PETROPHYSICAL MODELING WITH THE AIM OF PERMEABILITY ESTIMATION USING STONELEY-WAVE TRANSIT TIME

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Problem

The full sonic wave is suitable for determination the fracturing, anisotropy and permeability of the rocks

The determination of permeability is a difficult task, accuracy of the estimation can reach even 1-1.5 order of magnitude

(Accustic) methods of permeability estimation:

- On the basis of accustic measurements using Stoneley arrival times inversion
- With algorithms based on simplified, empirical observation
- In-situ permeability can be estimated with full wave logging

In recent years, those publications predomicated, in which simplified algorithm is used for permeability estimation.

They are looking for the difference between calculated and measured Stoneley wave curves

Aim

I want to determine a well useable regressional relation between Stoneley-index and the wideley used Timur permeability

I want to examine the model in wide interval of petrophysical parameters

I want to examine the noise sensitivity of the estimation

I want to test the model on field data

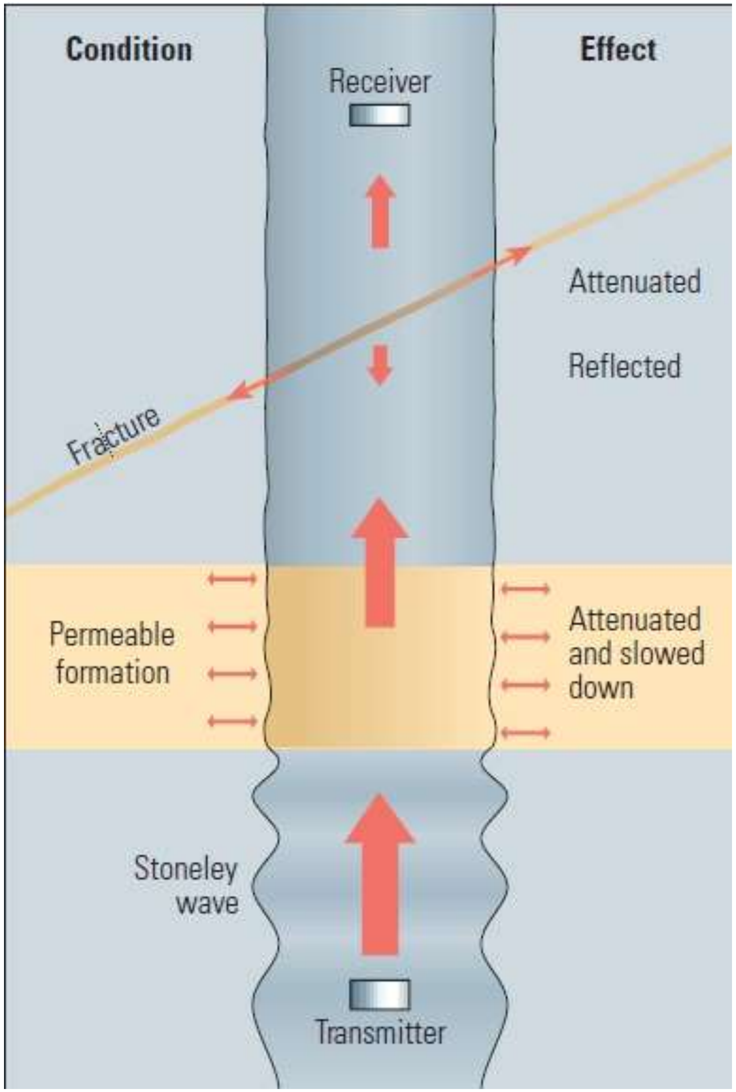
Sondes

- **Monopol tools**
  - The transmitter emits equal energy in all directions
  - The receiver is sensitive to the radial displacements
  - types:
    - Conventional monopol tools
    - **Monopol „array” tools**
- **Dipol tools**
  - The transmitter emits a signal in a selected direction
  - The shear wave velocity can be measured in slow formations, too
- Multipol „array” tools
  - They can containe both monopol and dipol tools
- Cross dipol tools
  - The anisotropy of rock formations is provadle
- Acoustic borehole imaging
  - The imaging sonde uses the acoustic response of rocks for imaging

Stoneley wave

- The full waveform (compressional, shear, surface and flexural waves)
- Surface wave
- The result of interaction of in fluid compressional wave propagation and in solid shear wave propagation
- Slightly dispersive
- If frequency is heading to zero, the wave becomes a tube wave
- The attenuation of amplitude exhibits frequency dependence
- It can propagate to big distances along the borehole
- It's frequency, generaly is 0kHz-10kHz; top: 500Hz
- Low frequency Stoneley waves are sensitive to formation permeability

  (they slow down relative to the impermeable medium)
- In permeable medium Stoneley waves slow down and attenuate

