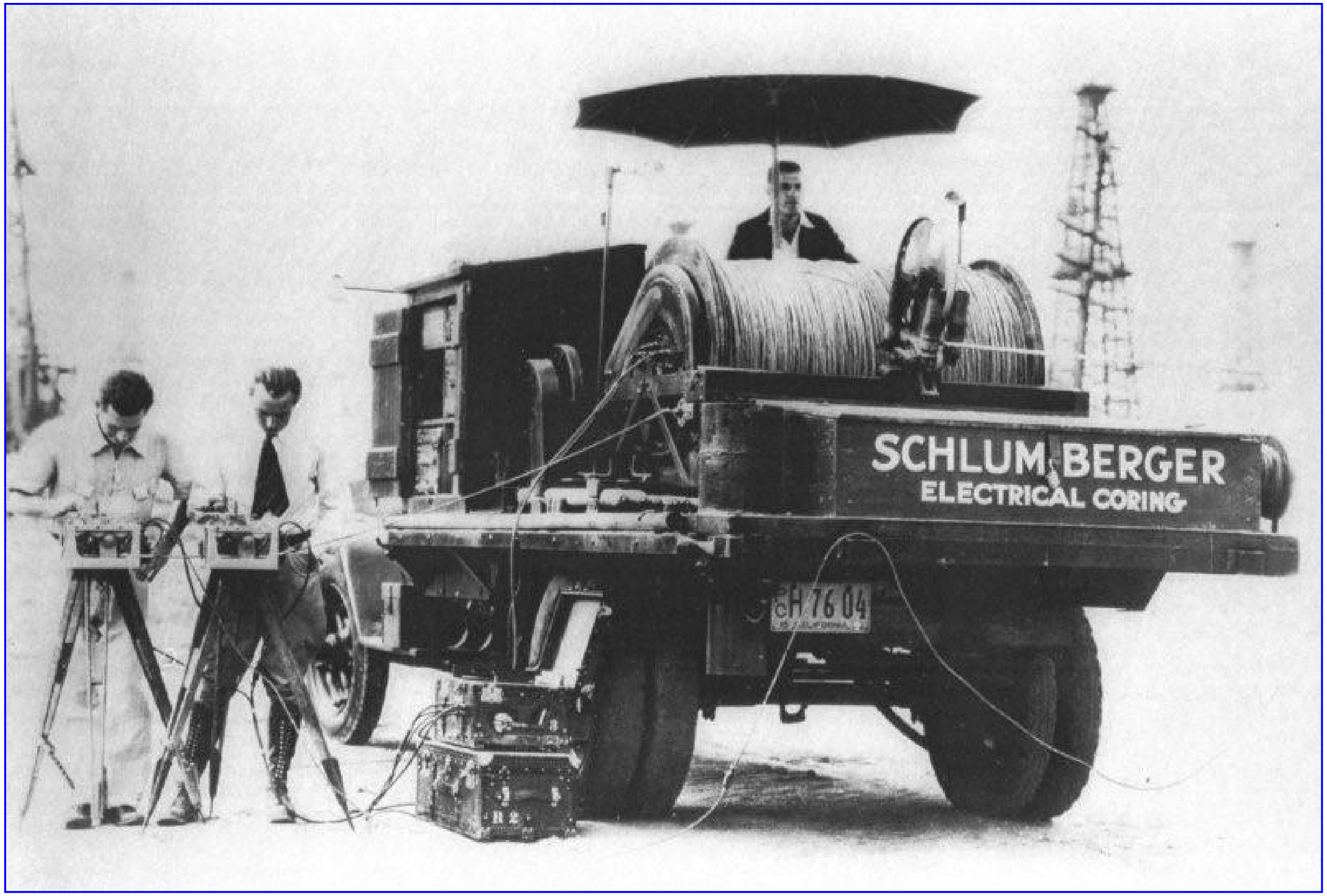
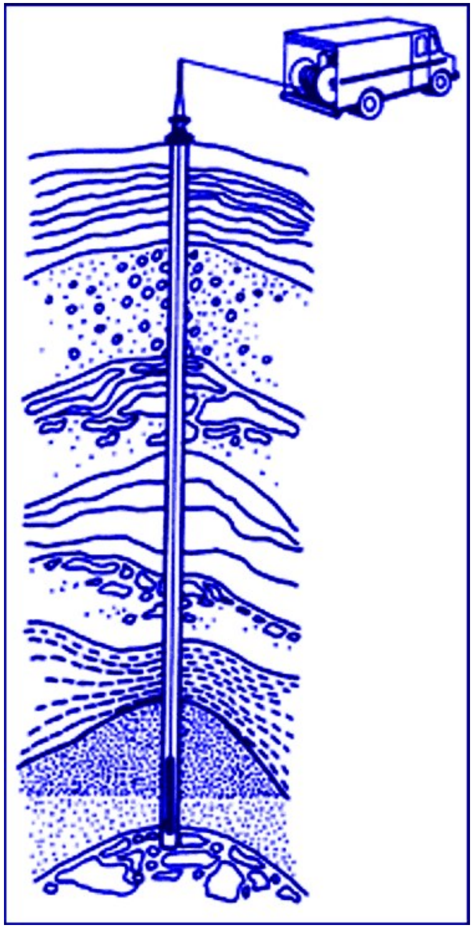
Introduction to the fundamentals of petrophysics and log evaluation





Wireline logs were first developed by the Schlumberger Brothers in the 1920’s.

Introduction

Downhole logging is the process of measuring physical, chemical, and structural properties of penetrated geological formations using logging tools that are either:

- *lowered into the borehole on a wireline cable (wireline logging),* or,
- placed just behind the drill bit as part of the drill pipe itself (logging-while-drilling).

The tools employ acoustic, nuclear, and electrical measurement techniques to acquire downhole logs of properties such as sonic velocity, density, and electrical resistivity.

The wireline cable provides real-time communication between the tools and the surface

Introduction

- Historical information
  - 200 B.C. Chinese cable tool
  - 1919 Rotary drilling
  - 1927 Electric well logging
  - 1940’s Neutron-gamma logging
  - 1950’s Neutron-neutron, sonic
  - End 1950’s induction, density , etc.

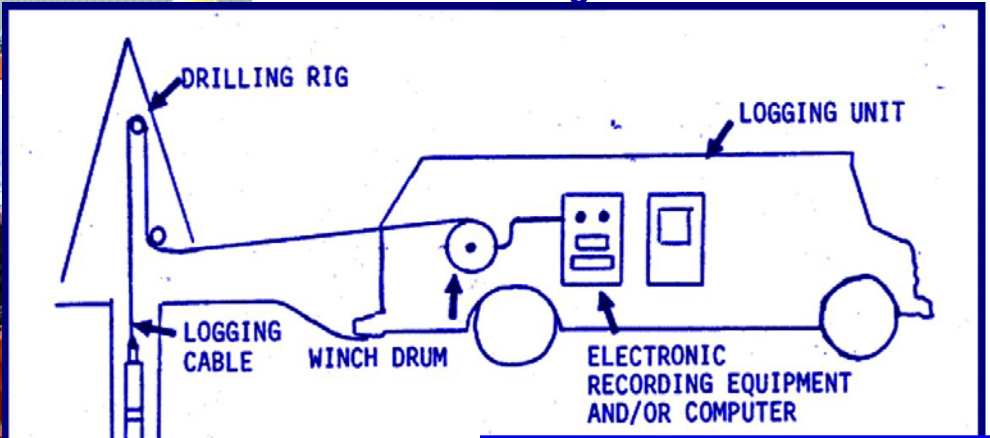
- Logging Costs
  - Exploration offshore: 6%
  - Exploration onshore: 18%

Introduction

A specially equipped truck lowers an assembly of electronic sensing devices to the bottom of the hole.

Winch and logging cable

After the cable has touched bottom, it is then reeled in slowly so the underground instruments can measure various characteristics surrounding the wellbore.



Basic construction

The printout (charts/graphs) generated in the computer truck is referred to as the “field print”.

