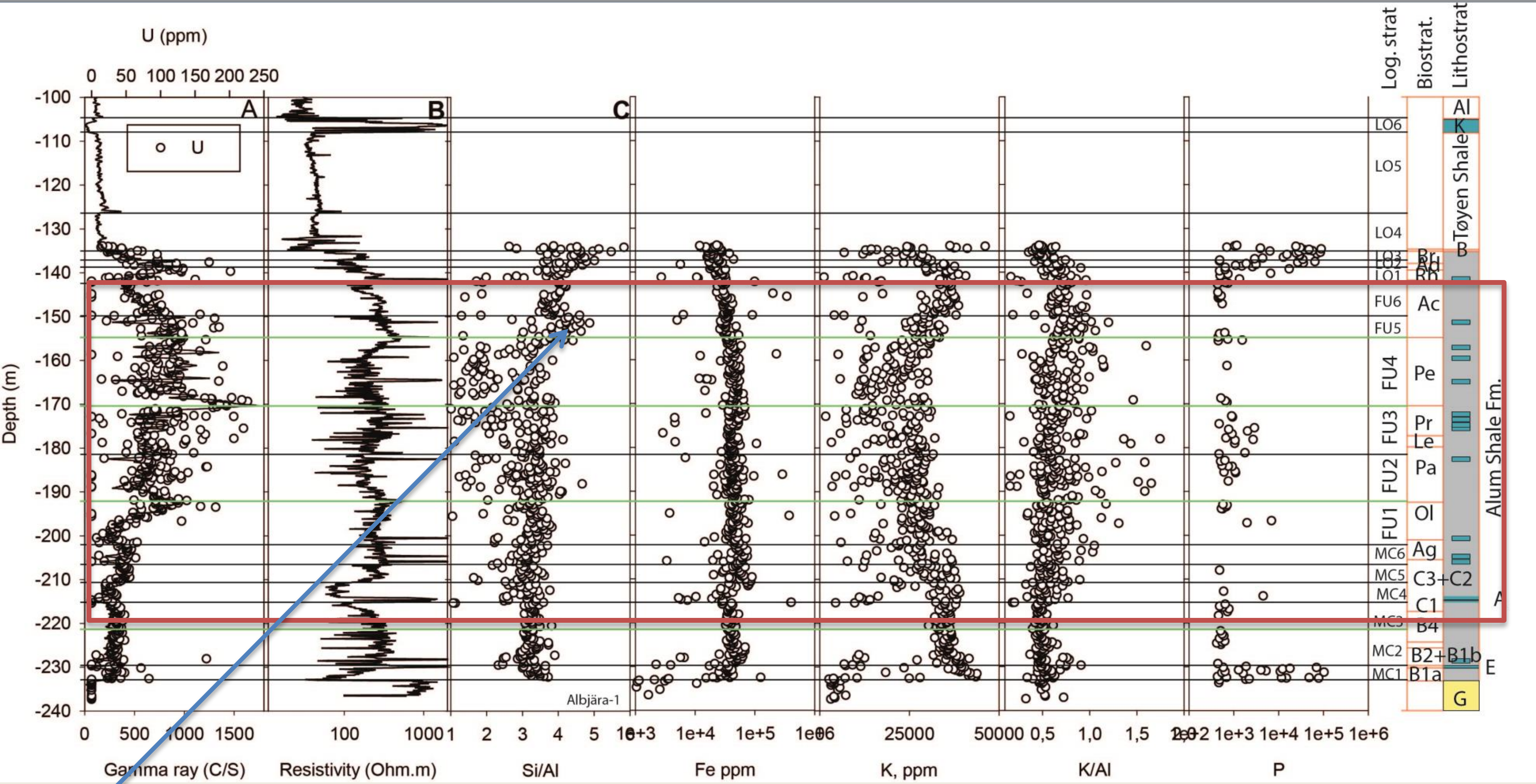


- Furongian is 60 m thick and represent the on average highest TOC interval

Albjära-1 core XRF data



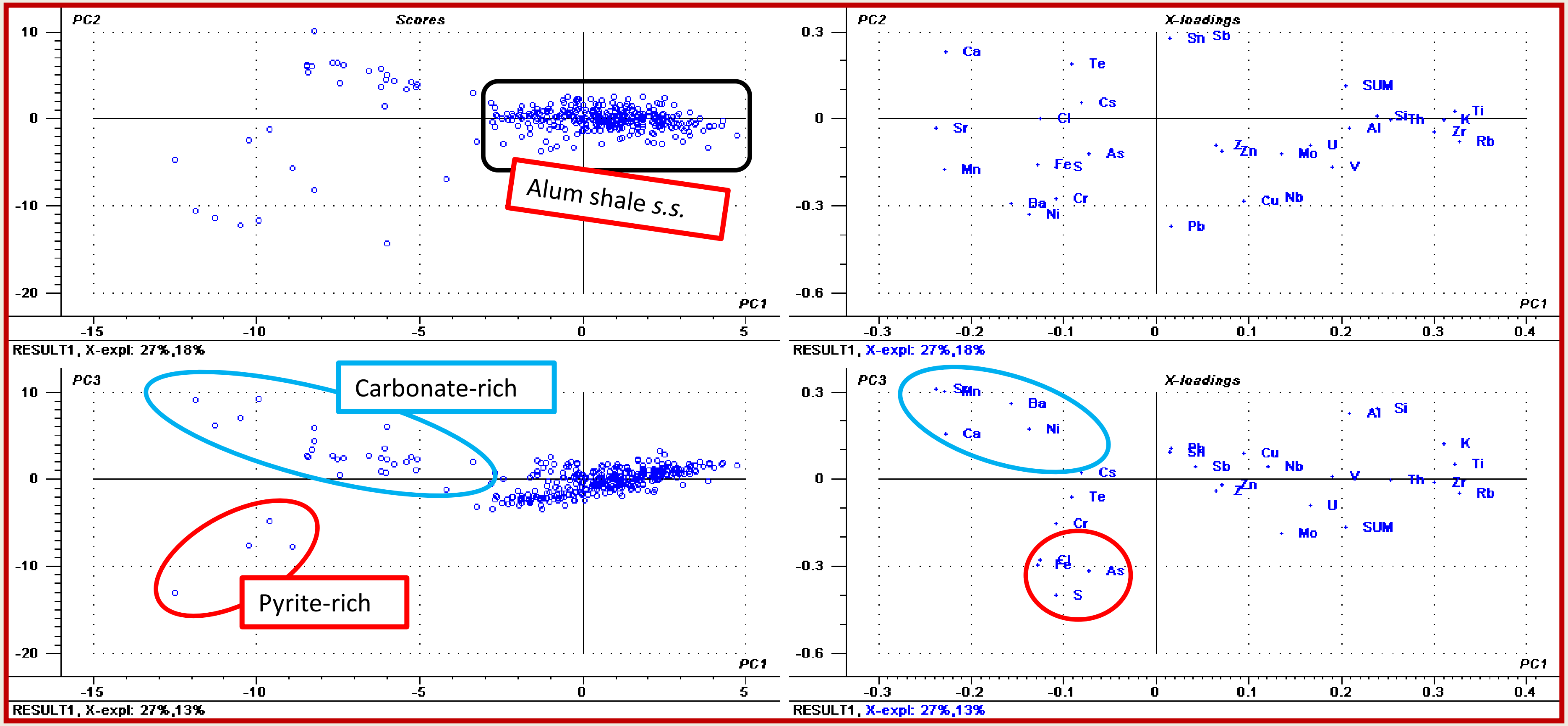
- Lowest Si content in the FU4 zone
  - Expected to be have the potential least rock strength



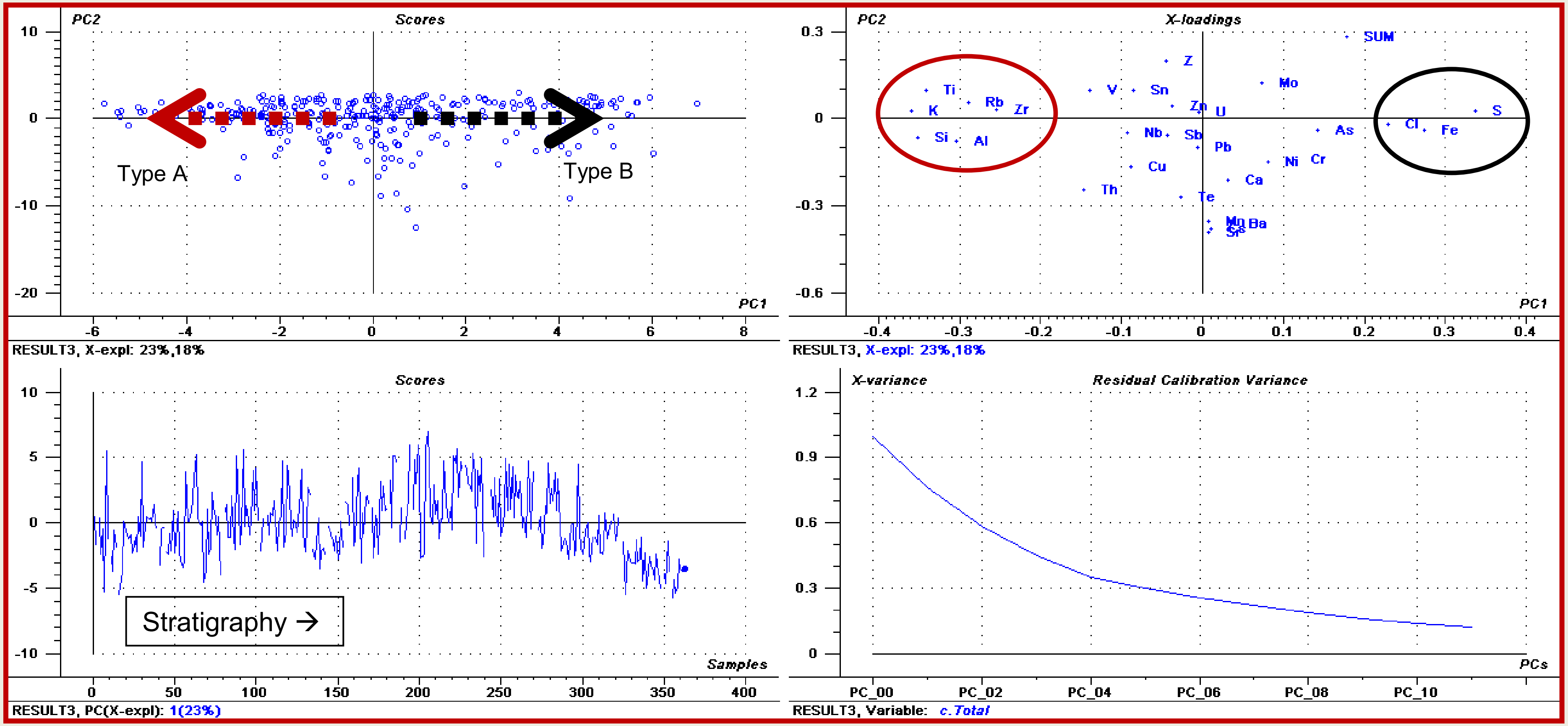
The Si/Al is fairly constant in the Furongian. Only the FU5 zone has relative high Si/Al ratio. This is also the zone with highest avg TOC content.

- High Si and highest Si/Al ratio in the zone FU5
  - Expected to have a potential high rock strength

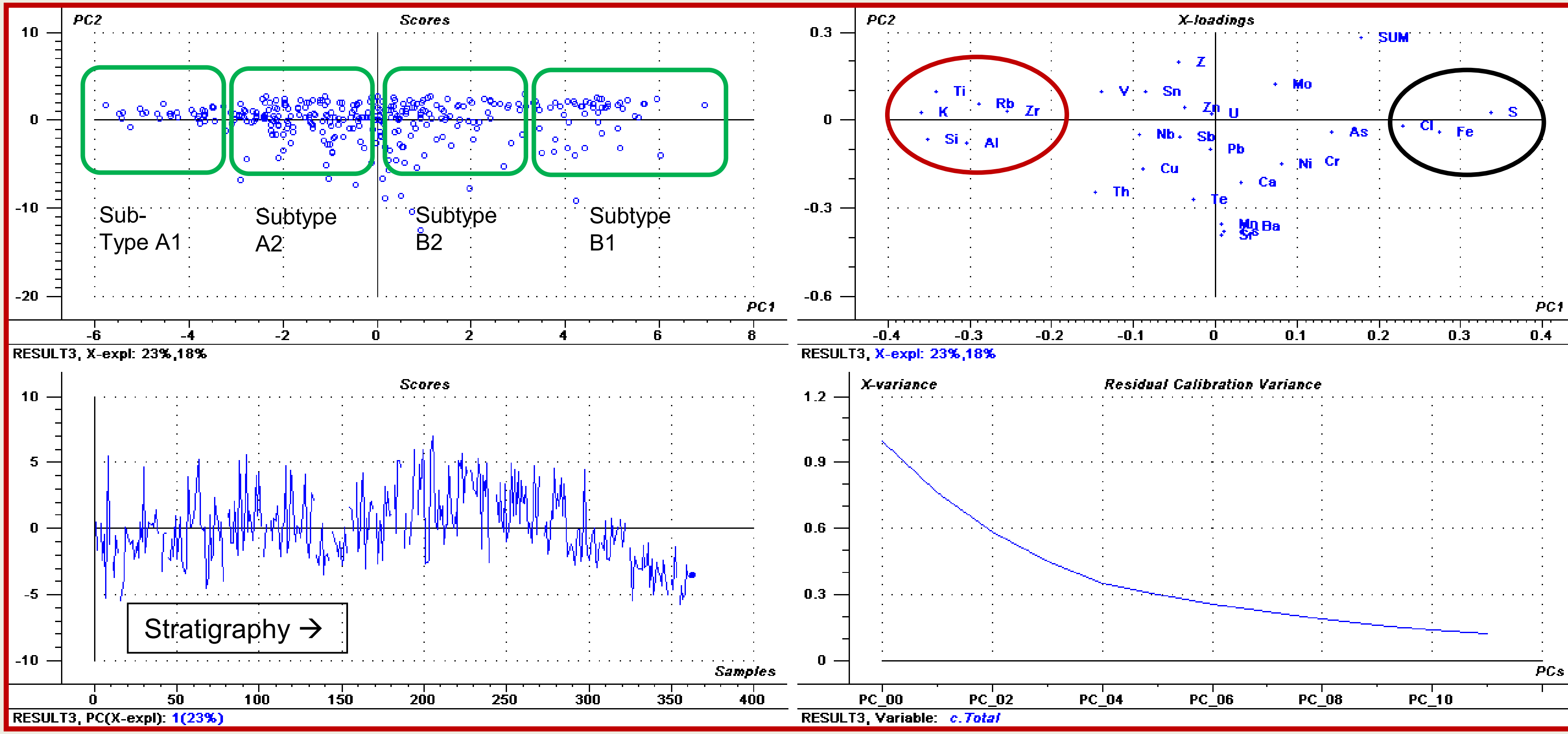
PCA analysis –Furongian only



Removing of outliers (concretions – non-shales).
Focus on Alum Shale s.s.

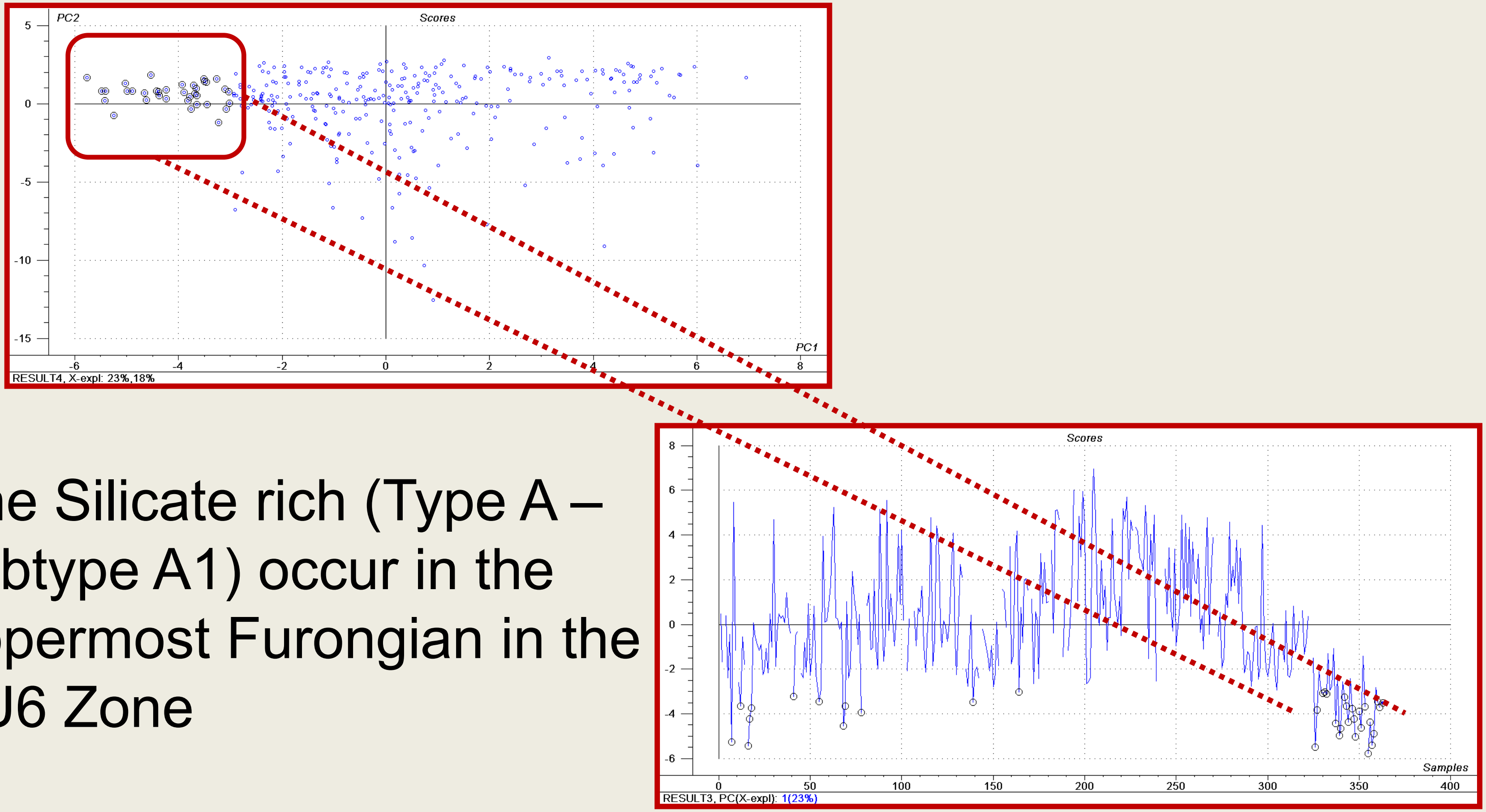


Two end-member system:
a silicate rich (Type A) and a sulphide rich (Type B)

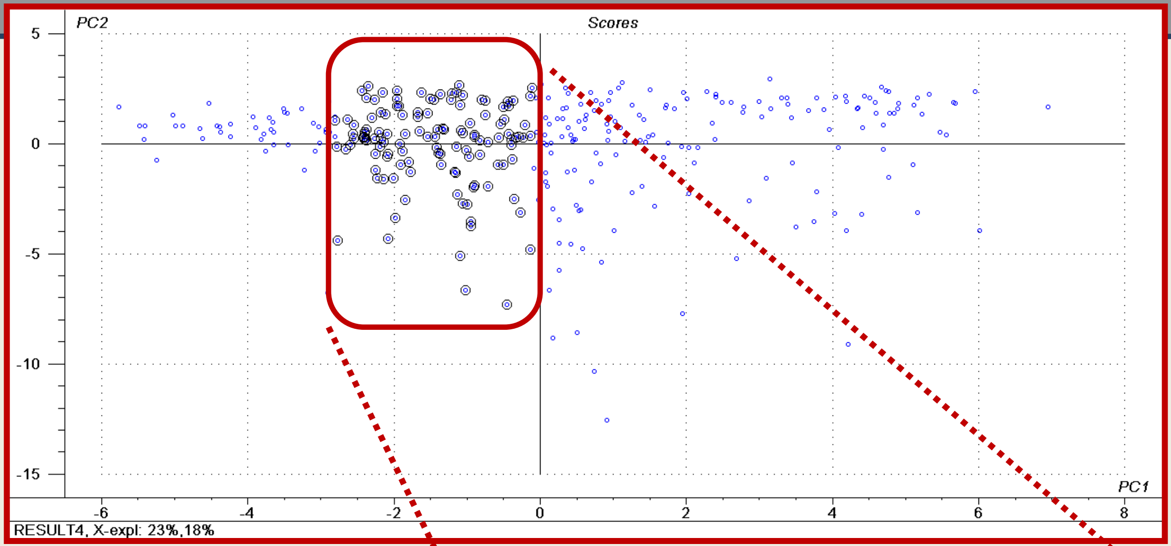


The two end-member system can be detailed:

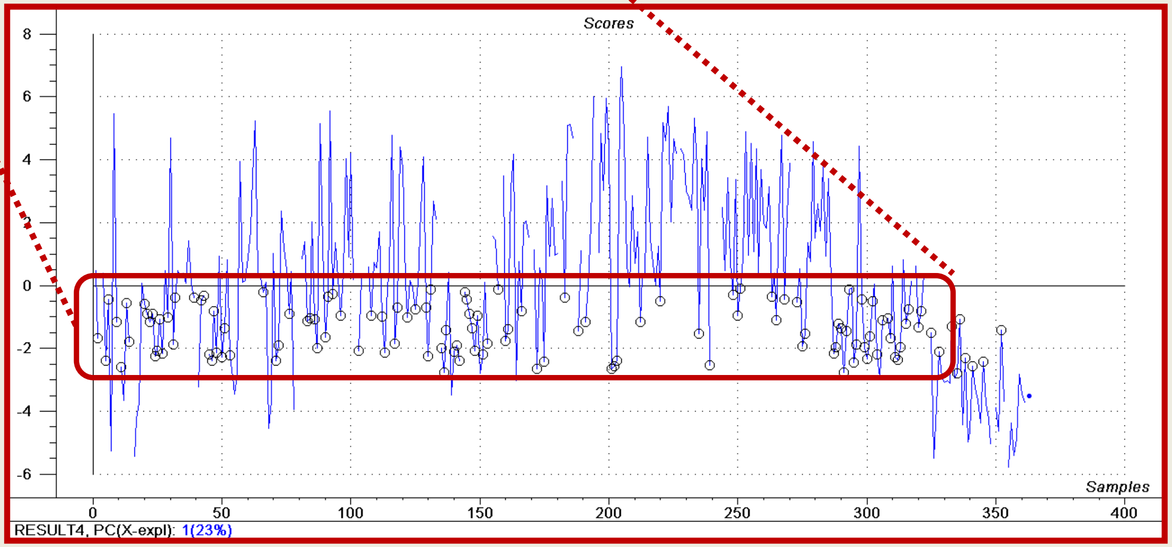
a silicate rich (subtype A1, A2) and a sulphide rich (subtype B1,B2)

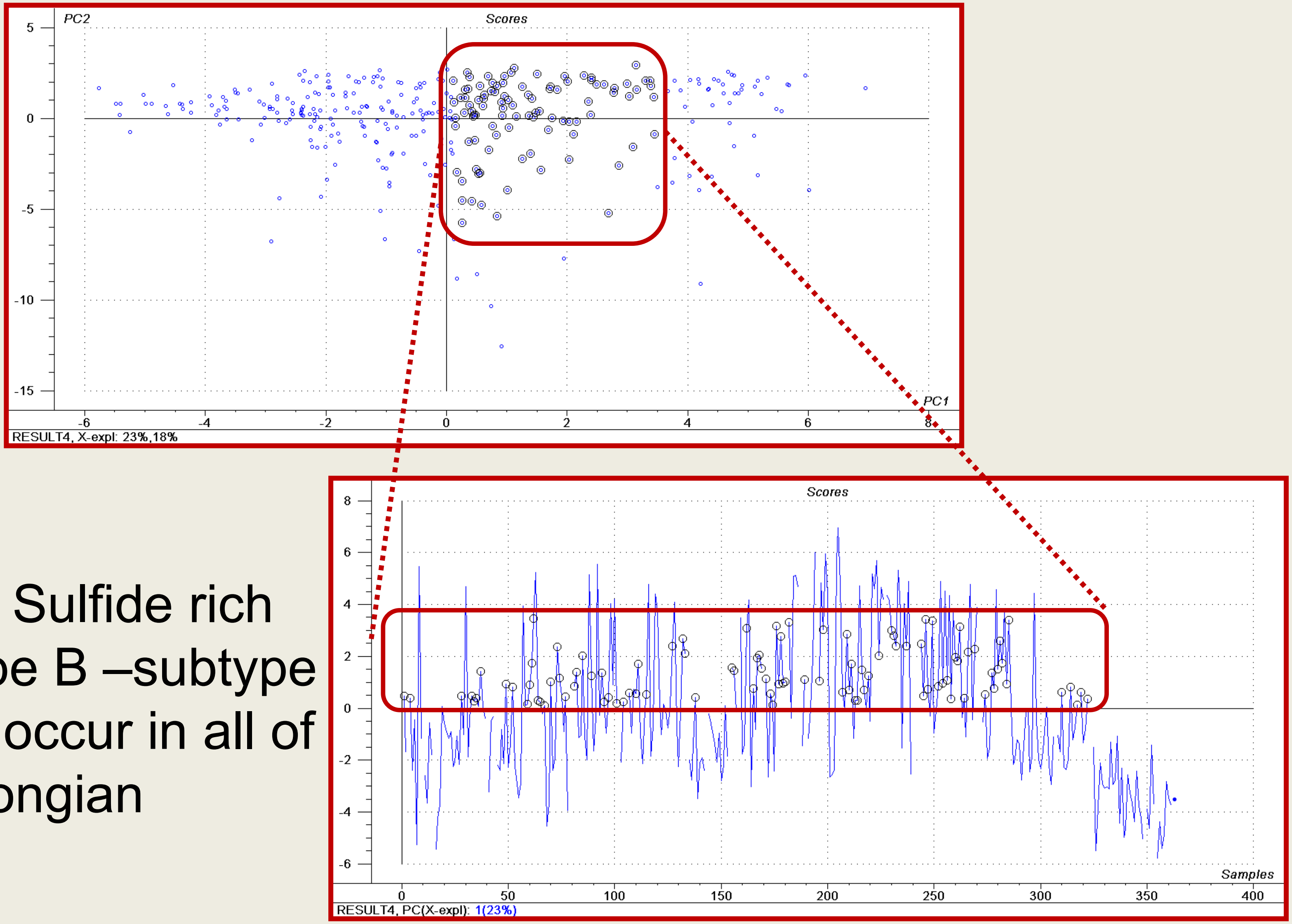


The Silicate rich (Type A – subtype A1) occur in the uppermost Furongian in the FU6 Zone

