

The IP response of black shales in the Oslo graben

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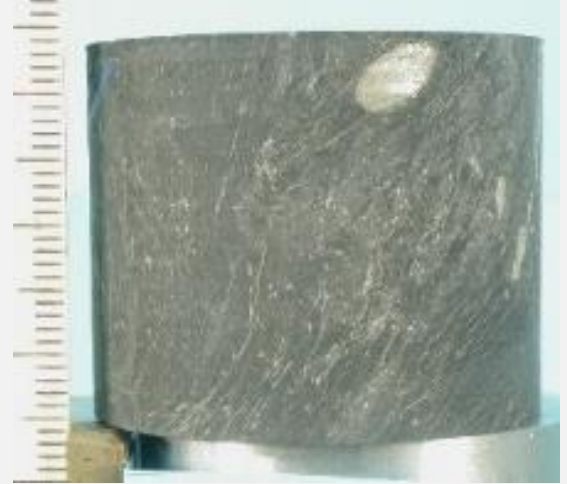
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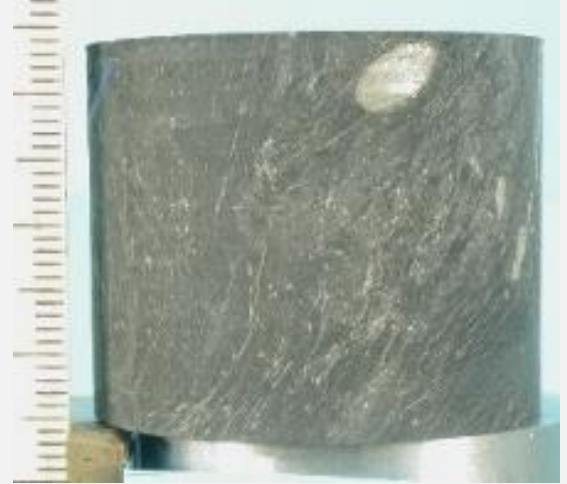
Black shale

- Anoxic sedimentation
 - Iron sulphides
 - Heavy metals
- Environmentally harmful
 - Sulfuric acids
 - Radon gas (carcinogenic)
 - Uranium up to 200 mg/kg
- Poor mechanical properties
- Swell under oxidation
- Strict handling. Must be deposited in an anoxic environment



Black shale

- Shale type classified by
 - neutralization/acidification potential NA/AP
 - Sulfur versus TIC (carbonates)
 - Fe/S ratio
 - Ratios of Si, Al, Ca, Fe, Mg, Na, K, Ti, Mn and P
- Should be possible to differentiate by ERT and IP.
- Black shale resistivity measured as low as $< 0.1 \text{ Ohmm}$ (by AEM, ERT and lab measurements)
- IP has so far been difficult to interpret



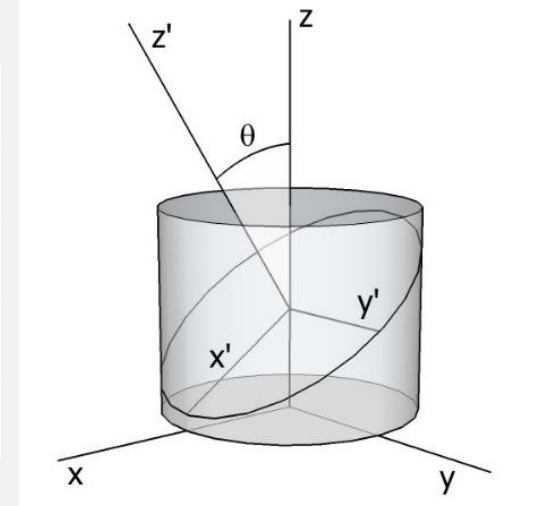
Slemmestad field site

- 2-3a: Alum (black shale)
- 3b α : Hagaberg (gray-green shale)
- 3b β : Galgeberg (black shale)
- 3c α : Huk (limestone)
- 3c β -3c γ : Limestone-rich shale
- 3c: Huk (limestone).
- 4a α : Elnes (gray-black shale)



Previous lab DC measurements

Alum shales	Sulphides (g/kg)	Uranium (mg/kg)
Gran	14-25	60-80
Oslo centre	30-40	80-200
Slemmestad	50	80-200
Jevnaker	25-37	>200