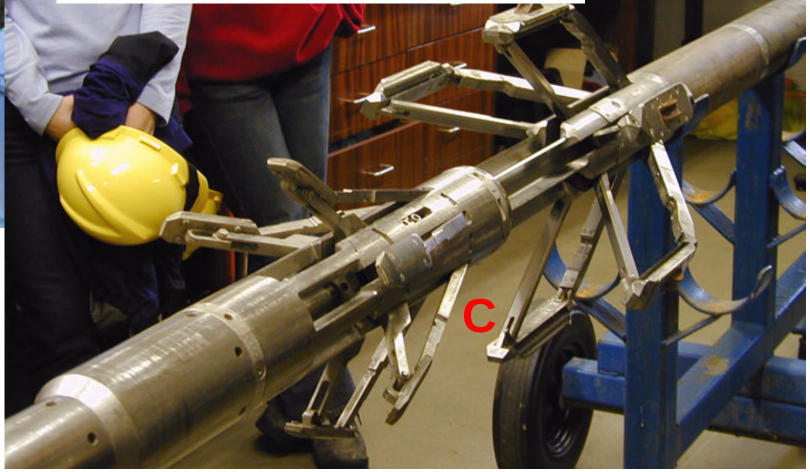
Truck

Introduction

Right: DAS system and open logging tool

Bottom: DAS system

Top: Cabin
Right: example of a dipmeter tool with centralizer (c)



Introduction

The downhole logs are rapidly collected, are continuous with depth, and measure in situ properties:

- They can be interpreted in terms of the formation's stratigraphy, lithology, and mineralogy.

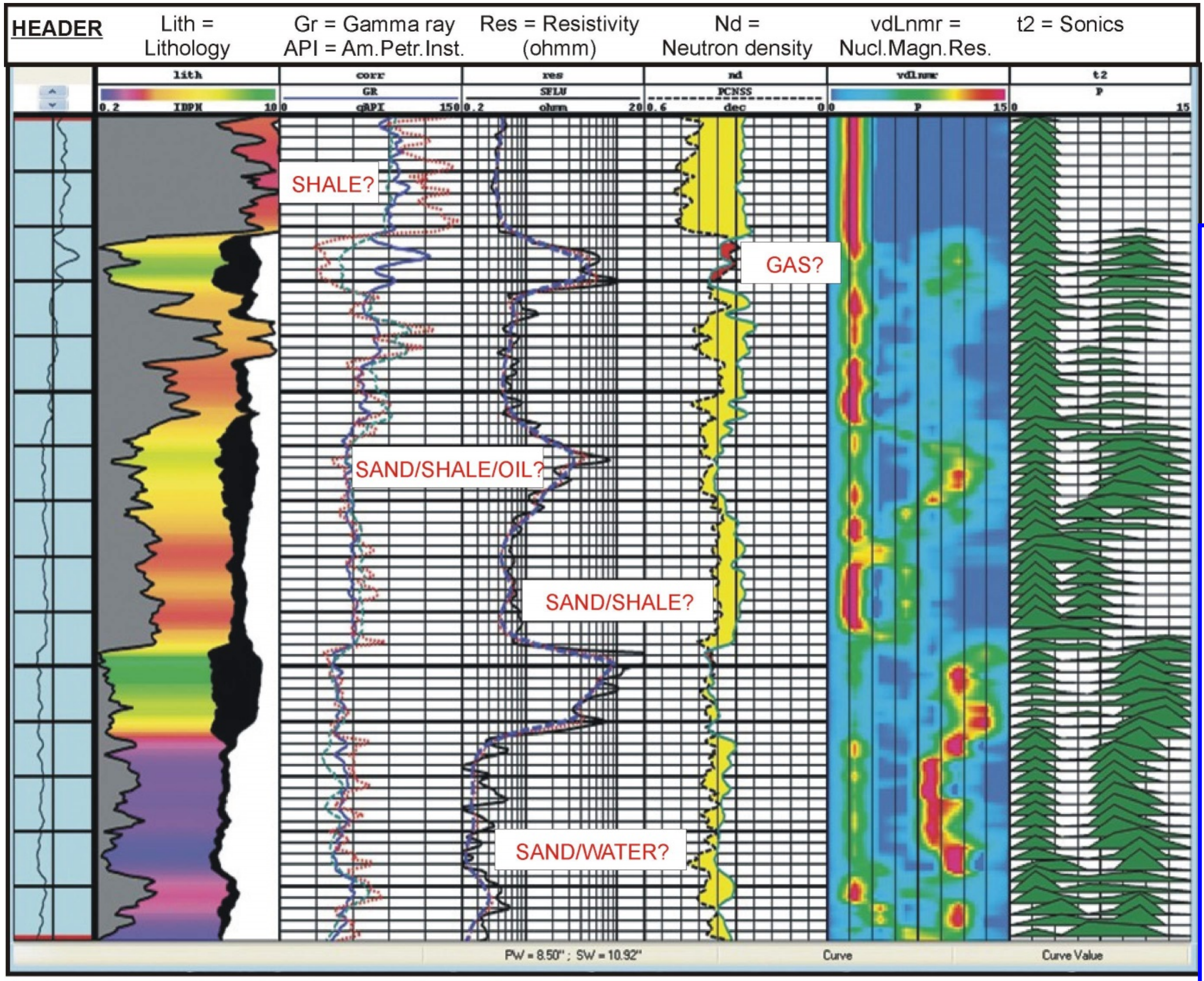
- The sampling interval is typically 15 cm, with a vertical resolution of about 35 cm. Some tools have a higher sampling interval and resolution to for example "image" sub-cm-scale.

- Logging tools are generally designed to measure formation properties some distance into the formation, to minimize the effects of variable borehole diameter and roughness.

- Logs also provide the major link between borehole and seismic section, ie. sonic velocity logs. Synthetic seismograms may be compared directly to the seismic section.

Introduction

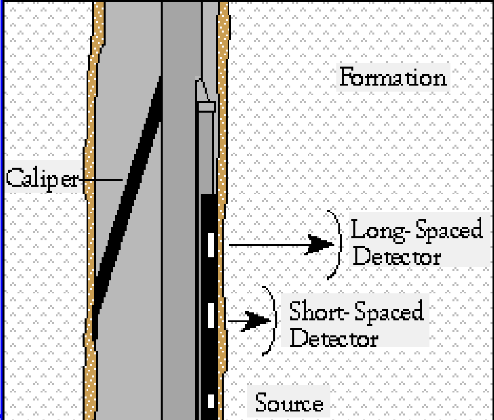
Example of logging results plus interpretation

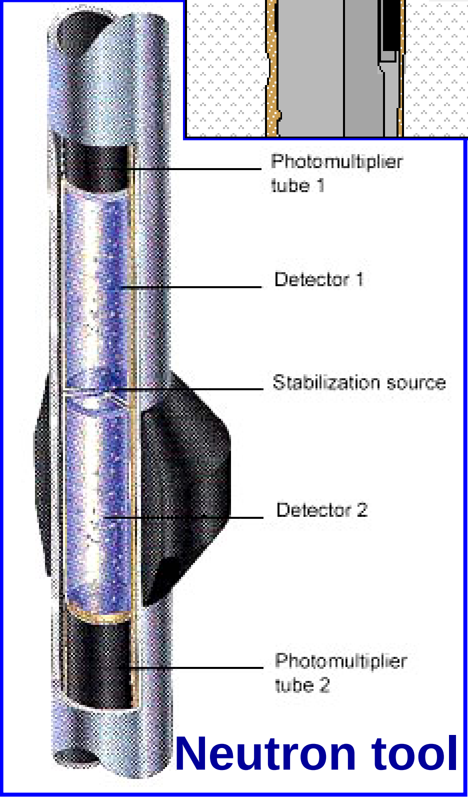


HEADER
Lith = Lithology
Gr = Gamma ray
API = Am.Petr.Inst.
Res = Resistivity (ohmm)
Nd = Neutron density
vdLnmr = Nucl.Magn.Res.
t2 = Sonics