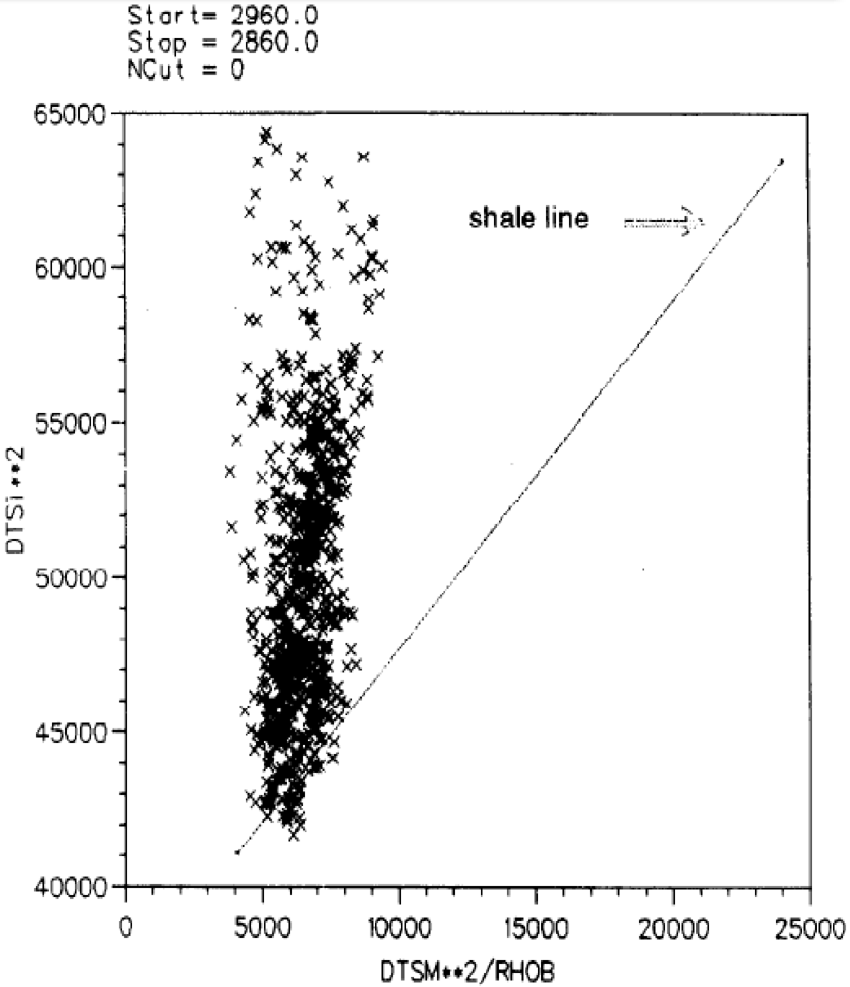


Permeability estimation from Stoneley waves

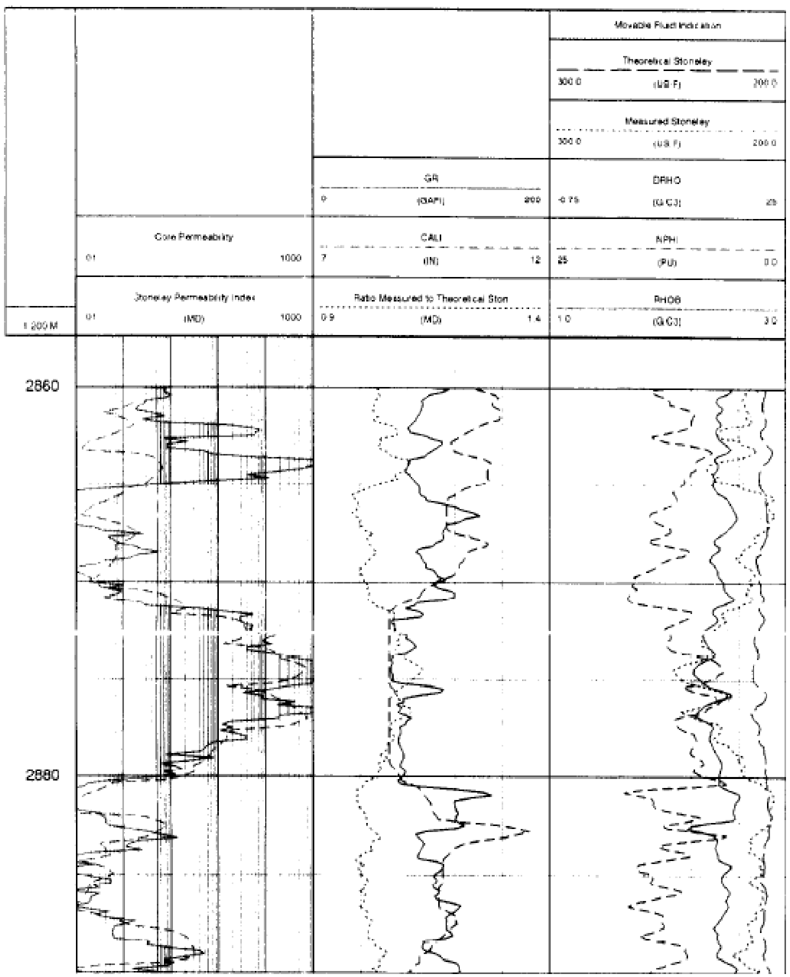
- It's base: the wave slowness increase at low frequency, in porous media
- **Buffin (1996) determination**: there is a good correlation between on core measured permeability and permeability index calculated from Stoneley component of full sonic waveform
- **Bala (2010)** described the relationship between Stoneley wave index and permeability measured in laboratory with a function which is linear on segments
- It provides permeability without knowledge of porosity
- Mutual relationship between logarithm of permeability derived from laboratory measurements and Stoneley wave index
- The permeabibility estimation from Stoneley waves is based on full waveform

Buffin's (1996) results

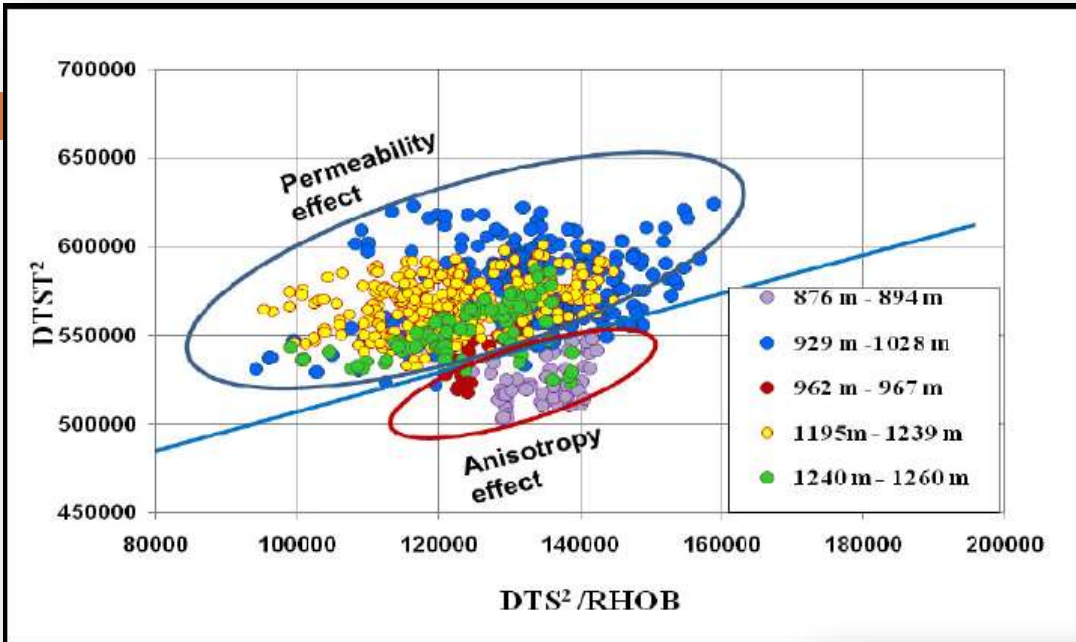
Measured Stoneley- and shear slowness crossplot