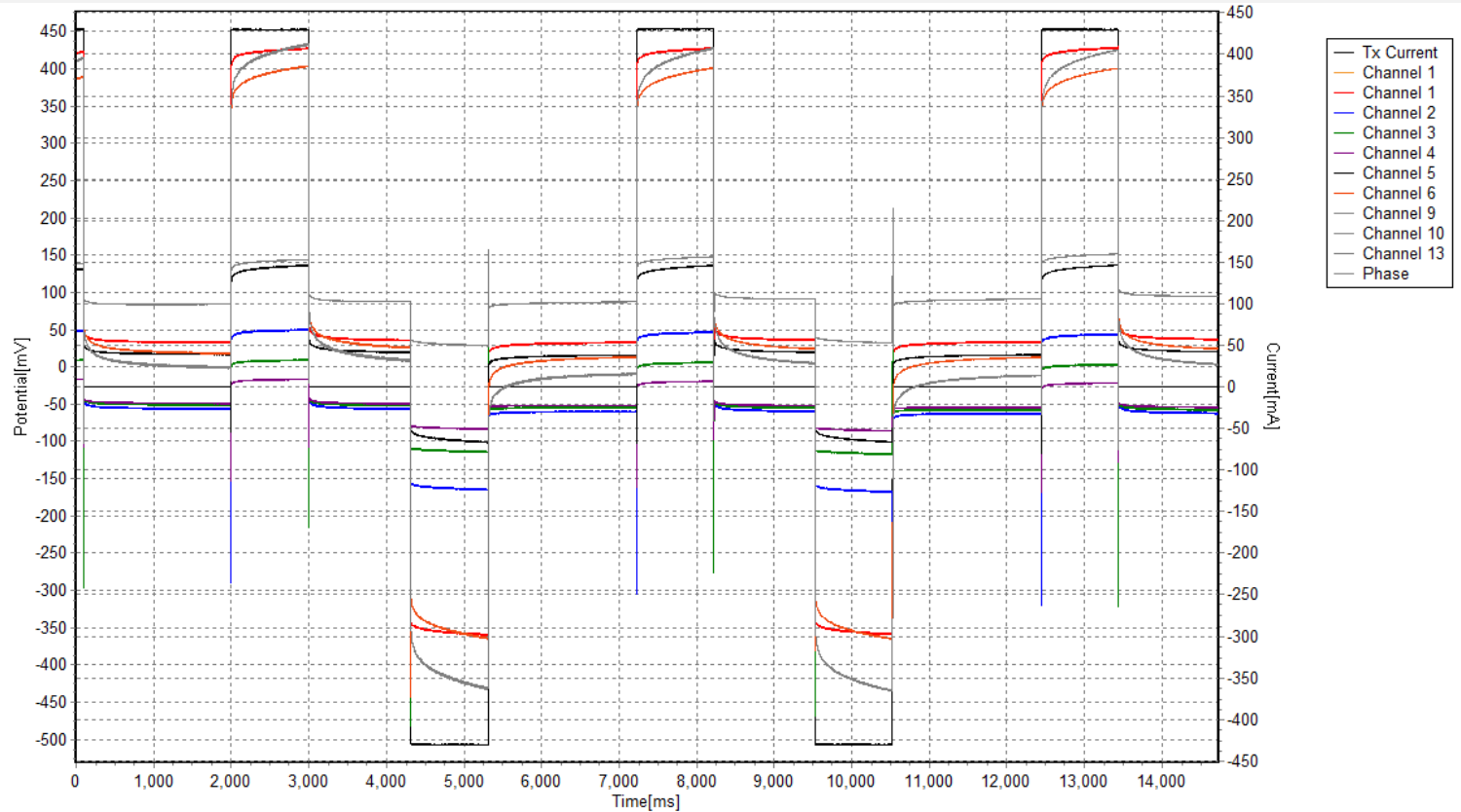
	4a α Elnes	3c α /3c γ Huk	3b β Galgeberg	3b α Hagaberg	2-3a Alun
$1/\sigma_{z'z'} (\Omega.m)$	84	540	0.54	240	0.13
$1/\sigma_{x'x'} (\Omega.m)$	44	43	0.25	110	0.025

Time-domain field survey

- ABEM Terrameter LS
- 12 Channels
- Gradient protocol
- 1.5 m electrode spacing
- 120 m total length
- $T_{on} = T_{off} = 1$ s
- Up to 5 cycles for stacking
- ~ no AC noise