Revised after: http://www.fugro-jason.com/images/logplot.jpg

Density tool

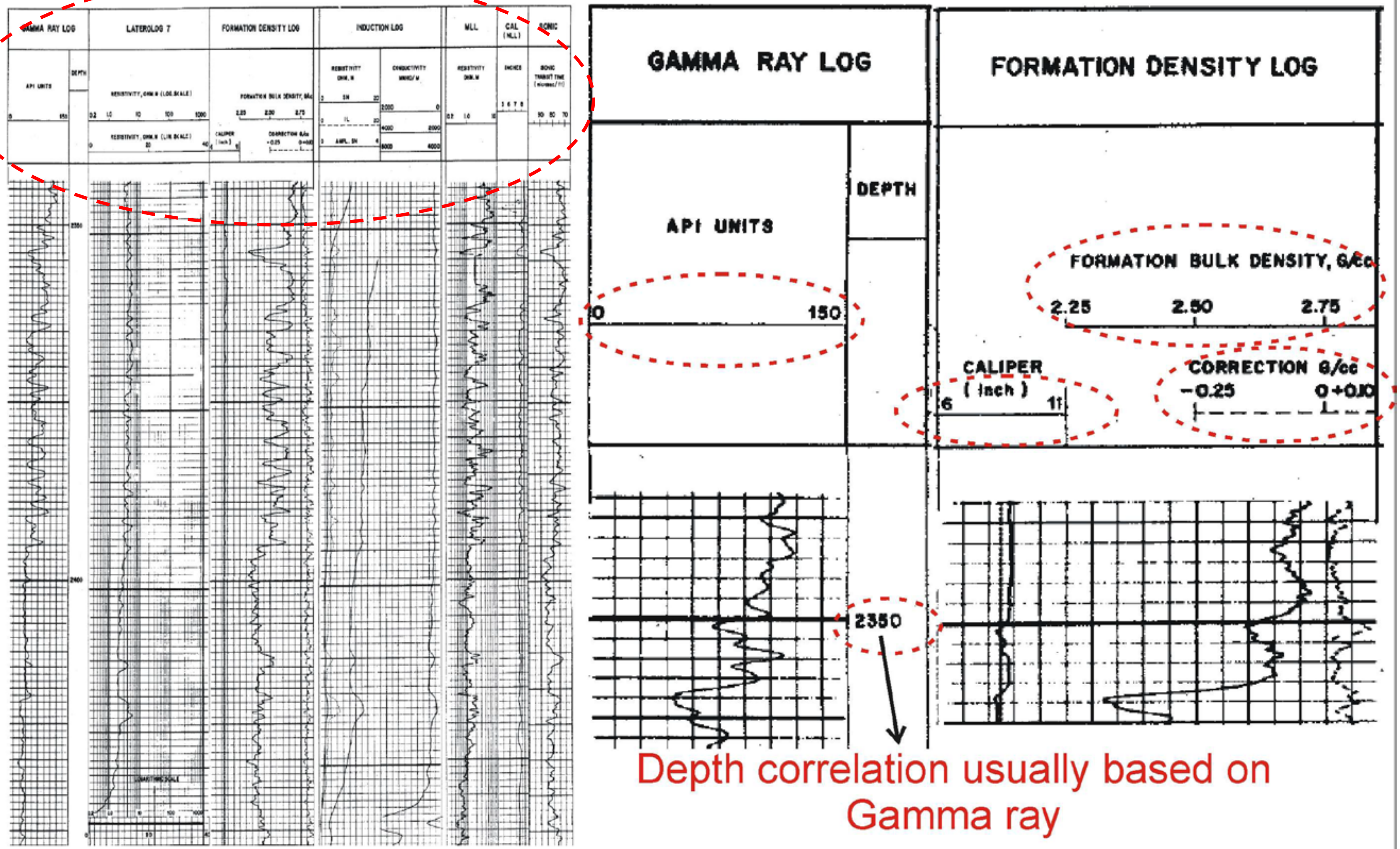




Neutron tool

Introduction

The log header gives you information of the scale of each tool that is used.



Depth correlation usually based on Gamma ray

Introduction

Downhole logs are complementary to core measurements. Advantages:

- In a hole with limited (damaged) core recovery, the depth location is uncertain; logs provide a continuous depth record of formation properties.

- In case of preferential core recovery of a certain rock type logs can reveal a more realistic stratigraphy.

- The in-situ nature of the downhole measurements differ from measurements on recovered cores: Absence of high-P,T causes expansion of gas and gas hydrates can dissociate.

- The core may be damaged by the coring process: rotary coring can grind up sediment, resulting in "biscuits" of coherent sediment in a ground-up matrix.

Introduction

Experience required for interpretation

- Technical Level
  - Tools: principles, geometry
  - Evaluation methods
  - Cores
- Disciplines
  - Geology
  - Reservoir engineering
  - Seismology, Economy
- Literature
  - Log Analyst, SPWLA symposia
  - SPE
  - books

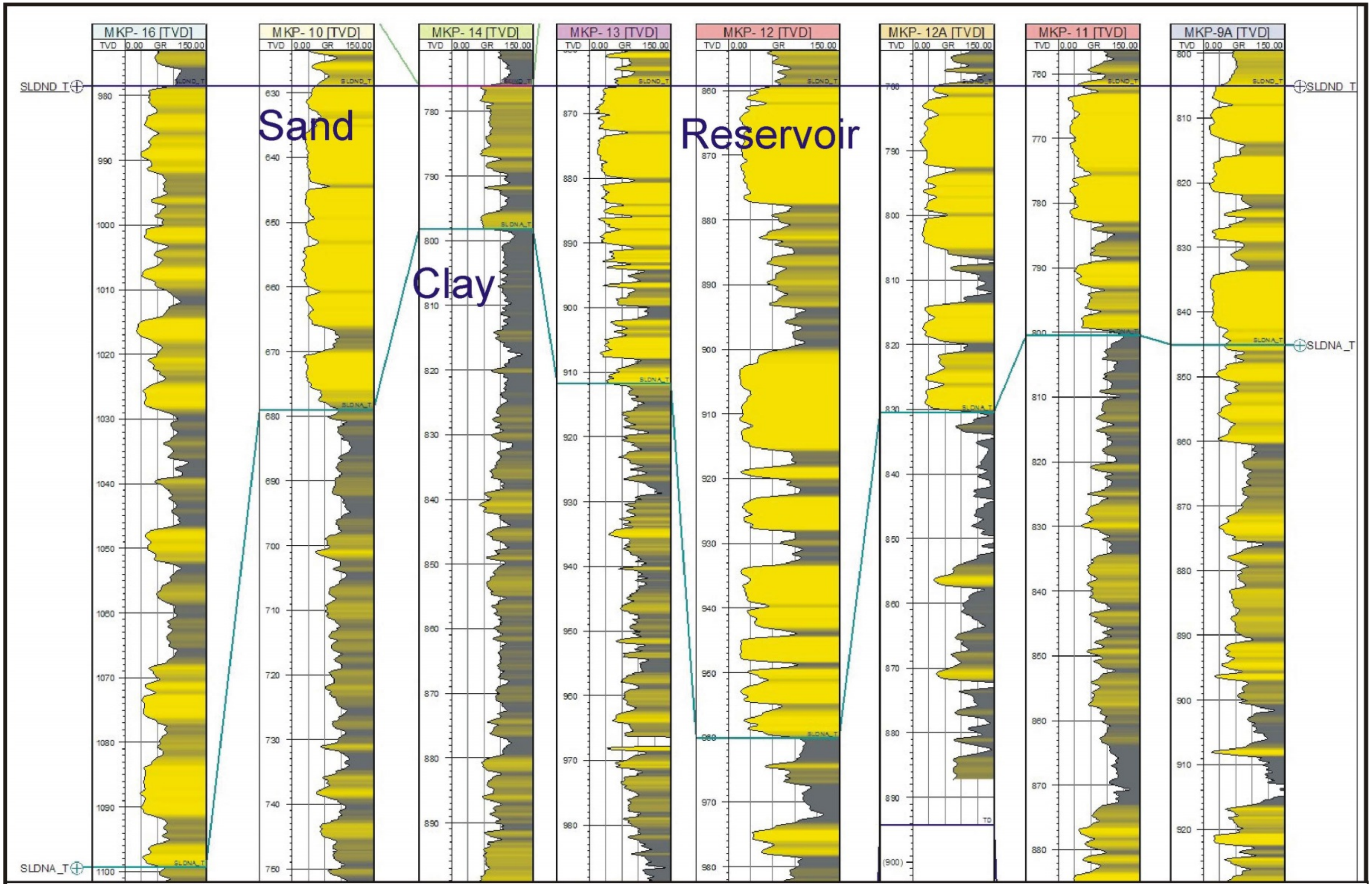
For the students available:

- Lecture notes TA3500 (paper)

On Blackboard:

- Lectures and assignments
- Excerpts from the Schlumberger log evaluation manual
- Old lecture notes and practical Dr. C. J. de Pater.
- Literature/website list.