The permeability estimation is based on the relationship of Stoneley-index and permeability derived from core data

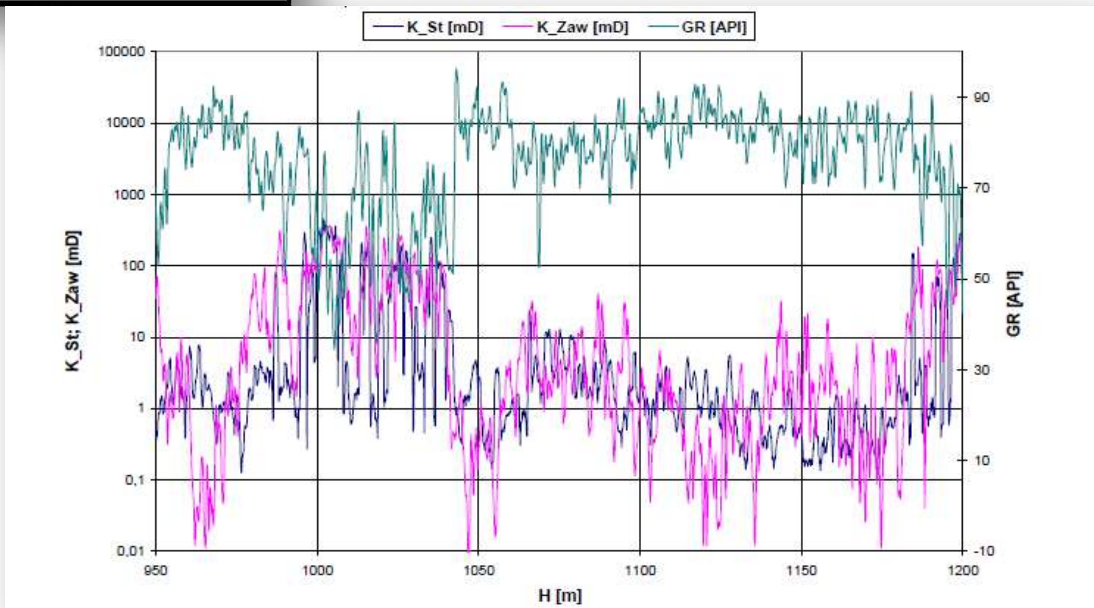


Bala's(2010)results

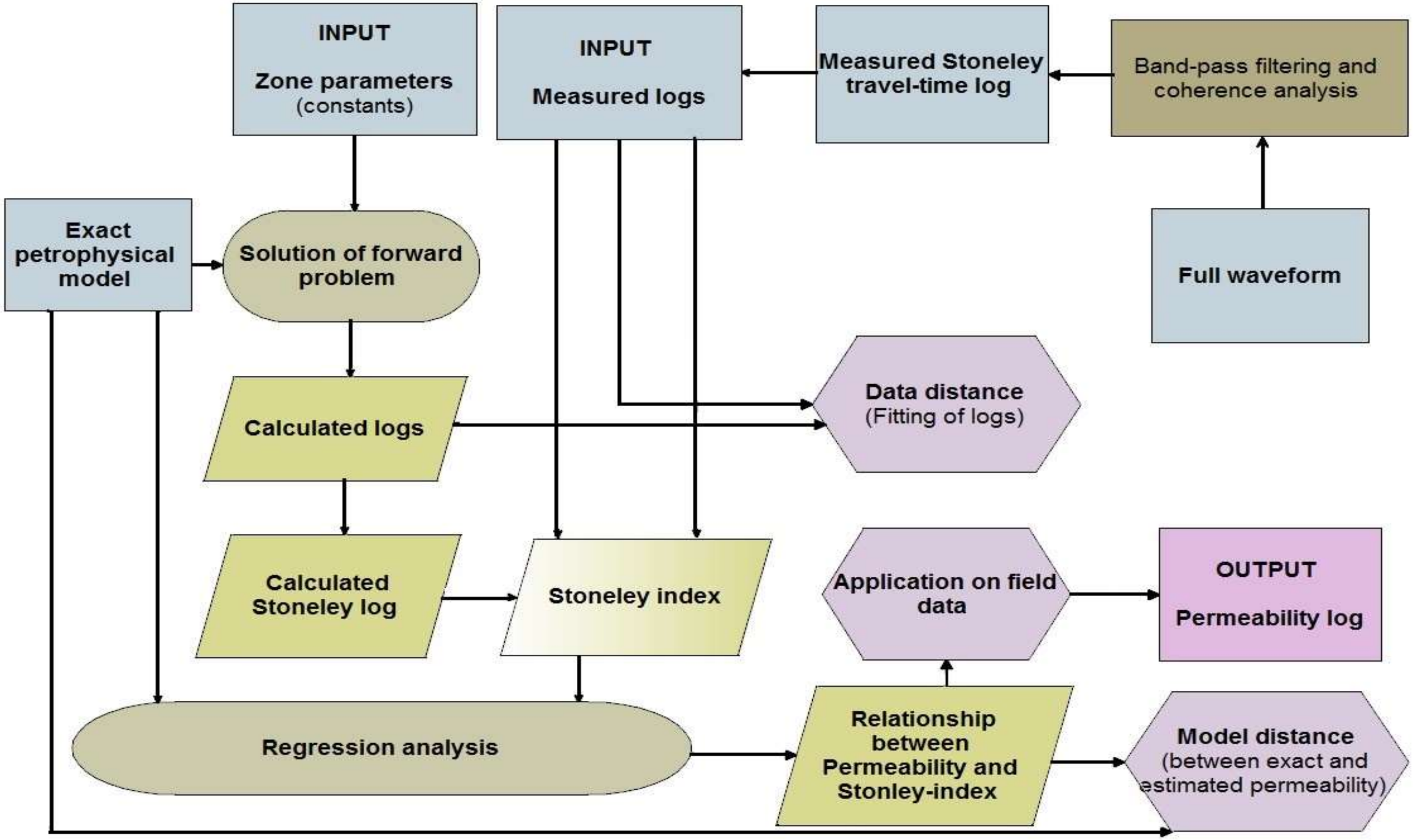


Relationship of measured Stoneley- and shear wave slowness

Comparison of permeability values derived from relation used by Bala and from Zawisza's equation



