Swedish Deep Borehole COSC-1 and a New Approach to Hydrogeologic Testing During Drilling

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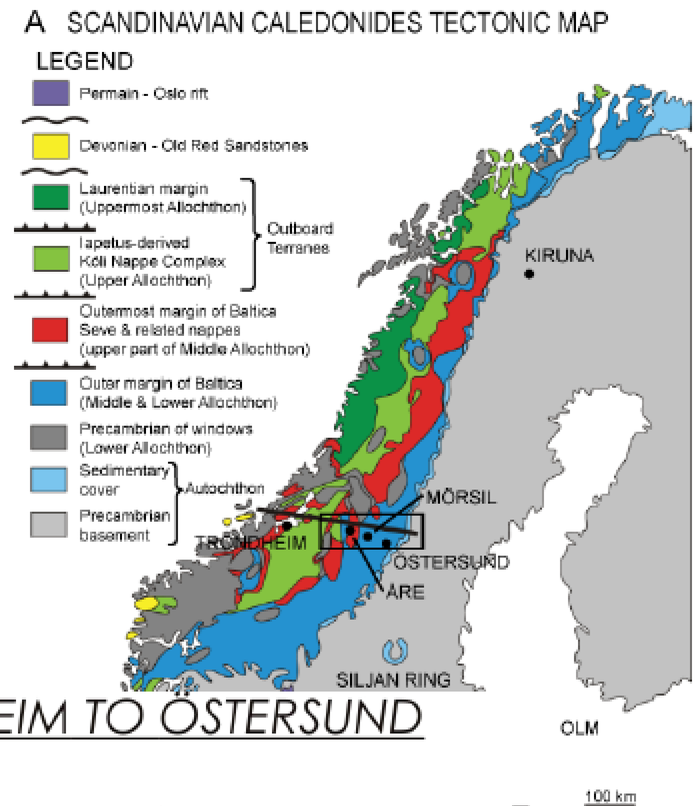
TALK OUTLINE

- COSC deep drilling project
  - Motivation
  - Drilling and coring, 1 May- 26 August, 2014
  - Measurements on site and core sample studies
- A new approach to hydrologic testing during the drilling period, using FFEC (Flowing Fluid Electric Conductivity) logging method
  - Perspective and opportunity
  - Data and tentative results
- Concluding Remarks and current status

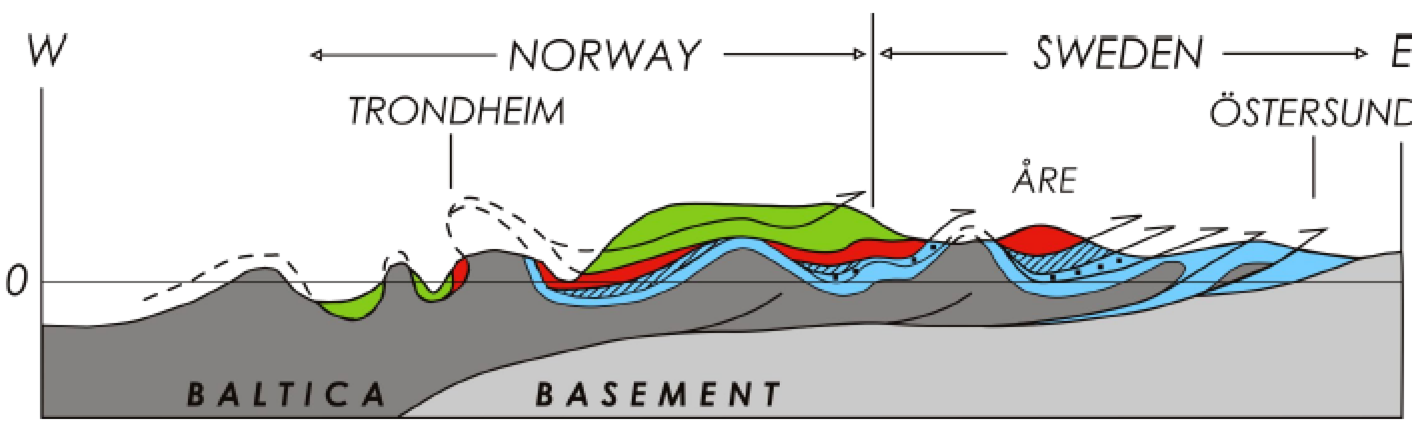
Collisional Orogeny in the Scandinavian Caledonides (COSC)

