Laboratório para Aplicações da RMN e Petrofísica
Universidade Federal Fluminense

1

NEW SOFTWARE SOLUTION FOR ESTIMATING PERMEABILITY THROUGH NMR-MICP DATA INTEGRATION

"NMR-MICP Integration & Permeability"

P.V. Mesquita, R. B. V. Azeredo, E. H. Rios, A. Souza, B. A. C. Silva, B. M. Faria.

2

Laboratório para Aplicações da RMN e Petrofísica
Universidade Federal Fluminense

OUTLINE

- BACKGROUND THEORY
- SOFTWARE'S MOTIVATION, GOALS AND MAIN FEATURES
- CONCLUSIONS AND CONSIDERATIONS FOR THE FUTURE

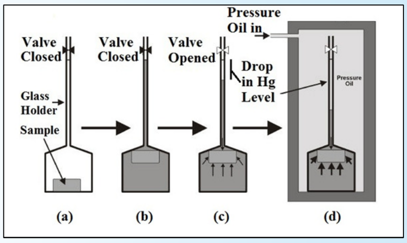
3

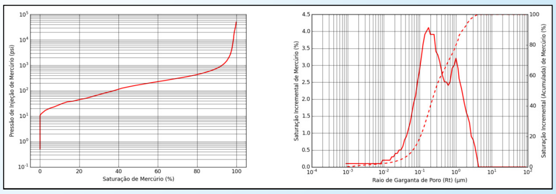
Laboratório para Aplicações da RMN e Petrofísica
Universidade Federal Fluminense

MICP IN FORMATION EVALUATION

www.perminc.com

- Laboratory Experiment to obtain the Cappilary Pressure curve from rock samples, by gradually injecting Mercury.
- The Cappilary Pressure curve can be converted to a "pore throat size" distribution ($R_t = \frac{2\sigma|cos\theta|}{P_c}$).
- Can be used to estimate permeability and several other types of petrophysical data.
- $K_{MICP} = a\phi^b {R_{trep}}^c$
- Can't be used downhole.
- Destroys the sample.





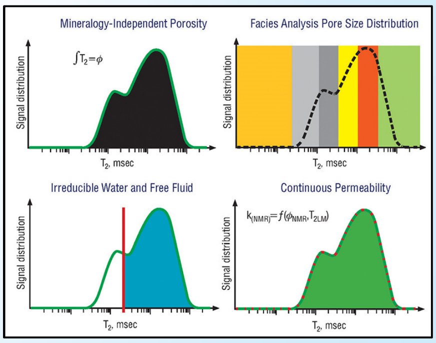
4

Laboratório para Aplicações da RMN e Petrofísica
Universidade Federal Fluminense

NMR IN FORMATION EVALUATION

Provides a single measurement ("T2 distribution"), that can be used to estimate (mineralogy-independent) Porosity (ϕ), pore size distribution (PSD), irreducible water saturation (SWI) and Permeability (k) of formations.

http://accutech.metadot.com/index.pl?r=1



www.spe.org/jpt/article/10327-technology-update-24

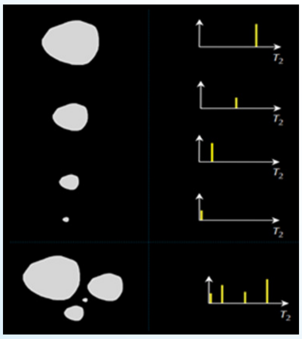
5

SPE International Brazil Section

LAR **Laboratório para Aplicações da RMN e Petrofísica**
Universidade Federal Fluminense

NMR PETROPHYSICS

$$\frac{1}{T_2} \cong \frac{1}{T_{2_{surface}}} = \rho_2 \left(\frac{S}{V}\right)_{pore}$$



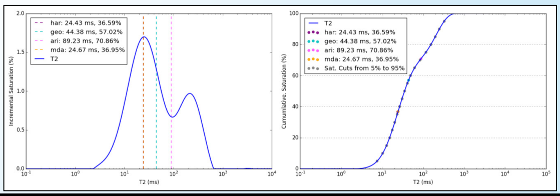
From "*NMR Logging - Principles ans Applications*"