The flowchart of modeling



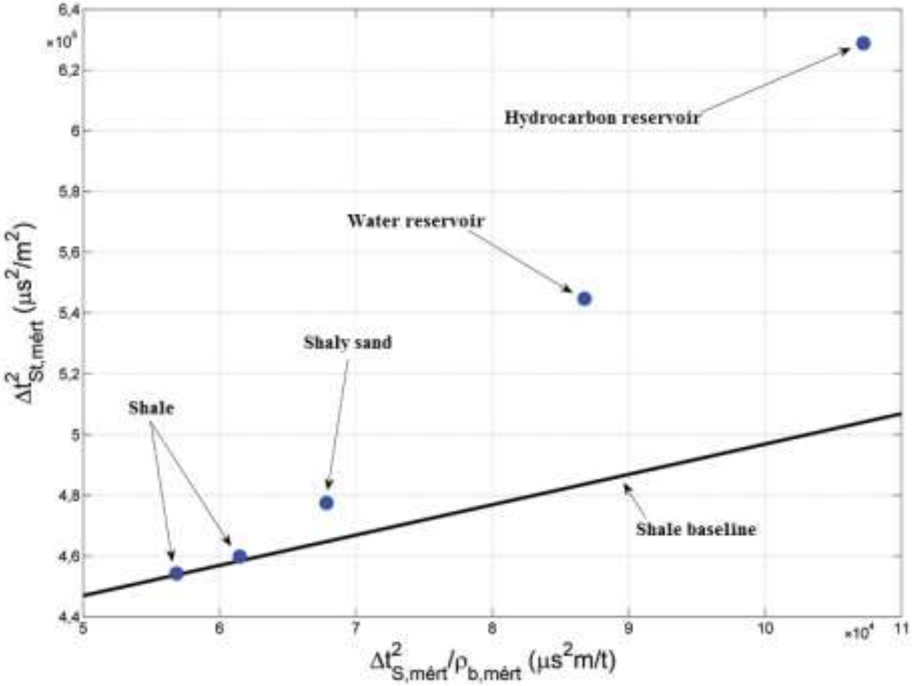
Synthetic model

Number of layers	Sequence	Layer thickness (m)	POR	SXO	VSH	SWIRR	DTS (μs/m)
1. layers	shale	5	0.15	1.0	0.5	0.6	691
2. layers	water-bearing	5	0.23	1.0	0.3	0.2	738
3. layers	shaly sand	3	0.07	1.0	0.8	1.0	674
4. layers	hydrocarbon-reservoir	7	0.25	0.7	0.1	0.2	793
5. layers	shale	5	0.1	1.0	0.7	0.8	678

Syntethic logs:

- Natural gamma
- Gamma-gamma (density)
- Shear wave travel time
- Stoneley travel time

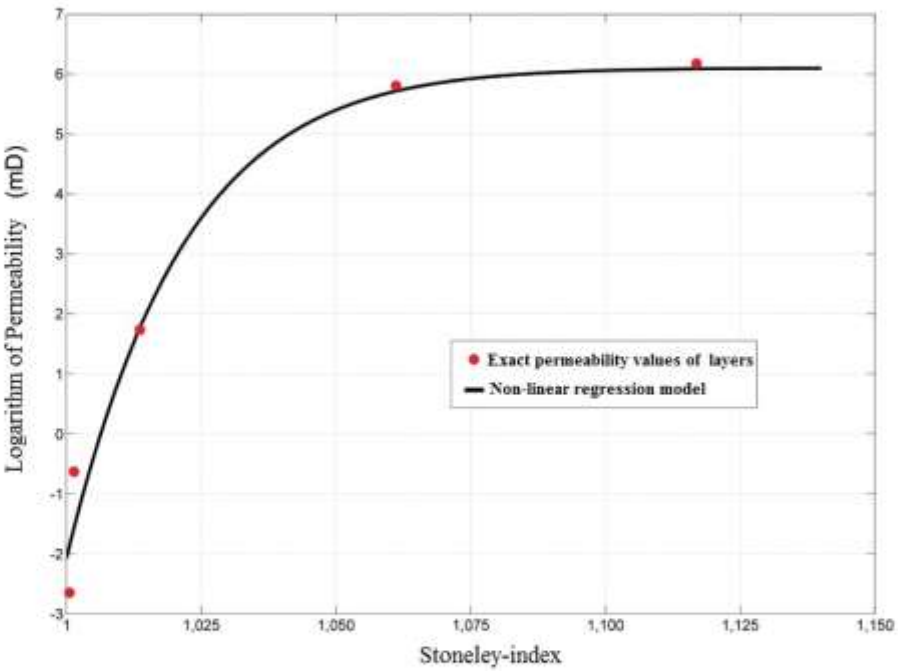
Homogeneous model



- Relationship of measured Stoneley wave slowness and shear wave slowness
- Shale Baseline: where the value of measured and calculated Stoneley is equal