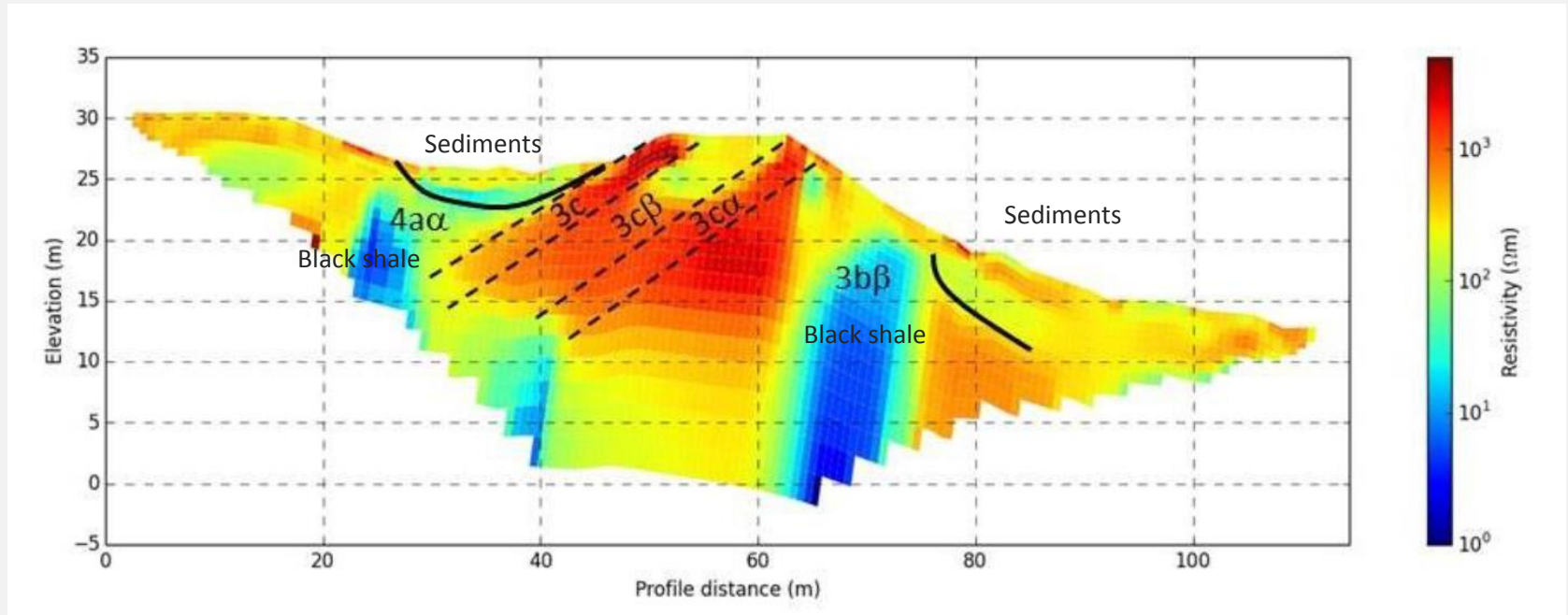


Decay curve example



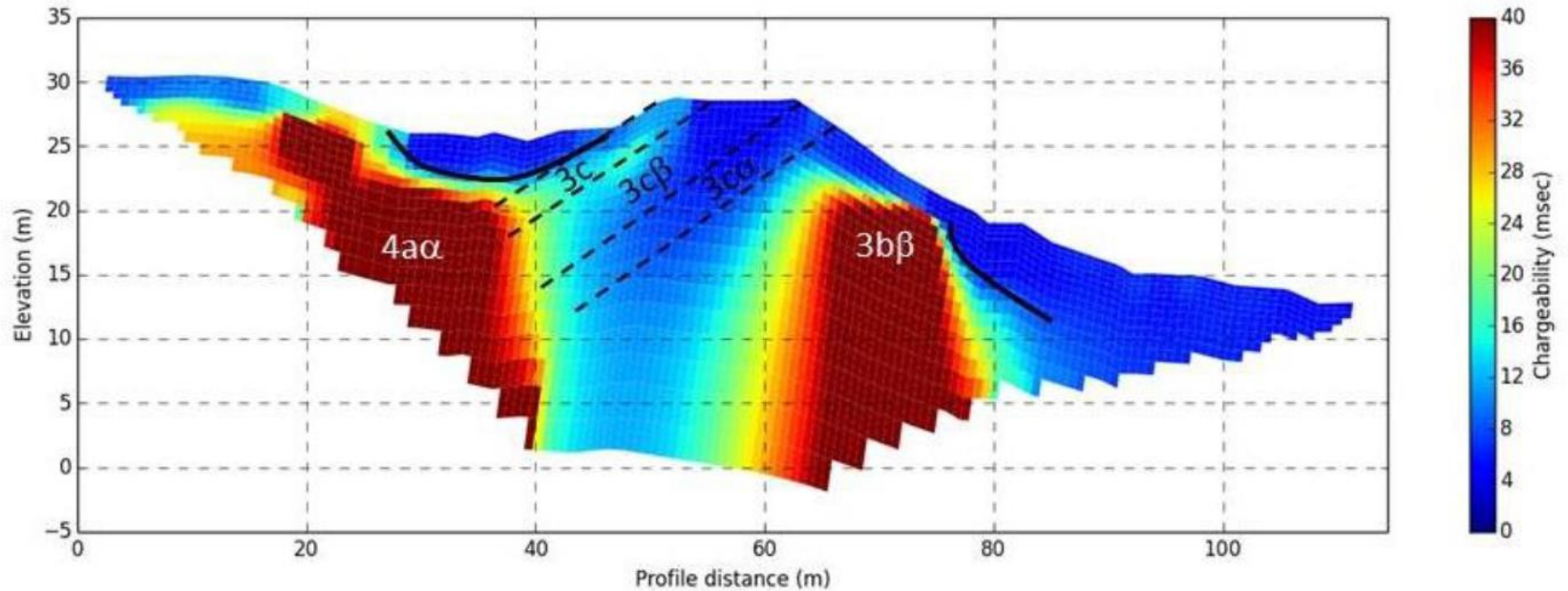
Resistivity model

(Res2DInv)