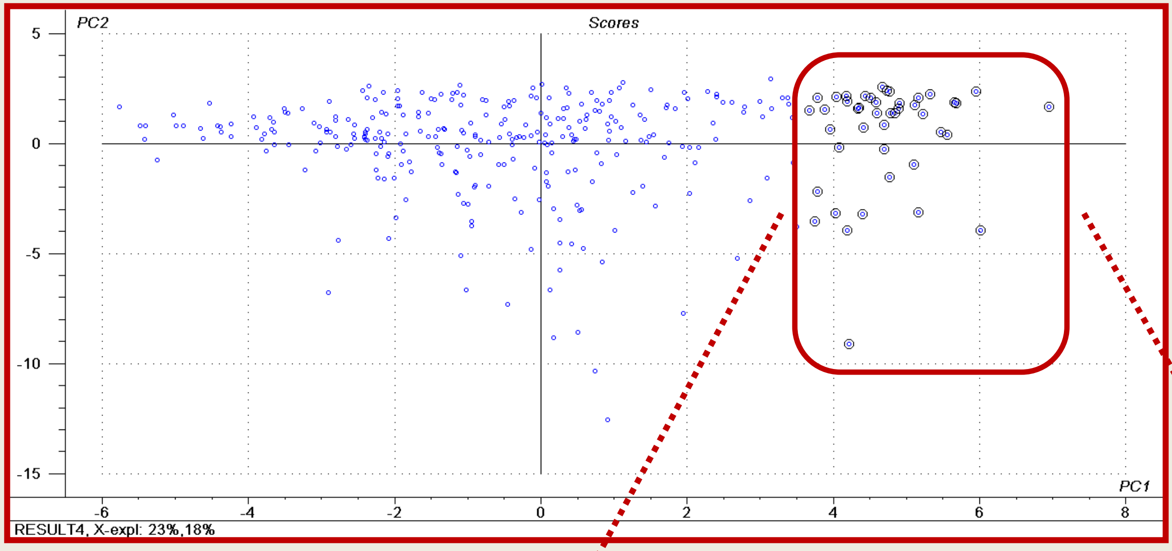


The Silicate rich (Type A –subtype A2) occur in all of Furongian

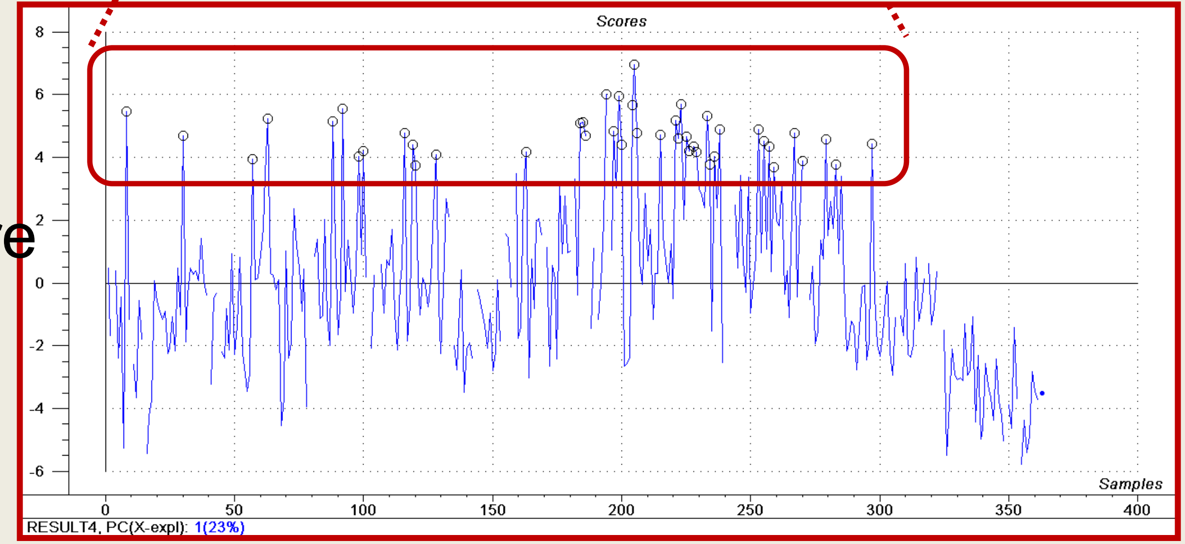




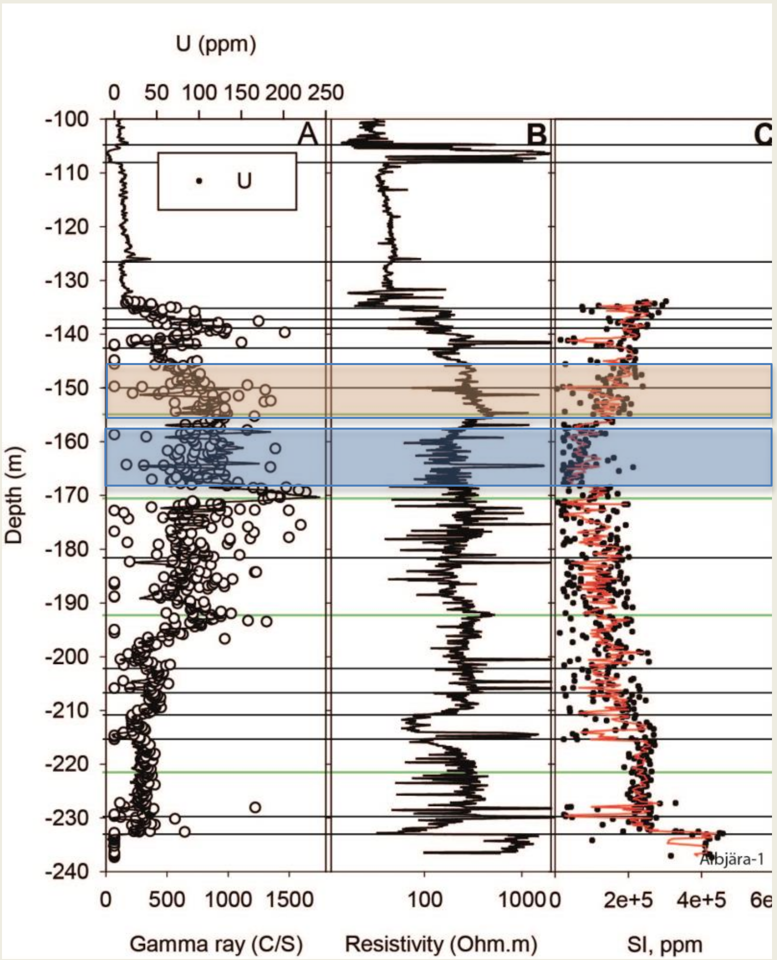
The Sulfide rich (Type B –subtype B2) occur in all of Furongian



The Sulfide rich (Type B –subtype B1) occur in all of Furongian but more common in the lower upper Furongian



Rock types and logs



Dominantly A types

Dominantly B types

- Integration of rock types and logs not yet done
- As it looks now the PCA defined Type B correspond to low resistive high GR intervals and the PCA defined Type A to high resistive high GR intervals
- Resistivity is, however, influenced by also carbonate and TOC content and on the amount of pyrite and how it is distributed (isolated crystals vs. in a connected framework)

Conclusions

- PCA analysis suggest the presence of a two end-member rock system in the Furongian: A relative silicate rich sulphide poor type (Type A and its subtype A1 and A2) vs. a relative silicate poor and sulfide rich type (Type B and its subtypes B1 and B2)
- Type A and B occur mixed with each other in the Furongian. In a few zones one type dominate over the other. This is seen in FU4 that is dominated by type B1 and in zone FU6 that are dominated by Type A1
- We expect that the types will have different properties.
  - Type B will have least rock strength relative to A due to its low siliceous content
  - Type B is expected to be more heterogeneous on a cm-dm scale due to its higher content of pyrite

Samples

- If both type are to be samples then these can be done in several intervals:
  - Type A in either
    - level 150-155 m (FU5)
    - level 190-192 m (FU1/2)
  - Type B in either
    - level 158-166 m (FU4)
    - Level 194-196 (FU1)
- If only one type for rock fluid interactions is needed then type B2 should be sampled since this type is the dominant rock type (mostly likely type to encounter) and provides an assumed low rock strength
- All types may be samples for Brinell rock strength

Sample requirements

- A sample interval:
  - 4 hole-round core samples (5.6 cm in diameter) each 2 inch high in total 8 inch long core section
  - Core preservation varies and final sampling level will be decide on core quality combined with the rock typing done by the PCA

3.3. Report on PCA on Ha-XRF in Sommerodde -Albjära

GEUS

PCA –Sommerodde-Albjära

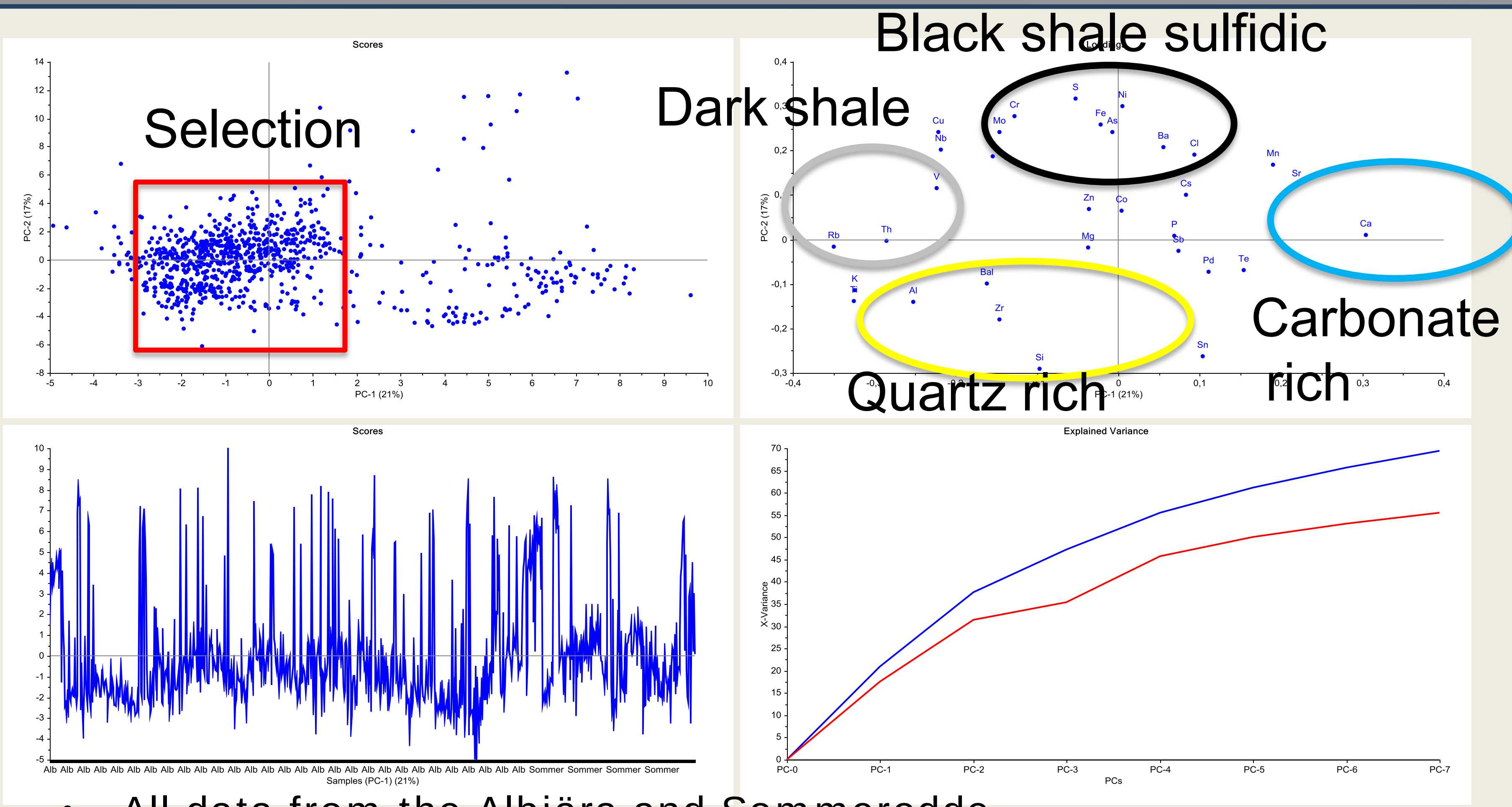
version 0: 3.6.2014

Niels Schovsbo, Kim Esbensen

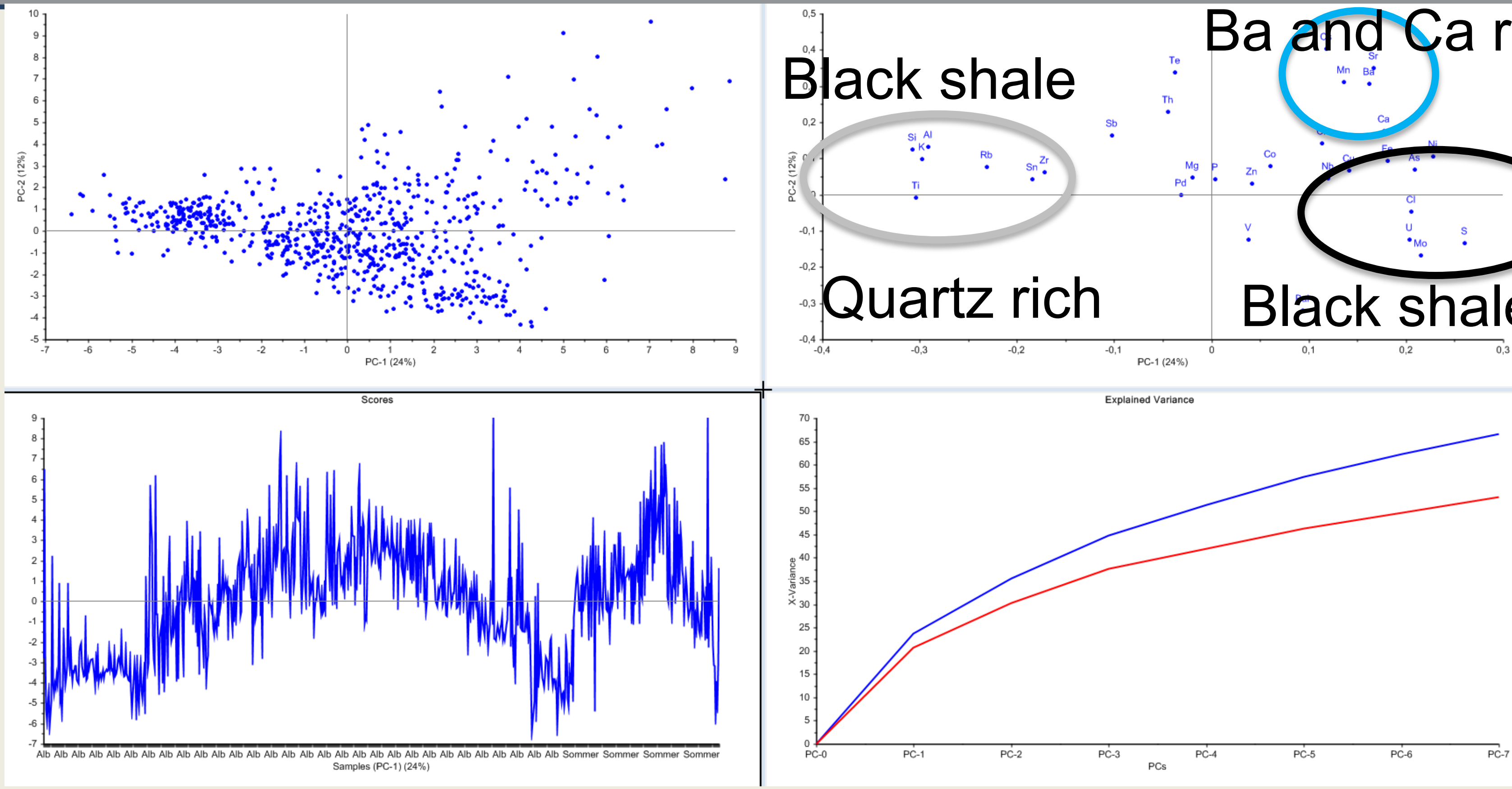
De Nationale Geologiske Undersøgelser for Danmark og Grønland
Klima-,Energi- og Bygningsministeriet

Status

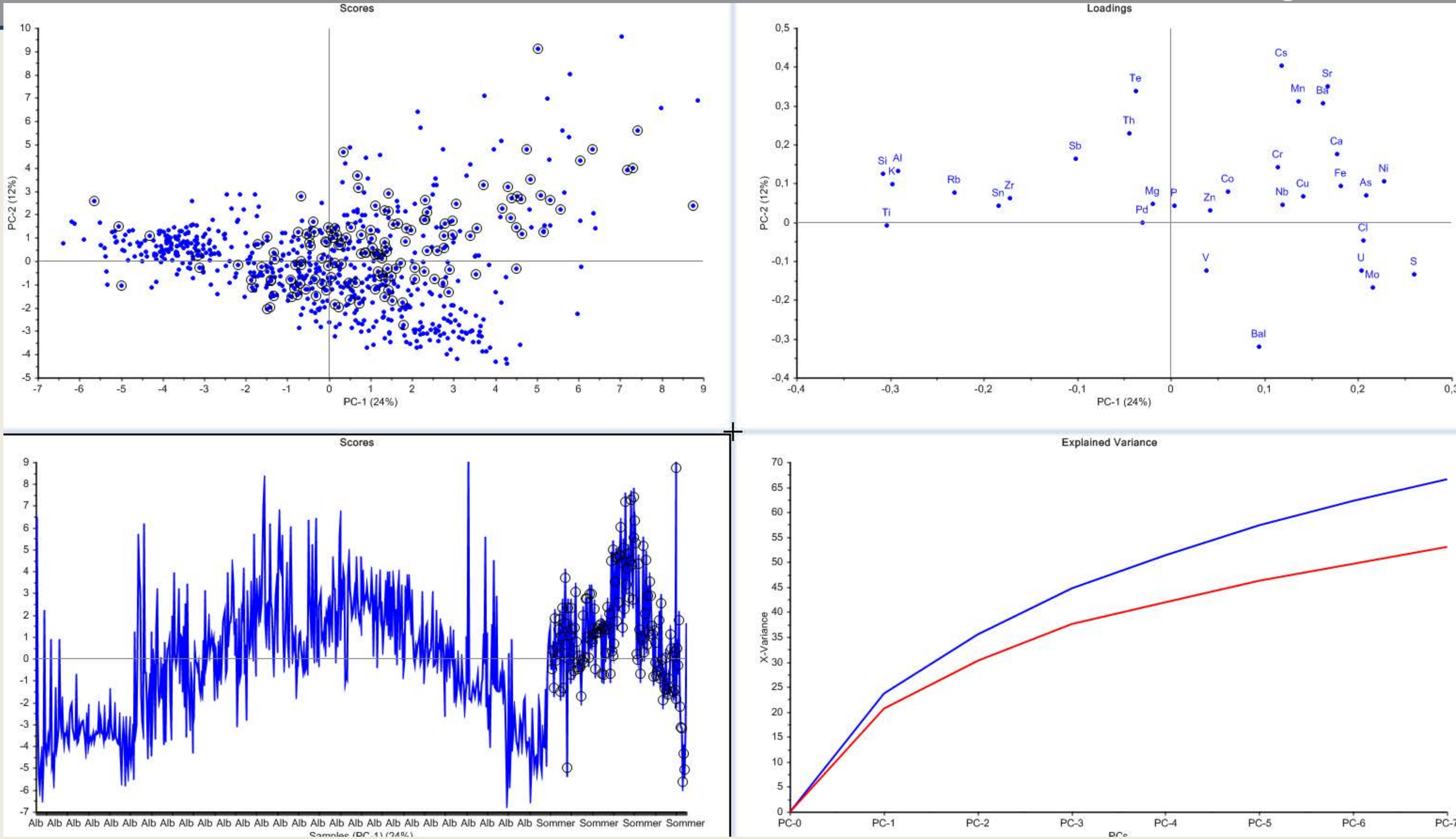
- PCA rock typing on Furongian section in Albjära done 21.05.2014
- XRF analysis Sommerodde completed pr. 30.05.2014
- PCA analysis of a joint Albjära-Sommerodde xrf data matrix was made on the 2.6.2014 in order to:
  - Examine effects of condensation (much thinner Sommerodde section compared to Albjära) on the PCA Rock types
  - Make qualified inputs to the justification of extrapolating rock strengths measured in Sommerodde to the Albjära



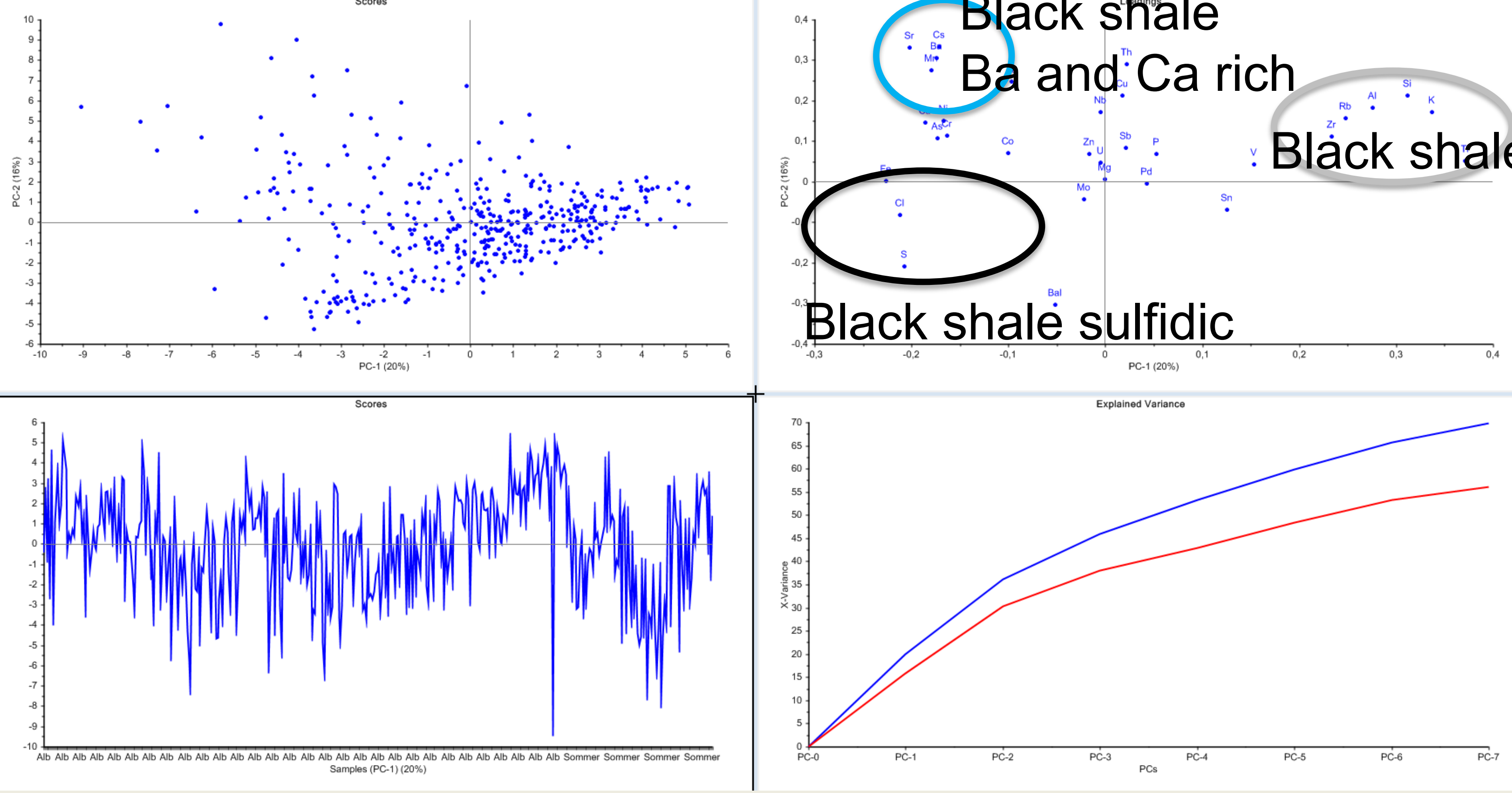
- All data from the Albjära and Sommerodde
- Scaled: mean and standard deviation
- Outliers defined: -3.0<pca 1<1.5
- Outliers represent mostly Sand stone, concretions of Ca, FeS2, Ba



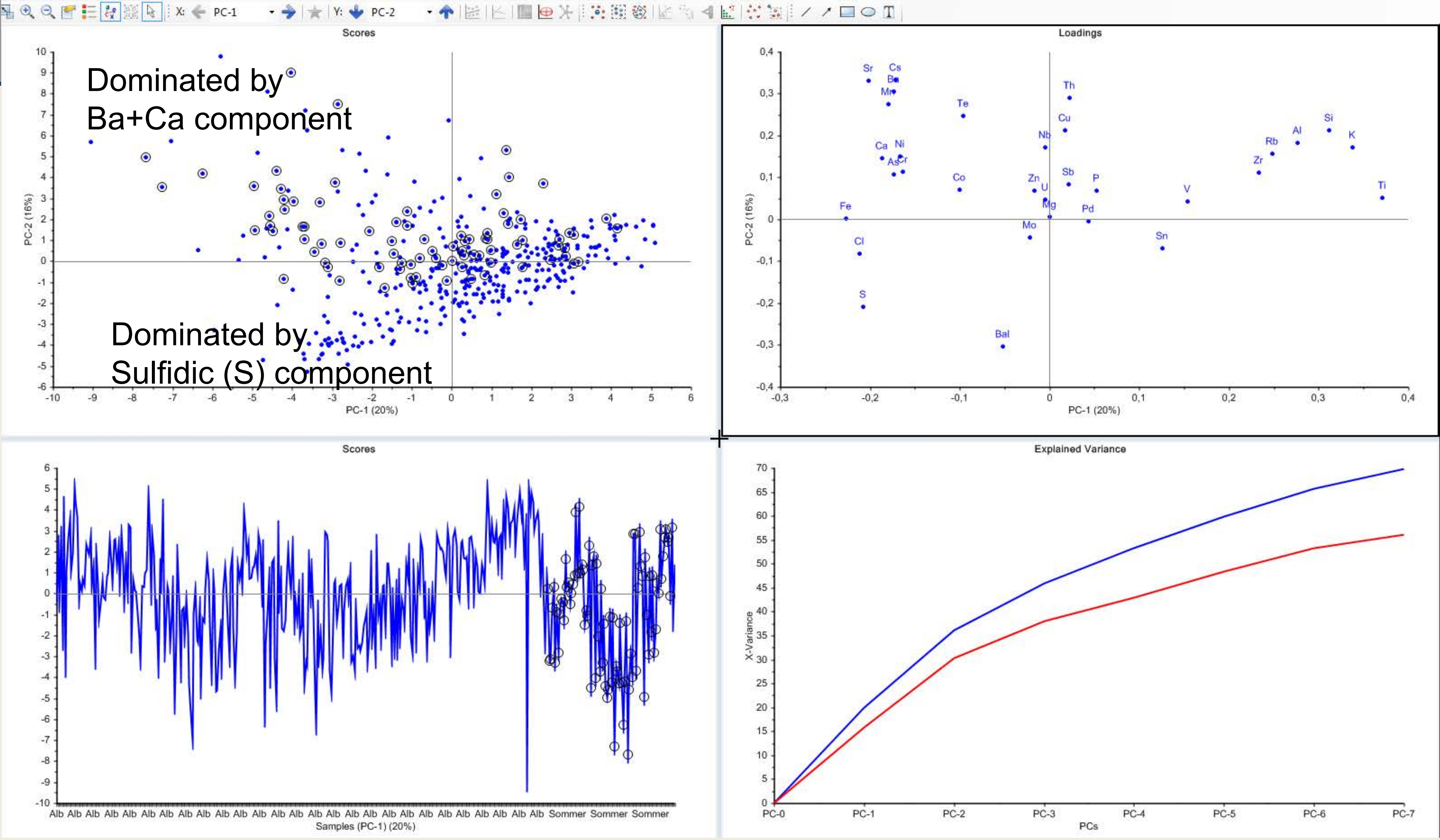
- PCA with no outliers
- Main rock types: A relative quartz rich low sulfidic rock end-member and A Black shale that sulfidic
- SAME types as defined in Albjära previously