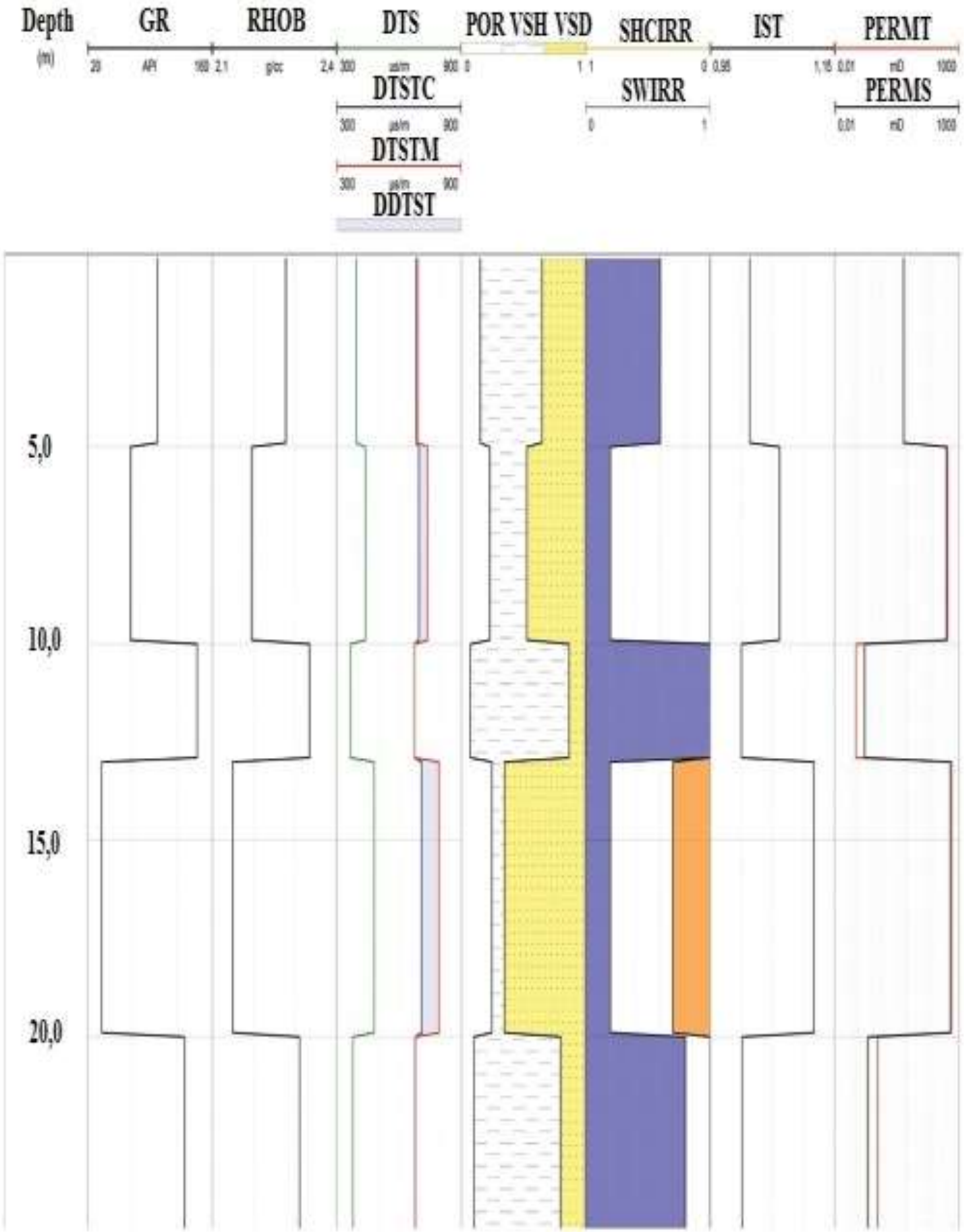
- Non- linear relationship between Stoneley-index and natural logarithm of Timur permeability
- Timur permeability: $k = 0.136 \cdot \frac{\Phi^{4.4}}{SWIRR^2}$
- The regression relationship:

$$\ln(PERM) = 854.8 \cdot (1 - 8300 e^{-16.5 \cdot I_{st}^4}) - 848.8$$

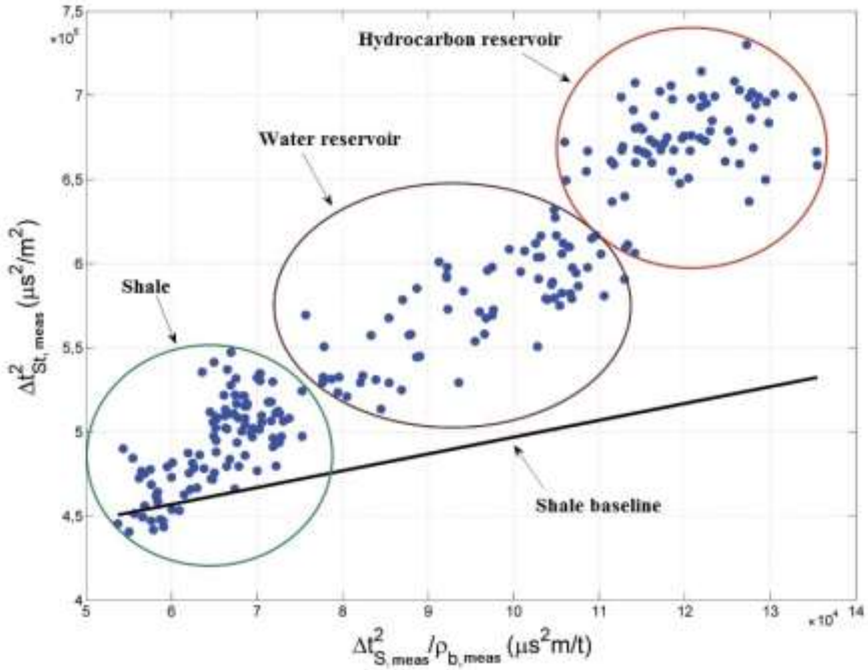


The result of permeability estimation

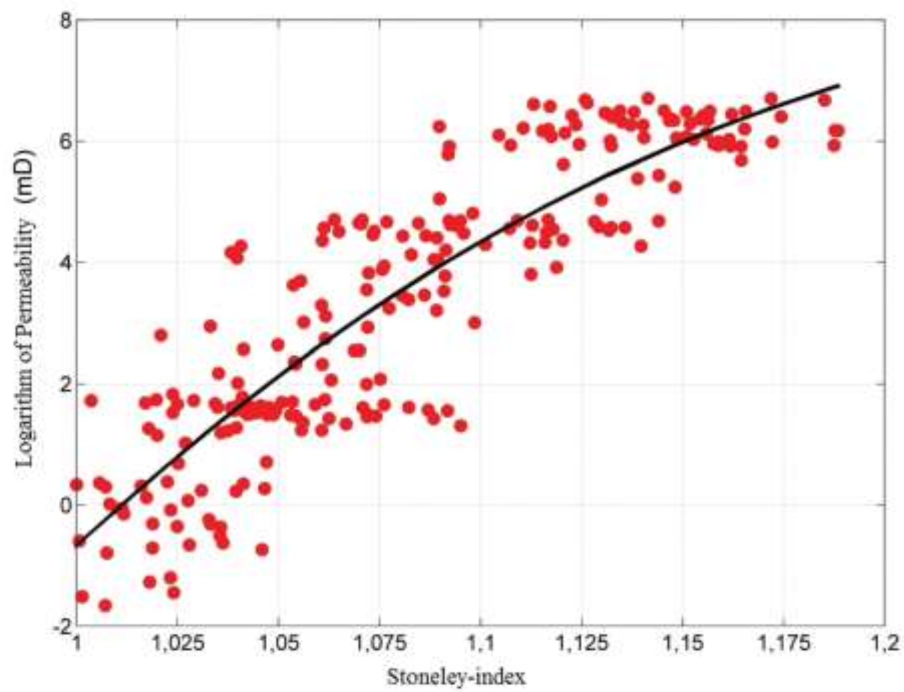
- ❖ **Illustration of resulting logs with WellCad software**
- ❖ **Illustrated logs:**
- ❑ GR –indicates the degree of the shale content, where it has a minimum, there is a big permeability
- ❑ RHOB log- the value decrease in the reservoirs and increase in shale
- ❑ DTS-DTSTC-DTSTM –shear wave-, measured and calculated Stoneley
- ❑ DDTST- the measured Stoneley slowness value increases in reservoirs , in shale: measured Stoneley= calculated Stoneley
- ❑ POR-VSH-VSD- it shows the bulk content
- ❑ SXO- constant
- ❑ SHCR= 1-SXO
- ❑ PERMT- permeability determined on the basis of Timur formula
- ❑ PERMS- permeability determined from Stoneley waves