Two coreholes to 2.5 km

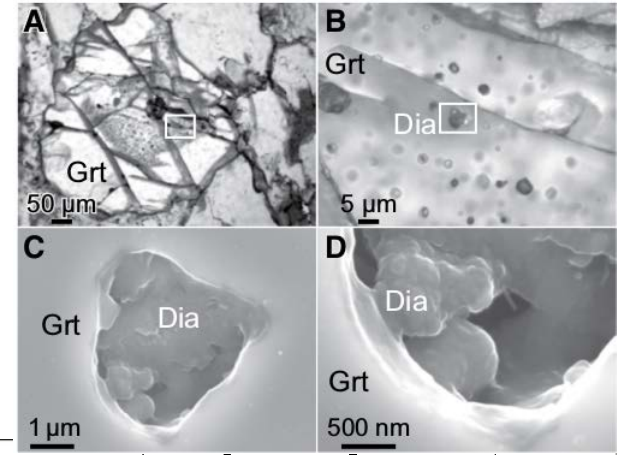
COSC-1 → Åre
COSC-2 → East of Mörsil



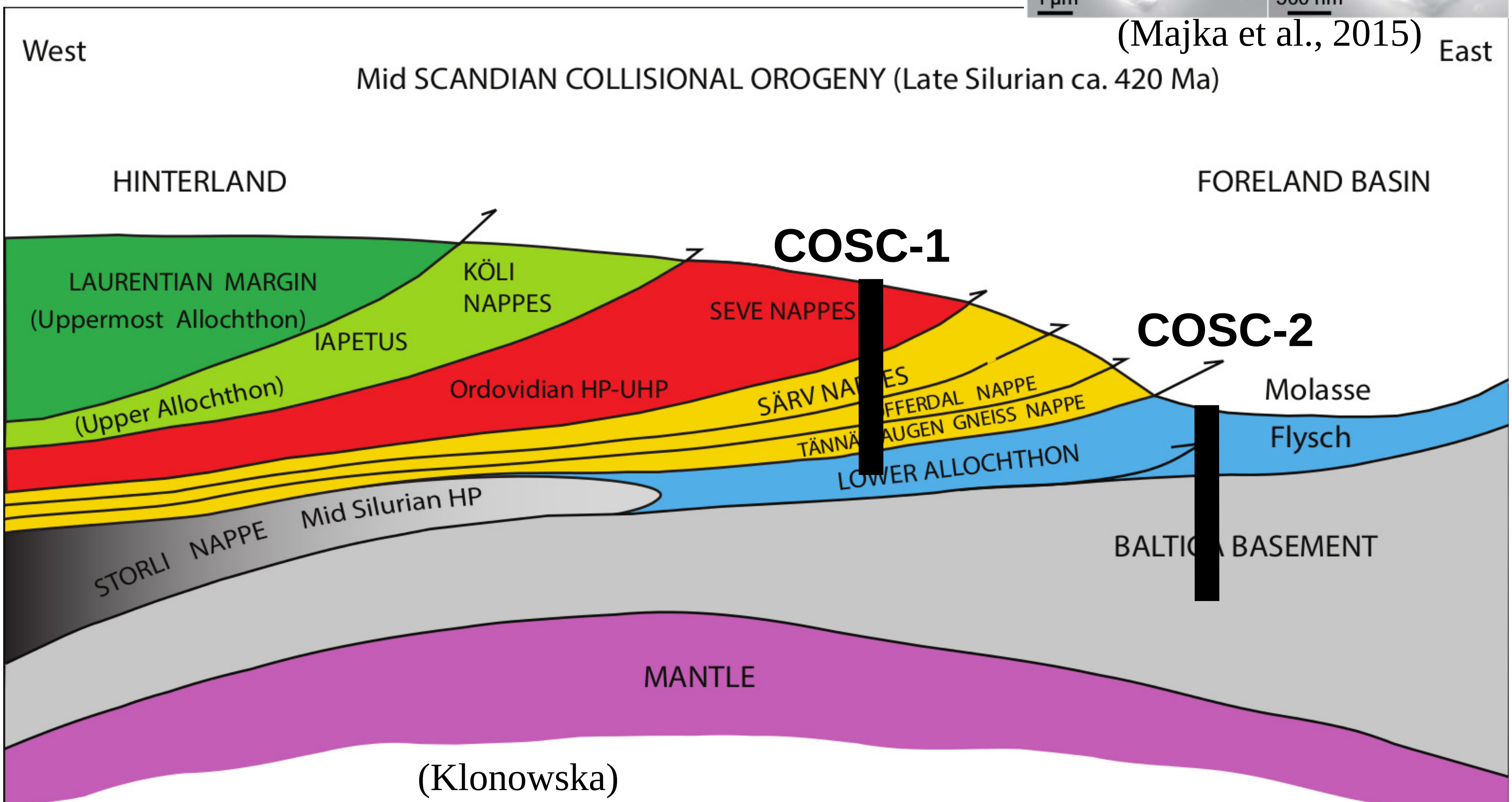
SKETCH SECTION FROM TRONDHEIM TO ÖSTERSUND



High grade Seve Nappe has been down to 100 km during the collision process (hot allochthon)



(Majka et al., 2015)



(Klonowska)

Schedule for COSC-1 Borehole

Aug 2013: Drilling of 100 m conductor borehole

1 May 2014: Core drilling of COSC-1 started

26 August 2014: Drilling completed at 2495 m

10-12 September and 10-12 October, 2014:
Geophysical logging by ICDP and Lund; VSP, Temperature logging etc. in between

2015 plus: Scientific borehole studies

Core drilling: 1 May to 26 August 2014

Bit type and hole size	Interval (m)	Recovery	m/day
HQ3 96mm	102-1616	100%	33-63
NQ 76mm	1616-2496	100%	36