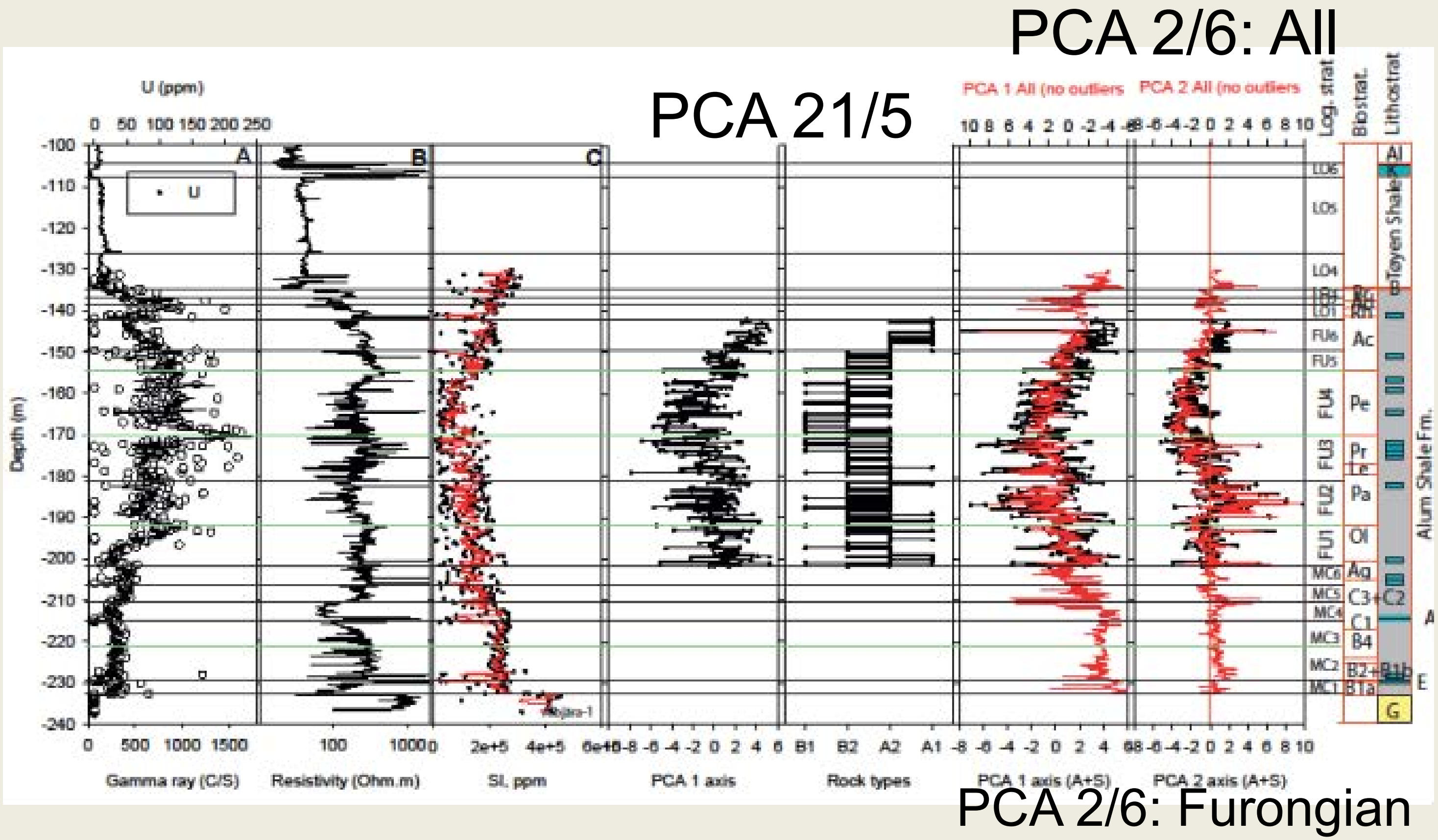
- Sommerodde occupies almost the same space in the PC-1 vs PC-2 plot as used by Albjära (marked as black dots)
- Sommerodde tend to be more dominate by a Ba+Ca rich PCA-2 component



- PCA on Furongian section in Albjära and Sommerodde only

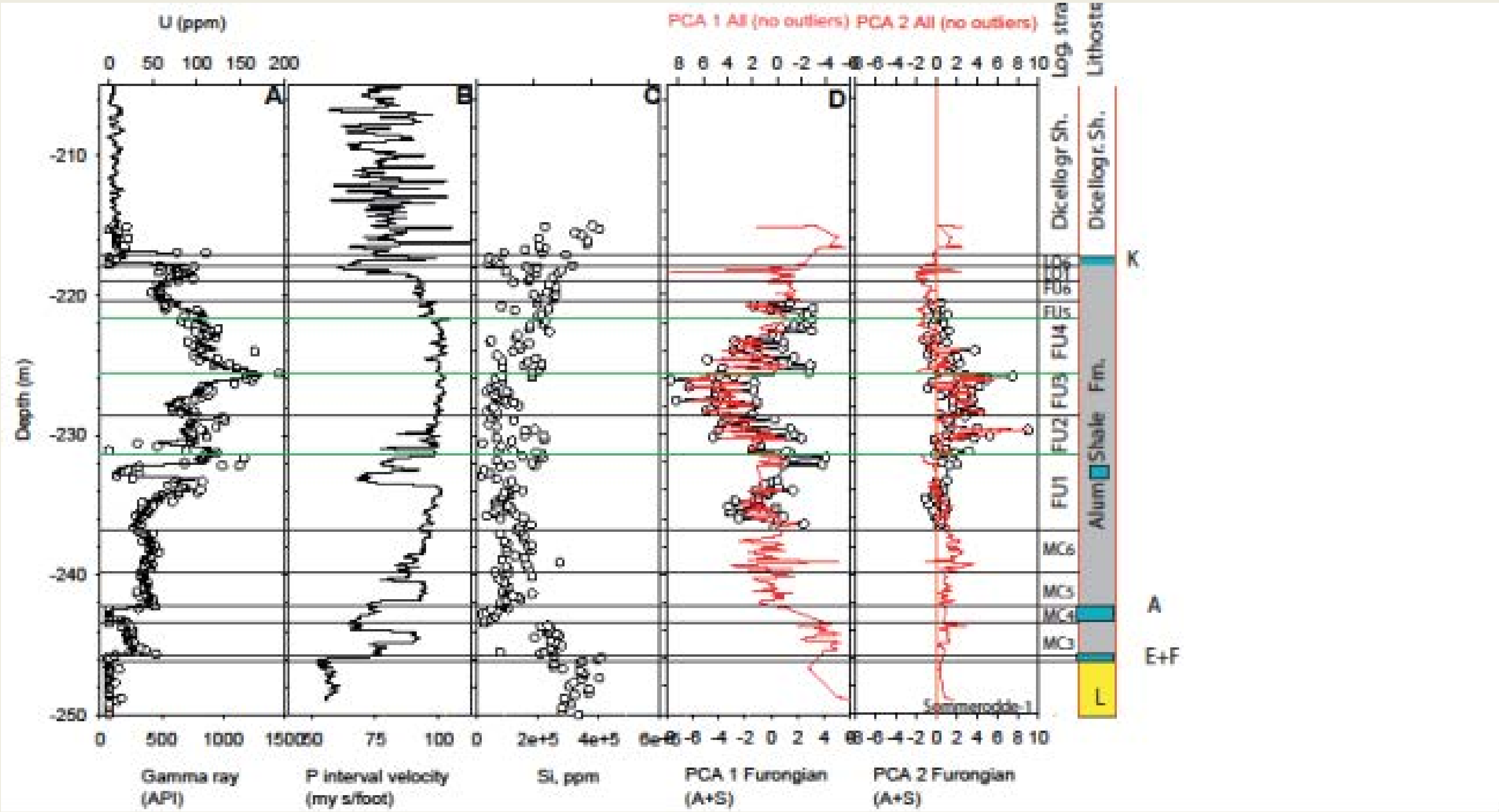


- Sommerodde and Albära similar PCA-1 scores.
- Sommerodde more positive PC-2 scores: Hence Sommerodde more dominated by Ba+Ca PCA-2 component whereas Albjära is more dominated PCA-2 Sulfidic component



Comparison between 3 PCA runs in Albjära:

- The output scores for the PCA made on the 21.5 and the two new PCA's are almost identical
- Stratigraphical development with sulfidic rock types domination in the Furongian (PCA-1)
- PCA-2 details variation of a Ba-Ca rich (positive) vs S negative component



- PCA in Sommerodde:
- Same stratigraphical development as in Albjära
- The Ba+Ca component are more dominant

Conclusions

- The PCA rock types defined in Albjära occurs in the Sommerodde
- The effect of condensation apparently did not affect the shale-sand type (PCA-1 axis)
- On the PCA-2 axis Sommerodde differ in terms of a Ca+Ba component that is expressed more clearly here versus a sulfidic component expressed more clearly in Albjära
- Petro-graphical evidence in the cores support this: In Sommerodde no Ba-concretions has been observed and the Ba occur with Ca in small crystals in the shale. Pyrite rich bands/concretions are also seldom

Geological interpretation

- The geological meaning of the difference of the PCA-2 component may be that Ca and Ba have been leached from the shale and precipitated as concretions in the Albjära-1 whereas Ca and Ba still occur in singles crystals within the shale in the Sommerodde

- In Albjära Pyrite rich bands occur more abundantly than in Sommerodde. In Albjära pyrite concretions is seen also

- This implies a difference in the early to late digenesis previously unknown. The difference may be an effect of condensation since burial may trigger concretion growth.

3.4. Report on: XRD analysis and PCA on XRD-XRF

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Report on:
XRD analysis

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Introduction

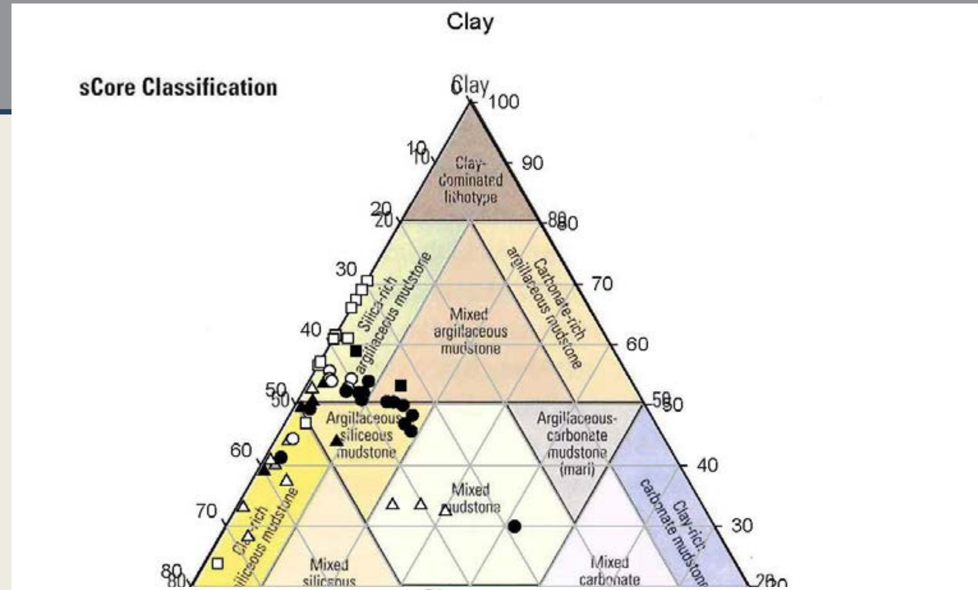
- This PowerPoint presents and evaluate 40 XRD analysis. XRF, TOC and TS data are also available on same samples.
- Data: 25 from Albjära-1, 10 from Sommerodde and 5 from Billegrav-2

- Deliverables:
  – Updated ternary diagrams
  – Modelled XRD ternary diagrams
  – PCA of XRD and XRF data

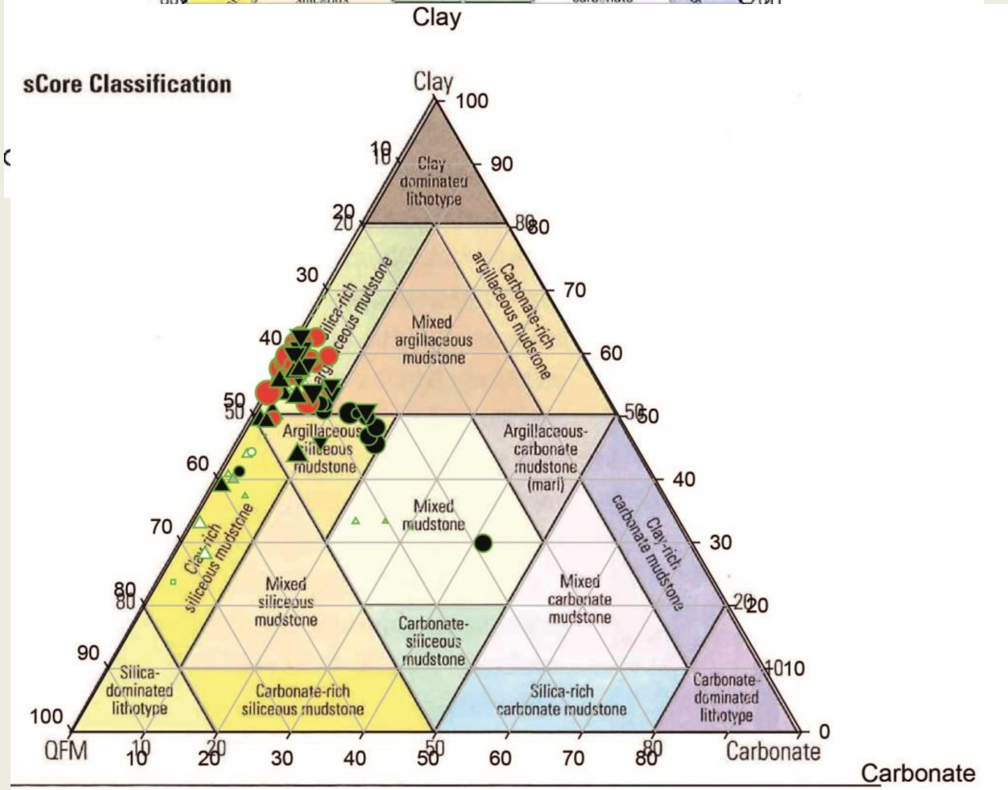
sample	quartz	albite	microcline	mica	chlorite	calcite	dolomite	pyrite	marcasite	anatase	gypsum	bassanite	barite	jarosite	copiapite	apatite
A-1_97-157	36.7(4)	4.2(2)	3.5(2)	42(1)	4.4(2)	0.9(1)	1.7(1)	0.6(1)		0.6(1)						5.5(2)
A-1_97-161	30.8(4)	3.8(2)	9.0(3)	52(2)		0.7(1)		1.7(1)		0.4(1)						1.1(1)
A-1_97-166	27.3(4)	3.2(2)	8.5(3)	55(2)				2.9(1)	0.8(1)	0.5(1)				1.8(2)		
A-1_79-023	30.1(4)	1.9(2)	7.1(3)	53(2)				3.0(1)		0.4(1)	1.0(2)			3.2(2)		
A-1_97-174	28.9(4)	2.5(2)	11.7(3)	50(2)				3.0(1)	0.6(1)	0.5(1)				3.0(2)		
A-1_79-024	26.4(4)	1.1(2)	4.4(3)	51(1)				0.4(6)		0.8(1)				2.0(2)	13.5(8)	
A-1b_112_238	27.9(3)	2.3(2)	6.7(3)	54(1)		0.3(1)		4.5(1)		0.8(1)	0.2(2)	0.1(1)		3.1(2)	0.6(2)	
A-1b_112_234	27.9(4)	1.8(2)	6.5(3)	54(2)		1.2(1)		4.2(1)		0.9(1)				2.9(2)	1.0(2)	
A-1b_112_230	28.2(3)	0.5(2)	5.0(3)	49(1)				0.8(1)		0.5(1)	1.3(3)	0.4(1)		1.6(2)	12.4(3)	
A-1b_112_225	26.9(4)	1.8(2)	7.2(3)	45(2)		5.4(1)		7.3(1)		0.5(1)	1.0(1)	1.4(1)		2.9(2)		
A-1b_112_221	28.4(4)	1.2(2)	7.2(4)	50(1)				5.1(1)		1.0(1)	1.1(6)		1.3(1)	2.1(2)	2.4(8)	
A-1b_112_219	27.4(4)	1.4(2)	5.8(3)	49(1)				2.5(1)		1.1(1)			0.6(1)	1.5(2)	11.2(8)	
A-1b_112_214	25.0(3)	1.7(2)	6.7(4)	56(1)				7.1(1)	0.4(1)	0.9(1)				2.0(2)		
A-1b_112_209	26.3(3)	1.4(2)	4.7(3)	55(1)		2.5(1)	2.5(1)	3.8(1)		0.8(1)	0.4(4)	0.5(1)	0.3(1)	1.4(2)		
A-1b_112_192	29.9(3)	1.0(2)	4.5(3)	49(1)		2.1(1)		5.7(1)	0.7(1)	0.7(1)	0.5(2)	0.9(1)	2.5(1)	2.1(2)		
A-1b_112_186	28.5(4)	2.1(2)	5.6(3)	53(2)				7.0(1)	0.8(1)	0.9(1)				1.8(2)		
A-1b_112_182	28.0(3)	2.2(2)	4.9(3)	51(1)		0.6(1)	7.2(2)	4.3(1)		0.9(1)				1.0(2)		
A-1b_112_179	29.3(4)	1.6(2)	4.9(3)	51(1)		1.1(1)		6.4(1)	0.4(1)	0.6(1)	0.6(3)	0.6(1)	0.7(1)	2.4(2)		
A-1b_112_177	29.5(3)	2.1(2)	3.6(3)	52(1)	2.4(2)	1.2(1)	2.9(2)	4.3(1)	0.3(1)	0.5(1)				0.8(2)		
A-1b_112_174	27.8(3)	2.7(2)	4.2(3)	53(1)	1.0(1)		2.5(1)	5.7(1)	1.0(1)	0.7(1)				1.0(2)		
A-1b_112_169	24.2(3)	3.2(2)	4.5(3)	51(1)	5.5(2)	2.0(1)		6.5(1)	0.4(1)	0.6(1)				1.8(2)		
A-1b_112_162	26.7(3)	3.1(2)	4.3(3)	51(1)	5.5(2)	0.8(1)		5.5(1)	0.6(1)	0.5(1)				1.9(2)		
A-1b_112_158	30.8(3)	2.8(2)	3.6(3)	49(1)	10.0(2)	1.6(1)		1.2(1)		0.6(1)						
A-1b_112_153	28.1(3)	3.4(2)	4.2(3)	47(1)	9.3(2)	3.1(1)		3.1(1)	0.6(1)	0.7(1)						
A-1b_112_147	28.8(3)	2.6(2)	4.7(3)	48(1)	9.1(2)	3.0(1)		2.8(1)	0.4(1)	0.7(1)						
SO1-60-218	39.3(4)	1.3(1)		39(1)	4.4(2)	10.5(2)		2.4(1)	0.3(1)	0.4(1)						2.5(1)
SO1-60-220	37.0(4)	1.5(1)		50(1)	3.5(2)	2.7(1)		4.0(1)	0.9(1)	0.6(1)						
SO1-60-221	33.9(4)	1.2(1)	1.7(2)	49(1)	0.6(2)	5.6(1)		6.6(1)	0.5(1)	0.6(1)						
SO1-61-223	29.0(3)		1.9(3)	46(1)		13.4(2)		7.7(1)	0.6(1)	0.8(1)		0.5(1)				
SO1-61-224	31.6(3)		2.8(3)	52(1)		2.8(2)		8.0(1)		0.6(1)		1.0(1)	1.3(1)			
SO1-62-226	29.1(4)		4.9(3)	54(1)		0.9(2)		9.1(1)		0.5(1)		1.6(2)				
SO1-62-228	29.2(3)		4.2(3)	48(1)		7.9(2)		8.8(1)		0.6(1)		1.4(2)				
SO1-64-234	27.0(3)	1.1(2)	6.8(3)	53(2)		0.5(1)		10.4(2)		0.7(1)		0.5(1)				
SO1-65-236	26.1(3)	1.4(2)	5.3(3)	49(2)		0.8(1)	6.4(2)	9.7(1)		0.5(1)		0.6(1)				
SO1-65-239	23.9(3)	2.1(2)	6.0(3)	54(1)				11.2(1)		0.7(1)				2.1(2)		
BG-2-22	42.3(4)	1.4(1)	2.0(3)	42.8(9)	3.3(2)	2.0(1)		4.2(1)	0.9(1)	0.7(1)			0.1(1)			
BG-2-23	33.2(4)	0.7(2)	4.3(4)	46.9(8)	1.7(2)	0.6(2)		10.9(2)	0.7(1)	0.9(1)			0.1(1)			
BG-2-25	31.6(4)	0.3(1)	5.0(4)	46(1)		3.7(2)		9.1(1)		0.8(1)			3.6(1)			
BG-2-26	30.8(4)	0.4(1)	5.2(4)	50(1)	0.5(1)	1.7(3)		8.3(1)		0.8(1)			2.3(1)			
BG-2-28	28.5(3)	1.7(2)	5.6(3)	47.7(9)	3.5(1)	2.2(3)		10.1(1)		0.6(1)						

XRD data as received. Number in brakes represent uncertainties on measurements . i.e. (30.1(4) translate to: 30.1 +/-0.4 wt)

- XRD analysis 1st May, 2014:

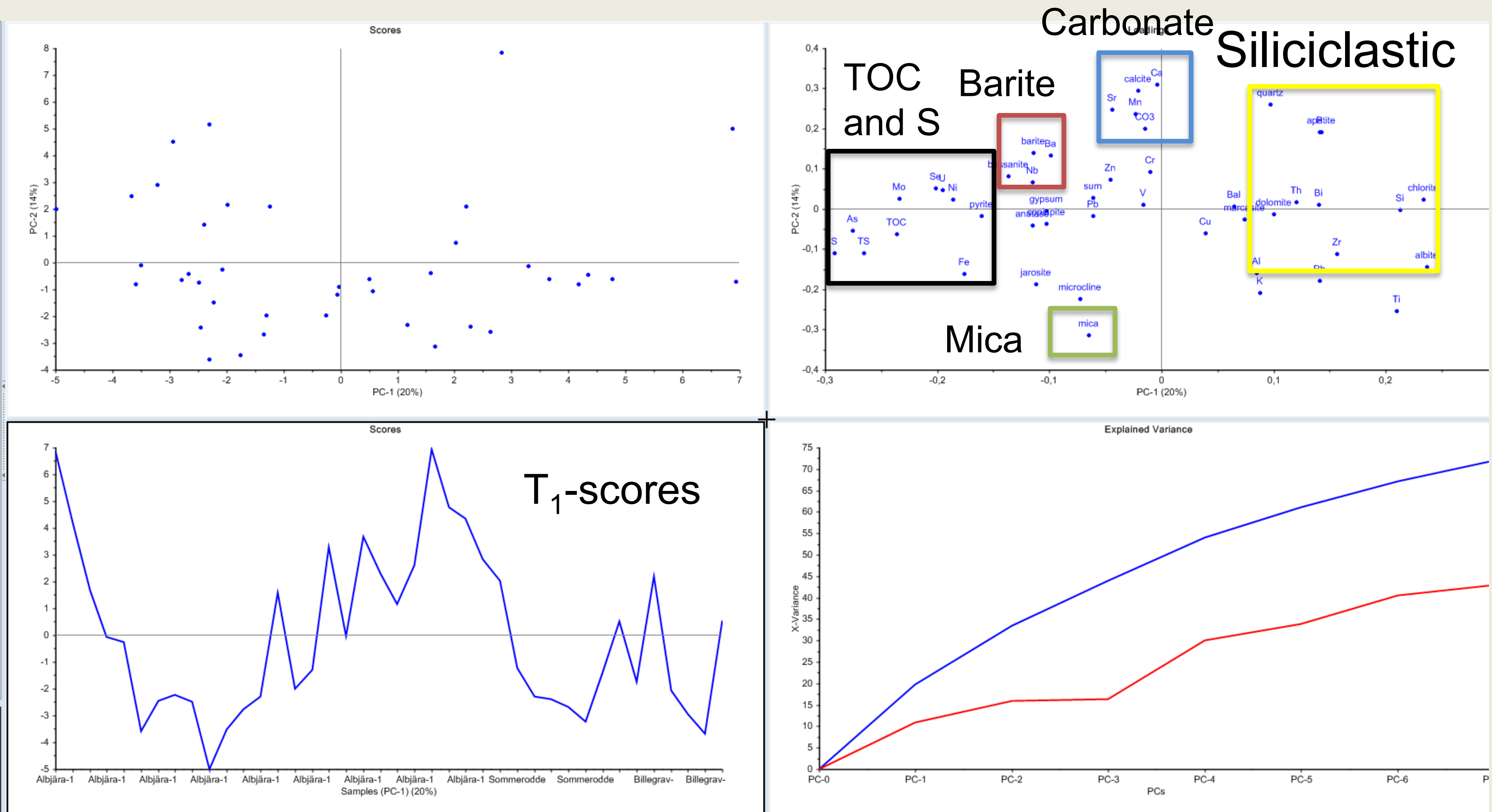


- With new data:
- New data confirms previous analysis: the Alum shale is a relative clay-rich shale
- QFM-clay ratio is between 40 and 50%, with a dilution trend towards carbonate



legend: red alum shale in Albjära-1, black: Alum Shale in Terne-1 (circle) and Bornholm (triangels). White: non alum shale. Symbols size proportional with TOC content.