Inhomogenous model



- Logs with 2% Gauss noise
- Relation between measured Stoneley slowness and shear wave slowness



- Non- linear relationship between Stoneley-index and natural logarithm of Timur permeability
- Exponential regression function fits well to the values of permeability
- Calculation of Permeability:

$$\ln(PERM) = 8.158 \cdot (1 - (29.2 e^{-3.716 \cdot I_{St}^{4}}) - 1.527$$

The result of permeability estimation

- ❖ **Illustration of resulting logs with WellCad software**
- ❖ **Illustrated logs :**

- ❑ GR – indicates the degree of the shale content, where it has a minimum, there is a big permeability
- ❑ RHOB - the value decreases in the reservoirs and increases in shale
- ❑ DTS-DTSTC-DTSTM- shear wave-, measured and calculated Stoneley
- ❑ DDTST- the measured Stoneley slowness value increases in reservoirs , in shale: measured Stoneley= calculated Stoneley
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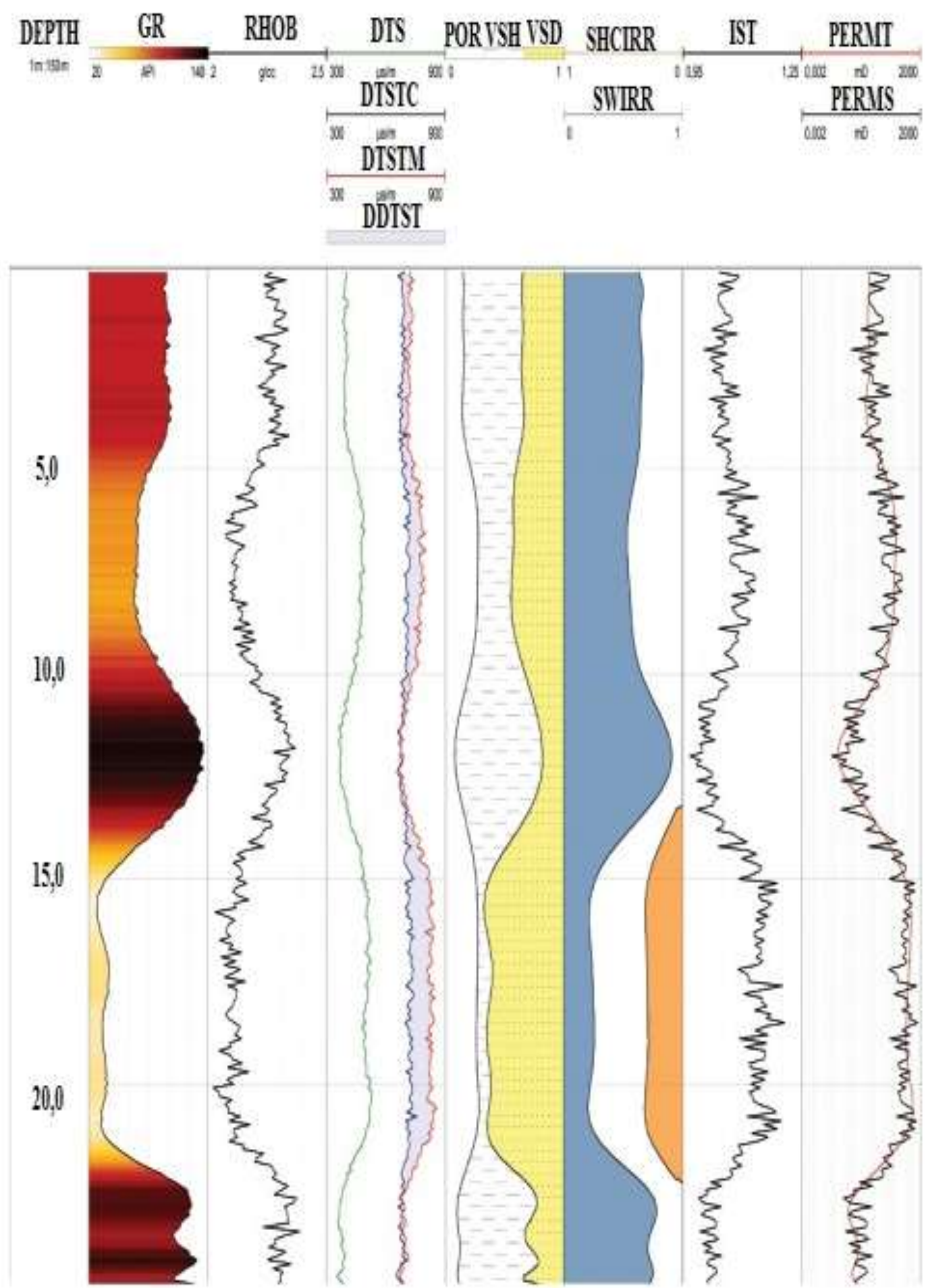
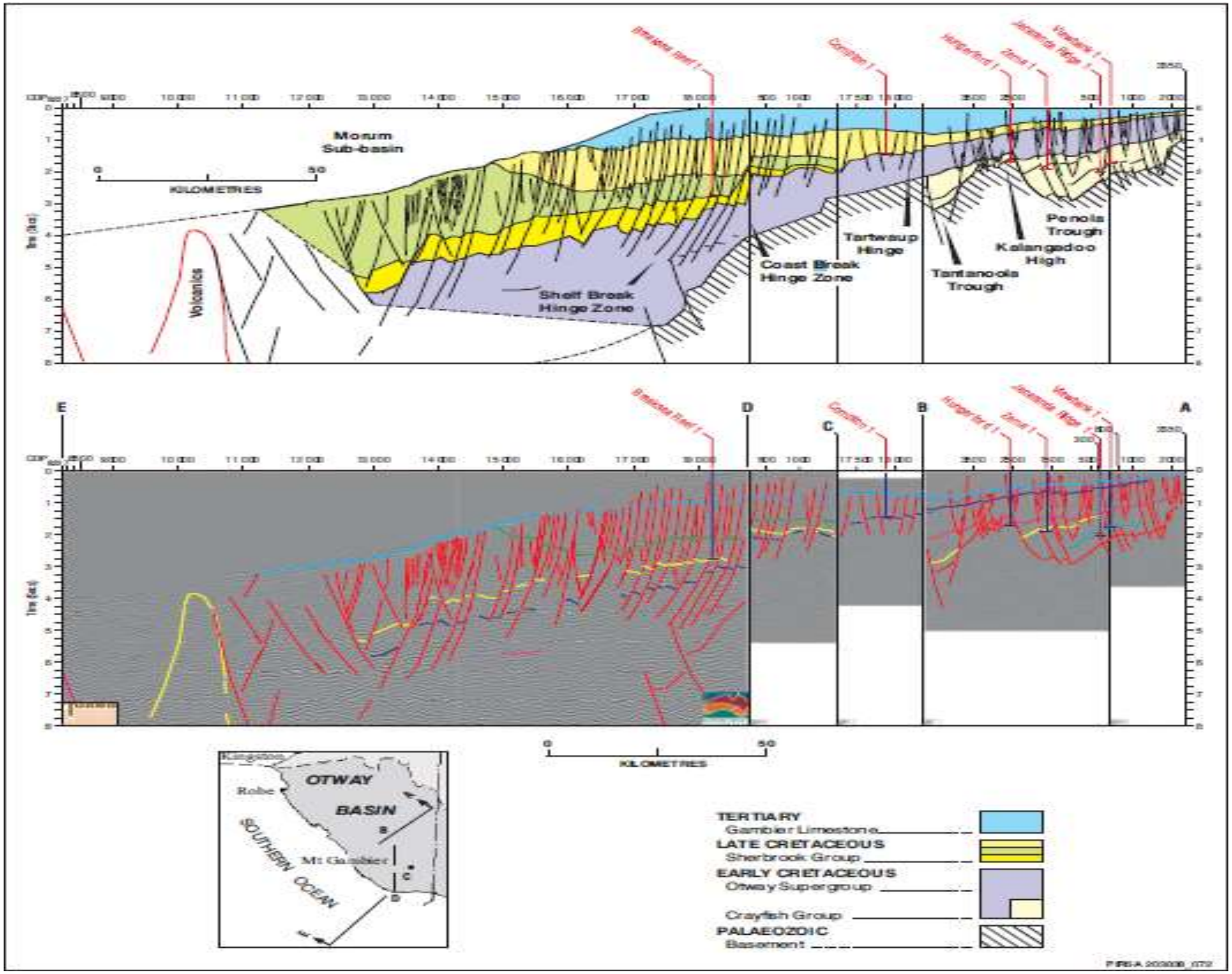