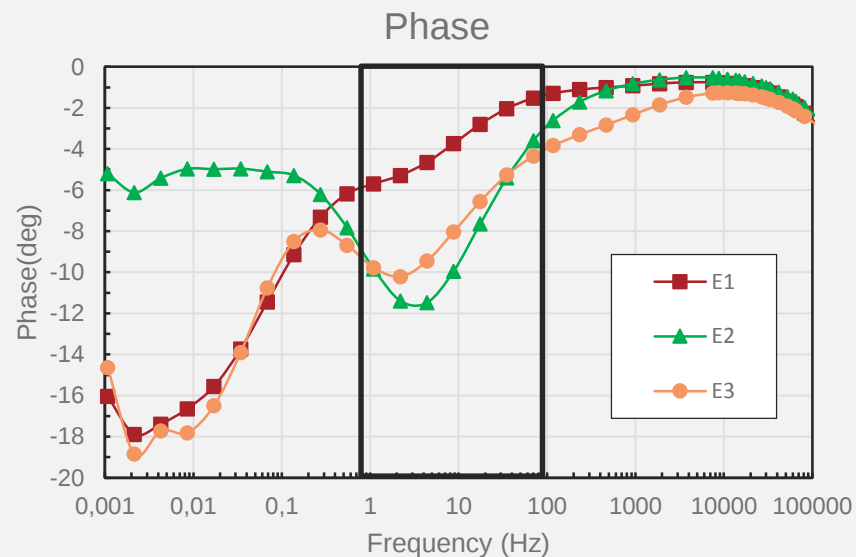
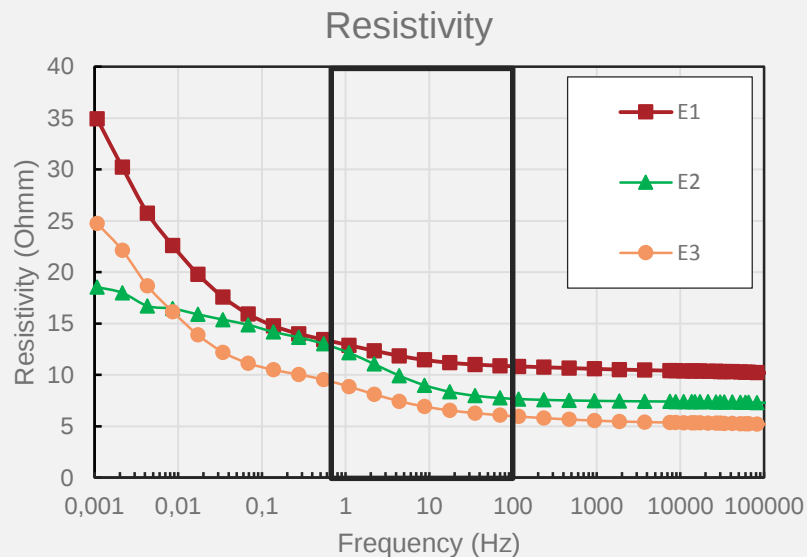


Chargeability model

(Res2DInv)