PCA: XRD-XRF data



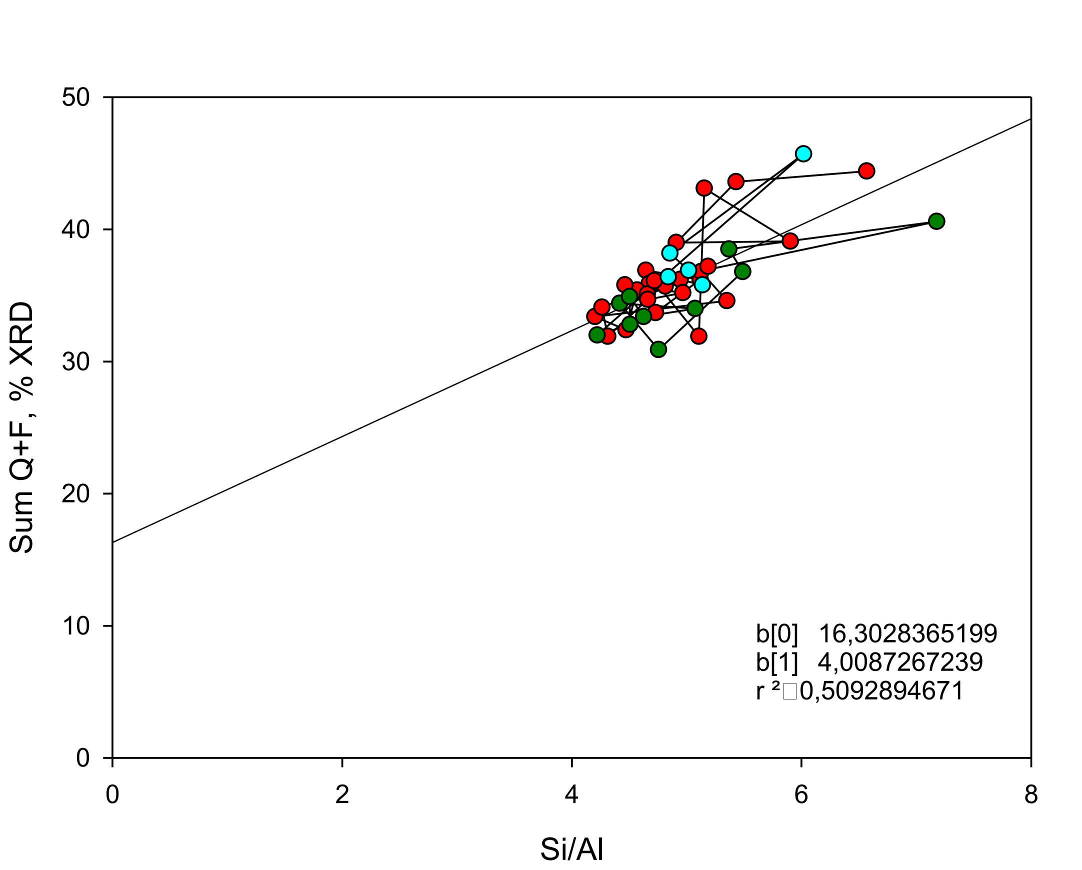
PCA of the XRD-XRF data set <u>confirms</u> previous mineralogical associations of the XRF dataset

Modelling of main mineralogical components

- For plotting in ternary diagrams, a simple relationship between main mineralogical components and XRF was established. This was subsequently applied to the full XRF data set in Albjära and Sommerodde
- Main motivation: Check if the XRF data indicate the presence of *other* compositions than those analysed by XRD

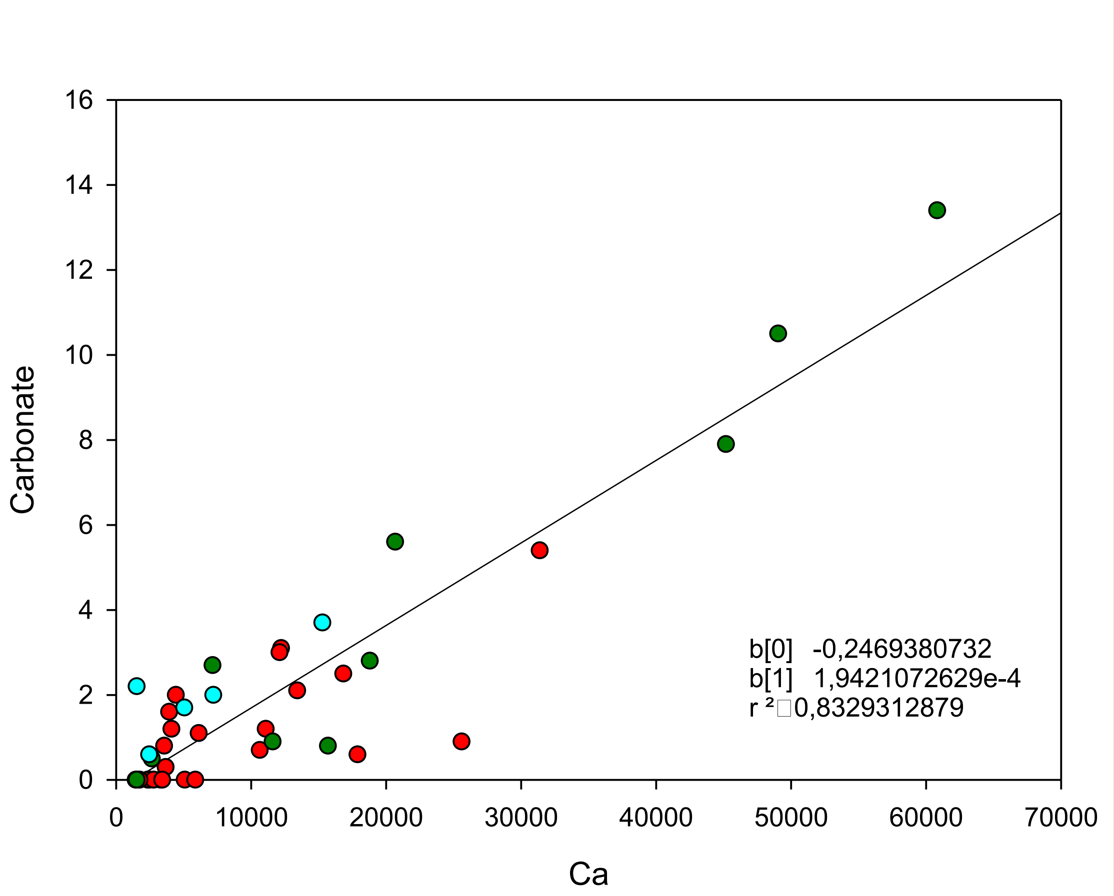
XRD-XRF relationships

Si/Al ratio used to ‘predict’ the sum Q+F



XRD-XRF relationships

- Ca to 'predict' Carbonate



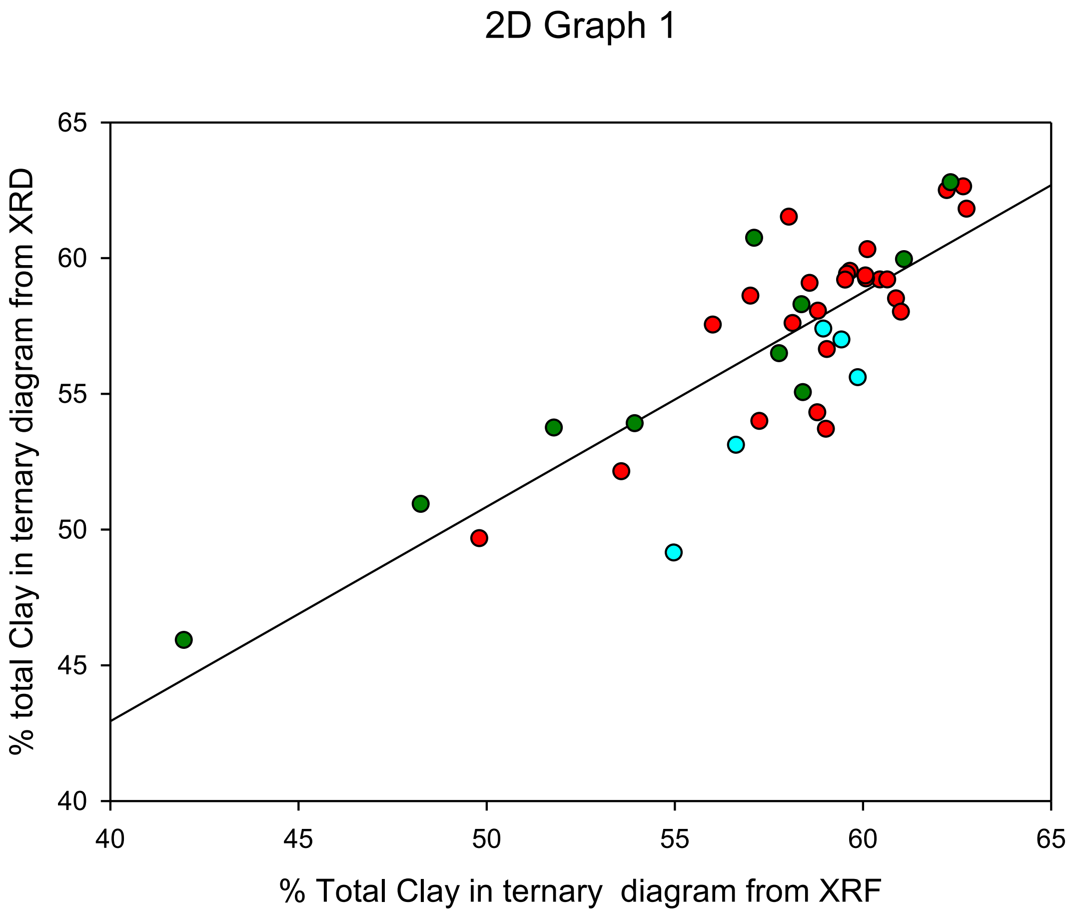
XRD-XRF relationships

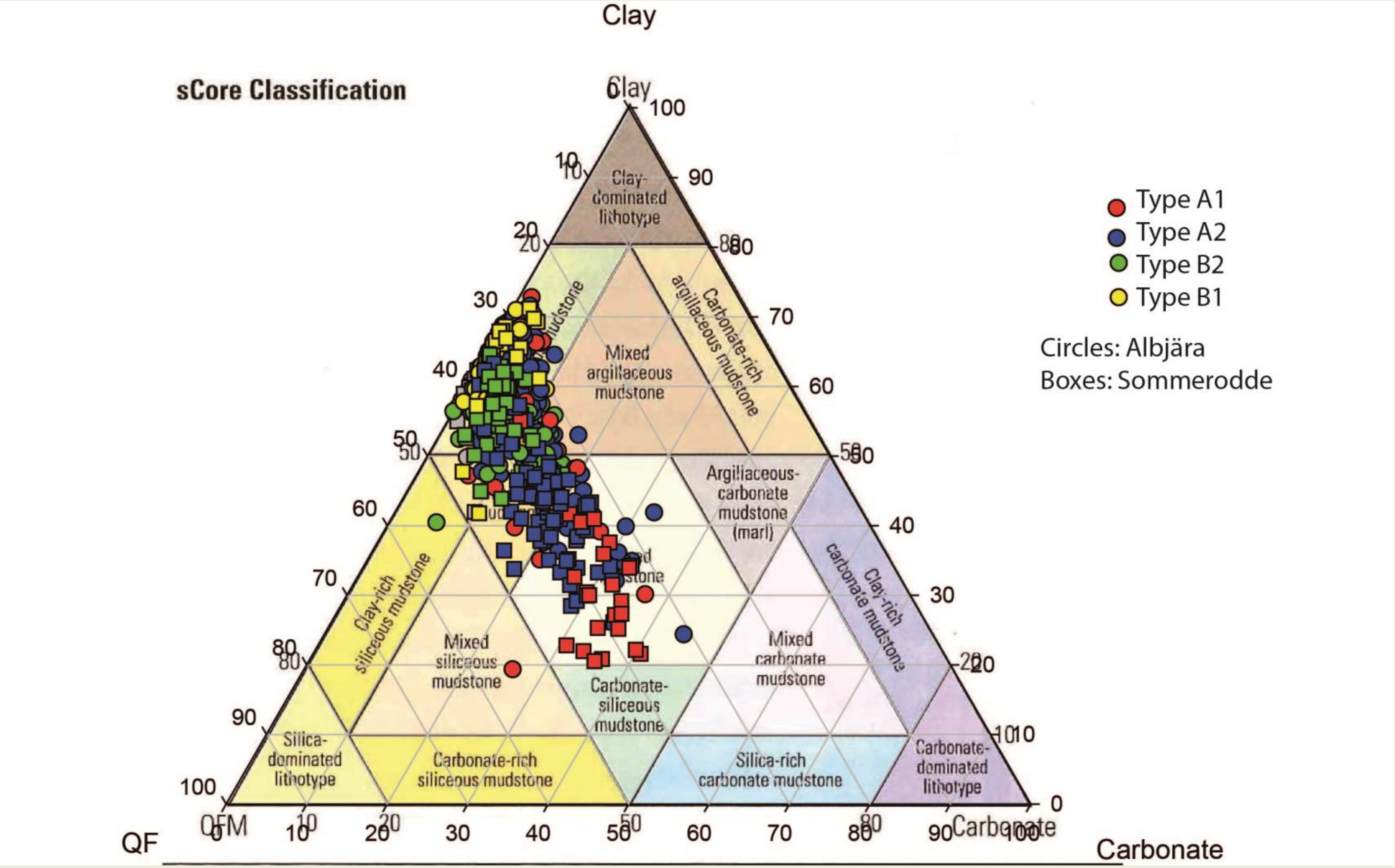
No similar proxy *for total clay*, which instead is estimated as "not accounted for", and corrected for as a matrix effect (M).

Total clay estimated as:

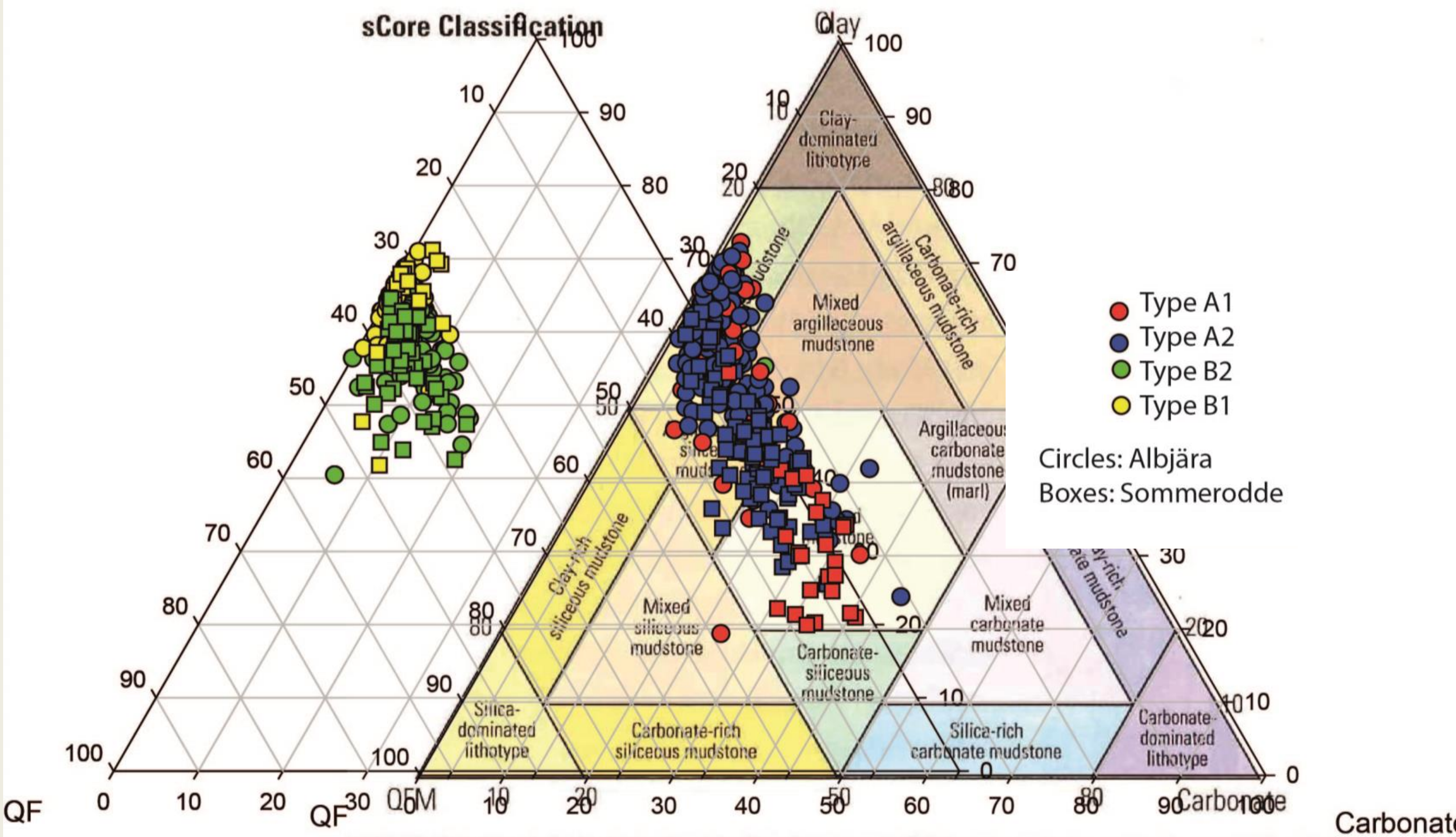
100 - QF- Carb – M

M = 5.04 +1.139e-4 S(XRF)





- XRF modelled position in ternary diagram is *similar* with respect to QF and total clay. The XRF data set contains samples with high(er) carbonate content. The rock types classes are from the PCA run 02062014.



- Rock types A and B have near identical QF to total clay ratios and differ only w.r.t. carbonate content
- Sommerodde tends to have *higher carbonate content* that the Albjära

Conclusions

- New XRD data confirms clay-rich nature of Alum Shale matrix
- PCA of combined [XRD,XRF] data set confirms association between main elements and mineralogical phases developed in previous project reports
- A simple model for XRF 'prediction' of main mineralogical components have been developed. Rock types are almost identical in terms of QF/total clay ratio, while differing mostly in their carbonate content
- This indicate that the Alum shale matrix (QF, total clay content) is *fairly homogeneous* and differs only in the amount of derived biogenic components (dilution effects)

3.5. Report on: compositional difference of the PCA-XRF defined rock types

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Report on: compositional difference of the PCA-XRF defined rock types

Niels H. Schovsbo, Kim Esbensen

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Klima-,Energi- og Bygningsministeriet

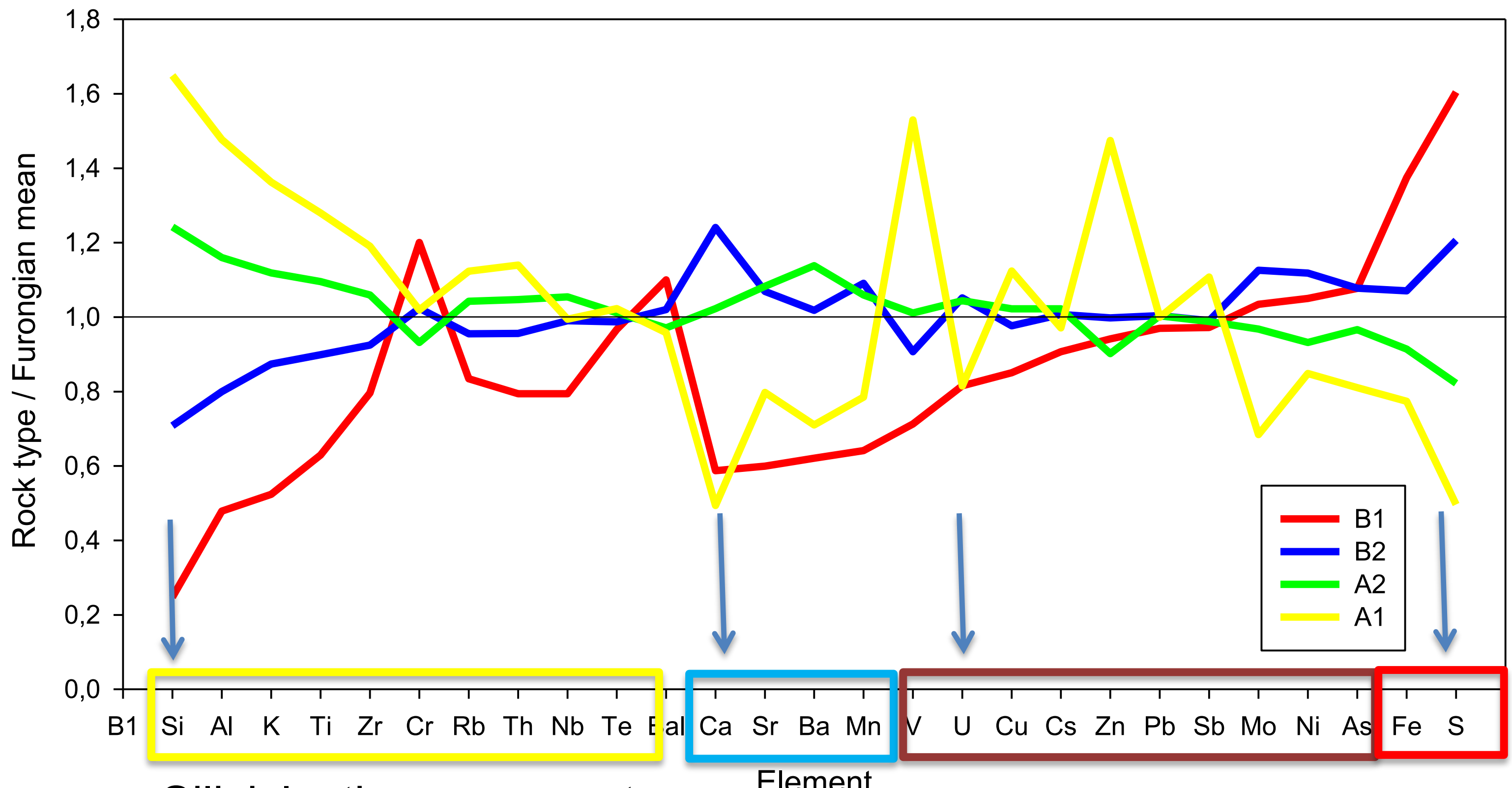
Introduction

- This PowerPoint presents composition and predicted rock strength of rock types defined by XRF-PCA
- Data input: data analytical chart of rock types (RT) in the Furongian section, Albjära and PLS-XRF predicted rock strength (Young’s Modulus)
- Deliverables:
  - Overview of XRF compositional differences (RT)
  - Rock type flag curves based on: **Si, K, S**

Rock type separators

- Diagram on next slide depict average RT compositions, normalised to the Furongian mean composition. Elements >1 are thus relatively enriched in the delineated rock type compared to average composition
- Elements are sorted according to main lithological associations

Albjära-1 (Furongian only)



Siliciclastic component

Carbonate and Barite Component

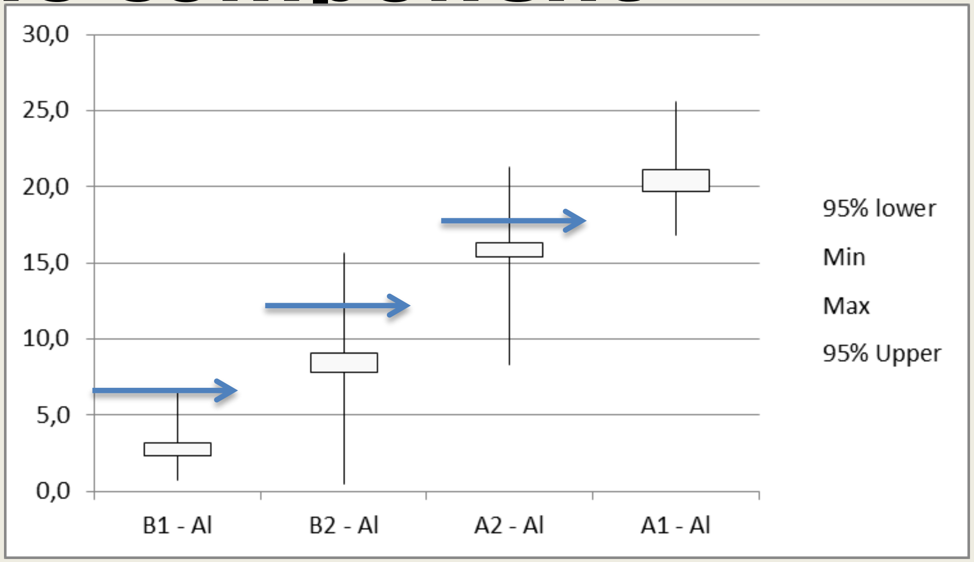
Trace elements

Sulfides

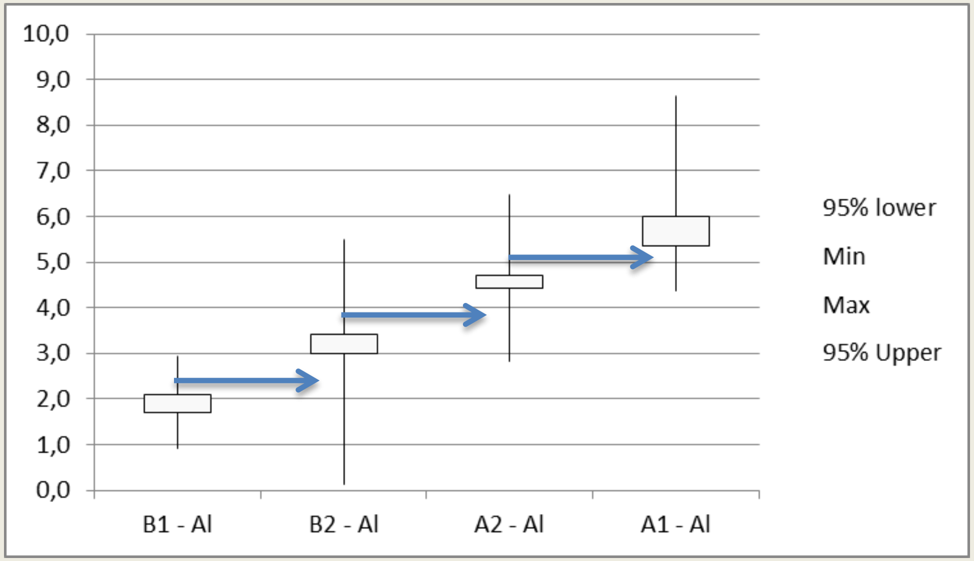
Discriminator elements (for each main element group) used in XRF-defining rock typing algorithm

Siliciclastic component

Si	B1 - Al	B2 - Al	A2 - Al	A1 - Al
95% lower	2,3355	7,8136	15,4128	19,7082
Min	0,7617	0,5067	8,3048	16,8164
Max	6,7430	15,6521	21,2747	25,5846
95% Upper	3,1856	9,0919	16,2819	21,1461
Mean	2,7606	8,4528	15,8473	20,4272



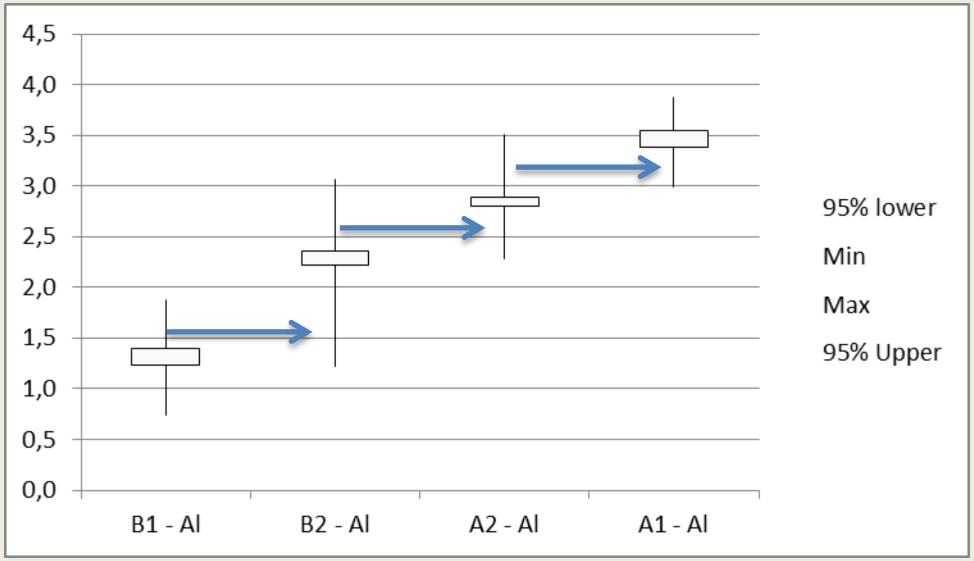
Al	B1 - Al	B2 - Al	A2 - Al	A1 - Al
95% lower	1,7110	2,9974	4,4223	5,3625
Min	0,9026	0,1182	2,8130	4,3570
Max	2,9355	5,4818	6,4917	8,6468
95% Upper	2,0925	3,4051	4,7048	6,0101
Mean	1,9018	3,2012	4,5636	5,6863



Rock type A is relative [Si, Al] rich; Si can be used as a main flag for discrimination A *vs.* B rock types

Siliciclastic component (cont.)