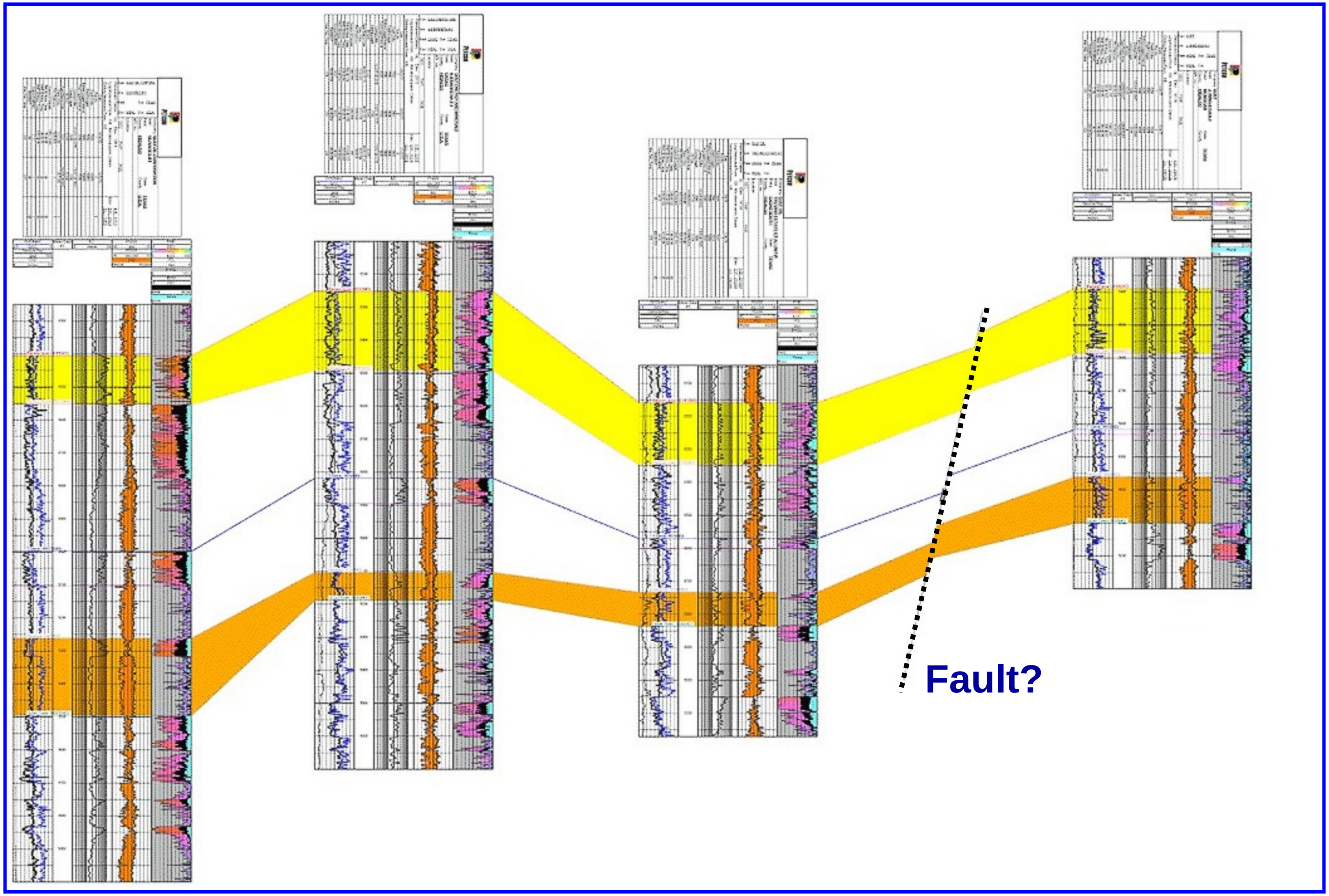
Introduction



Example 1

Correlation of well logs: Lateral continuity of the reservoir rocks

Introduction



Example 2

Petrophysical evaluation data sources.

DIRECT INFORMATION	ROCK FRAGMENTS & FLUIDS - drill cuttings, mud shows - sidewall samples, cores or core slices - production tests, formation wireline samplers drill-stem tests	
INDIRECT INFORMATION:	WIRELINE LOGS	
	PHYSICAL PHENOMENON	MEASURED PARAMETER
	acoustic - waves gamma / gamma scattering thermal neutron density thermal neutron decay neutron activation natural gamma radiation spontaneous potential electromagnetic waves 35 Hz -20 kHz 100 Mhz-2 GHz nuclear magnetic proton resonance	sonic velocities acoustic impedance electron density photoelectric cross section hydrogen density thermal neutron cross section elemental concentrations Curie / Bequerel / API / REM membrane potential electric resistivity / conductivity dielectric permitivity free hydrogen index spin lattice relaxation time

Objectives of a petrophysical interpretation

LOCATION:	reservoir / coal / mineral - layers
DETECTION:	fluid content water / oil / gas / pollutant coal / ore body
EVALUATION: (for all applications)	lithology mechanical properties gross / net thickness
ROCK PROPERTIES	
hydrocarbon & water reservoirs	porosity / permeability capillary properties salinity / hardness of the water original hydrocarbon saturation movable hydrocarbon sat. residual hydrocarbon sat. % oil/gas/water reservoir pressure
coal	moisture content ash content fixed carbon content
minerals / soil mechanics	ore content and grade fluid/gas content

Objectives of a log evaluation

- Locate
  - reservoir versus non-reservoir
- Detect
  - fluid content: water / oil / gas
- Evaluate
  - lithology
  - net/gross thickness
  - porosity and permeability
  - % oil / gas / water - original/movable/residual hydrocarbon
  - salinity of the water
  - capillary properties
  - hardness / strength rock
  - reservoir pressure

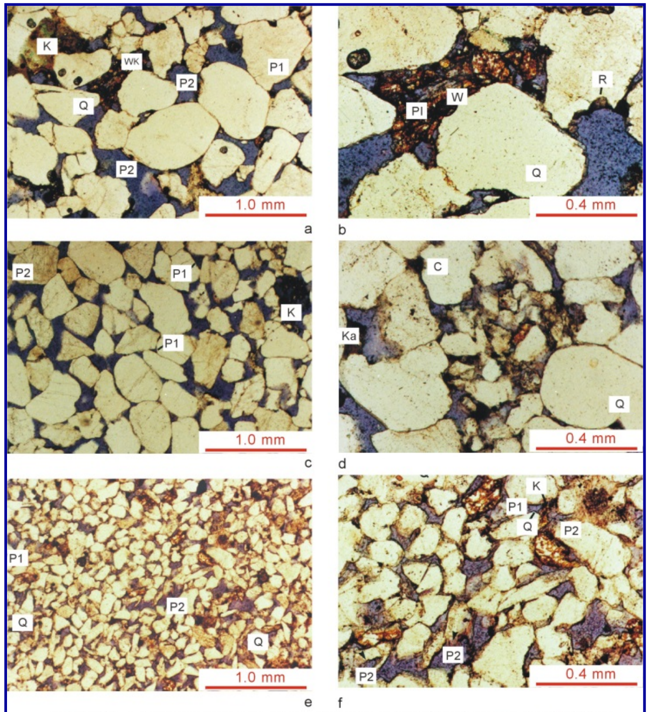
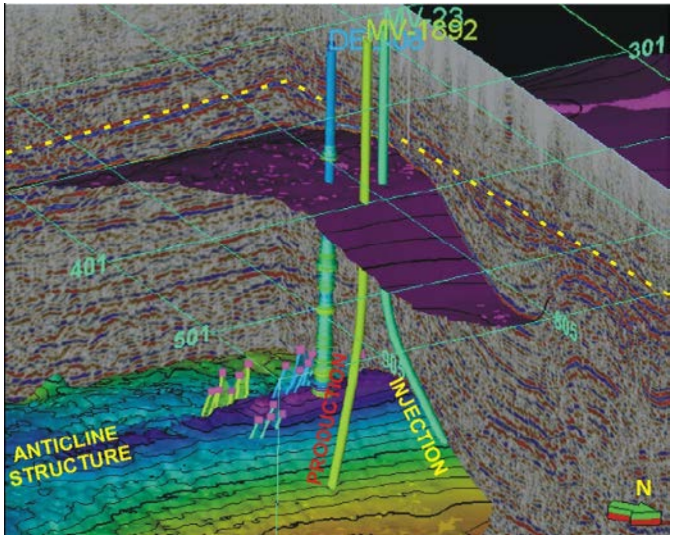


Photo 3.1: a. to f.: Microphotographs, plane polarized light: Q;quartz, K; K-feldspar, Ka; kaolinite/illite, V; volcanic relics; R; residues, Porosities: P1; primary, P2; secondary, Pi; intra-granular, W; weathering, C; corrosion.