Estimating permeability (k)

$$k = a\phi^b \left(\frac{V}{S}\right)_{pore}^c$$

$$k_{NMR} = a\phi^b (\rho_2 T_{2_{rep}})^c$$

$$k_{SDR} = a'\phi^b (T_{2_{logmean}})^c$$



6

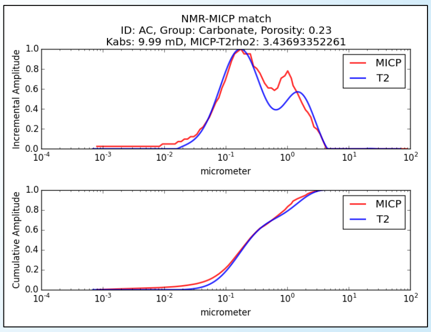
SPE International Brazil Section

LAR **Laboratório para Aplicações da RMN e Petrofísica**
Universidade Federal Fluminense

NMR-MICP INTEGRATION

MARSCHALL, D.et al: ***Method for correlating NMR relaxometry and mercury injection data***. *SCA Conference*, 9511, p. 1-12, 1995.

- Found a simple way to correlate the PTD from MICP with the pseudo-PSD from NMR.
  - $R_t = \gamma \rho_{eff} T_2$
  - $K_{NMR-MICP} = a\phi^b \left(\rho_{eff} T_{2_{rep}}\right)^c$



7

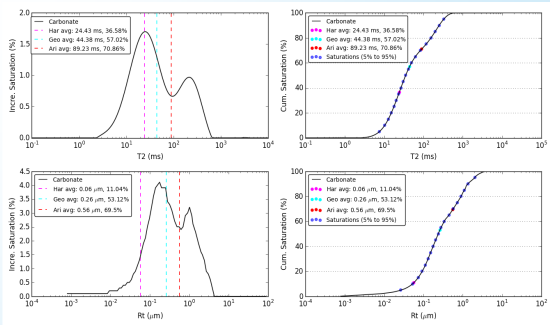
SPE International Brazil Section

Laboratório para Aplicações da RMN e Petrofísica
Universidade Federal Fluminense

NMR-MICP INTEGRATION

RIOS, E.H.; et al. ***NMR permeability estimators under different relaxation time selections: a laboratory study of cretaceous diagenetic chalks***. SPWLA, 55th Annual Logging Symposium, 2014

- Different metrics to obtain the **representative** value from T2 and Rt distributions.
  - $K_{NMR} = \alpha\phi^b {T_{2rep}}^c$
  - $K_{MICP} = \alpha\phi^b {R_{t\,rep}}^c$
- Sized-Scaled estimators – Simple match between MICP (PTD) and NMR (PDS).
  - $s_{Hg\,rep} = \frac{R_{t\,rep}}{T_{2rep}}$
  - $K_{S_{Hg}} = \alpha\phi^b \left(s_{Hg\,rep} T_{2rep}\right)^c$



8

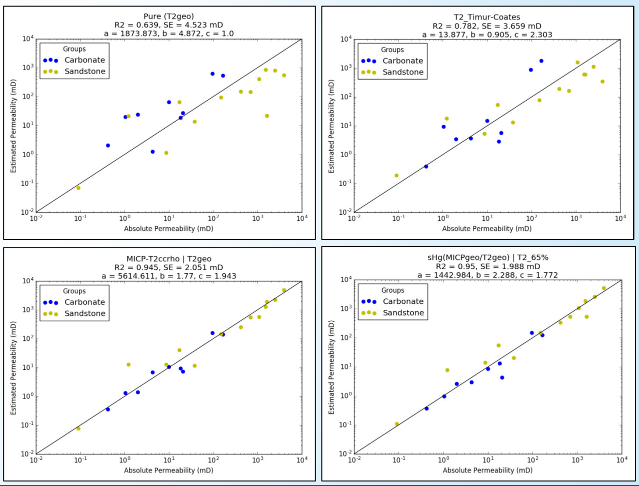
SPE International Brazil Section

Laboratório para Aplicações da RMN e Petrofísica
Universidade Federal Fluminense

PERMEABILITY ESTIMATION IMPROVED

Classical estimations

NMR-MICP estimations



9

SPE International Brazil Section

UFF LAR **Laboratório para Aplicações da RMN e Petrofísica**
Universidade Federal Fluminense