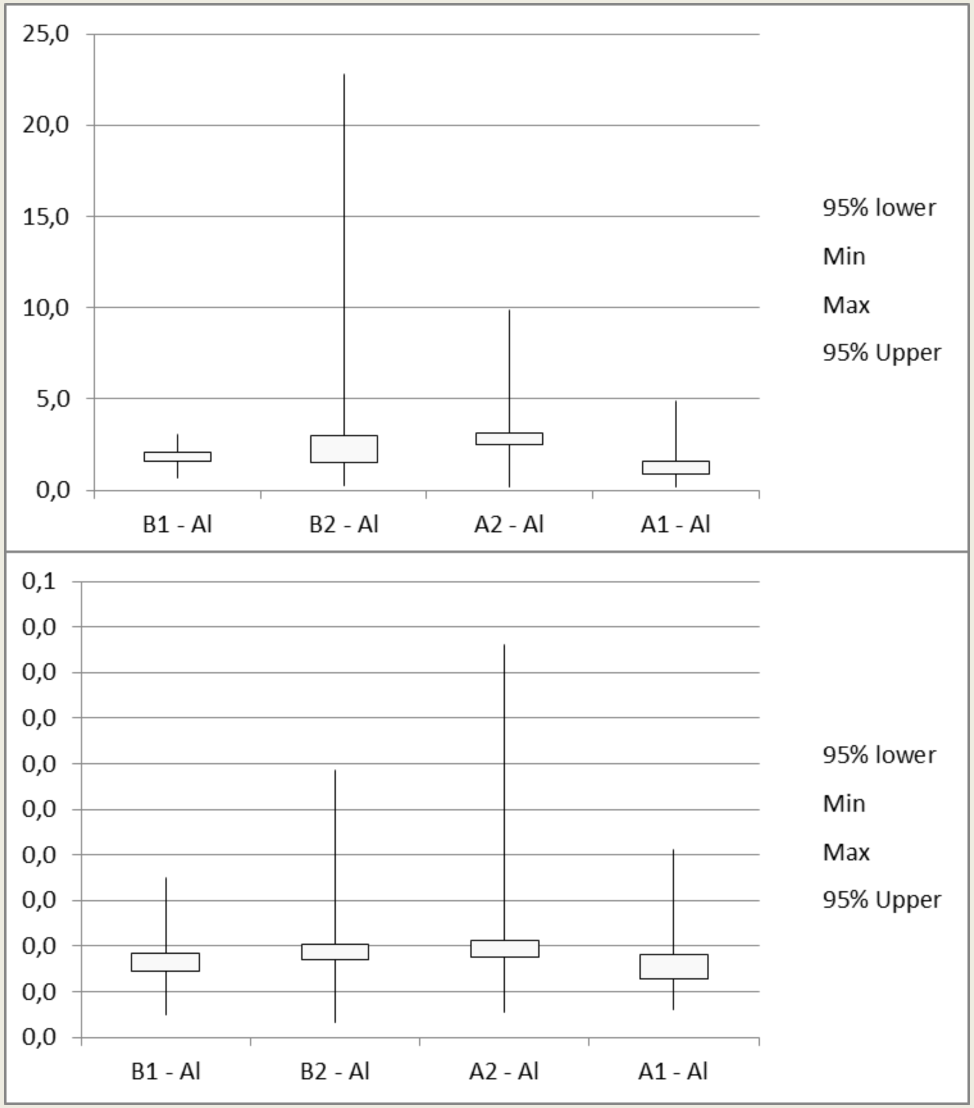
K	B1 - Al	B2 - Al	A2 - Al	A1 - Al
95% lower	1,2370	2,2224	2,8014	3,3793
Min	0,7428	1,2224	2,2851	2,9920
Max	1,8790	3,0657	3,5105	3,8725
95% Upper	1,3965	2,3603	2,8845	3,5470
Mean	1,3167	2,2913	2,8429	3,4631



Rock type A is also relatively K-rich; K may also perform as a flag for the A *vs.* B rock type discrimination

Ca	B1 - Al	B2 - Al	A2 – Al	A1 – Al
95% lower	1,5932	1,4855	2,4787	0,8489
Min	0,6931	0,2277	0,2059	0,1804
Max	3,0877	22,7765	9,8729	4,8642
95% Upper	2,0782	2,9638	3,1316	1,5807
Mean	1,8357	2,2246	2,8052	1,2148

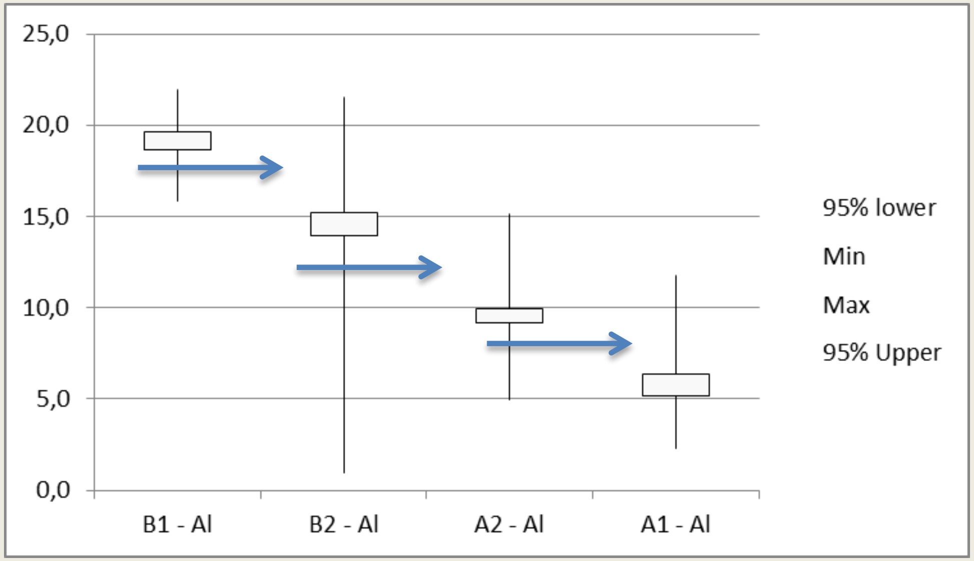
U	B1 - Al	B2 - Al	A2 - Al	A1 - Al
95% lower	0,0072	0,0085	0,0088	0,0064
Min	0,0024	0,0016	0,0027	0,0031
Max	0,0174	0,0293	0,0430	0,0206
95% Upper	0,0091	0,0101	0,0106	0,0090
Mean	0,0082	0,0093	0,0097	0,0077



Ca and U show a minor ability to be helpful in rock type discrimination, but partially overlapping statistics does not provide any significant separations.

Sulphides (S)

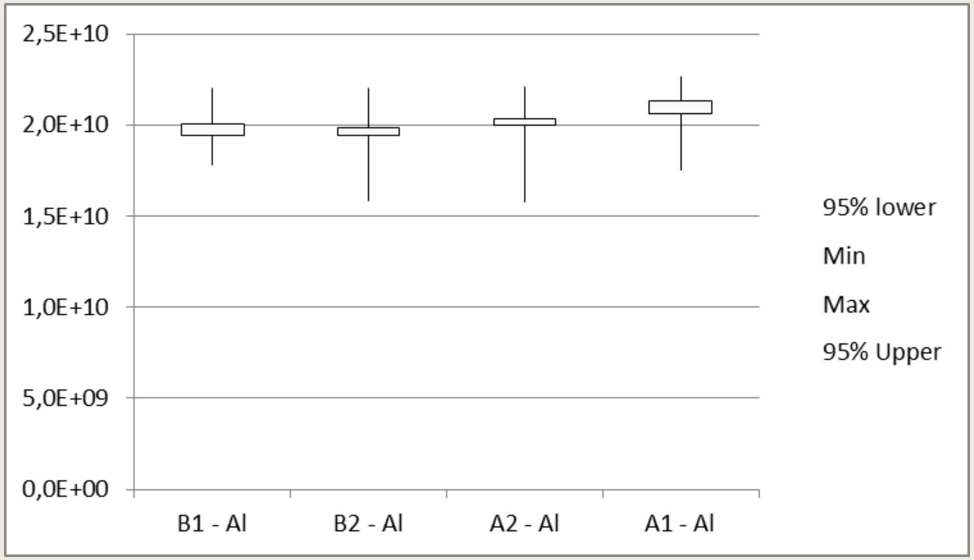
S	B1 - Al	B2 - Al	A2 - Al	A1 - Al
95% lower	18,6533	13,9452	9,1887	5,1533
Min	15,8422	0,9574	4,9616	2,2683
Max	21,9251	21,5142	15,1389	11,7598
95% Upper	19,6478	15,2155	9,9531	6,3482
Mean	19,1505	14,5804	9,5709	5,7508



Rock type B is relatively S-rich - S content Would appear to be a very good separator between the 4 rock types

Predicted Young modulus

E, Pa	B1 - Al	B2 - Al	A2 - Al	A1 - Al
95% lower	1,95E+10	1,94E+10	2,00E+10	2,06E+10
Min	1,78E+10	1,58E+10	1,58E+10	1,76E+10
Max	2,20E+10	2,20E+10	2,21E+10	2,26E+10
95% Upper	2,00E+10	1,98E+10	2,03E+10	2,13E+10
Mean	1,97E+10	1,96E+10	2,01E+10	2,10E+10



PLS predicted Young modulus show that the Alum Shale lies around 20 Gpa.
Rock type B1 is the weakest and the A1 type is the strongest. There is a gradual transition in the strength between the rock types

XRF discriminators based on XRF

Rock types from XRF		
Si_flag	**K_flag**	**S_flag**
=IF(SI<5.5;"B1"; IF(SI<12;"B2"; IF(SI<17;"A2";"A1")))	=IF(K/10000<1.8;"B1"; IF(K/10000<2.6;"B2"; IF(K/10000<3.1;"A2";"A1")))	=IF(S/10000>16;"B1"; IF(S/10000>12;"B2"; IF(S/10000>8;"A2";"A1")))

The PCA defined rock types does not correlate precisely with the above rock type flags.
Use all three and solve for any inconsistencies with further analysis

Rock types from Predicted E
=IF(E/1000000000<20;"B1 or B2"; IF(E/1000000000<20.45;"A2";"A1"))

Predicted E provide less accurate rock type predicting but allow for a main type A or B

Conclusions

- Compositional differences between PCA-XRF rock types are delineated and single element rock types discriminators developed
- The PLS predicted rock types (defined elsewhere) suggest that rock type B is the weakest, and A1 the strongest (higest E) in the Alum Shale
- *XRF-discriminators can be further developed*

3.6. Predictions of Young's Modulus in Terne and Albjära and in Rock types

GEUS

Feasibility report: Predictions of Young's Modulus in Terne and Albjära and in Rock types

22 June 2014

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Klima-,Energi- og Bygningsministeriet

Introduction

- A series of PLS models is developed in order to assess relationships between rock strength (E) and XRF & log responses. Sommerodde-1 furnished the calibration data, as this is the only complete drill-core penetrating the Alum Shale with a full complement of XRF, logs data (incl. Vs and E):

- 1) Predictive models [Yong's modulus] in the Terne-1 well - based on logs
- 2) Predictive model [Young's modulus] in the Albjära-1 well - based on XRF

- In order to examine the most influential XRF elements w.r.t. prediction ability, the PLS models [XRF-based] covered three alternative X-matrix configurations:

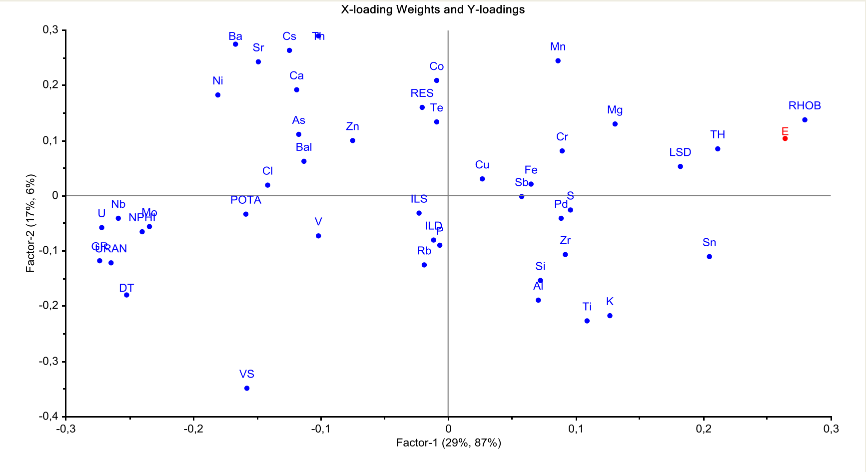
- Full data set [logs, XRF]
- Reduced (*see results*)
- Limited to U, K, Th (*so-called* 'spectra gamma log elements')

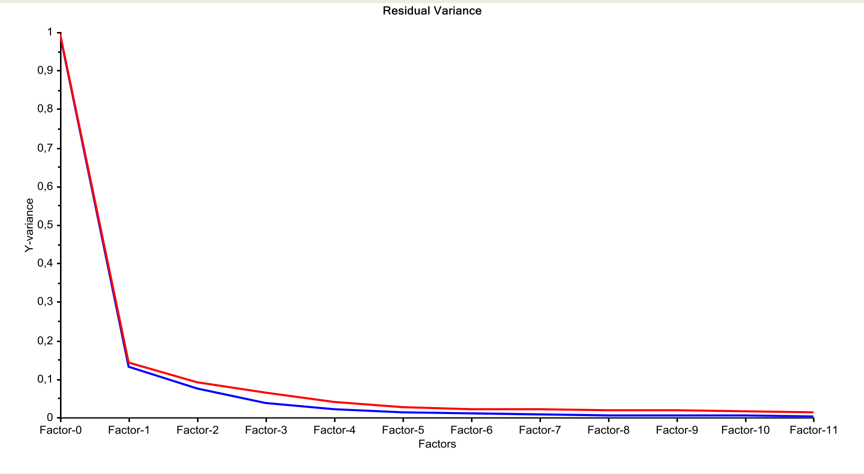
- Deliveries:
- PLS model descriptions, incl. validations, for the three alternative models (above)
- Prediction of E-values in Terne-1 and Albjära-1, based on the successfully calibrated Sommerodde-1 models

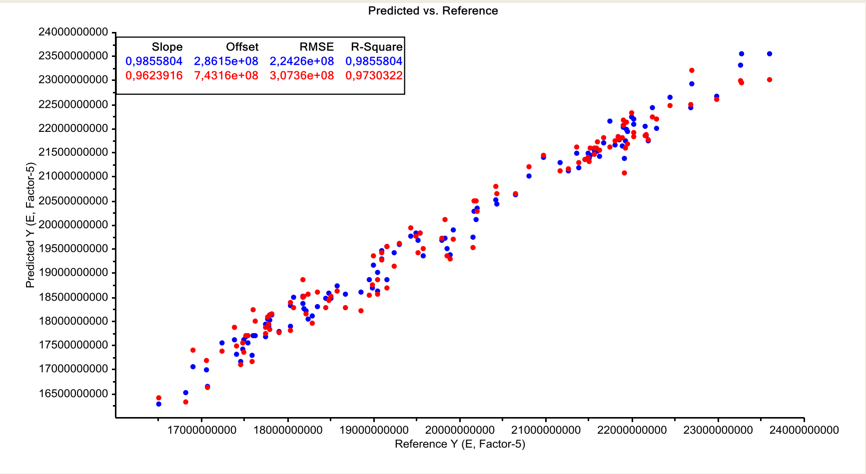
PLS model on Sommerodde-1: [XRF, logs] *combined*

Scores

Data input from the Sommerodde-1 well.
Input similar as the PCA matrix (from which outliers have been removed: in this model outliers were the sandstone and carbonate concretions]:
PLS1 model, 2-seg X-val, X = [logs, XRF], y = E.
It is possible to establish an excellent model for E-prediction based on logs + XRF data. Slope: 0.96; r^2: 0.97 This model uses all information available!



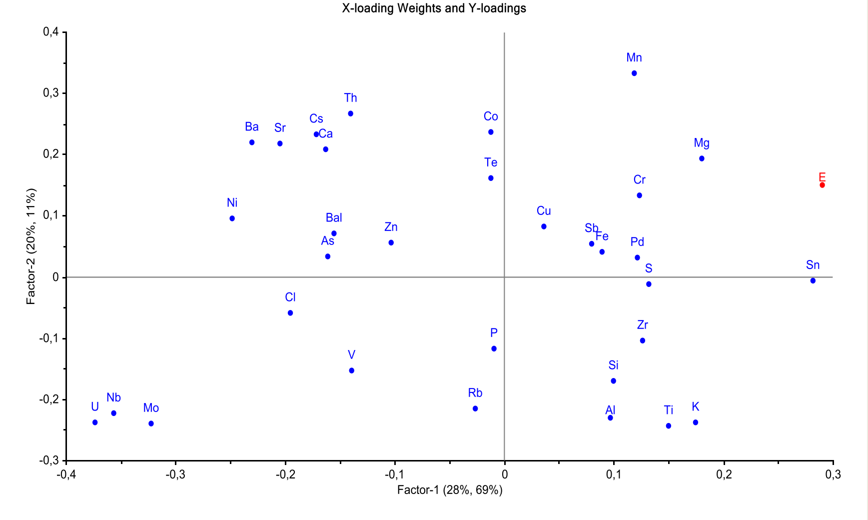


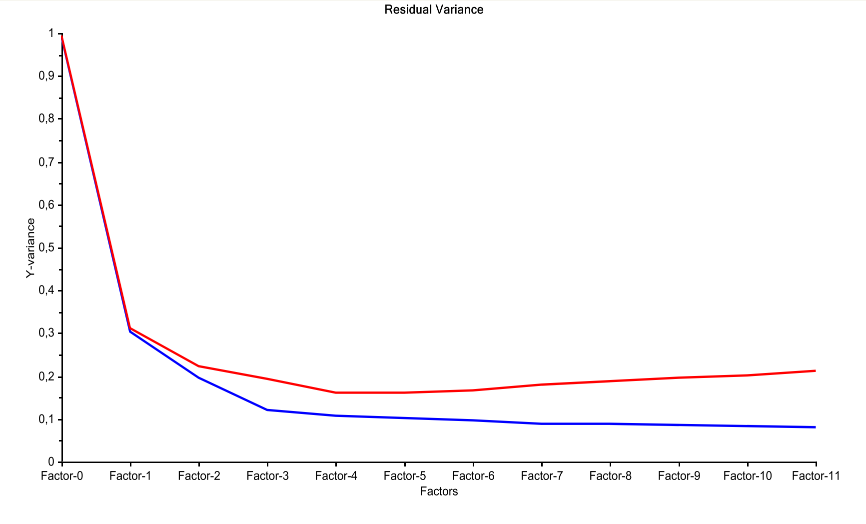


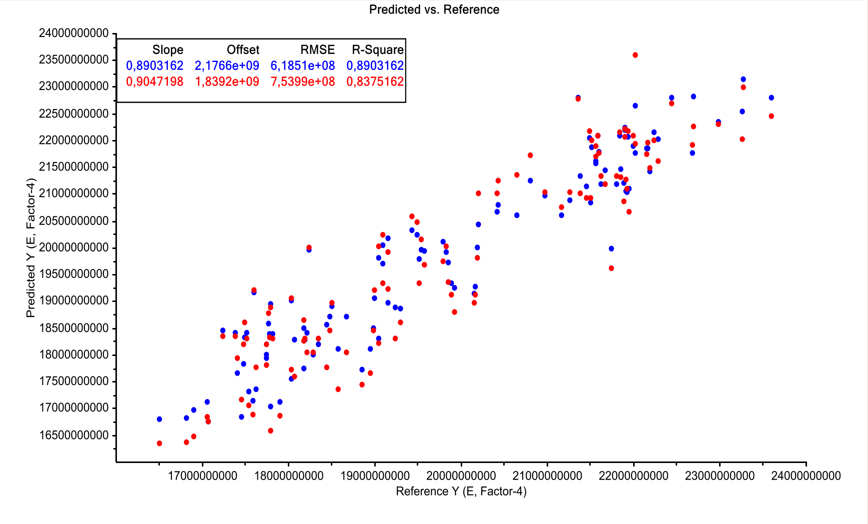
PLS model on Sommerodde-1: [XRF] *only*

PLS1 model, 2-seg X-val, X = [XRF], y = E. It is possible to establish a semi-acceptable model for E-prediction, based solely on XRF data. Slope: 0.90; r^2: 0.84

This model uses only the XRF information available. The fact that the prediction quality decreases indicate that features not contained in the chemical composition also influences E. These would be features broadly identified as "fabric- related" properties.



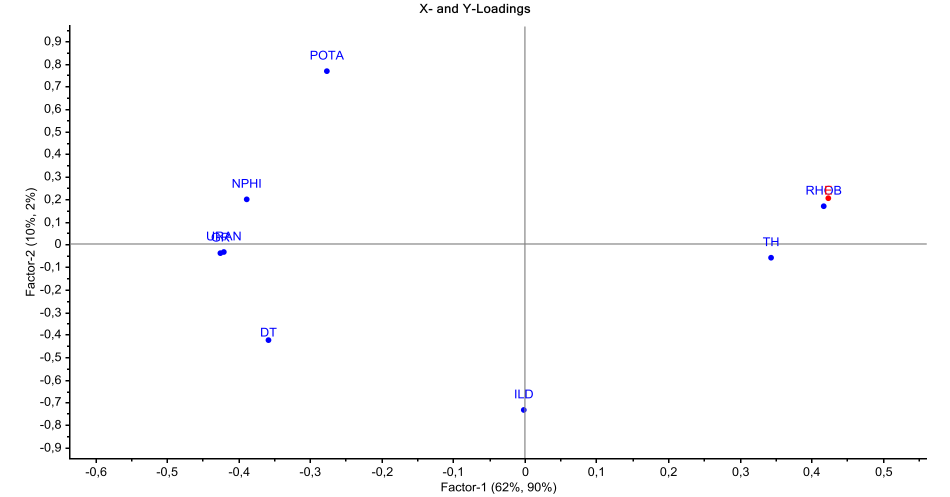


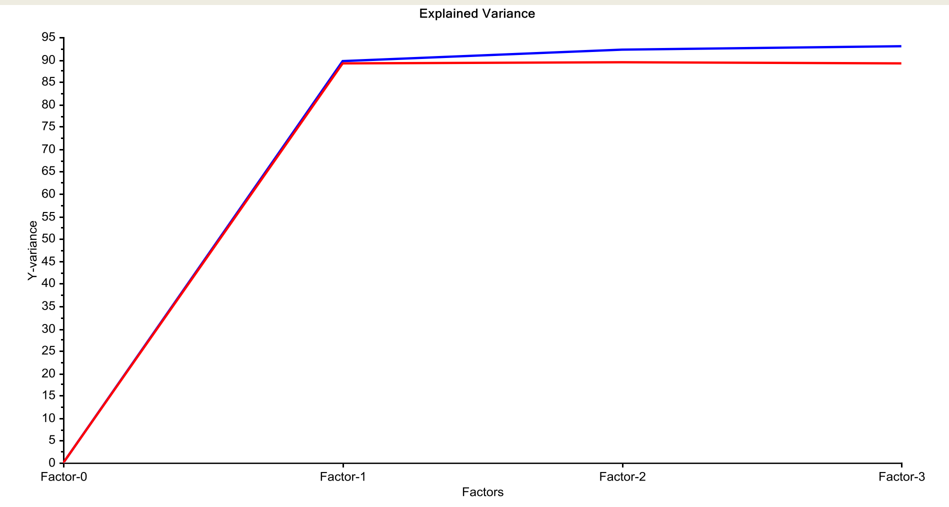


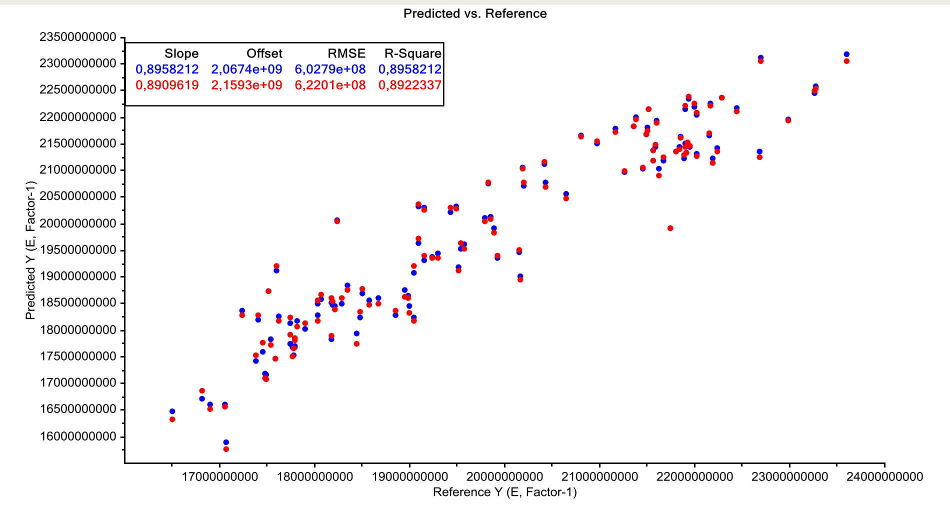
PLS model on Sommerodde-1: [log] *only*

PLS1 model, 2-seg X-val, X = [logs as in Terne-1], y = E
X = [reduced to identical log suite as in Terne]. This gives a quite acceptable E-prediction model validation, slope: 0.89; r^2: 0.89.

This model uses only the logs suite in common with those in Terne.-1. Young's modulus show strong positive correlation with density and Th, while negatively correlated to to uranium and DT. The fact that the prediction quality is slightly better than XRF is as expected, because logs better capture the rock "fabric".