Complex impedance lab measurements*



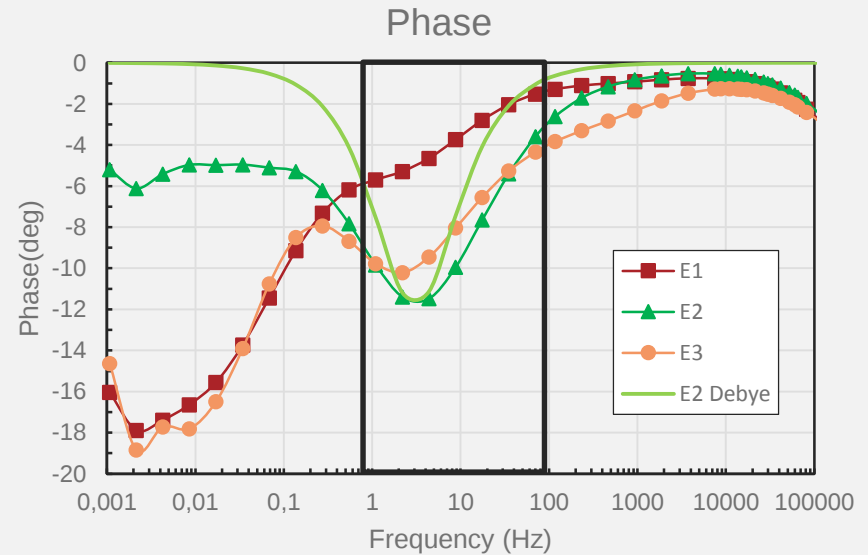
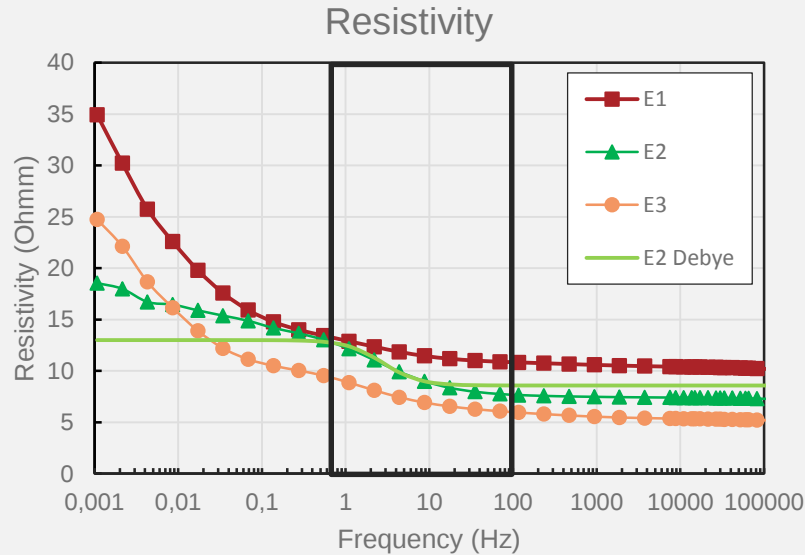
«Chameleon» setup, Radic Research

Current density: ~ 0.1 A/m², ~ 1 A/m², ~ 10 A/m².

Mineralizations < 1 mm

Conducting minerals may touch and form large aggregates.