MOTIVATION

Different a,b,c:
- Constant
- Constrained
- Unconstrained

Dataset with "50" samples, each with T2 and Rt distribution with 256 points each

$$k_\phi = a\phi^b$$

$$k = a\phi^b \left(\frac{V}{S}\right)^c_{poro}$$

$$k_{MICP} = a\phi^b (R_{t_{rep}})^c$$

$$k_{RMN} = a\phi^b (\rho_{1,2_{eff}} T_{2_{rep}})^c$$

$$k_{RMN} = a'\phi^b (T_{2_{rep}})^c$$

$$K_{Coates} = (\frac{FFI}{BVI})^a (\frac{\phi}{c})^b$$

$$K_{S_{Hg}} = a\phi^b \left(s_{Hg_{rep}} T_{2_{rep}}\right)^c$$

$$s_{Hg_{rep}} = \frac{R_{t_{rep}}}{T_{2_{rep}}}$$

$$T_{2_{harmonic}} = \frac{\sum_{i=1}^n \phi_i}{\sum_{i=1}^n \phi_i / T_{2_i}} \quad \& \quad R_{t_{harmonic}} = \frac{\sum_{i=1}^n \phi_i}{\sum_{i=1}^n \phi_i / R_{t_i}}$$

$$T_{2_{logmean}} = \frac{\sum_{i=1}^n \phi_i \log10(T_{2_i})}{\sum_{i=1}^n \phi_i} \quad \& \quad R_{t_{logmean}} = \frac{\sum_{i=1}^n \phi_i \log10(R_{t_i})}{\sum_{i=1}^n \phi_i}$$

$$T_{2_{arithmetic}} = \frac{\sum_{i=1}^n \phi_i T_{2_i}}{\sum_{i=1}^n \phi_i} \quad \& \quad R_{t_{arithmetic}} = \frac{\sum_{i=1}^n \phi_i R_{t_i}}{\sum_{i=1}^n \phi_i}$$

$$T_{2_{X\%cutoff}} = PCHIP(T_2, X\%) \quad \& \quad R_{t_{X\%cutoff}} = PCHIP(R_t, X\%)$$

$$\max CC(\rho_2) = \max \sum_i A_{MICP}(r_i) \, . \, A_{RMN}(r_i = 2\rho_{2_{eff}} T_2)$$

$$min\left(\sum_i \left(\log k_{abs_i} - \log a + b \log \phi_i + c \log(param0_i * param1_i)\right)^2\right)$$

$$R^2 = \left[\frac{\sum_{i=1}^N (\log k_{est_i} - \log \bar{k}_{est})(\log k_{abs_i} - \log \bar{k}_{abs})}{\sqrt{\left(\sum_{i=1}^N (\log k_{est_i} - \log \bar{k}_{est})^2\right)\left(\sum_{i=1}^N (\log k_{abs_i} - \log \bar{k}_{abs})^2\right)}}\right]^2 \quad \& \quad RMSEP = antilog \sqrt{\frac{1}{N}\sum_{i=1}^N \left(log\, k_{est_i} - log\, k_{abs_i}\right)^2}$$

10

SPE International Brazil Section

UFF LAR **Laboratório para Aplicações da RMN e Petrofísica**
Universidade Federal Fluminense

NMIP's GOALS

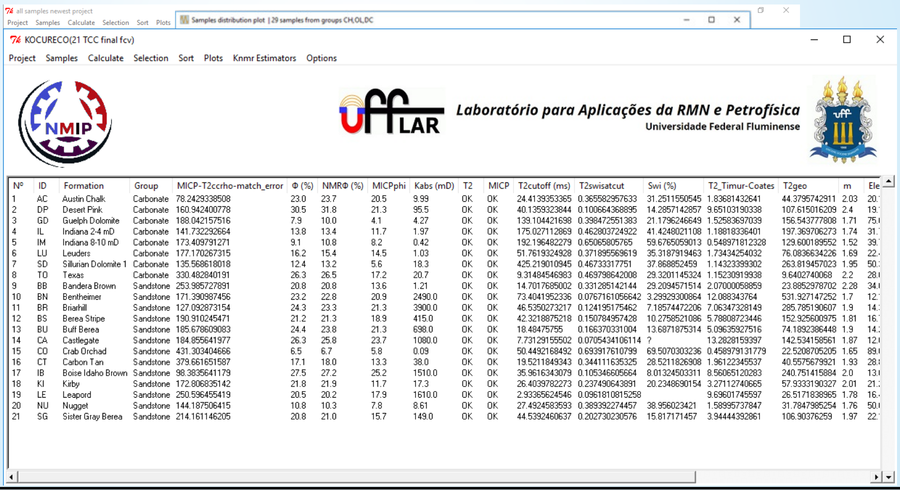
1. Handle big datasets RCA and SCAL data or log.
2. Automate calculations of all required parameters (means, cutoffs and ρ values) from NMR and MICP distributions.
3. Enable fast evaluation of these permeability estimators.
4. Facilitate the interpretation of results and comparison with the others models.