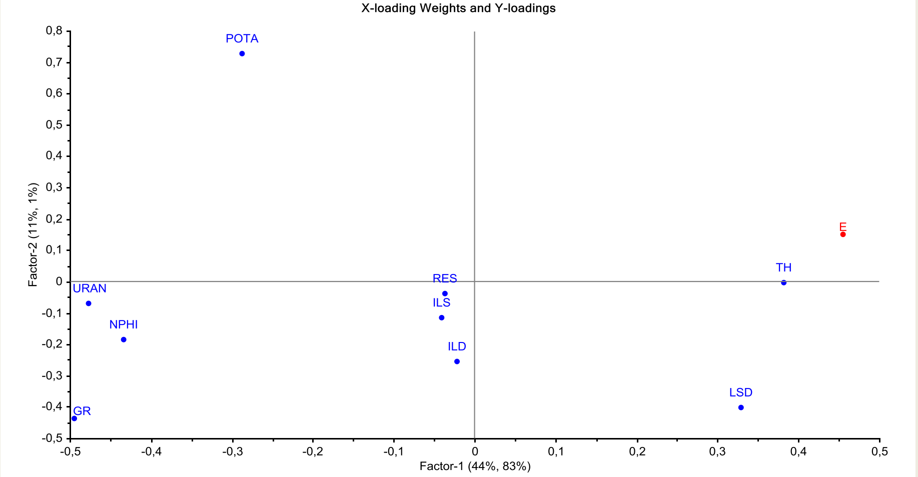


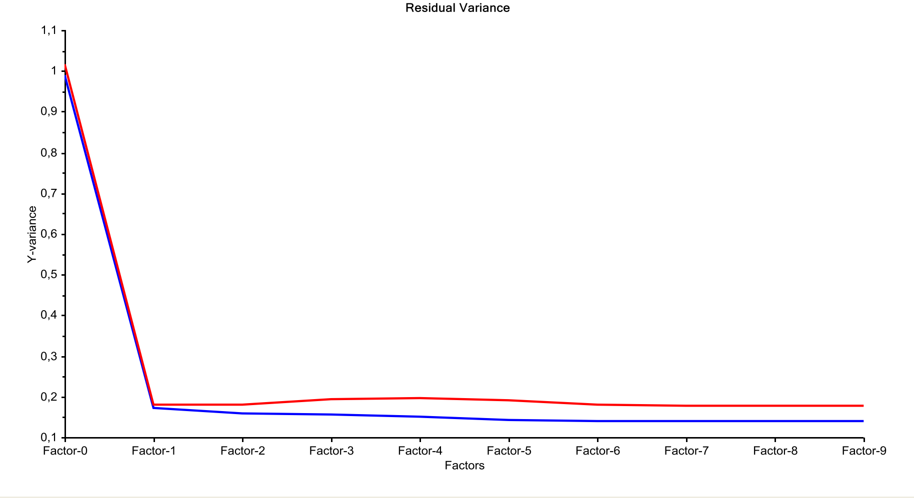
PLS [logs] (*no* Vs, RHOB, DT)

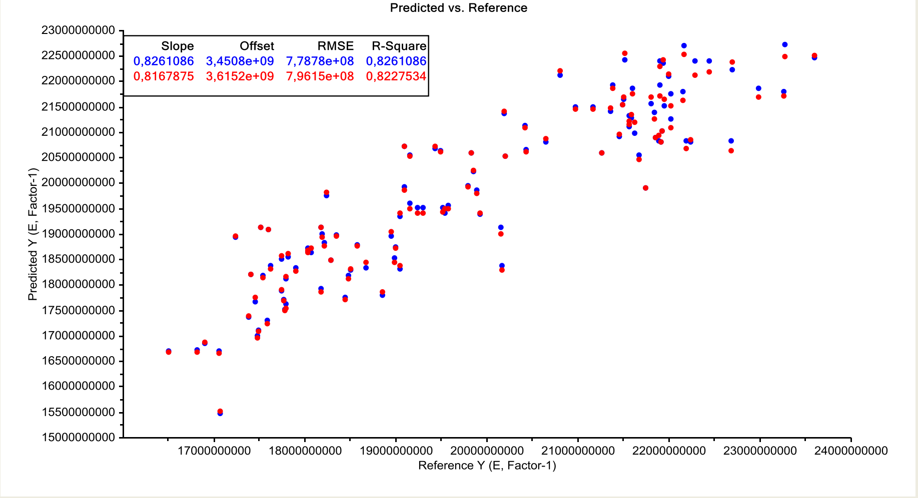
Scores

PLS1 model, 2-seg X-val, X = [logs], y = E This model (based on logs alone) is *without* DT, VS, RHOB, i.e. the three logs tools from which the E-modulus values are derived. The degree to which E-prediction is still possible is manifested by slope: 0.82; r^2: 0.82, i.e. only a first order prediction validation)
This illustrates that VP/VS measurements contains valuable information that cannot be substituted.
(again identified as “fabric” related properties).

Factor-1 (44%, 83%)



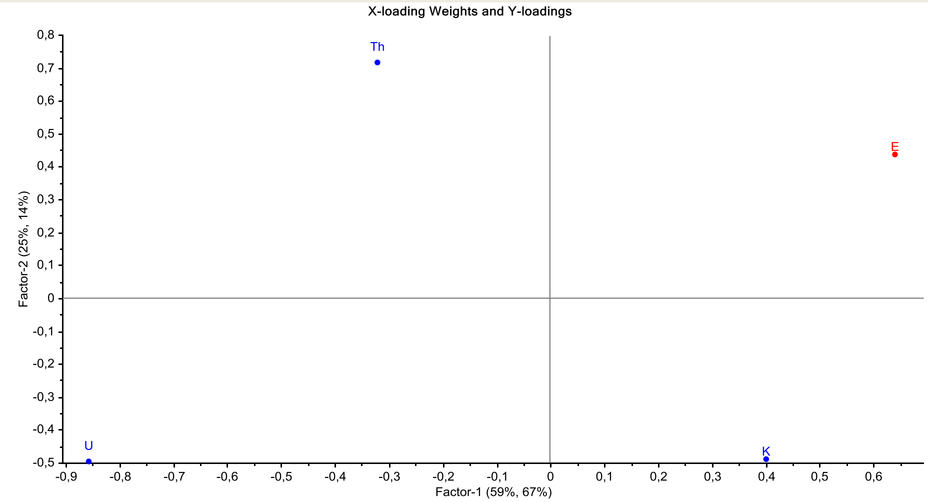


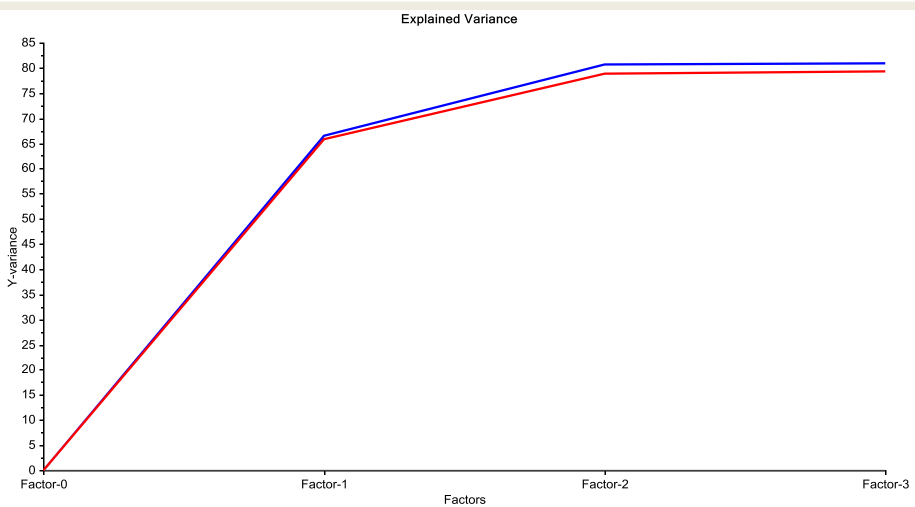


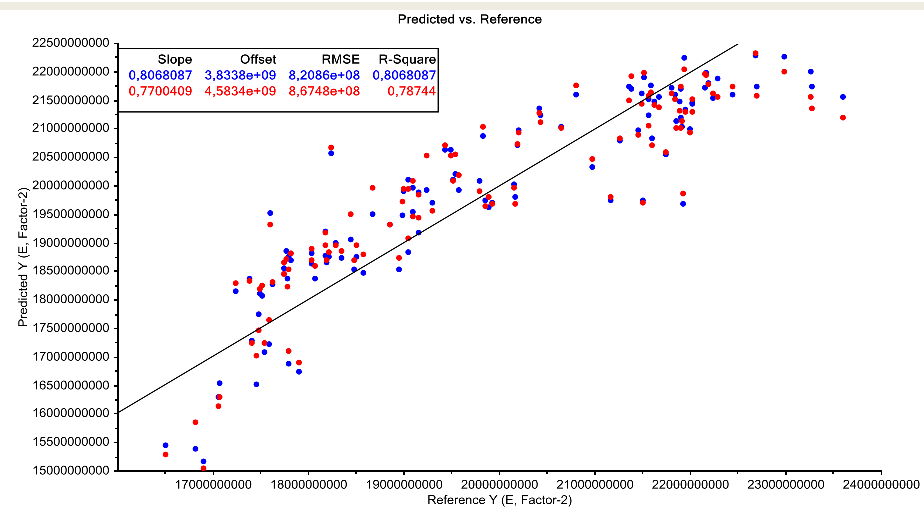
PLS [spectral gamma log]

PLS1 model, 2-seg X-val, X = [XRF]. X = [U, TH, K], y = E. Based on three X-variables alone [*'Spectral gamma log-chemistry'*], the degree to which E-prediction is possible, is reflected by slope: 0.77; r^2: 0.79 – which is most likely not precise enough?

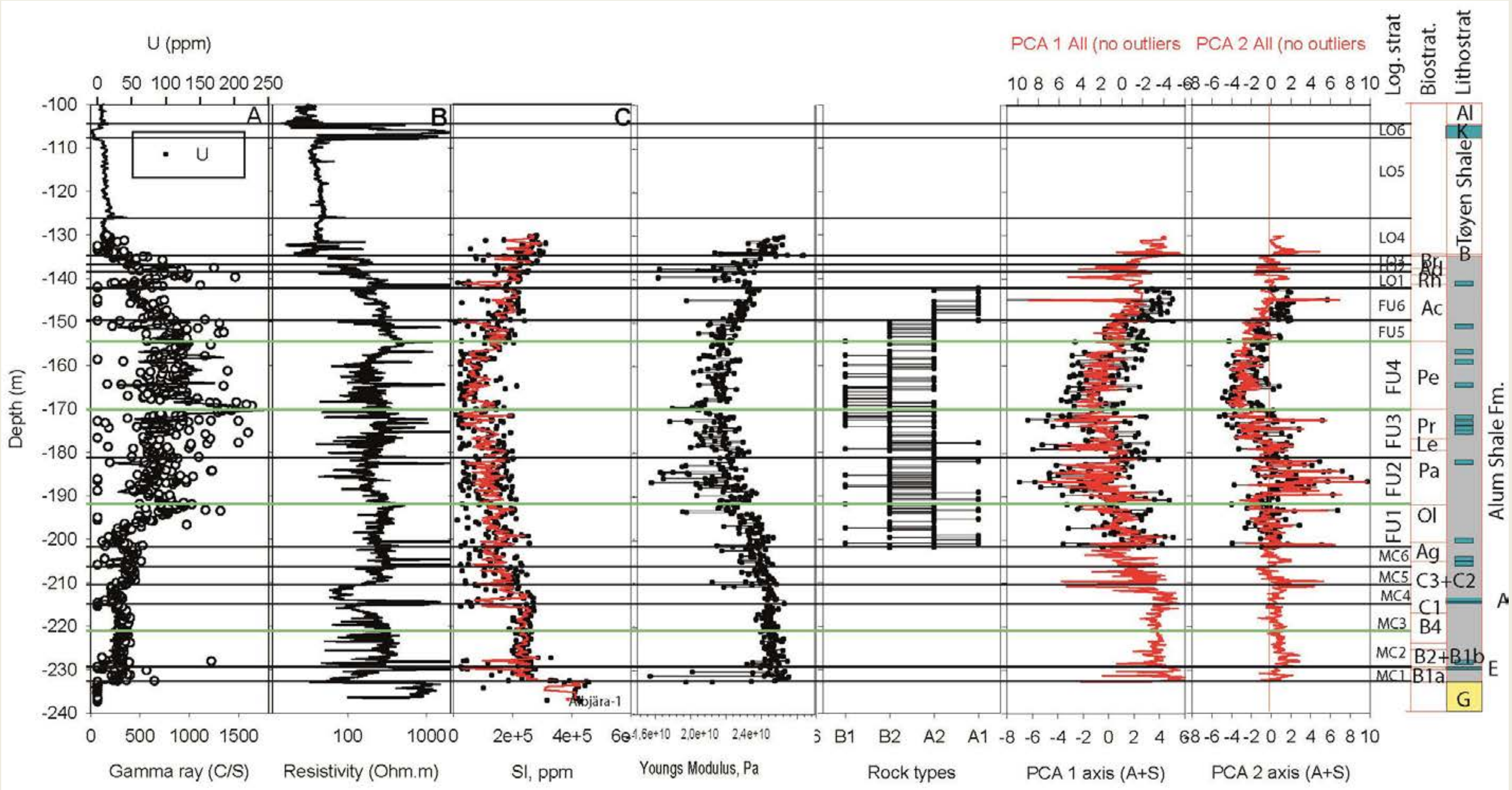
This illustrates that with a very modest logging program some indication of the Young's modulus can be obtained. It *might* be possible to calibrate a PLS model with better prediction performance, based on improved log data quality (higher resolution, dedicated outlier rejection …)







Prediction of Young's modulus in Albjära-1



- Young’s Modulus predicted based on the Sommerodde PLS model (see next slide). The E modulus is observed to follow the reference logs in Sommerodde-1 with strong correlation

Linear regression algorithms

Coefficients used to predict E from XRF data

	B_0	2,24E+10
Coef	Al	4365,789
Coef	As	-3171557
Coef	Ba	-21852,7
Coef	Bal	-2521,21
Coef	Ca	-2295,67
Coef	Cl	-1118374
Coef	Co	-61841,1
Coef	Cr	3107647
Coef	Cs	-4890826
Coef	Cu	1080086
Coef	Fe	3603,579
Coef	K	22193,34
Coef	Mg	32118,33
Coef	Mn	183103,3
Coef	Mo	-3928095
Coef	Nb	-6,23E+07
Coef	Ni	-1393595
Coef	P	-27288,9
Coef	Pd	2,67E+07
Coef	Rb	-3035315
Coef	S	2172,543
Coef	Sb	1,18E+07
Coef	Si	1079,37
Coef	Sn	3,62E+07
Coef	Sr	-2065777
Coef	Te	-535965
Coef	Th	-4,25E+07
Coef	Ti	107759
Coef	U	-5278376
Coef	V	-158556
Coef	Zn	-74463,9
Coef	Zr	4787023
E=Al*coef+As*coef +		

For the prediction to be valid the XRF method in Albjära should be calibrated to Sommerodde-1.

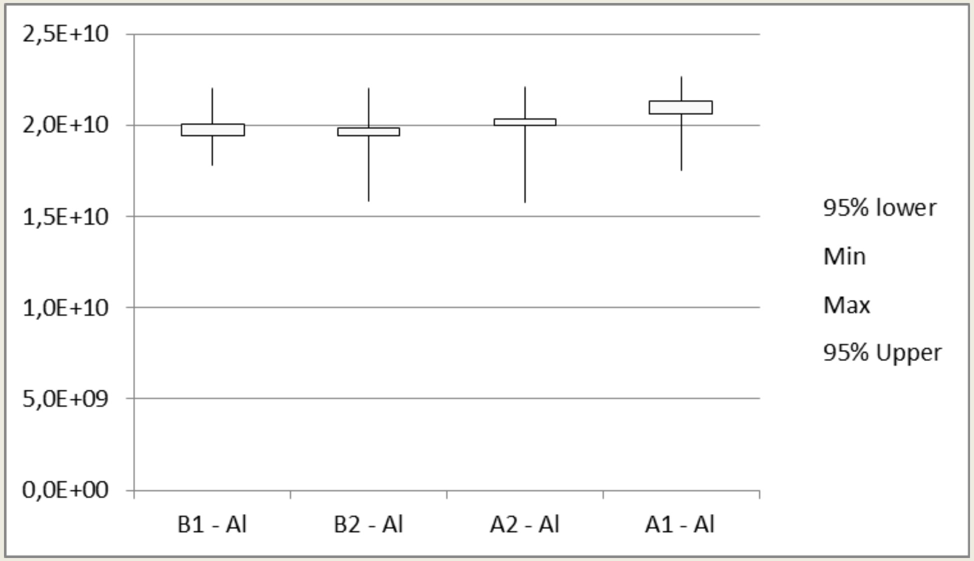
The same xrf-tool and analytical set-up was used for both wells

For prediction not all elements have equal importance (right)

PLS from a *reduced* data input matrix is a doable option and the predictive performance can be evaluated

Predicted Young modulus

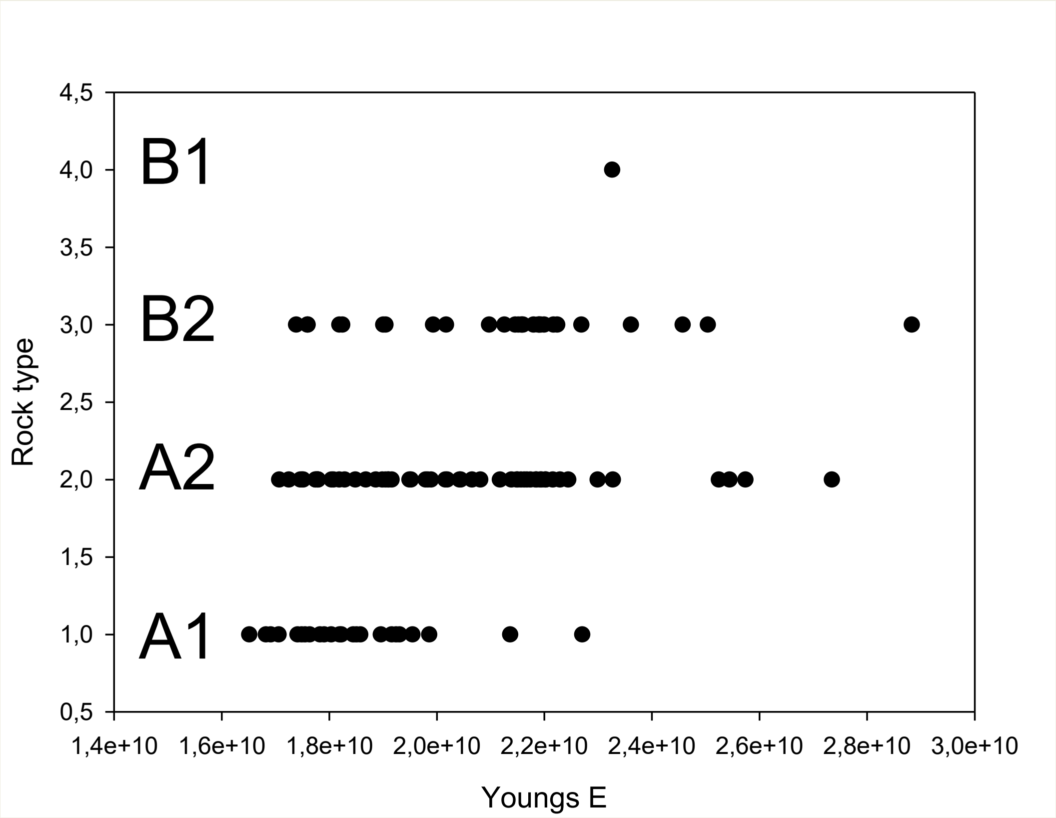
E, Pa	B1 - Al	B2 - Al	A2 - Al	A1 - Al
95% lower	1,95E+10	1,94E+10	2,00E+10	2,06E+10
Min	1,78E+10	1,58E+10	1,58E+10	1,76E+10
Max	2,20E+10	2,20E+10	2,21E+10	2,26E+10
95% Upper	2,00E+10	1,98E+10	2,03E+10	2,13E+10
Mean	1,97E+10	1,96E+10	2,01E+10	2,10E+10



PLS-predicted Young modulus show that the Alum Shale generally lies around 20 Gpa. Rock type B is the weakest (19,7 GPa and the A1 type is the strongest 21,0 GPa). There is a gradual transition in the strength between rock types

Predicted E provide less accurate rock type predicting but does discriminate between main rock types A or B

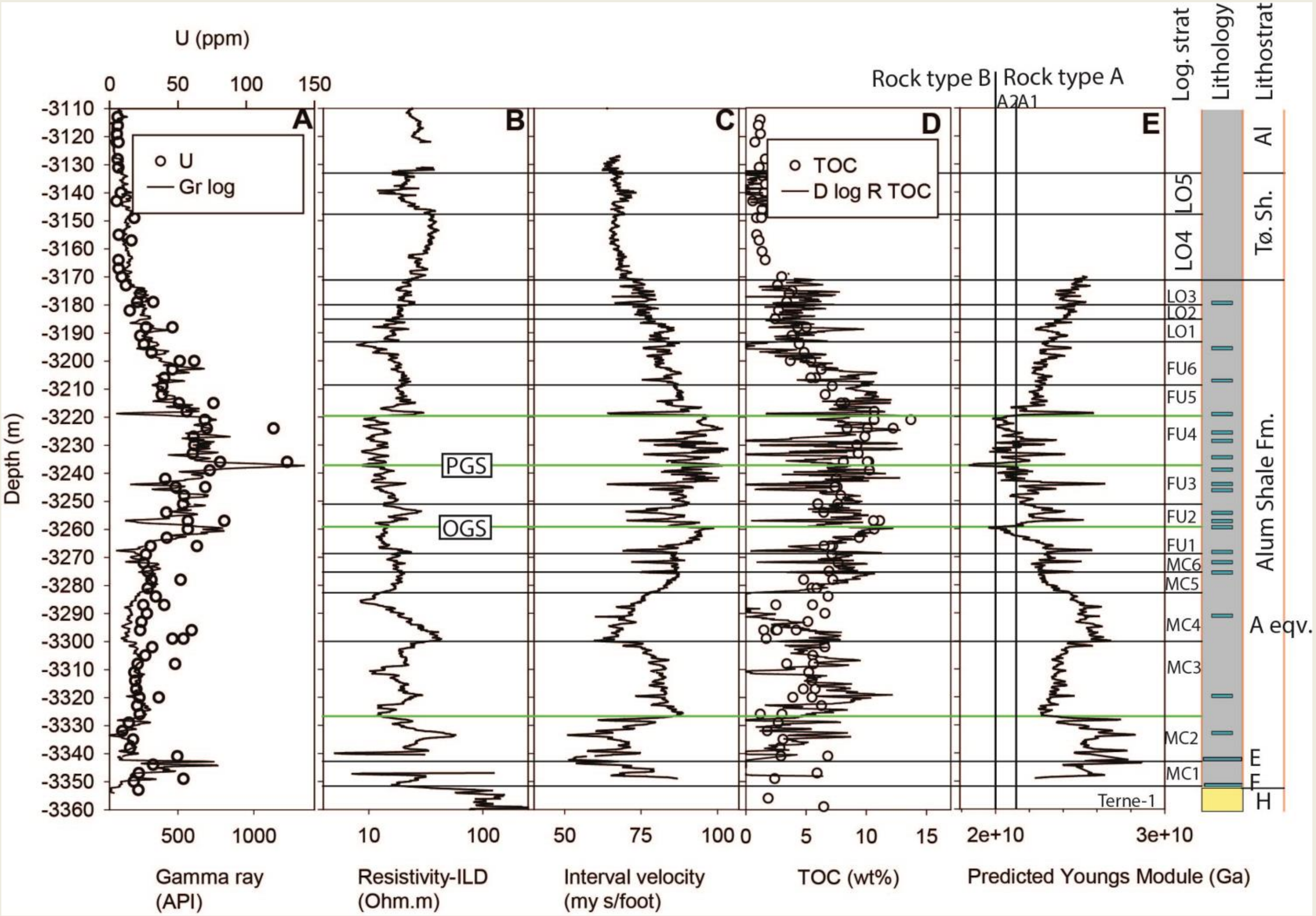
Rock types from Predicted E
=IF(E/1000000000<20;"B1 or B2"; IF(E/1000000000<20.45;"A2";"A1"))



(from PowerPoint PCA 3/6-2014)

- From previous Sommerodde comparisons between rock types and E, similar finding of E in rock type A and B was observed:
- Young's modulus (E) exhibit higher values in the B rock type (siliceous shale) versus the A type (sulfidic type)

Predicted E *vs.* rock types in Terne-1



- Predicted rock strength in Terne is *higher* than in Sommerodde. Consequence rock types predicted from E is mainly of the A types ….

Linear regression algorithms

Coefficient used to predict E from logs limited to those also in the Terne-1 well

B_0	B_0	2,70E+10
Coef	DT	-8,12E+07
Coef	RHOB	2,28E+09
Coef	GR	-1380644
Coef	ILD	-9412081
Coef	NPHI	-8,19E+07
Coef	POTA	-1,86E+08
Coef	TH	4,95E+07
Coef	URAN	-7822388
E=B_=+DT *Coef+Rhob*Coef+ ….		

Prediction of E in Terne-1

Log calibration:

- Prediction of E from logs requires that the logs are calibrated i.e. that the tool responses are identical. For Sommerodde and Terne this is not always the case and the difference will degrade the validity of predicted E-values. For E-prediction re-scaling of K, Th, GR and U in Terne to similar values and ranges as in Sommerodde was performed, since these were interpreted to be critical for the calibration modelling. In the PLS model auto-scaled data are used (mean/1 standard deviation); this could be done for all or for selected logs. This PLS-model optimisation is not carried out yet.

Ambient conditions:

- The bore-hole conditions are unlike each other in Terne and Sommerodde i.e. the formation fluid are likely less salty in Sommerodde, the depth difference (Terne is aprox 3 km deeper than Sommerodde) likely means that sonic and porosity logs will be different due to compaction a.o.

Prediction of E in Terne-1 (cont.)

- The Predicted E in Terne are significantly higher than those seen in Sommerodde. Since E is expected to be higher in Terne-1 due to higher present day burial (+ 3 km), this may be as expected.