COSC-1 datasets

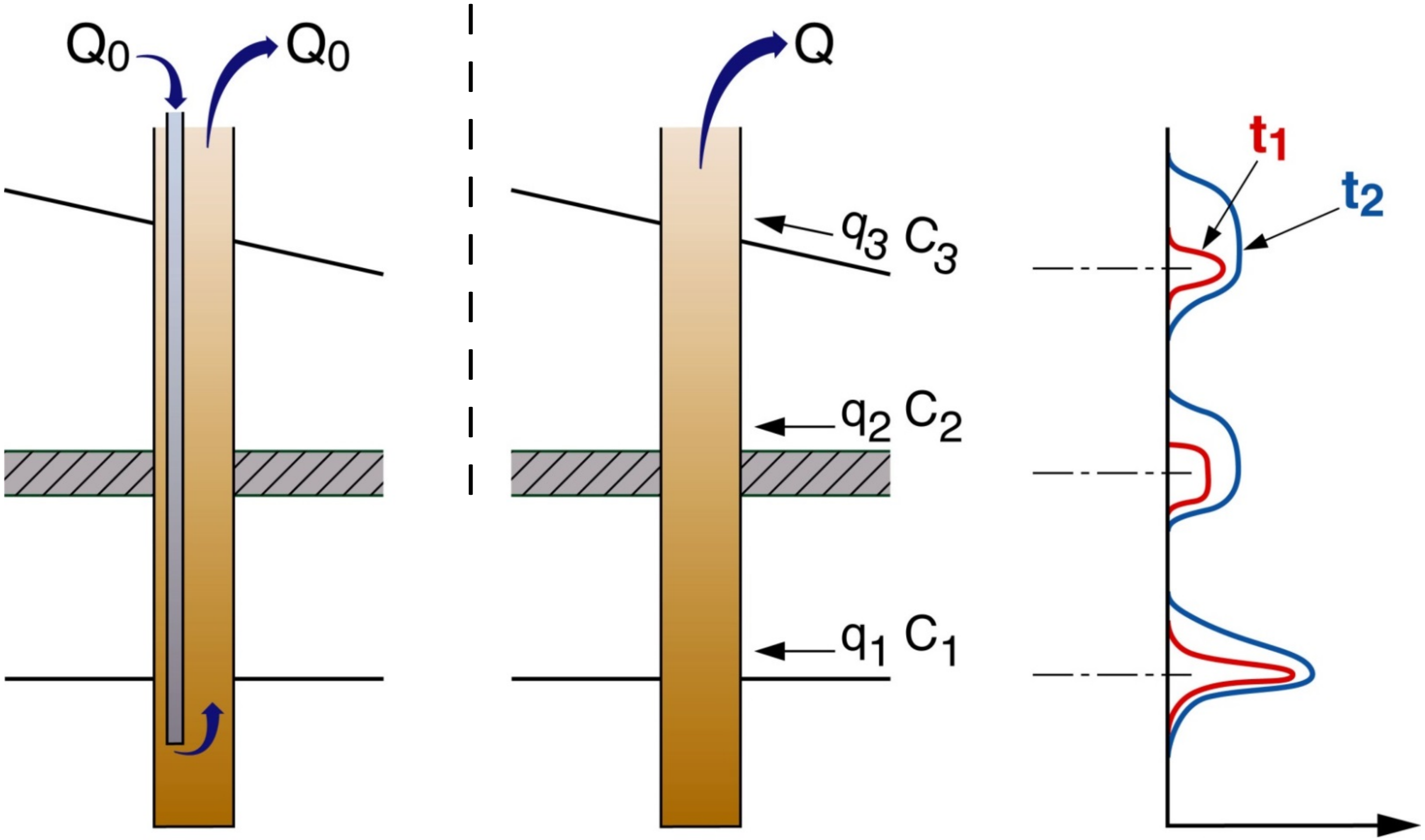
Drilling the hot allochthon

- Drill core metadata
- Unrolled core scans
- Core box images
- Certain geophysical core parameters (multi-sensor core logger)
- XRF geochemical data (R&D collaboration with Minalyze AB, Sweden)
- Geological core description
- Mud parameters
- On-line gas analysis of gases extracted from the drilling mud (OLGA)
- Technical/operational data from the drill rig and driller's reports
- Downhole logging data

Objectives of Hydrologic Testing

- *In situ* measurements to determine hydrogeologic structures, particularly hydraulic faults/fractures
- Measurements on permeability, porosity, and water chemistry, as a function of depth along boreholes, to determine relevant physio-chemical processes
- *In situ* evaluation of pressure heads and local stresses, as well as natural regional flow, recharge and discharge zones: state of the geologic system
- *Obtain data for understanding water flow system in deep subsurface and its role in geological processes*