Final goal: Estimation of reserves



- HydroCarbon-Initially-In-Place:

$$HCIIP = V_b R_{net/gross} \phi S_{hc} \frac{1}{F_{V,hc}}$$

  - V_b = Gross rock bulk volume
  - $R_{net/gross}$ = Net over Gross ratio
  - ϕ = Porosity, fraction of bulk volume
  - S_{hc} = Initial hydrocarbon saturation, fr.p.v.
  - F_{Vhc} = Initial hydrocarbon Formation Volume Factor

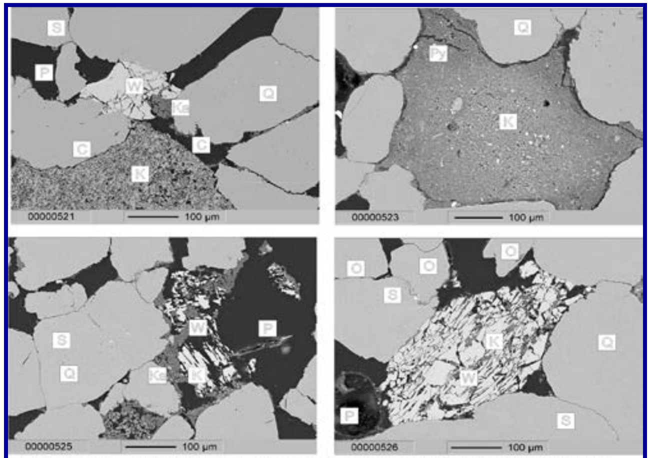
- Reserves
  - RF = Recovery Factor

$$Reserves = HCIIP \times R_f$$

How to work

Procedure in well log analysis

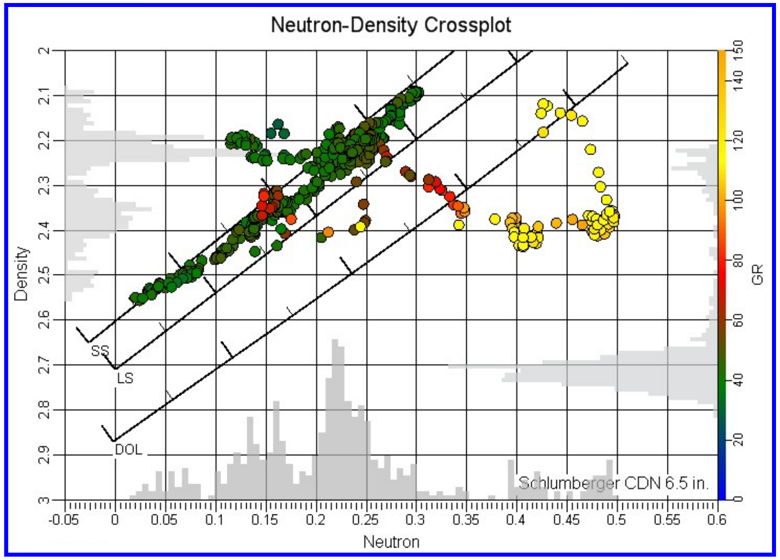
- Correlate Logs, Quality Check
- Apply Environmental corrections
- Determine General Petrophysical Parameters using:
    1. Cuttings, Cores etc.
    2. Drilling Information
    3. Crossplots of the logs: Density-Neutron Porosity
- Shale Volume
    1. Gamma Ray with several methods
    2. (Spontaneous Potential)
    3. (Density-Neutron Porosity)
- Porosity
    1. Density
    2. Neutron log with Corrections
    3. Sonic
    4. Combinations of FDC, Neutron, SONIC (PE)

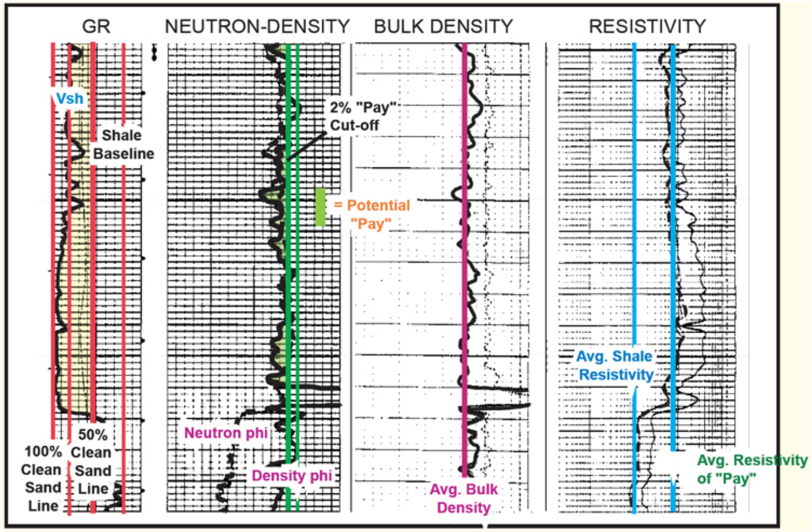


Microprobe microphotographs with a Jeol JSM-200 T200. Spot analysis are giving an element composition which is used for mineral identification. Sample specifications; all photos 20.0k, 200x. K; K-feldspar, Q; quartz, Ka; kaolinite, Py; pyrite, O; quartz overgrowth, W; weathering C; corrosion, P; pore space, S; sutured grain contacts.

How to work

- Resistivity
- Water Saturation
    1. Archie
    2. Dual-Water
    3. Waxman-Smits
    4. Capillary Pressure Curves
- Average porosity, Hydrocarbon Saturation and Columns
- Special Subjects:
    - Routine and special core analysis
    - Permeability from logs

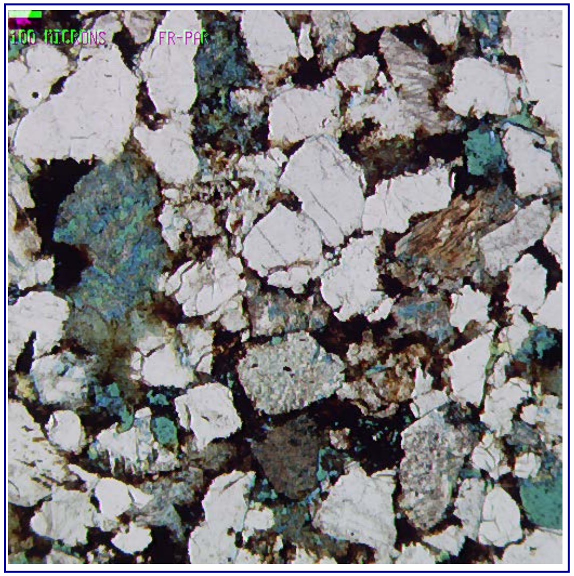




In-situ conditions

What’s present in the sub-surface?

- **Rock types**
- **Mineral composition**
- **Temperature**
- **Pressure**
- **Fluid/gas occurrence**



In-situ conditions: Rock composition

In general rock consists of minerals, grouped in certain shapes, with openings that can be filled.

- Minerals are the structure elements of rocks.
- Groups of grains or minerals can be arranged in layers, lenses, etc. and represent a part of its geological history
- Rock is filled with cracks, and pores and cut by heterogenous discontinuities like fractures and divisions between layers
- Pores and cracks can be filled withfluids and gas. These fluids/gases and rock affect each other chemically and physically. Dissolution and precipitation strengthens or weakens rocks
- Although residual stresses are not a part of the composition of rock, stress impact affects its characteristics.

In-situ conditions: Water composition

What are the references for water/brine?

Main elements dissolved in (mainly from Turekian, 1972)

	Sea water in μg/l	Fresh water μg/l
Cl	$1.94 * 10^7$	7800
Na	$1.08 * 10^7$	6300
Mg	$1.29 * 10^6$	4100
S	$9.04 * 10^5$	5600
Ca	$4.11 * 10^5$	15000
K	$3.92 * 10^5$	2300
Br	67300	20
C (inorganic)	28000	11500
N	15000	n.a.
Sr	8100	70
O	6000	n.a.
B	4450	10
Si	2900	6100
F	1300	100

Most relevant minerals, composition, density and main occurrence

(from Carmichael, 1985 and Schlumberger 1989)

Presence in %, of the actual mineral composition	
Mineral	12
Quartz	12
Potash feldspars	39
Plagioclase feldspars	5
Micas	5
Amphiboles	11
Pyroxenes	3.6
Olivines	4.6
Clay minerals and Chlorite	1.5
Calcite and Aragonite	0.5
Dolomite	1.5
Magnetite and Titanomagnetite	4.9
Others like Garnet, Kyanite, etc.	accessory
Coal and hydro-carbons	Unique!
	--------+
Total	100