- The overall stratigraphical trends in the E values in Terne-1 is very similar to the observed in Sommerodde as well as that predicted in Albjära-1

Prediction of Rock Types in Terne-1

- PLS models for prediction of rock types were tested, aimed to predict the PCA 1 component and the XRF defined rock type as well as flags i.e. Si, Al, S. No PLS predictive model that has high statistical significance was observed

- As a predictor for Rock type A vs. B, E modulus is used as it gives good *separation* in the Albjära-1 well between A and B types

- Predicted E is higher in Terne-1 than in Sommerodde/Albjära, from which follows that the modelled Rock types are dominated by Rock type A. Rock type B occur in selected log zones in the Furongian. This stratigraphical mode was also expected based on the distribution of rock types in Albjära-1

PLS - Conclusions

- Based on the full complement of [logs, XRF] X-data, excellent data models can be established

- Different 'pruning' of the X-variable data set, allow the conclusion that E-prediction based on logs alone is eminently possible, also with many X-variable set reduction possibilities. It is also possible to base E-prediction only on three 'elemental logs' [U, Th, K], although with a somewhat reduced prediction validation result

- It is desirable that TOTAL specifies quality thresholds for accuracy (*slope*) and precision (r^2) after which multiple alternative improved PLS prediction models can be tested

3.7. Alum Shale lithologies

Alum Shale lithologies

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Klima-,Energi- og Bygningsministeriet

Main lithologies

- Three main lithologies in the Alum Shale Formation (ASF) of southern Scandinavia:
  - A few thin primary bioclastic limestones (< 1 m thick)
  - Sporadic to common stinkstone concretions (secondary limestone), accounting for < 5% of stratigraphic thickness
  - Alum Shale mudstone

In south central Sweden is also seen numerous layers of bioclastic stinkstone; they may account for 50% or even more of the stratigraphic thickness. This facies does not occur in southernmost Sweden-Denmark

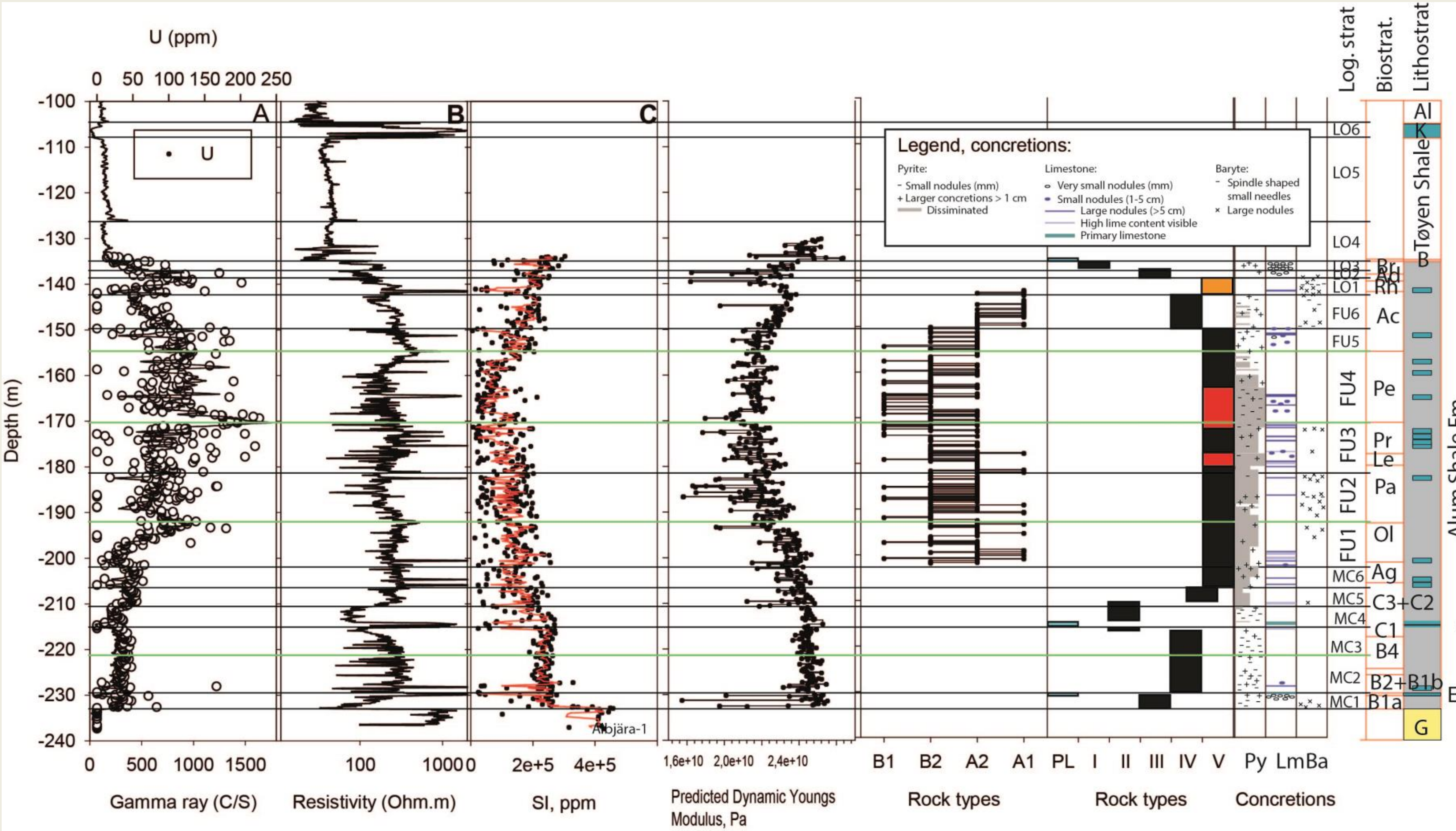
Main lithologies: Primary limestone

- Thin marker beds associated with major sea level lowstands: Forsemölla Lmst, Exsulans Lmst, Andrarum Lmst.
- Deposition took place during incipient sea level rise after lowstand peak, i.e. TST
- 0.2 to 1 m thick, mainly Middle Cambrian
- Only in Oslo: Incipiens Lmst in middle Tremadocian. Unlikely but could theoretically be present in northern Jutland
- Bjerkåsholmen Fm on top of ASF of same type

Main lithologies: Concretions

- Early concretions, mostly 0.1-0.5 m thick, rarely > 2 m long
- Most common in the Furongian, less common in Middle Cambrian and lower Tremadocian, absent in basal Middle Cambrian and middle-upper Tremadocian
- Usually semi-continuous stinkstone bed present at the base of the Furongian, 0.2-0.5 m thick

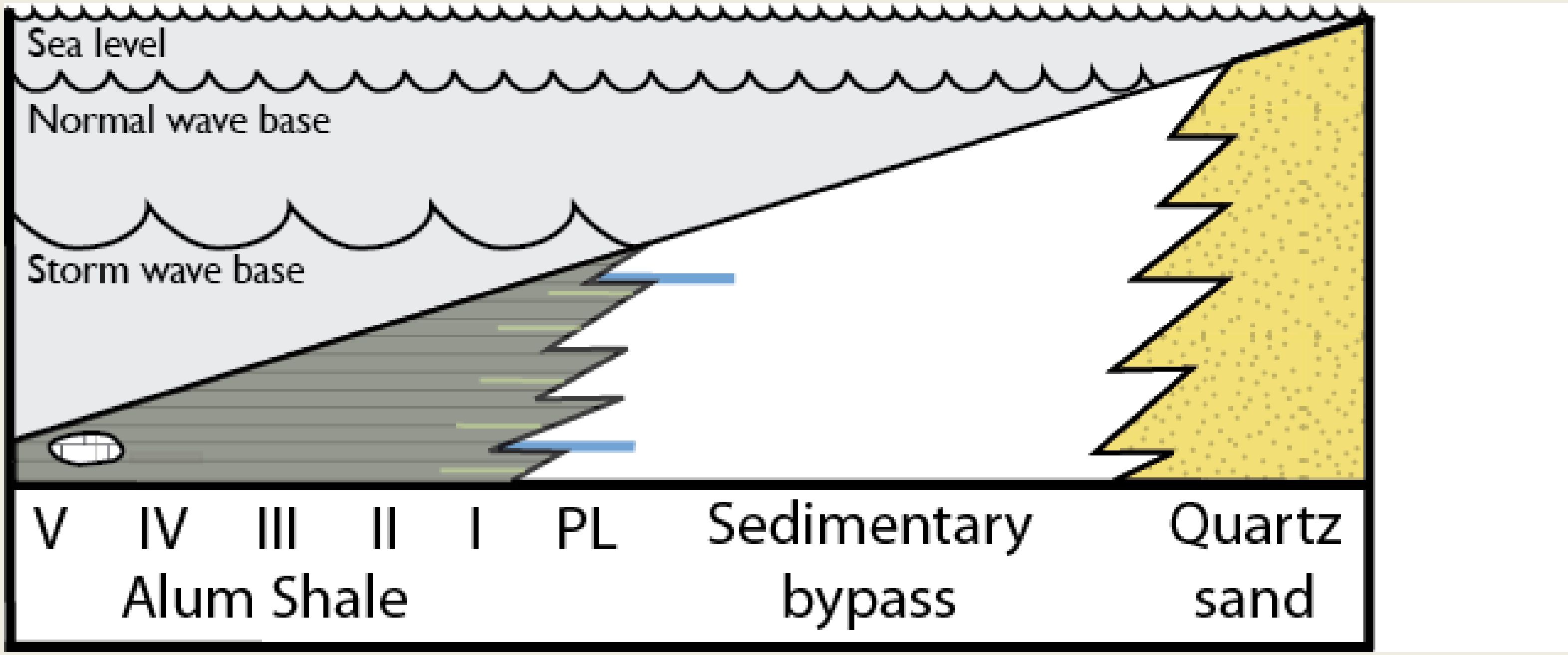
Albjära-1 summary lithologies



Main lithologies: Alum Shale mudstone

- Five subtypes recognized
- Labelled I to V
- Subtype I shallowest and best oxygenated facies; Subtype V deepest, most oxygen depleted facies
- Subtype V further subdivided into highly pyritic and barite-containing subfacies

Simplified facies model



Sedimentary bypass on inner shelf is a medial Middle Cambrian-Tremadocian phenomenon. Here wide facies belt with greenish mudstone in the early Mid Cambrian

Main lithologies: Alum Shale mudstone

- Sub-type I:
  - Silt streaked laminated Alum Shale with thin silt bands, < 2 cm thick, increasing in abundance upwards. No stinkstone concretions. Some irregularly shaped pyrite concretions up to a couple of cm. TOC content low to moderate.
  - Sub-type I characterizes the interval c. 136.8-top of formation (upper part of the Tremadocian). The same facies is locally seen in the Middle Cambrian of eastern Scania.

Main lithologies: Alum Shale mudstone

- Sub-type II:
  - Bands of blackish shale alternating with bands of dark grey shale; individual shale bands are from 1-5 cm thick. No limestone concretions. Low/very low TOC content and macroscopic pyrite content moderate; low content of dissiminated pyrite (macroscopic inspection).
  - Occurs primarily above the Andrarum Limestone up to about 209-210 m in the Albjära core (upper boundary gradual over a metre). This interval is much more expanded in the Terne-1 well. AS sub-type II (more blackish than greyish) also occurs down to 0.75 m below the Andrarum Lmst in the Albjära core.

Main lithologies: Alum Shale mudstone

- Sub-type III:
  - Blackish laminated mudstone with numerous very small rounded limestone nodules, 0.5-1 cm in diameter. No visible dissiminated pyrite, macroscopic pyrite nodules rare; no large stinkstone concretions. Comparatively low TOC.
  - Present below Exsulans Lmst and in a short interval in the Tremadocian between 136.8-138.7 m.

Main lithologies: Alum Shale mudstone

- Sub-type IV:
  - Comparatively homogenous, laminated Alum Shale; macroscopic pyrite rare and low content of dissiminated pyrite. A few stinkstone concretions . TOC content moderate.
  - Characterizes the Middle Cambrian interval between the Exsulans and Andrarum limestones except immediately below the Andrarum Limestone (= type C). Sub-type IV also characterizes the uppermost part of the Furongian and the basal Tremadocian, interval c. 150-142.2 m

Main lithologies: Alum Shale mudstone

- Sub-type V-a:
  - Blackish, laminated, usually highly pyritic (dissiminated) shale with occasional stinkstone nodules (more common than in the other Alum Shale sub-types). Comparatively large pyrite nodules occur (up to some 5 cm diameter), but dissiminated pyrite dominates. High TOC content.
  - Characterizes 206.6-c. 150 m (base of *A. pisiformis* Zone - most of the Furongian).
  - In particular the interval 162.6-171.5 m but also 176.9-179.8 are very rich in dissiminated pyrite (subtype V-b). [Please note that a large limestone concretion occupies 163.7-164.5 m].
  - Dissiminated pyrite less common between c. 197-202.2 m
  - Interval 210-206.6 m transitional between subtypes IV and V

Main lithologies: Alum Shale mudstone

- Sub-type V-c:
- Laminated Alum Shale containing barite, occurring as whitish nodules, often rhomb-shaped, up to c. 1 cm in diameter, concentrated in certain horizons. TOC content moderate. No large limestone concretions seen in the Albjära core.
- Barite and pseudomorphs after barite common at several levels in the Furongian Alum Shale of Bornholm and eastern Scania but for unknown reasons rare in the Albjära core.
- Sub-type V-c characterizes 142.2-138.70 m (Tremadocian). Barite particularly common 140.2-139.5 m and rare/sporadic above this level, where pyrite in bands (dissiminated) instead is common.

Conclusions 1

- An full core evaluation of the Albjära-1 core is presented including:
  - Log and biostratigraphical breakdown
  - Sedimentological facies characterisation
  - Distribution of concretions of pyrite, limestone and barite
  - High resolution handheld-XRF logs including 33 elements
  - PCA rock typing based on hXRF
  - Prediction of the Edyn

Conclusions 2

- The full core evaluation show that there is good relationship between sedimentological defines facies and the XRF-PCA defined rock typing.
- The sedimentary facies had basin wide distribution and the same facies types/rock types are expected in Vensyssel-1

4. Interpreted data

Interpreted data are included on the attached CD in the files Table 1-6.

Appendix A: Log stratigraphical breakdown of the Alum Shale

As backbone for the analysis of rock types a new log stratigraphical breakdown of the Alum Shale is presented (Schovsbo & Nielsen unpublished). The log-based stratigraphy is based on the analysis of the wells in Scania were detailed biostratigraphical control exist.

Gamma ray log and biostratigraphy

The Alum Shale is well known for its high uranium content which leads to exceptional high GR readings compared also to TOC rich upper Ordovician to Lower Silurian shales. Highest Gr reflecting occur in the Furongian notably in the Peltura zones within a few m thick interval that marks the base on the new *Peltura* zones (Nielsen et al. in press). This GR spike is termed the “*Peltura* GR spike” (PGS). Slightly lower but equally important for correlations is a marked gamma ray high in the top most part of the Olenus Zone. This spike is here termed the ‘*Olenus* Gr-Spike’ (OGS). Other biozone which boundaries are characterised by less conspicuous increase in GR include the top Agnostus pisiformis Zone, the top L. lejopyge Zone. The not un-common link to biozone boundaries reflect a common forcing between faunal dynamics and depositional environment that lead to U fixation. An overview is shown in Table A-1).

The U/TOC in the Alum shale follows the stratigraphy. In thermally mature Alum shale the ratio is almost fixed at about 5 in the Middle Cambrian (Schovsbo 2002). In the Furongian the U/TOC is much more variable and may exceed 20.

Formation resistivity

In the Alum Shale the stratigraphical variation in the resistivity log show an overall resemblance with the variation depicted by TOC. This is also as expected base on the work by Passey et al. (1990).

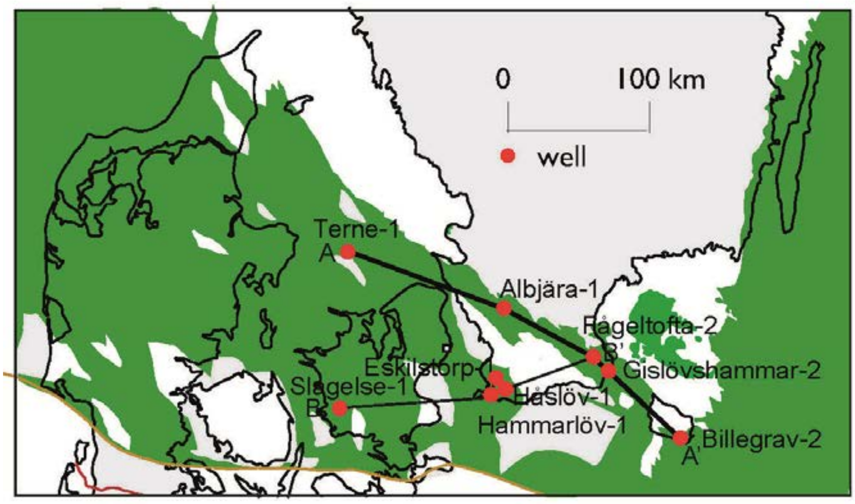


Figure A-1: Wells used in the stratigraphical analysis.

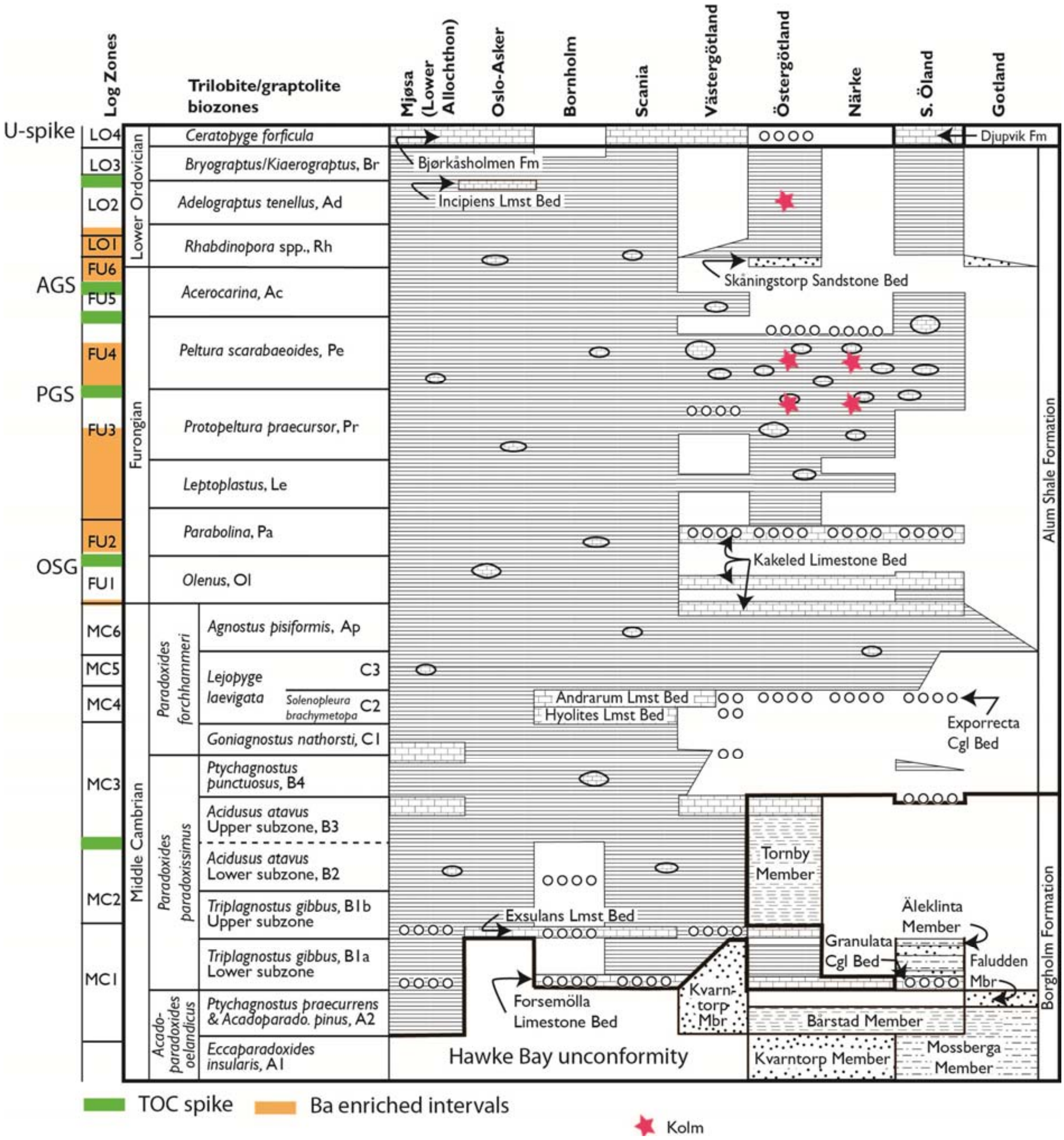


Figure A-2: Relationship between logstratigraphy and biostratigraphy. OGS, PGS and AGS referees to Olenus Gamma ray spike, Peltura Gamma ray spike and Acerocare Gamma ray spike. Green lines indicate that the log zone boundary co-inside with a TOC maximum. Red stars indicate the occurrence of Kolm nodules in Central Sweden (see Schovsbo 2002).

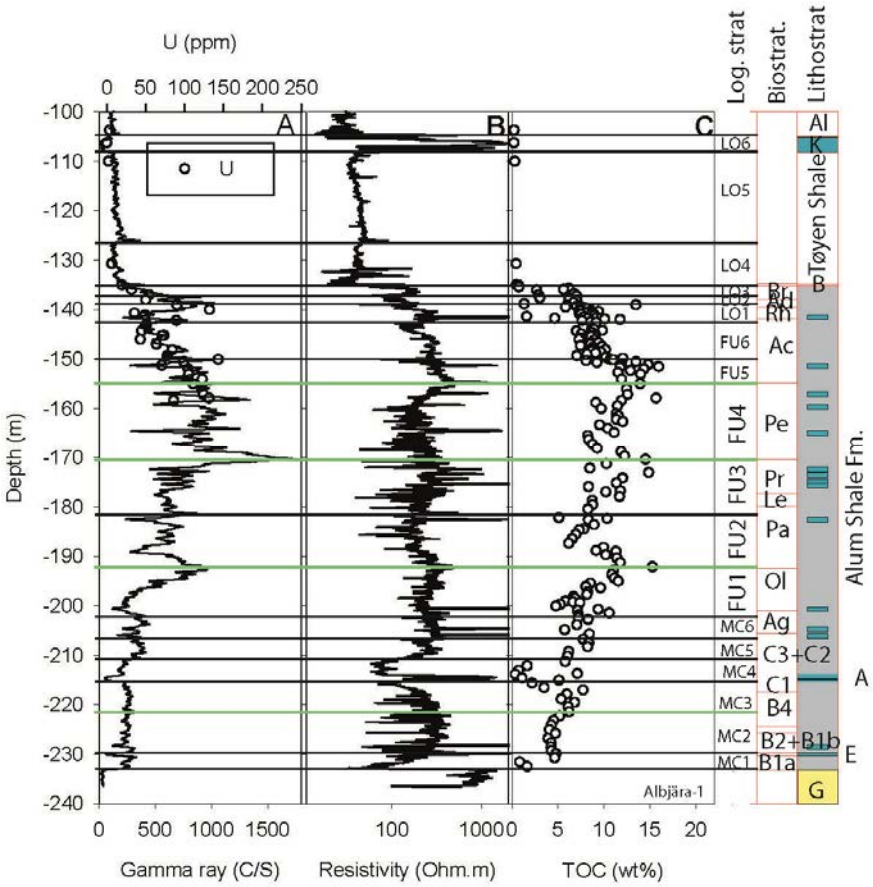


Figure A-3. Synoptic log of the Albjära-1 well. Legend: yellow: sandstone; dark brown: dark shale; blue: limestone beds and carbonate cemented shale. Stratigraphical abbreviations referee to Figure A2.

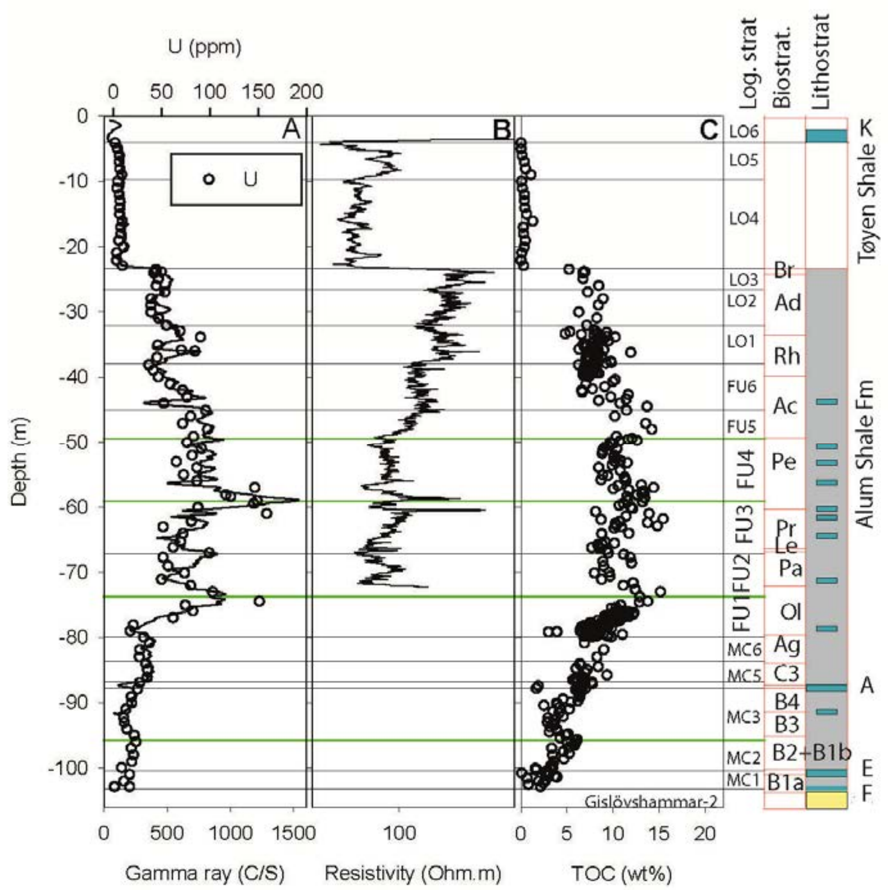


Figure A-4. Synoptic log of the Gislövshammar-2 well. Legend: yellow: sandstone; dark brown: dark shale; blue: limestone beds and carbonate cemented shale. Stratigraphical abbreviations referee to Figure A2.

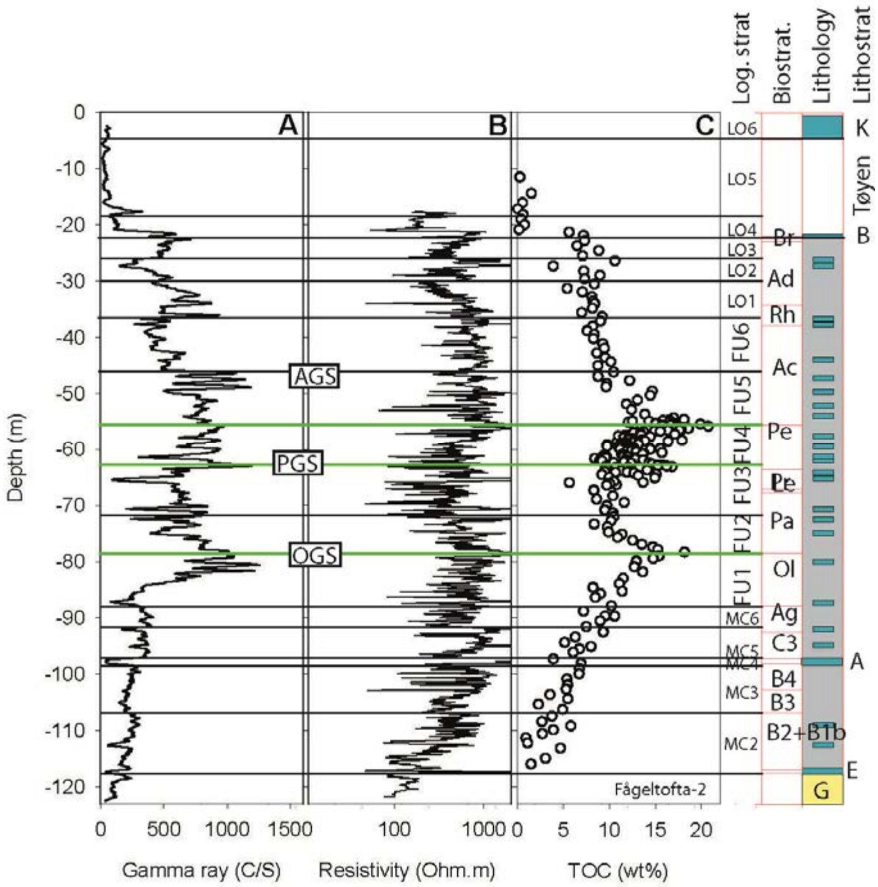


Figure A-5. Synoptic log of the Fågeltofta-2 well. Legend: yellow: sandstone; dark brown: dark shale; blue: limestone beds and carbonate cemented shale. Stratigraphical abbreviations referee to Figure A2.