Complex impedance lab measurements*

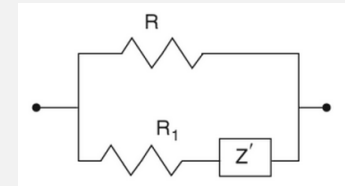


$$m = 0.34$$

$$\tau = 0.4 \text{ s}$$

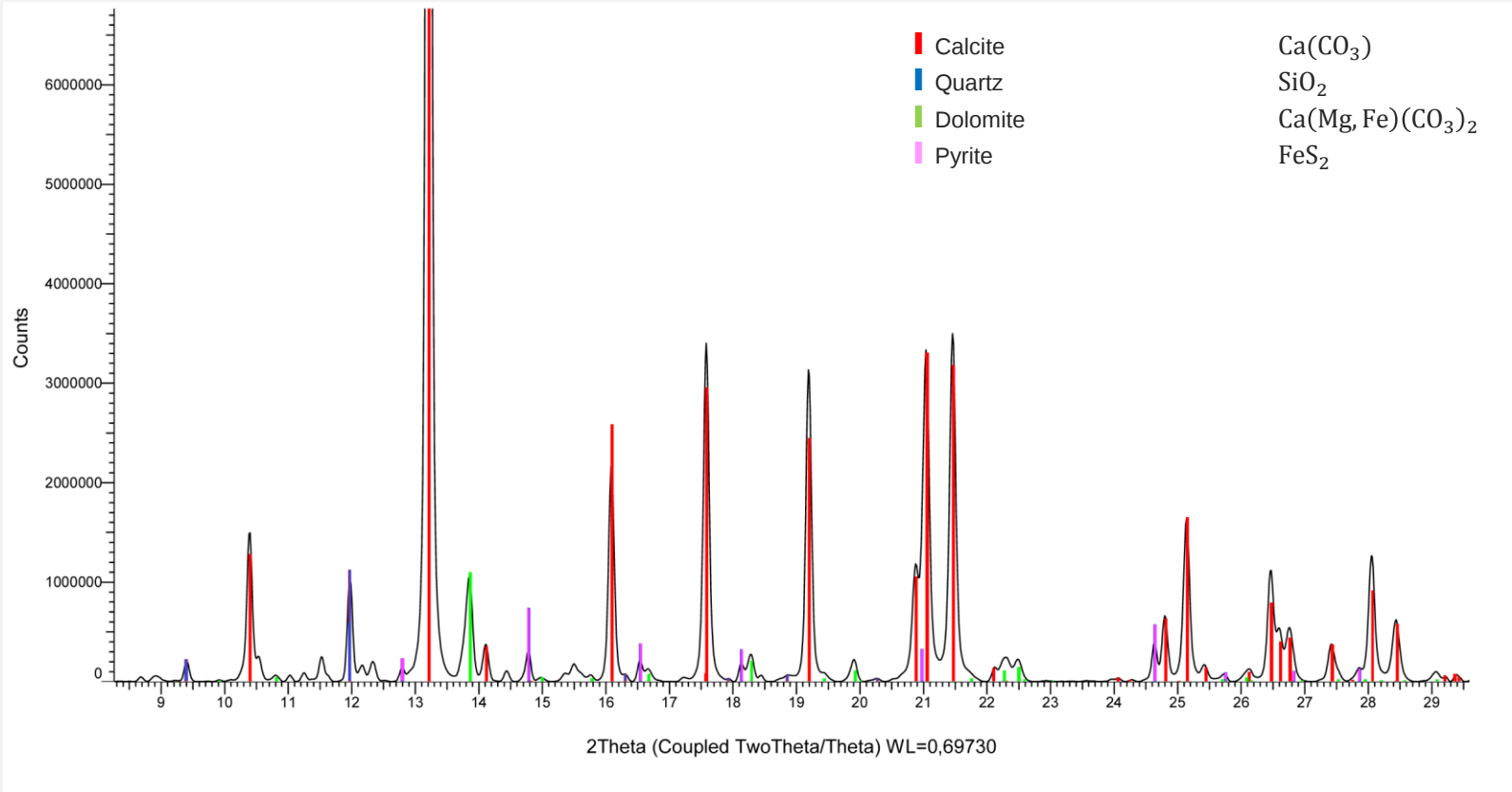
$$(c = 1)$$

$$m = \frac{R}{R + R_1}$$

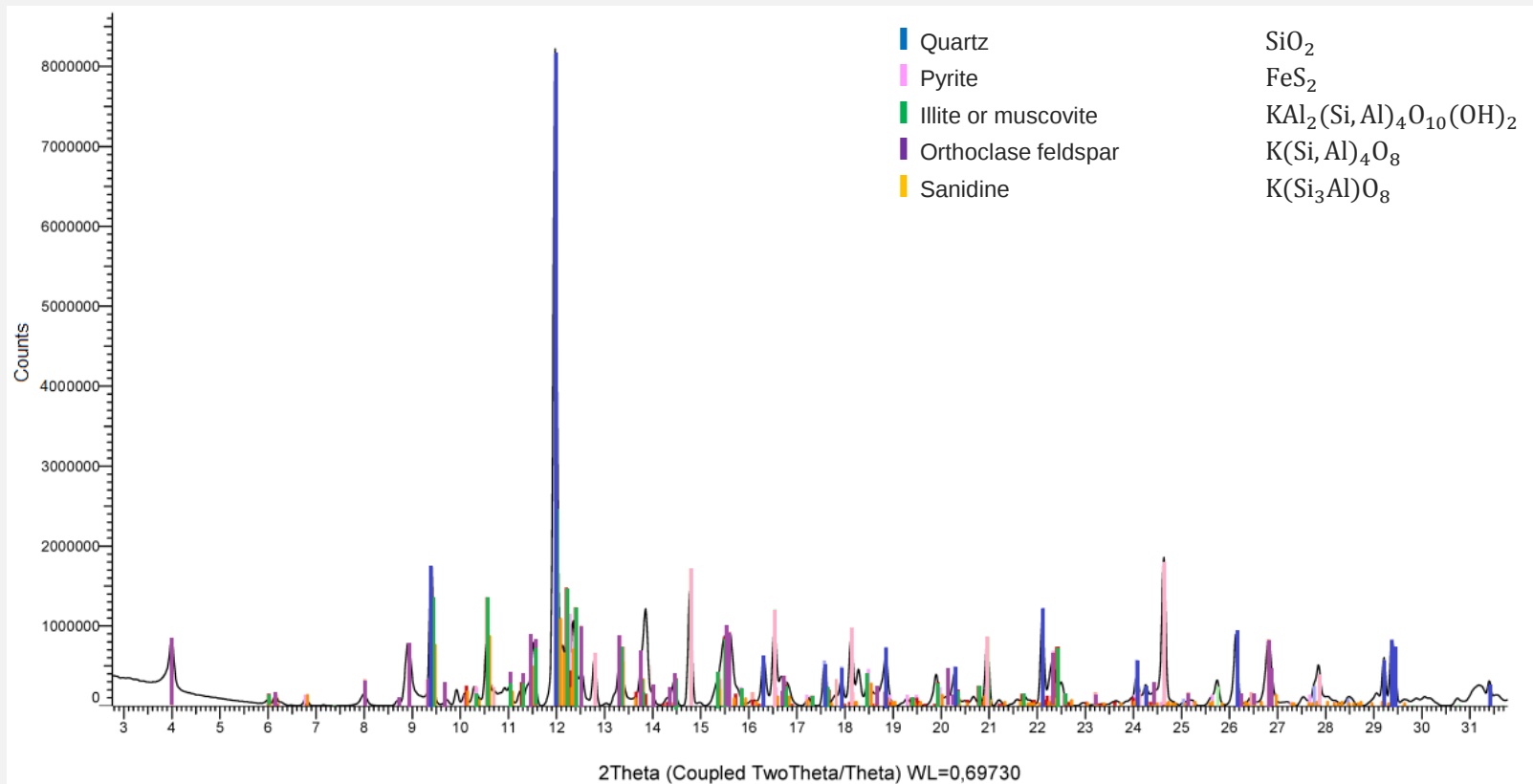


A more prominent impedance step (larger m) in E2 than in E1 and E2. Happens at 3 Hz.