FFEC (Flowing Fluid Electric Conductivity) Logging Method



Initial Replacing Borehole Water

FEC Logging (several times) while Pumping at Q

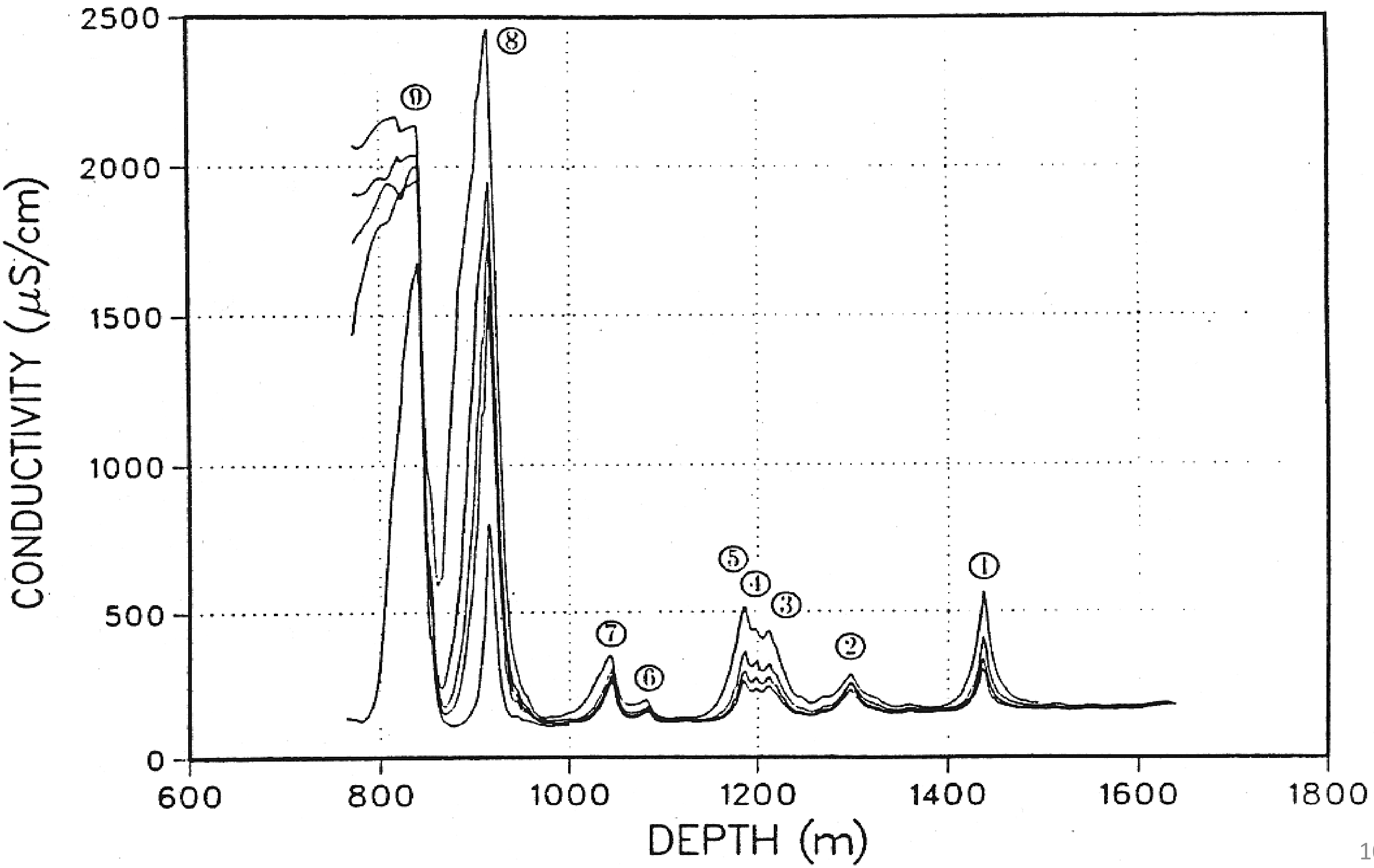
First FEC profile obtained before Q turned on.
Δ(FEC)= FEC(Q)-FEC(Q=0)

Area under each peak ≈ $q_i C_i \times \Delta t$
Skewness of peak upwards → q_i
Reproducing area and skewness → C_i and q_i, and then q_i → T_i

Application to 1700-m Leuggern Borehole (NAGRA)

Data over 750–1650 m; constant Q=20 L/min

(Five fluid conductivity profiles over three days)



Parameters obtained by matching field data

Peak Number	x_i (m)	t_i (hours)	q_i (10^{-6} m^3/s)	C_i (kg/m^3)
1	1440	16	0.65	0.50
2	1300	15	0.60	0.45
3	1215	16	0.55	0.45
4	1200	27	0.25	0.40
5	1188	27	0.65	0.43
6	1085	24	0.20	0.37
7	1048	24	0.60	0.48
8	918	13	0.75	5.50
9	843	11	17	0.95

$K = 1.0 \times 10^{-3}$ m^2/s and **Q = 1.3 L/min**

Inflow zone initial pressure heads can be obtained from FFEC logging with two pumping rates *Q* and *Q+ΔQ*

$$q_i = \frac{2\pi T_i^* (h_i - h_{wb})}{\ln(r_i / r)} = T_i (h_i - h_{wb})$$

$$\frac{T_i}{T_{tot}} = \frac{\Delta q_i}{\Delta Q}$$

→ $$\frac{(h_i - h_{avg})}{(h_{avg} - h_{wb})} = \frac{q_i / Q}{\Delta q_i / \Delta Q} - 1$$

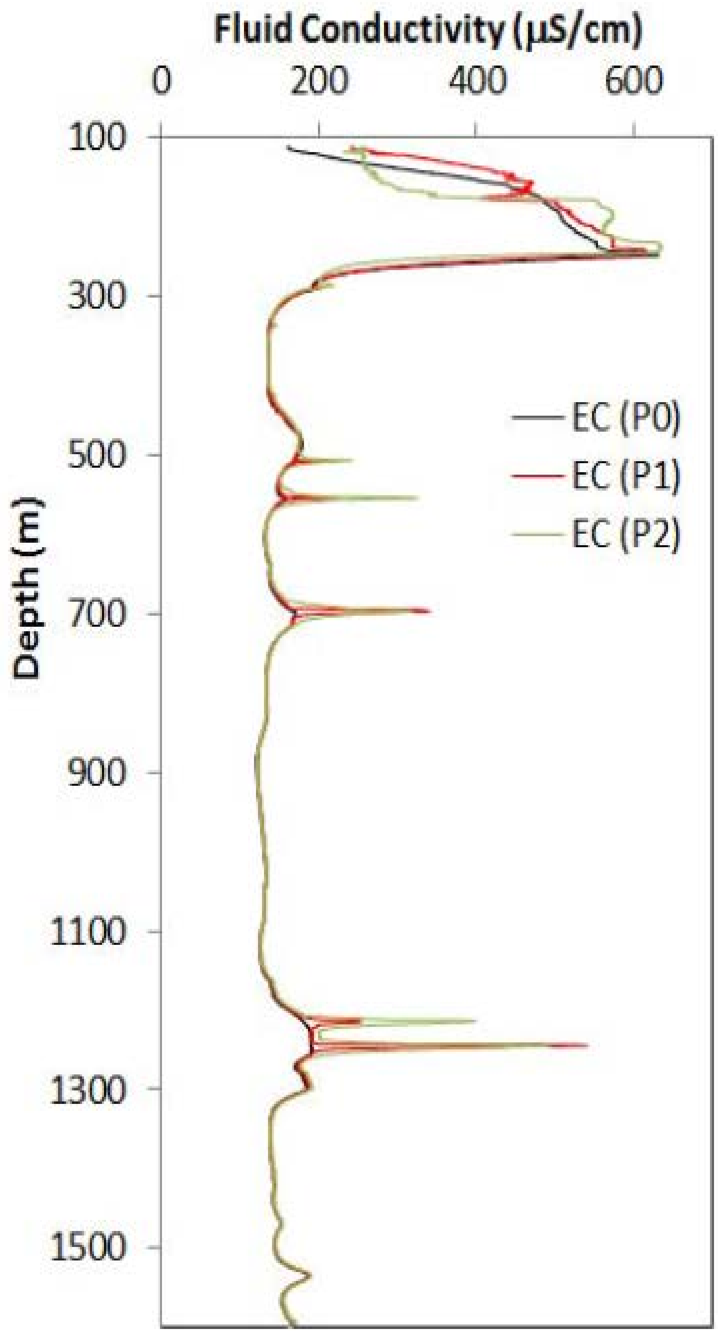
→ Thus, the FFEC test yields C_i, q_i (i.e., T_i) and $\mathbf{h_i}$