Name	Composition	Density kg/m^3 x 10^3
Silicates		
Olivine	$(Mg,Fe)_2.SiO_4$	3.2 - 4.14
Garnet	$(Fe,Mg,Ca)_3.(Fe,Al)_2.(SiO)_3$	3.75 - 4.25
Pyroxenes	$(Ca,Mg,Fe,Al).[(Al,Si)O_3]_2$	3.2 - 3.5
Amphiboles	$Ca_{0-2}.(Mg,Fe,Al)_{5-6}.[(Al,Si)_4O_{11}]_2.(OH)_2$	3 - 3.2
Quartz	SiO_2	2.65
Feldspar	$(Na,K,Ca).Al.(Al,Si)_3.O_8$	257 - 2.76
Micas	$K_{0-1}.(Mg,Fe,Al)_3.(Al,Si)_3.O_{10}.(OH)_2$	2.7 - 3.2
Clay minerals	$(K,Na,Ca,Mg)_{0-2}[(Al,Si)_8.O_{20}](OH)_{2-4}n(H_2O)$	2.5 - 2.65
Carbonates		
Calcite	$Ca.CO_3$	2.72
Dolomite	$(Ca,Mg).CO_3$	2.85
Siderite	$Fe.CO_3$	3.96
Sulphides & sulphates		
Pyrite	FeS	5.02
Galena	PbS	7.6
Sphalerite	ZnS	4.1
Gypsum	$CaSO_4n(H_2O)$	2.31
Anhydrite	$CaSO_4$	2.96
Oxides		
Haematite	Fe_2O_3	5.28
Magnetite	Fe_3O_4	5.20
(Hydro)-Carbons		
Coal	C:H:O - Antracite; 93:3:4, Bituminous; 82:5:13	1.8 - 1.2
Oil	$n(CH)_2$	0.85
Natural Gas	$C_{1.1}H_{4.2}$	0.83 * 10^{-3}

In-situ conditions: Rock composition

Classification based on clastic fragments

Texture; grain size	Group name	Composition
Cobbles, pebbles, granules	Blocks to gravel	Rounded & angular fragments
Coarse; > 2 mm	Breccia	Large angular fragments
	Conglomerate	Large rounded fragments
Medium; 2-0.0265 mm	Sandstone	Quartz, feldspar, clay Quartz, feldspar, micas Quartz (feldspar)
Fine; 0.0265-0.0039 mm	Silt	Mainly quartz and clay Quartz, carbonate cement
Very fine; < 0.0039 mm	Clay	Compacted clay Clay, organic matter & some sulphides

Classification based on chemical components

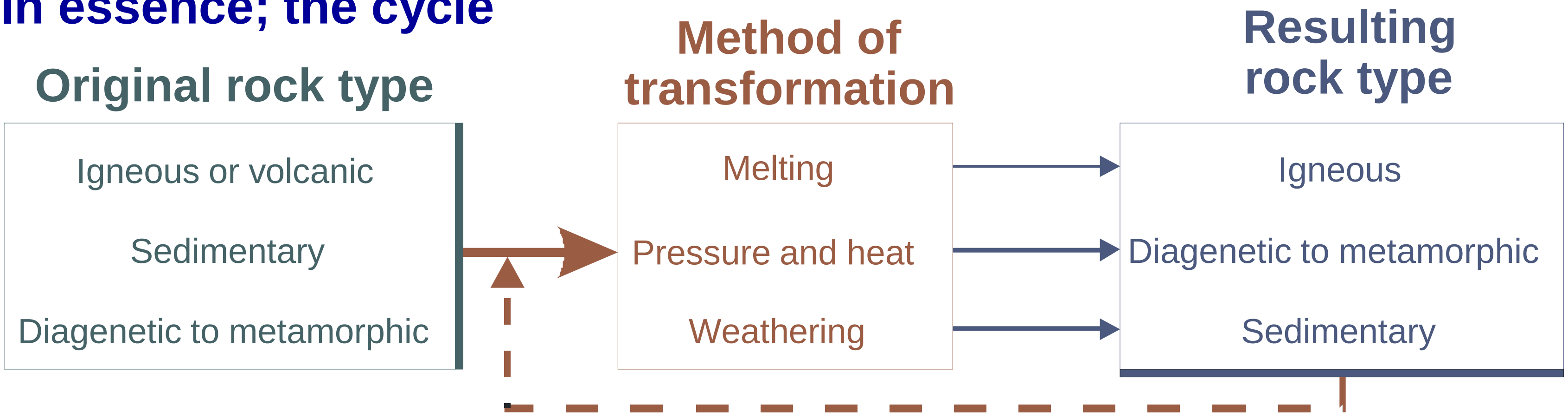
Group name	Example	Composition
Limestone	Chalk	Micro fossils, micro parts of shells etc., clay
	Boundstone	Fossil components bound together by organic growth
	Crystalline limestone	Crystal grains of calcite & relics of ghost structures.
Dolomite	Dolomitic limestone	Dolomite
Chert	Chert	Micro-grains of hydrated silica, light coloured
Flint	Flintstone	Micro-grains of hydrated silica, dark coloured
Evaporites	Gypsum	Gypsum
	Rock salt	Halite, sylvite, aragonite

In-situ conditions: Rock composition

Classification based on bio-organic components

Group name	Example	Composition
Coal	**Peat**	**Decaying wood in disintegrated plant debris**
	Brown coal or Lignite,	**Humic (<40 % water) coal with vegetal structures**
	Bituminous to Antracite	**Organic sediment (< 40% ash) composed of polymers of cyclic hydrocarbons and low water content**
Asphalt	**Tar**	**Migrated and solidified immature petroleum. Black to dark brown.**
Limestone	**Coquina**	**Fossil fragments, loosely cemented like sand.**

In essence; the cycle



The generic relationship of rocks (revised after Ho et al., 1989)

EFFECTS OF T,P,t ON IN-SITU ROCK

TEMPERATURES

- Geothermal gradient
- T-aspects of chemical reactions
- T-aspects fluid salinity & resistivity

PRESSURES

- Pressure gradients
- Overpressures

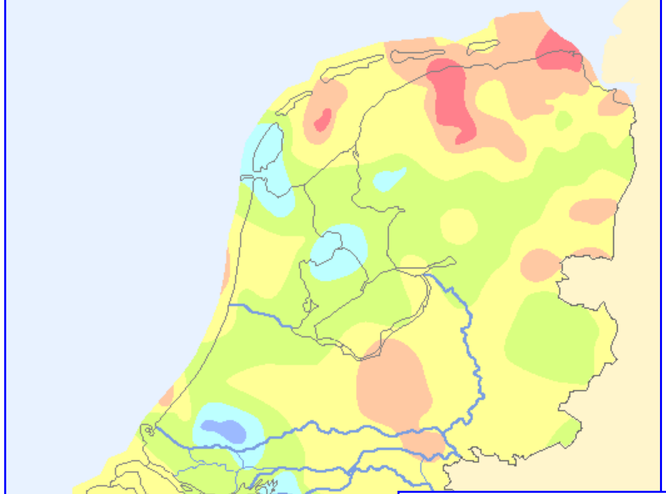
EFFECTS OF TIME

In-situ conditions: P,V,T,t
TEMPERATURES

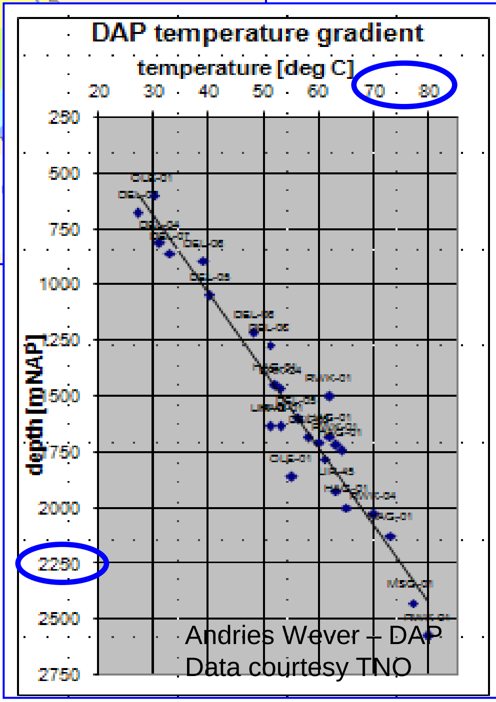
* Geothermal gradient

$$G_t = \frac{T_f - T_s}{D}$$

G_t	**Geothermal gradient (°C/km)**
T_f	**Formation temperature (°C)**
T_s	**Surface temperature (°C)**
D	**Depth (km)**