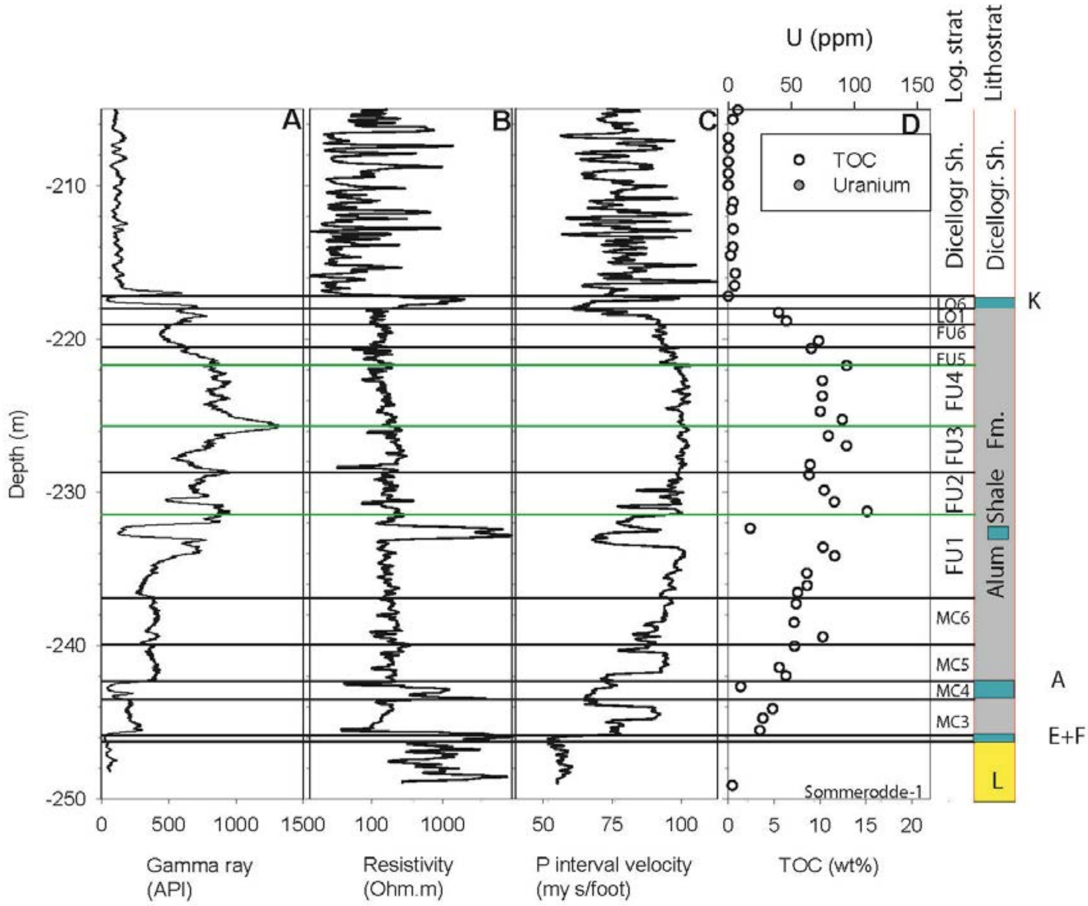


Figure A-6. Synoptic log of the Sommerodde-1 well. Legend: yellow: sandstone; dark brown: dark shale; blue: limestone beds and carbonate cemented shale. Stratigraphical abbreviations referee to Figure A2.

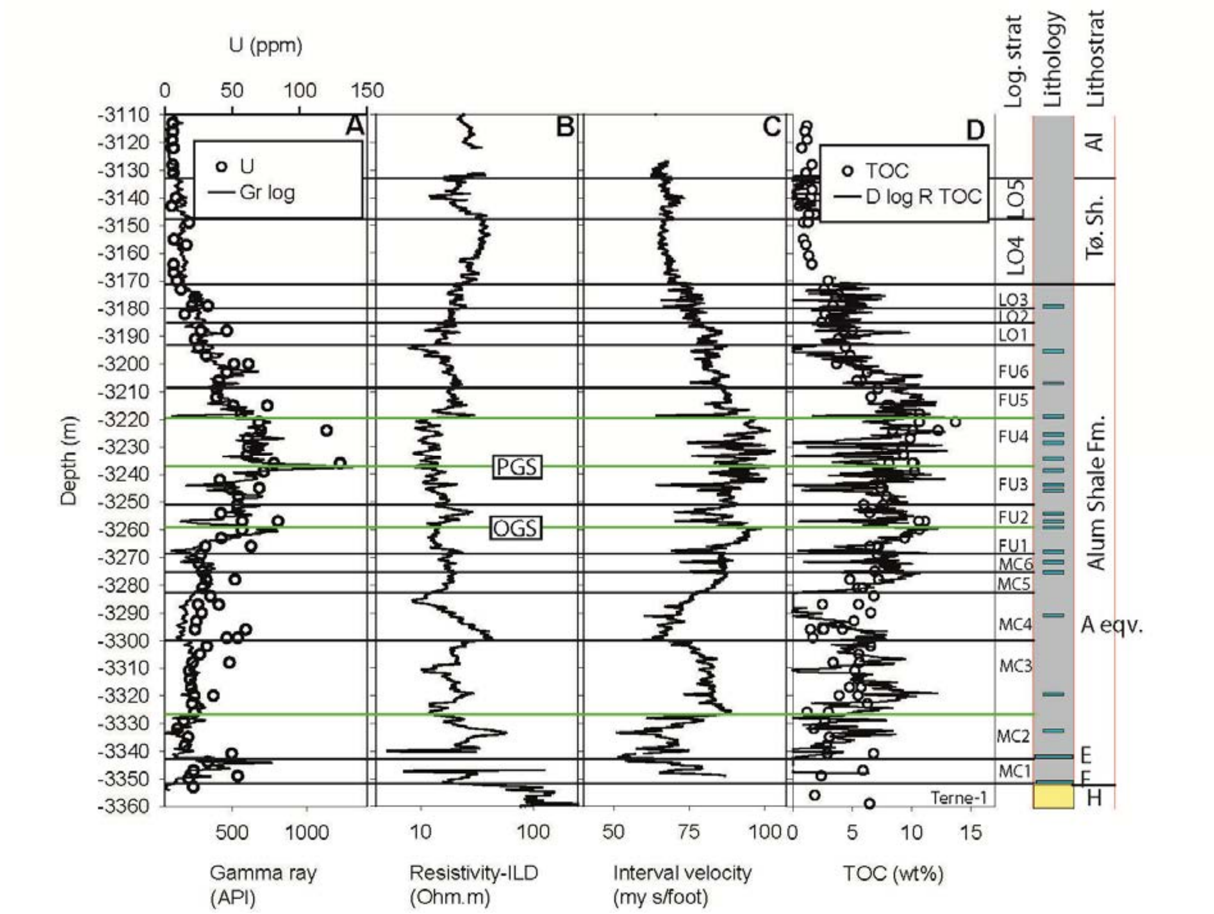


Figure A-7. Synoptic log of the Terne-1 well. Legend: yellow: sandstone; dark brown: dark shale; blue: limestone beds and carbonate cemented shale. Stratigraphical abbreviations referee to Figure A2.

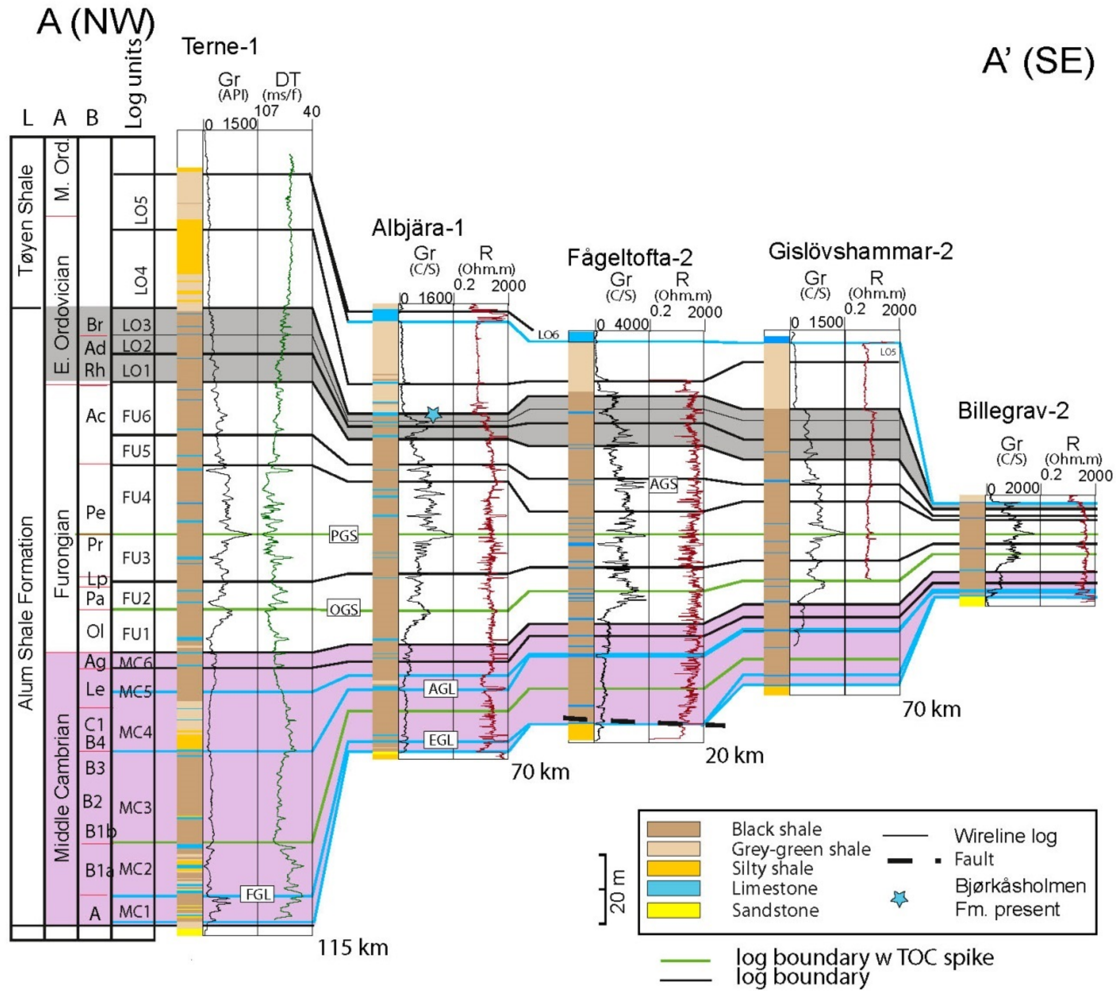


Figure A-8: Correlation profile (see Figure A1). Stratigraphical abbreviations referee to Figure A2.

Appendix B: Lithological logs

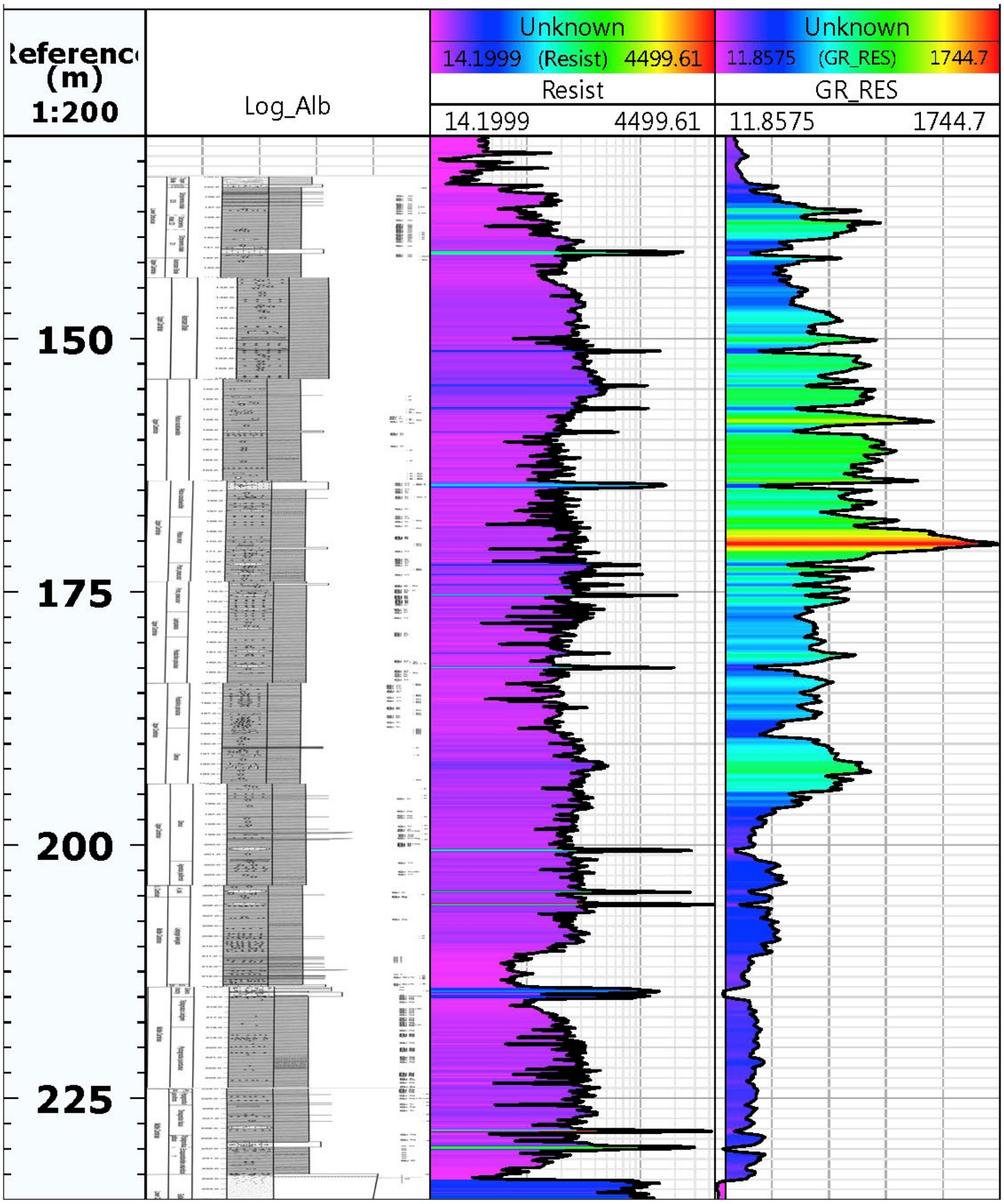


Figure B-1: Lithology and log responses (GR, Resistivity) in the Albjära-1 bore hole. The lithological log is from Lauridsen (2000). Note that there is a very good agreement between Resistivity spikes and logged carbonate beds/concretions.

Appendix C: Geochemical profiles

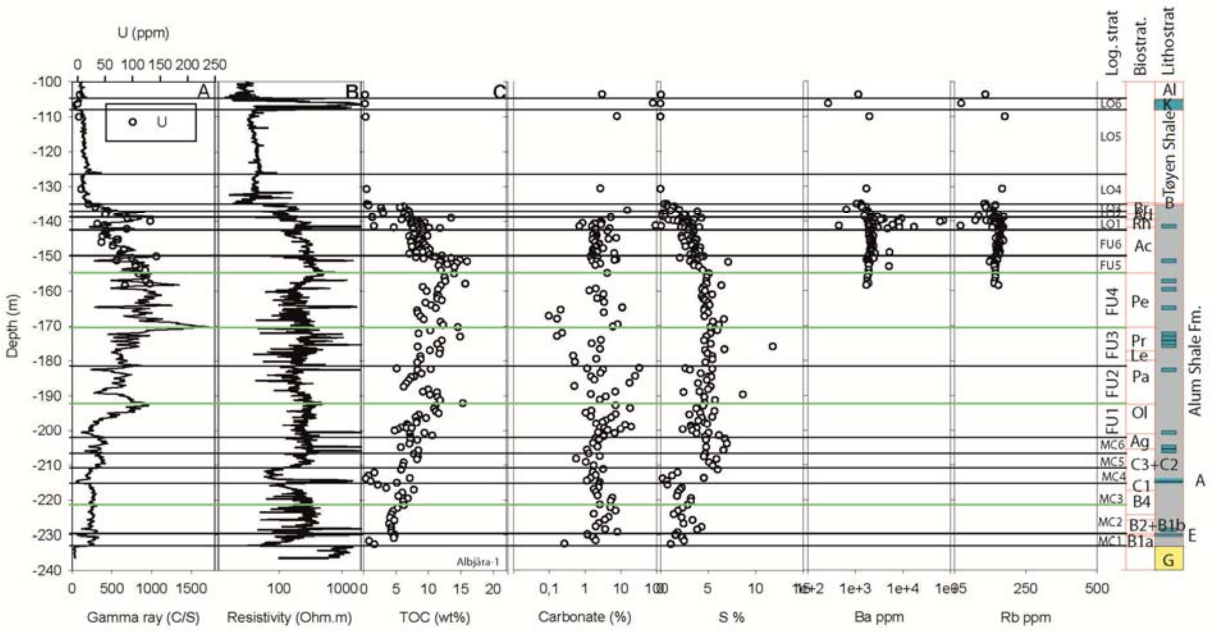


Figure C-1: Geochemical profiles in the Albjära-1 well.

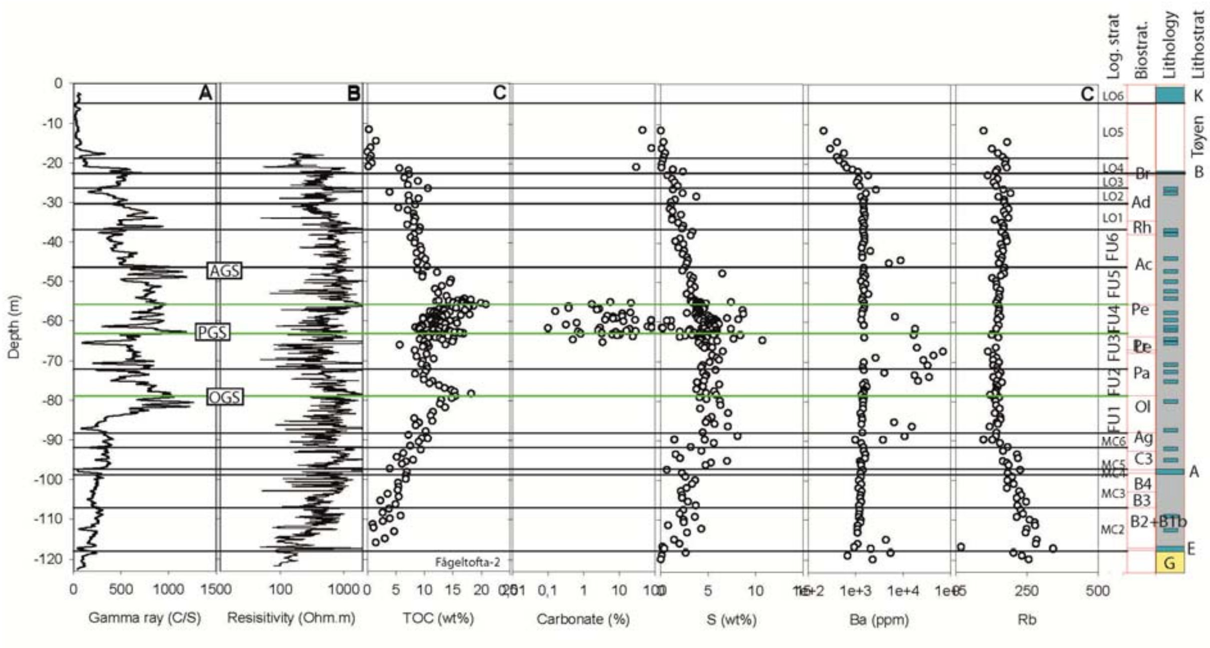


Figure C-2: Geochemical profiles in the Fågeltofta-2 well.

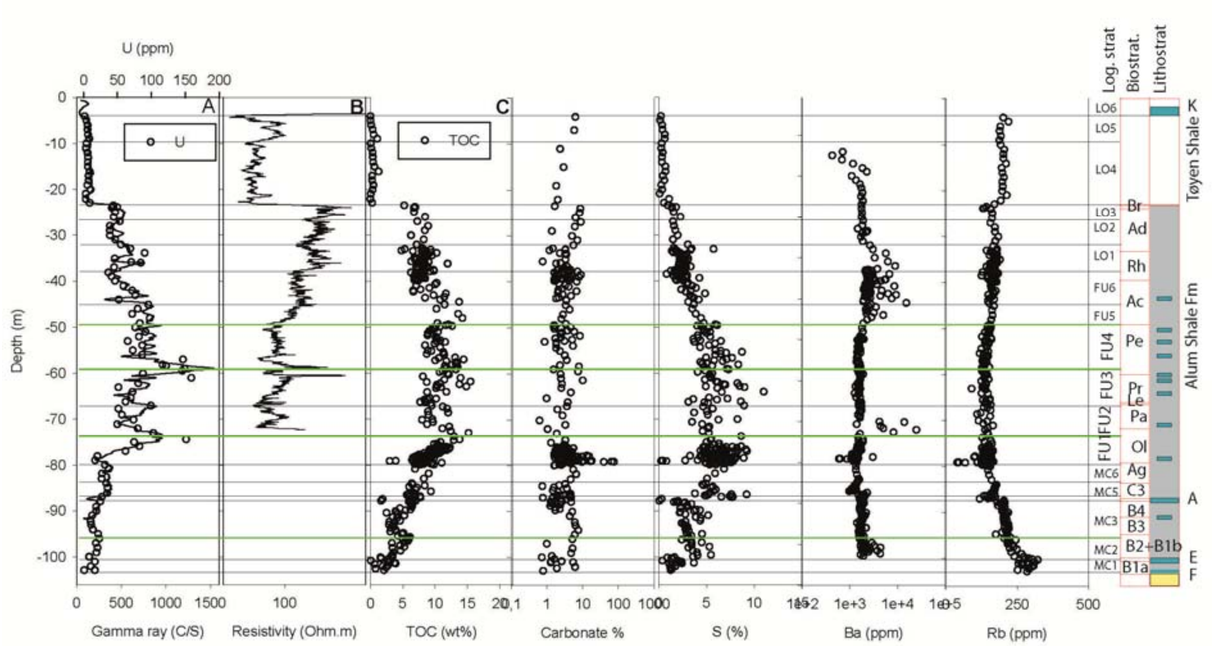


Figure C-3: Geochemical profiles in the Gislövshammar-2 well.

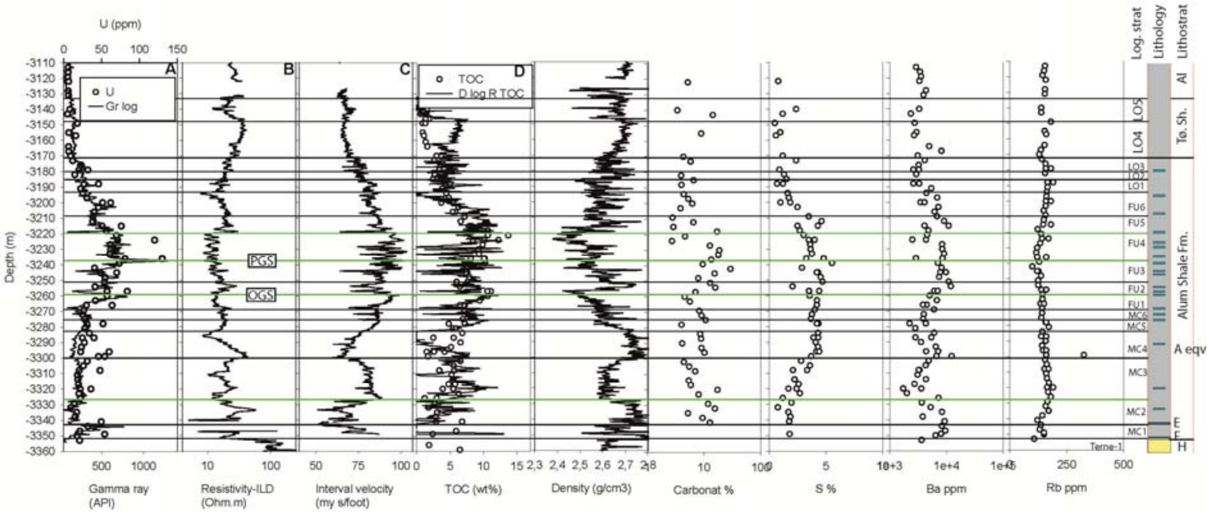


Figure C-4: Geochemical profiles in the Terne-1 well.

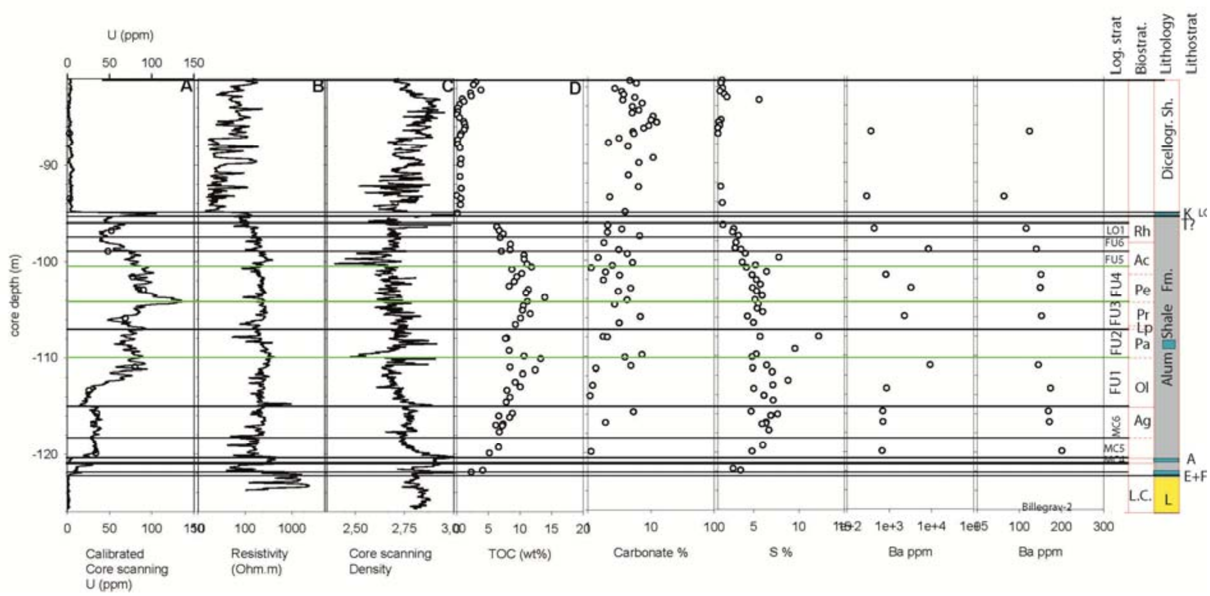


Figure C-5: Geochemical profiles in the Billegrav-2 well.

Appendix D: TOC distribution

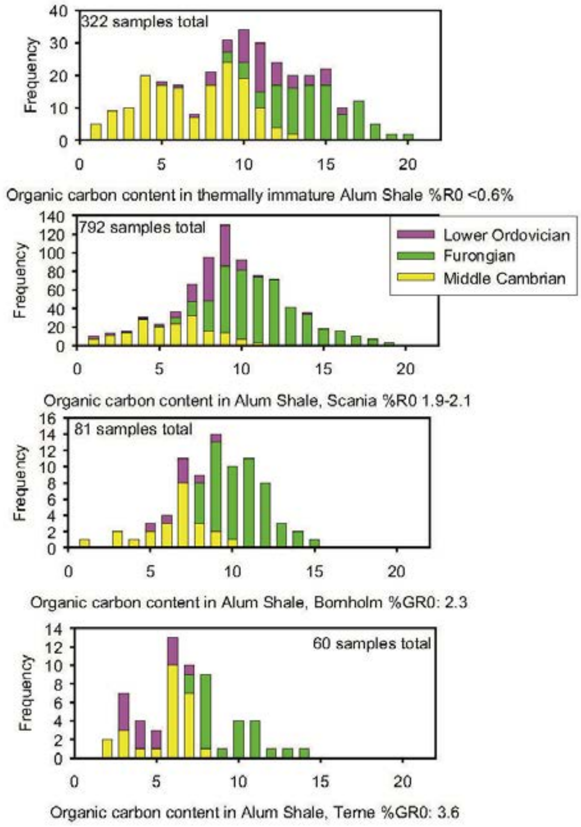


Figure D-1: Histograms of the TOC variation in the Alum Shale in maturity intervals.