Perspective

- Hydrogeologic testing is ***not normally done*** during the drilling period
- If drilling encounters a major flow zone as indicated by large drilling fluid loss, then either the zone is cemented to enable drilling to continue, or drilling is stopped to allow drill stem testing (DST) for determining if the zone represents a major (petroleum) reservoir
- DST requires special downhole instrumentation with packers, etc., and can test only that particular (high) flow zone
- Low-flow hydraulic zones are not studied

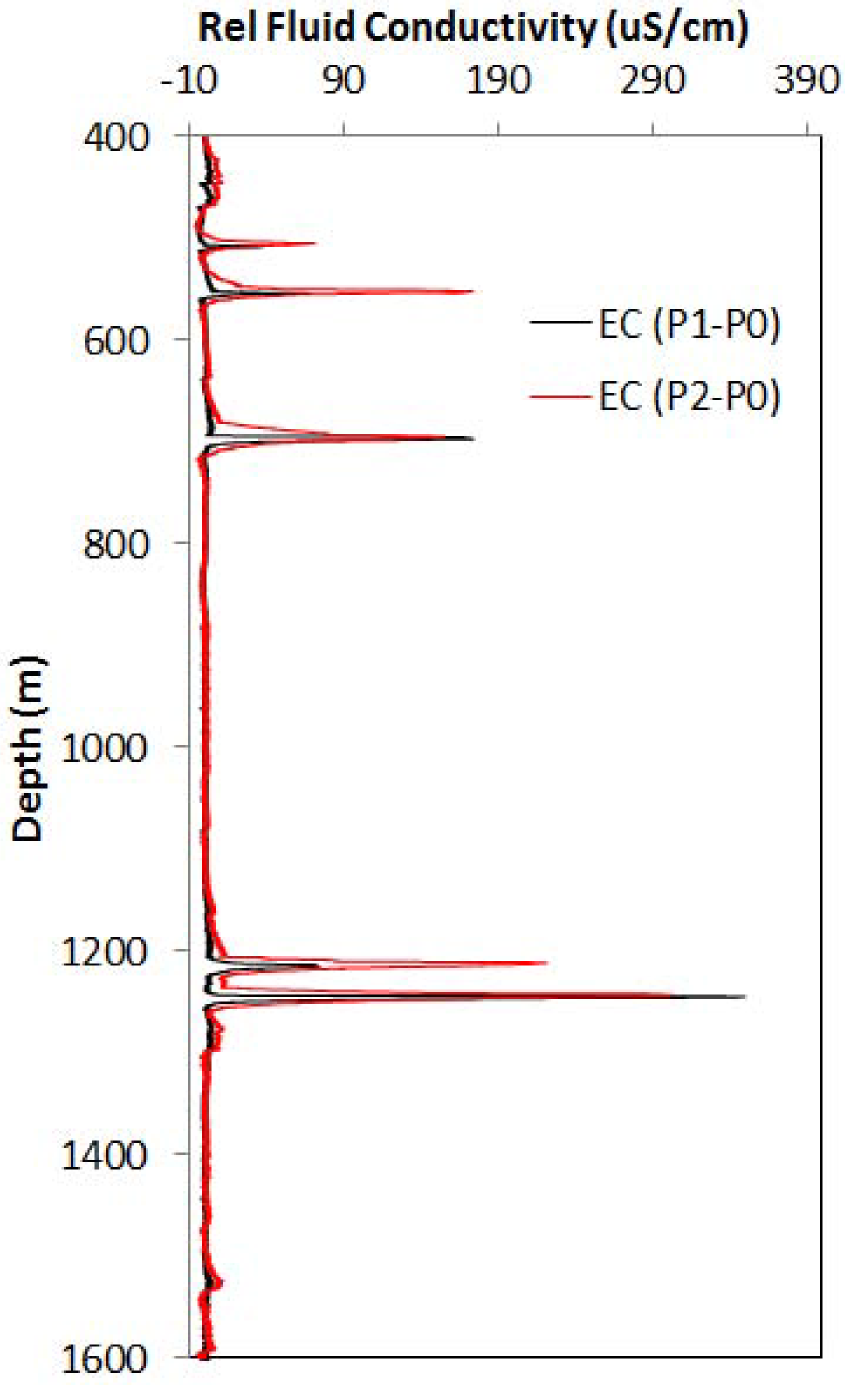
Opportunity

- Flowing fluid electric conductivity (FFEC) logging can efficiently survey hydraulic conductivity values all along the borehole, *including those of small flow zones*
- Requires no special instruments, just a standard EC/T probe and a pump, usually available at drill site
- The regular drilling schedule of COSC-1 borehole allowed *one day of rest per week*. Before rest, the drilling string is pulled and drilling fluid is washed out
- This provides an opportunity to conduct FFEC test in the one-day break in drilling, with minimum impact on drilling schedule