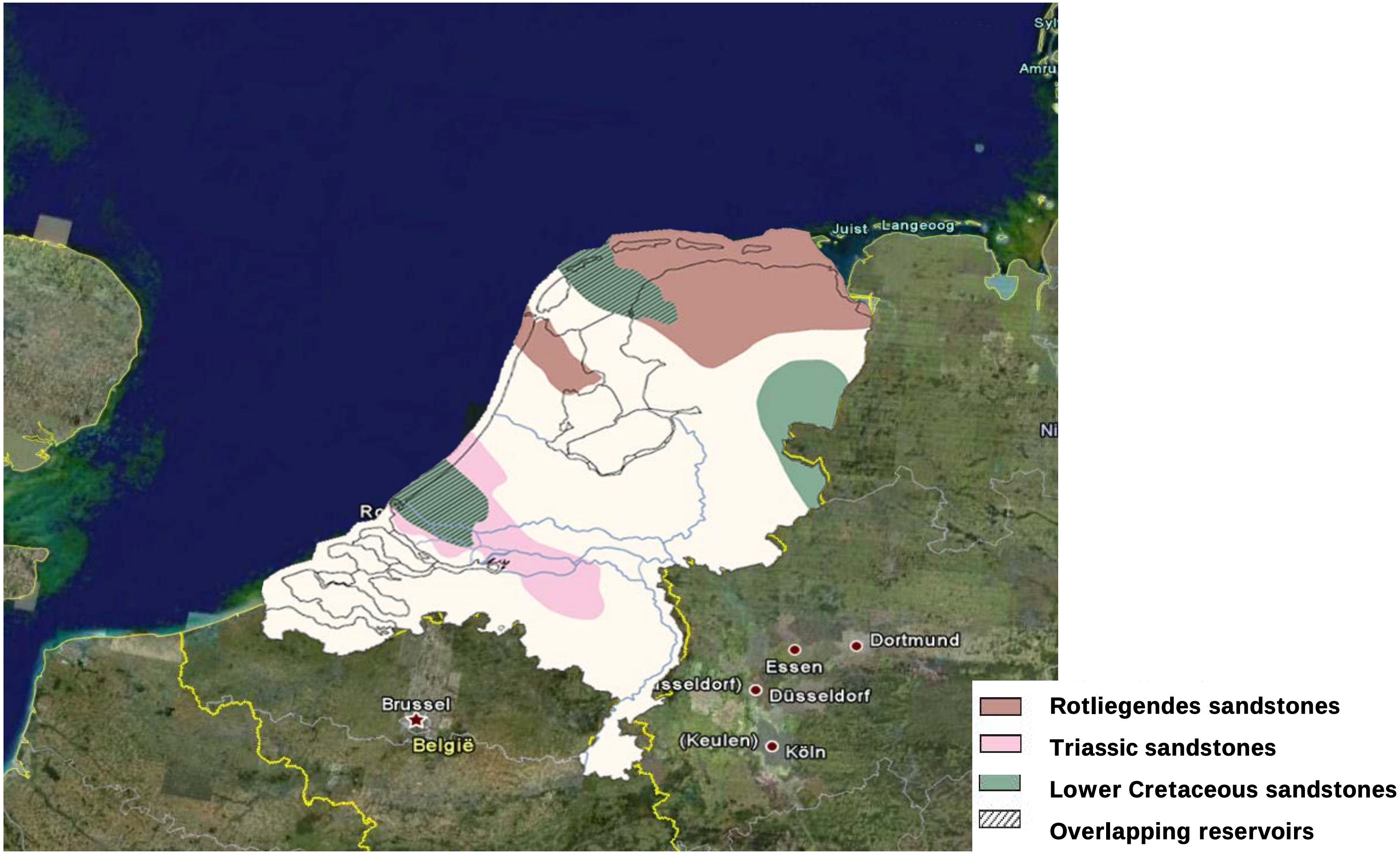


Geothermal Energy by A. Lokhorst & Th.E. Wong. in: Geology of the Netherlands, Edited by Th.E. Wong, D.A.J. Batjes & J. de Jager. Royal Netherlands Academy of Arts and Sciences, 2007



Andries Wever – DAP
Data courtesy TNO

Geothermal Potential



Lokhorst & Wong, 2007

Google Earth

In-situ conditions: P,V,T,t

TEMPERATURES

* T-aspects of chemical reactions

$$k = Ae^{\frac{-E_a}{RT}}$$ or $$\ln k = \ln A - \frac{E_a}{RT}$$

k : the rate constant

A : pre-exponential factor, depending on environment and mineral types

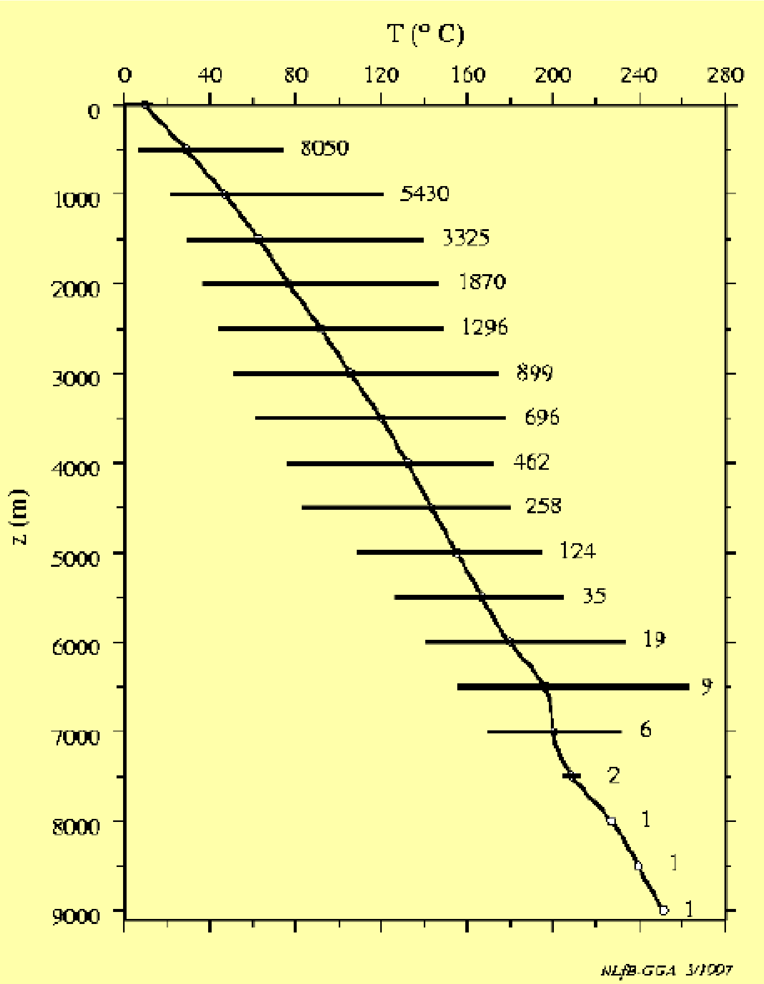
E_a : the activation energy of the reaction (J)

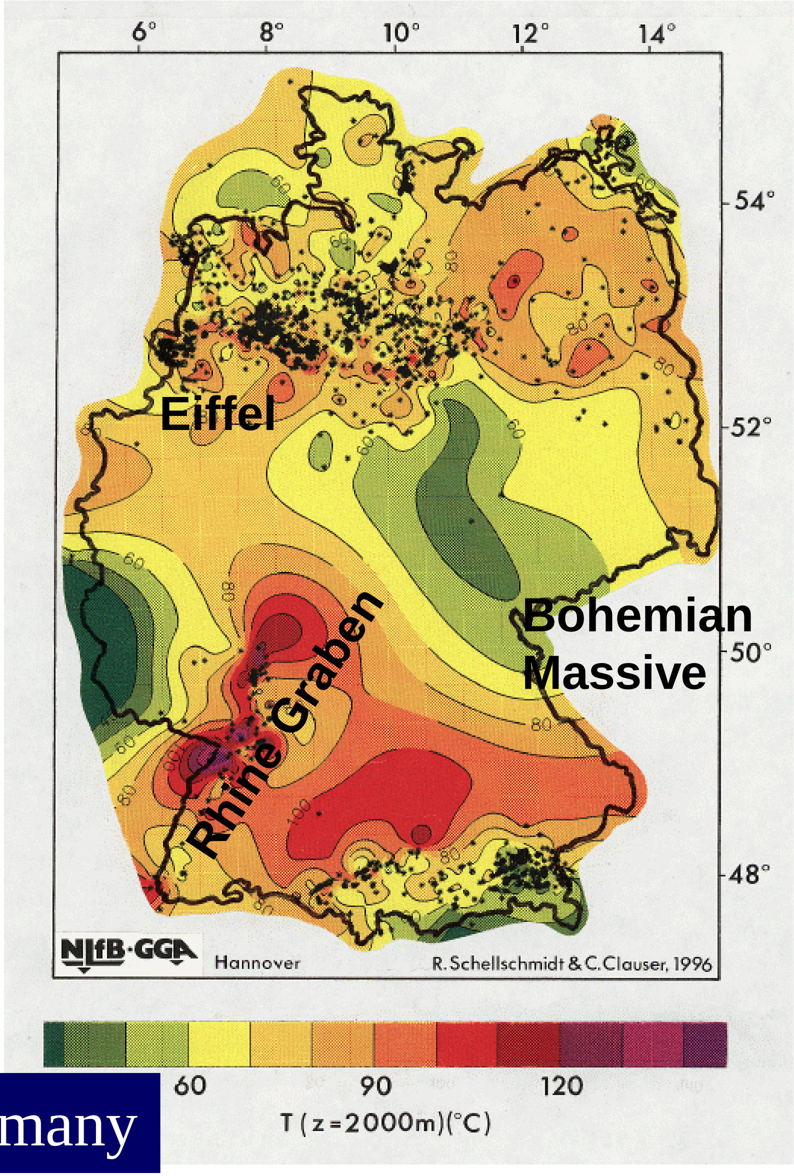
R : gas constant (J/K.kmol)