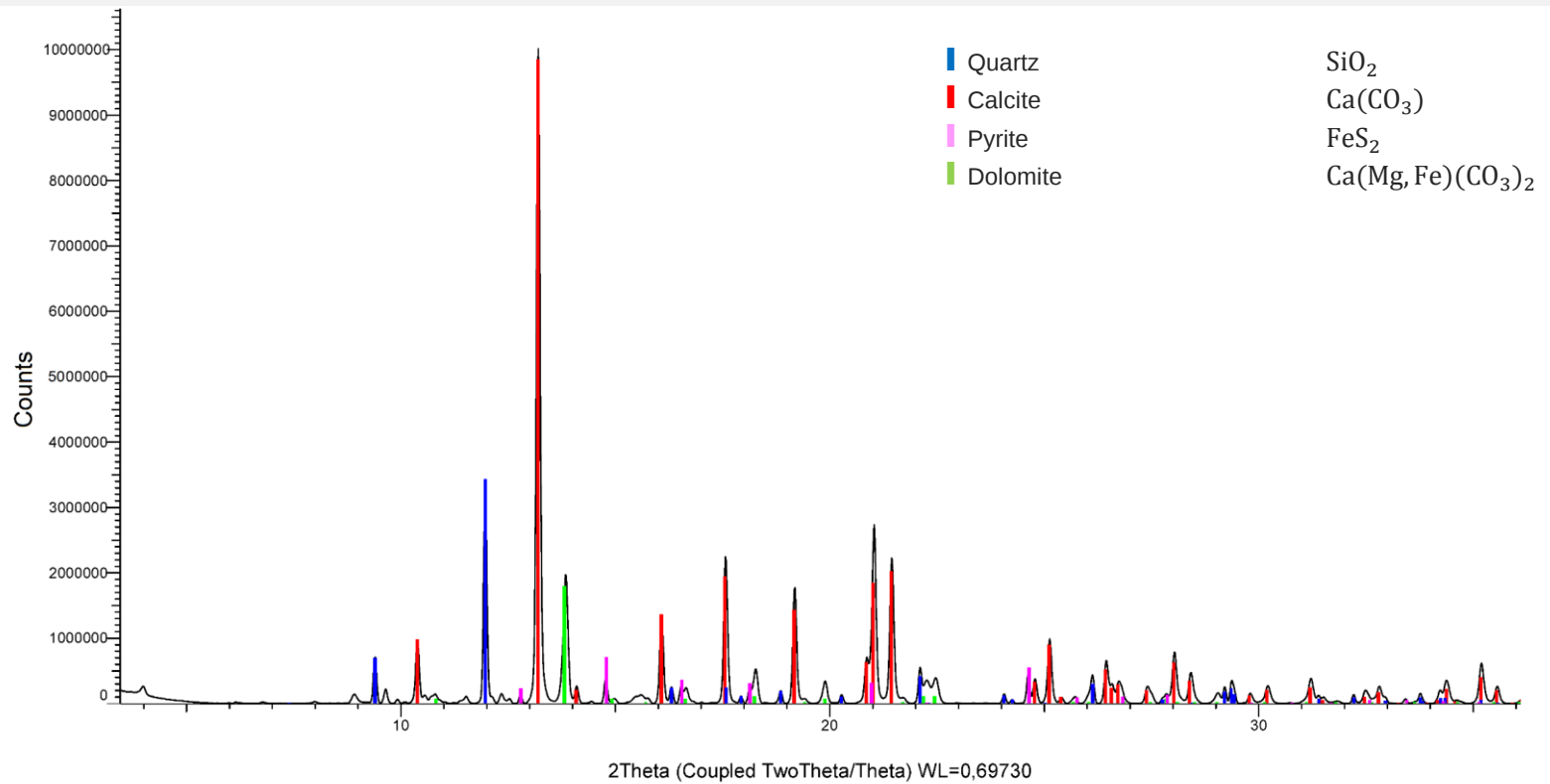
SXRD Diffractograms E1



E2



E3



SXRD

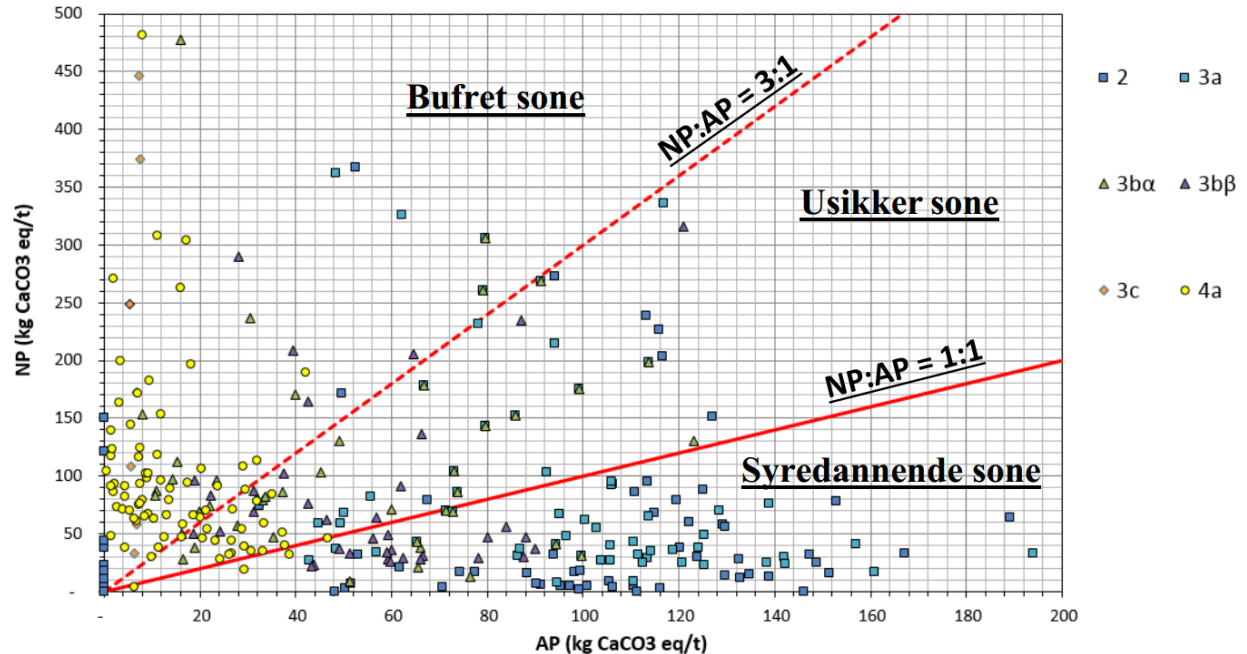
- ↗ E1: Lots of Calcite, also Dolomite, quartz and pyrite.
- ↗ E3: Less Calcite, Dolomite, Quartz and Pyrite
- ↗ E2: No Calcite, almost no Dolomite.
 - Quartz and Pyrite are dominating
 - Clay and other minerals (Illite, Muscovite, Orthoclase feldspar, Sanidine).
- ↗ We observe that the samples with a large amount of sulphides versus carbonates have the largest polarization in the complex impedance measurements.

Acidification potential

- NP ~ % TIC : Neutralizing potential of carbonates (i.e. Calcite and Dolomite)*
- AP ~ % S : Acidification potential of sulphides (i.e. Pyrite)*

Estimates:

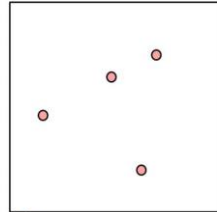
- E1 and E3: NP/AP > 1
- E2: NP/AP < 1



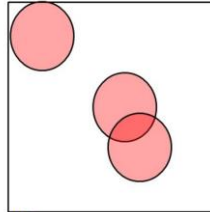
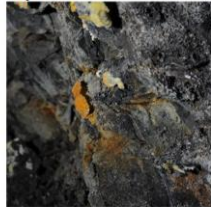
E1, E3



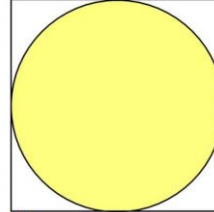
E2



a)



b)



c)



Contact area of sulphide mineral grains govern the reducing and acidification capacity.

A) Elnes, b) Galgeberg, c) Alun

Smaller mineral grains → larger contact area

Conclusions

- Time-domain field IP survey is well suited to map black shale
- We also observe that the samples with a large amount of sulphides versus carbonates have largest chargeability in the complex impedance measurements.
- We therefore propose that Pyrite is the main mineral contributing to polarization as electronic conducting mineral grains
- The large phase shift at very low frequencies observed in E1 and E2 could be due to large agglomerates of carbonates which are not present in E2, but also sample anisotropy or water saturation differences.



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