- Fiuid Electric conductivity (FEC) measured by moving an EC/T probe down the borehole
- P0 is FEC profile obtained when there is **no pumping** at the start of the one-day drilling break
- Then water is pumped out of the borehole at a low rate.
- P1 and P2 are FEC profiles at two times **after pumping start**

- Operation problems from 100m down to 300m: select to study only section from 400m to borehole bottom (1610m)



- Plots of (P1-P0) and (P2-P0) show 5 major hydraulic zones from 400m to 1610m, borehole depth at the time of test
- These are zones where sampling for chemical and microbiological studies should be made

	Peak Depth	Time delay	Profile 1		Profile 2	
Peak	(m)	T0 (h)	C, (g/L)	q, (mL/min)	C, (g/L)	q, (mL/min)
1	339	0	0.40	6	0.40	6
2	507	1.32	0.40	10	0.40	10
3	554	1.39	0.45	25	0.45	25
4	696	0	6.40	1.4	3.20	2.8
5	1214	1.98	0.35	40	0.35	40
6	1245	0	5.80	2.5	2.40	5

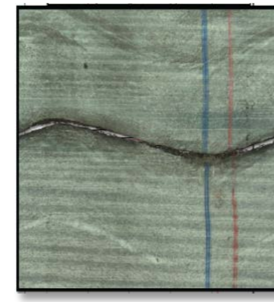
These are very preliminary results:

A flow rate of 20 mL/min with a drawdown of 70 m corresponds to an eff. hydraulic transmissivity of $3x10^{-9}$ m^2/s (or fracture aperture of 10 µm)

Identified 8 hydraulic zones in COSC-1

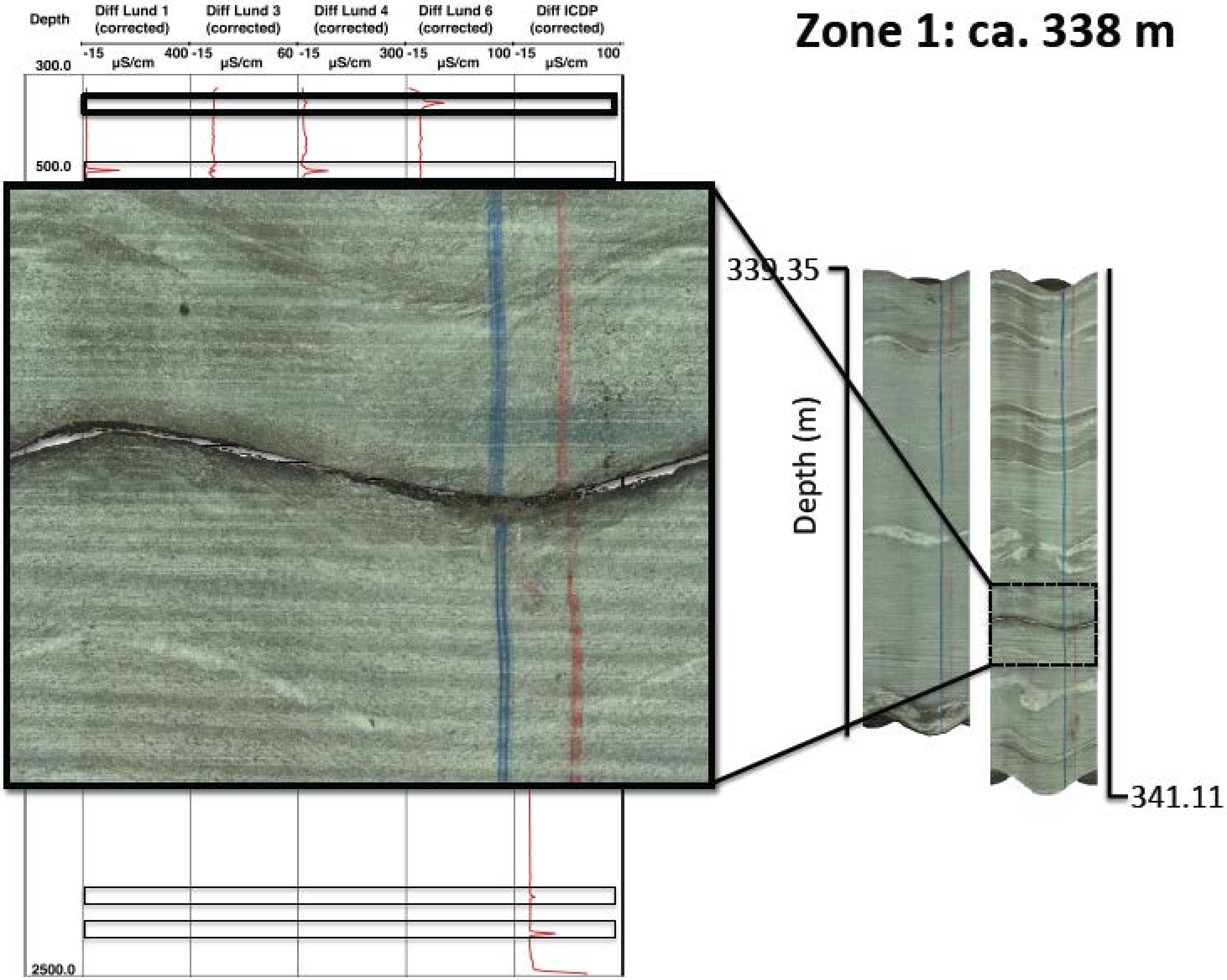
Depth of hydraulically active zones	2014-07-10 Lund-1 Test	2014-10-11 ICDP Test	2014-10-15 Lund-2 Test
340 m	(√)		√
510 m	√		**
550 m	√		**
690 m	√		√
1210 m	√		√
1250 m	√		√
2300 m		√	
2380 m		√	