The testing of the model

Noise [%]	Model distance (%)	Rank correlation	„a" coefficient	„b" coefficient	„c" coefficient	„d" coefficient
1	3.67	0.99	11.75	17.81	3.55	-5.45
2	6.86	0.98	3.34	13.31	2.14	3.45
3	9.83	0.98	4.06	5.64	1.75	2.36
4	11.86	0.98	3.88	3.71	1.43	2.45
5	12.09	0.96	2.24	4.52	1.18	3.95

- Changing the level of random noise which is superspposed on data, model distance, rank correlation and variation of coefficients will be examined
- Increment of the noise: 1-5%
- Values of rank correlation are similar

Application on In-situ data

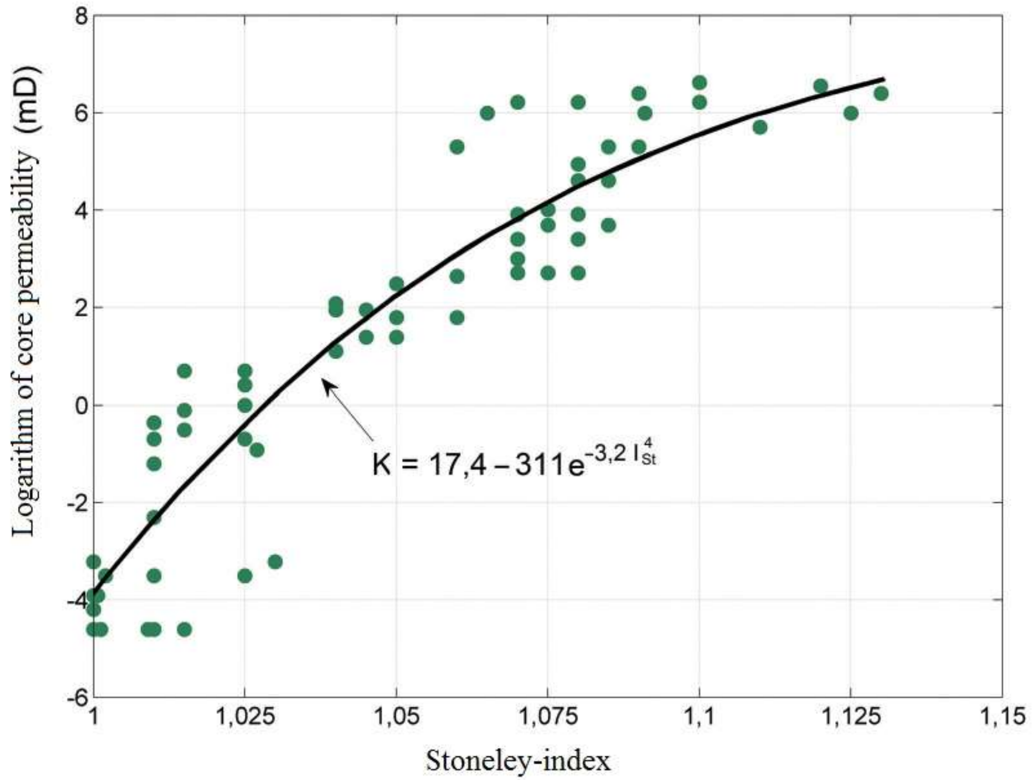


Examination on field data

- The main producer gas rezervoir in the Otway-basin is the Pretty Hill Formation. Its porosity is over 25%, permeabilities in excess of 1000 mD, and has flowed over 451 000 m^3 gas per day on test
- Good relation between Stoneley-index and estimated permeability
- Formula of estimated permeability:

$$\ln(PERM) = 12.8 \cdot (1 - 24.3 e^{-3.2 \cdot I_{St}^4}) - 4.6$$

- I calculated model distance, rank correlation, linear correlation between core data and my calculated data
- On base of rank correlation , close correlation between data can be observed
- Good accordance between estimated permeability and core data



Model distance	Rank correlation	Linear correlation	coefficient „a”	coefficient „b”	coefficient „c”	coefficient „d”
6.96%	0.98	0.78	12.81	24.29	3.248	-4.581

The result of permeability calculation

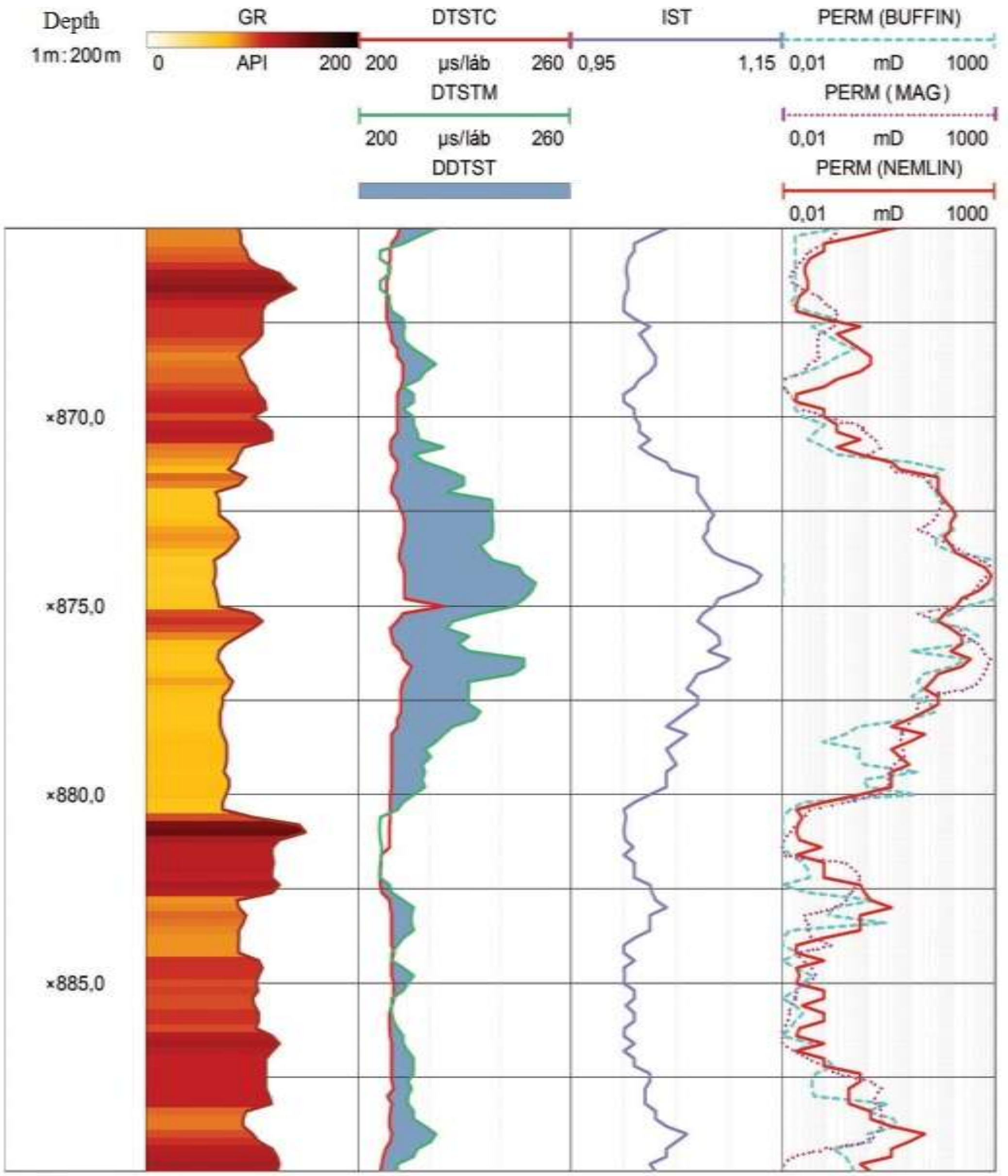
- **Illustration of resulting logs with WellCad software**

- Represented depth interval: 2865-2890m

- **Illustrated logs :**

  - GR –indicates the degree of the shale content, where it has a minimum, there is a big permeability
  - DTSTC-DTSTM- measured and calculated Stoneley
  - DDTST- difference between measured and calculated Stoneley

    (it indicates the permeable zones)
  - IST- Stoneley index
  - PERM(Buffin)- Permeability determined by Buffin
  - PERM(Core)- core permeability data
  - PERM(NEMLIN)- calculated permeability from data determined by me



Summary

In this study, I further developed a method, that can be found in literature. This method is suitable for the estimation of permeability

This method is based on non-linear approximation (better approach than the existing linear or linear by segments models)

The measurement of Stoneley wave slowness ensures the determination of permeability variations

The advantage of this method is, that it provides (independent) interpretational result,which is based on direct method

It can be a quick and effective method for determination of permeability based on logs and the use of independent result can increase the reliability of permeability

Acknowledgement

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- Thanks to dr. Peter Norbert Szabó for his consultancy and for his help

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Thank you for your attention!

Good Luck!