T : Temperature (K)

Note:
The rate of reaction more or less doubles with every 10 °C in rise of temperature.

Thermal Properties





Spread in geothermal gradients over Germany

TU Delft

In-situ conditions: P,V,T,t

TEMPERATURES

* T-aspects fluid salinity & resistivity

$$S_1 = \frac{S_2}{\rho_{sol}} * 1000$$

S_1 **: salinity in ppm**
S_2 **: salinity in g/l**
ρ_{sol} **: solution density in g/l.**

$$R_{wT2} = R_{wT1}\left(\frac{T_1 + 6.77}{T_2 + 6.77}\right)$$

Fluid resistivity: Two temperatures

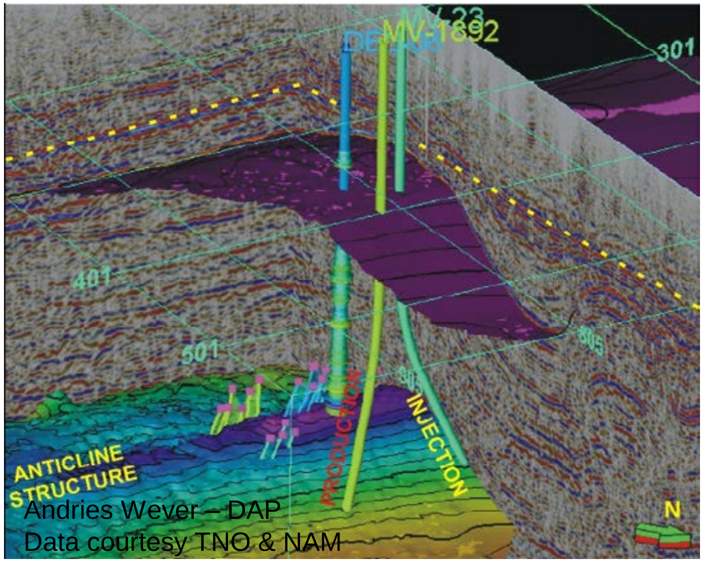
$$R_{wT2} = R_{w75}\left(\frac{81.77}{T_2 + 6.77}\right)$$

Fluid resistivity: One reference temperature

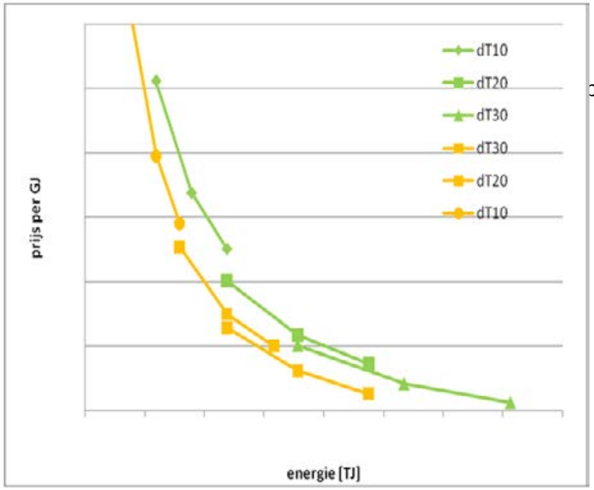
$T_{1,2}$ **: temperatures at specific depths (°F)**

$R_{wT1,2}$ **: water resistivities at the respective temperatures (ohm.m).**

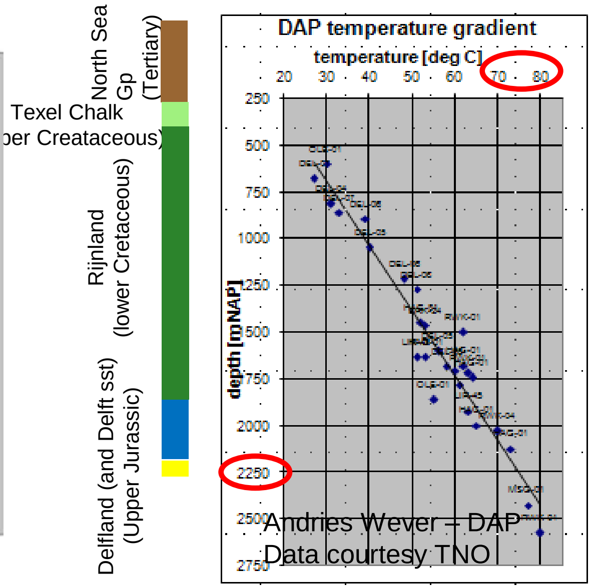
R_{w75} **: water resistivity at a reference temperature of 7f°F (ohm.m).**



Andries Wever – DAP
Data courtesy TNO & NAM



Guus Willemsen – DAP & IF Technology



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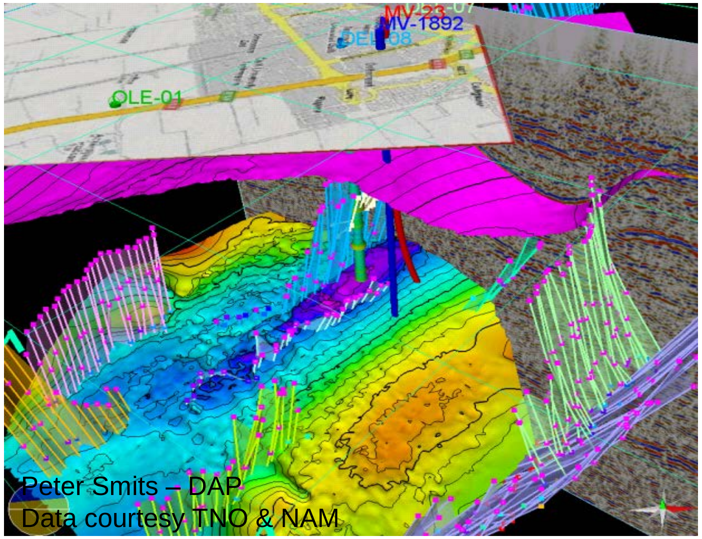
Data courtesy TNO



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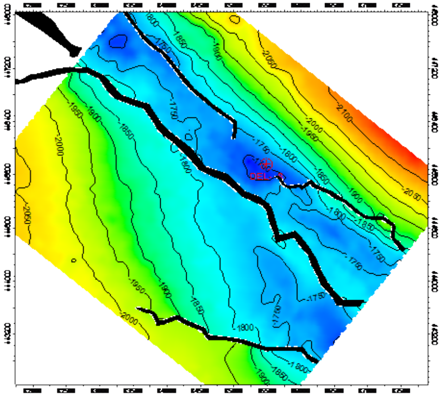

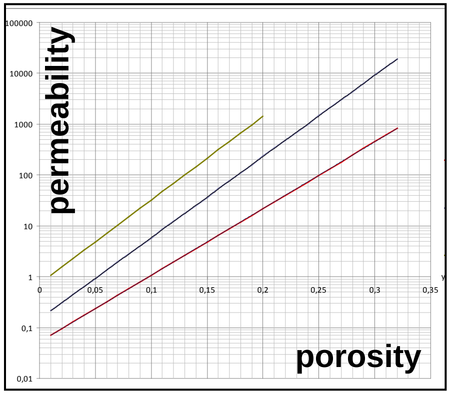

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