Looking at cores
and identifying flowing fractures

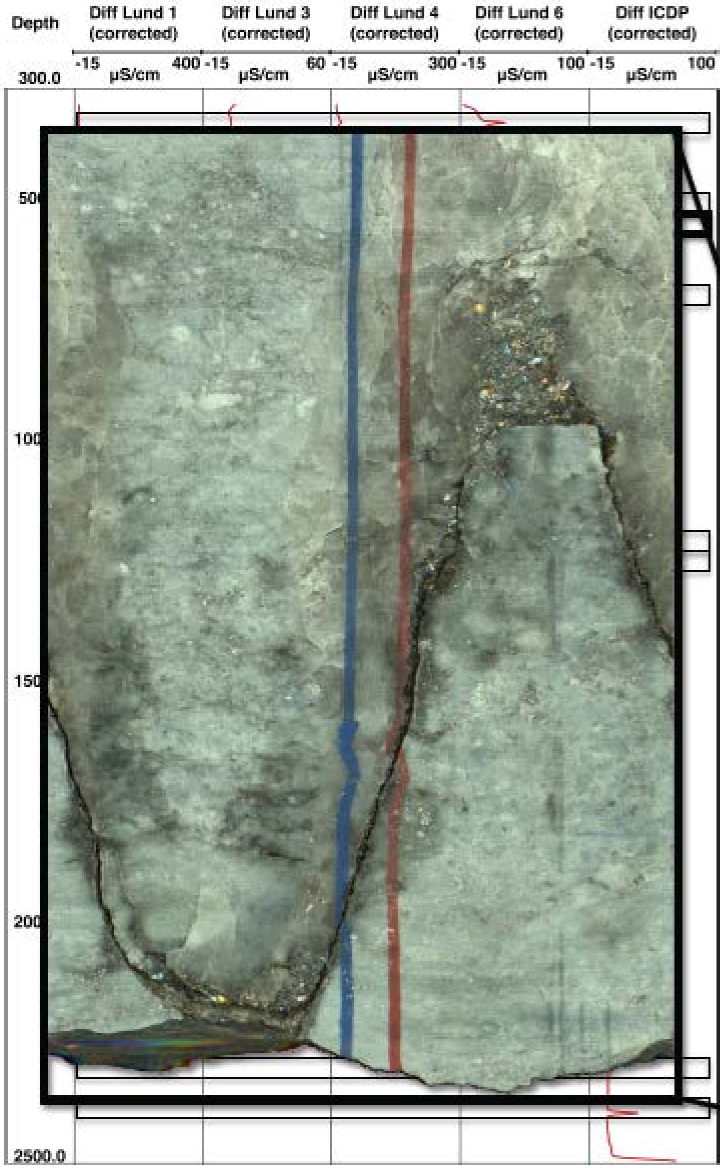


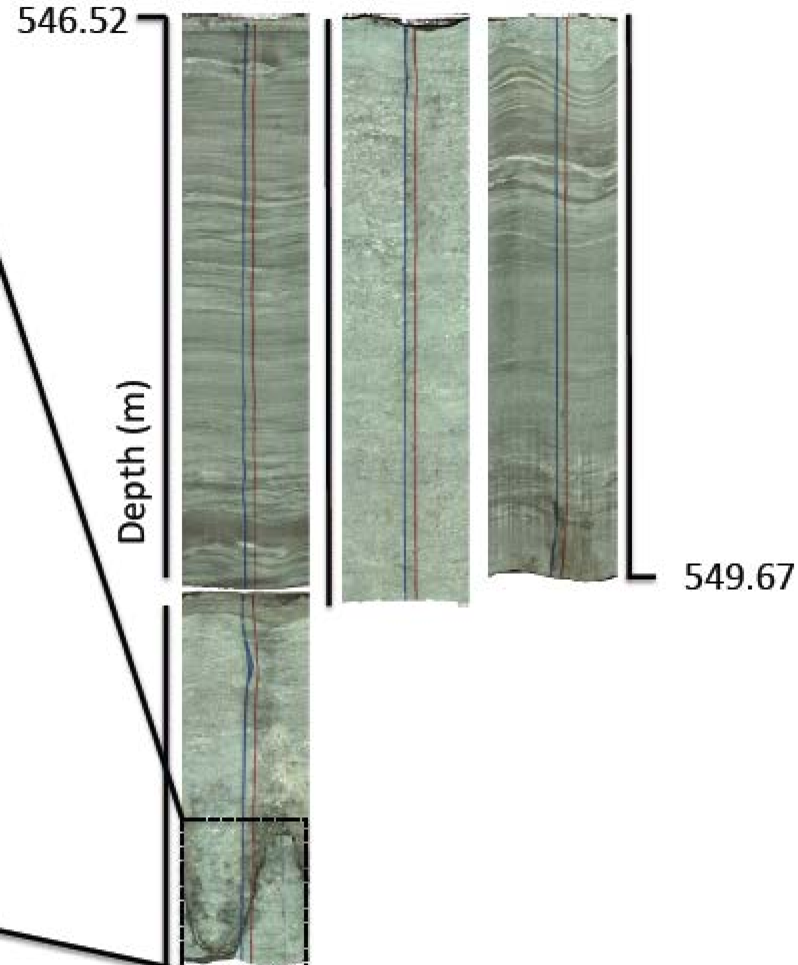
Core samples with inflow fractures at all 8 inflow zones have been identified

Zone 1: ca. 338 m

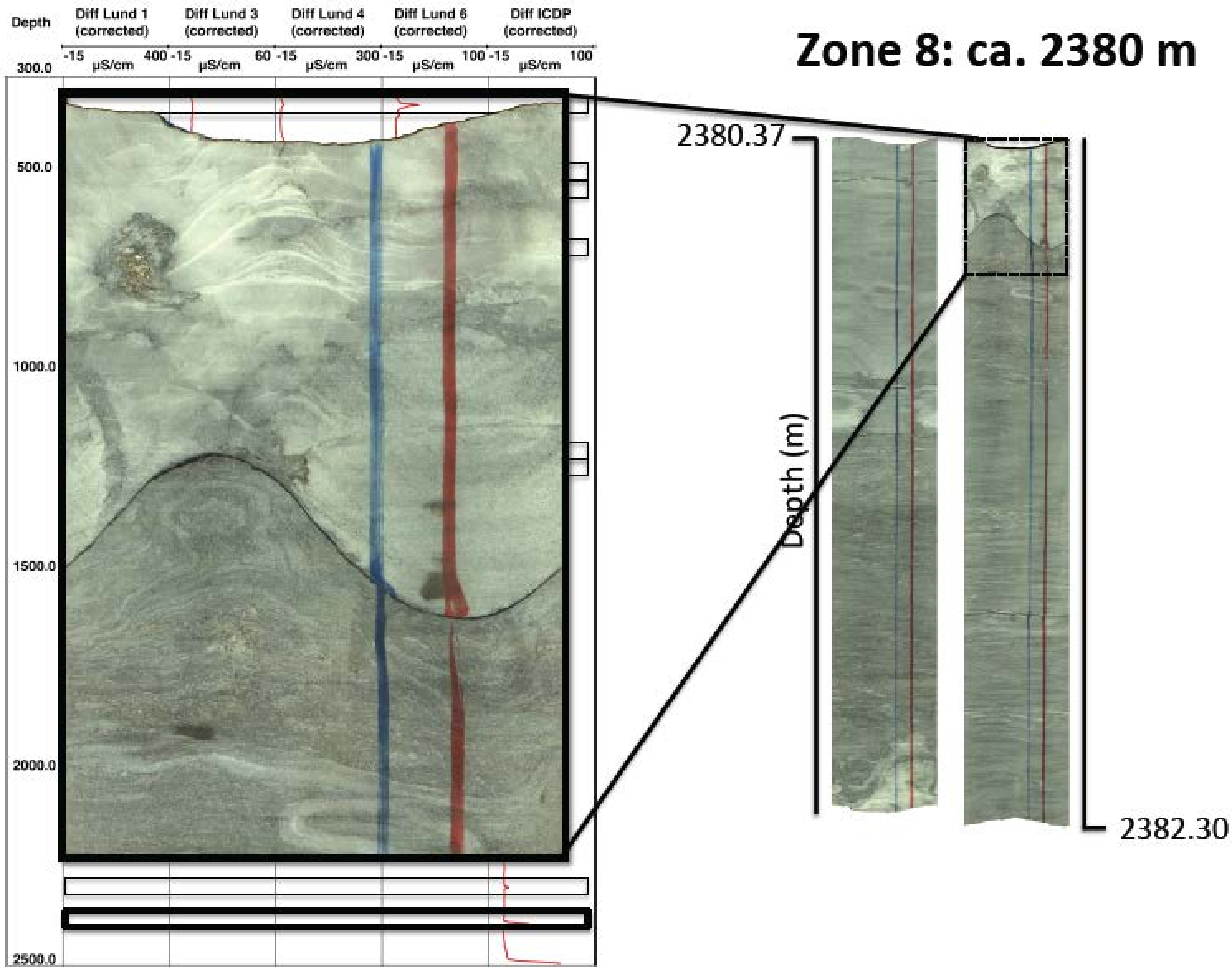


Zone 3: ca. 552 m





Zone 8: ca. 2380 m



Concluding Remarks

- Hydrogeologic measurement based on the FFEC logging method is recommended for testing during drilling period with minimum impact on drilling schedule.
- It is an efficient and effective method to obtain hydrogeologic active zones all along the borehole to the drilling depth, including the low-flow zones.
- In particular, all the inflow zones can be identified and their hydraulic conductivity and water salinity estimated (with possibly their in situ initial pressure)
- Results are important to understand the deep hydrogeologic system and the locations for chemical and microbiological sampling.

Drill site today:
Borehole is open to 2500 m and available for science

Jan-Erik Rosberg, Engineering Geology, Lund University

Current plans for study of core samples

Physical property	*Institute*
Ultrasonic velocity at confining pressure + anisotropy	UAlberta, CurtinU, ETHZ, Luleå
Uniaxial/triaxial compressive tests	Luleå, UAlberta
Seismic attenuation	CurtinU, ETHZ?
Permeability of rock matrix	ETHZ?
Anisotropy of magnetic susceptibility	Uppsala
Thermal conductivity & pressure relief	Uppsala
Thermal conductivity & secific heat	RuhrUBochum
dry and saturated and with confining pressure)	
Permeability (as a standard at RUB, porosity, density	RUB
and ultrasonic velocities are measured on beforehand)	