11

SPE International Brazil Section

LAR Laboratório para Aplicações da RMN e Petrofísica
Universidade Federal Fluminense

1 – ROCK SAMPLE MANAGEMENT



Nº	ID	Formation	Group	MICP-T2ccrho-match_error	Φ (%)	NMRΦ (%)	MICPphi	Kabs (mD)	T2	MICP	T2cutoff (ms)	T2swisatcut	Swi (%)	T2_Timur-Coates	T2geo	m	Ele
1	AC	Austin Chalk	Carbonate	78.2429338508	23.0	23.7	20.5	9.99	OK	OK	24.4139353365	0.365582957633	31.2511550545	1.83681432641	44.3795742911	2.03	20.
2	DP	Desert Pink	Carbonate	160.942400778	30.5	31.8	21.3	95.5	OK	OK	40.1359323844	0.100664368895	14.2857142857	9.65103190338	107.615016209	2.4	19.
3	GD	Guelph Dolomite	Carbonate	188.042157516	7.9	10.0	4.1	4.27	OK	OK	139.104421698	0.398472551383	21.1796246649	1.52583697039	156.543777808	1.71	75.
4	IL	Indiana 2-4 mD	Carbonate	141.732292664	13.8	13.4	11.7	1.97	OK	OK	175.027112869	0.462803724922	41.4248021108	1.18818336401	197.369706273	1.74	31.
5	IM	Indiana 8-10 mD	Carbonate	173.409791271	9.1	10.8	8.2	0.42	OK	OK	192.196482279	0.65065805765	59.6765059013	0.548971812328	129.600189552	1.52	39.
6	LU	Leuders	Carbonate	177.170267315	16.2	15.4	14.5	1.03	OK	OK	51.7619324928	0.371895569619	35.3187919463	1.73434254032	76.0836634226	1.69	22.
7	SD	Sillurian Dolomite 1	Carbonate	135.568618018	12.4	13.2	5.6	18.3	OK	OK	425.219010945	0.46733317751	37.868852459	1.14323399302	263.819457023	1.95	50.
8	TO	Texas	Carbonate	330.482840191	26.3	26.5	17.2	20.7	OK	OK	9.31484546983	0.469798642008	29.3201145324	1.15230919938	9.6402740068	2.2	28.
9	BB	Bandera Brown	Sandstone	253.985727891	20.8	20.8	13.6	1.21	OK	OK	14.7017685002	0.331285142144	29.2094571514	2.07000058859	23.8852978702	2.28	34.
10	BN	Bentheimer	Sandstone	171.390987456	23.2	22.8	20.9	2490.0	OK	OK	73.4041952336	0.0767161056642	3.29929300864	12.088343764	531.927147252	1.7	12.
11	BR	Briarhill	Sandstone	127.092873154	24.3	23.3	21.3	3900.0	OK	OK	46.5350273217	0.124195175462	7.18574472206	7.06347328149	285.785190607	1.9	14.
12	BS	Berea Stripe	Sandstone	190.910245471	21.2	21.3	18.9	415.0	OK	OK	42.3218875218	0.150784957428	10.2758521086	5.78808723446	152.925600975	1.81	16.
13	BU	Buff Berea	Sandstone	185.678609083	24.4	23.8	21.3	698.0	OK	OK	18.48475755	0.166370331004	13.6871875314	5.09635927516	74.1892386448	1.9	14.
14	CA	Castlegate	Sandstone	184.855641977	26.3	25.8	23.7	1080.0	OK	OK	7.73129155502	0.0705434106114	?	13.2828159397	142.534158561	1.87	12.
15	CO	Crab Orchad	Sandstone	431.303404666	6.5	6.7	5.8	0.09	OK	OK	50.4492168492	0.693917610799	69.5070303236	0.458979131779	22.5208705205	1.65	89.
16	CT	Carbon Tan	Sandstone	379.661651587	17.1	18.0	13.3	38.0	OK	OK	19.5211849343	0.344111635325	28.5211826908	1.96122345537	40.5575679921	1.93	28.
17	IB	Boise Idaho Brown	Sandstone	98.3835641179	27.5	27.2	25.2	1510.0	OK	OK	35.9616343079	0.105346605664	8.01324503311	8.56065120283	240.751415884	2.0	13.
18	KI	Kirby	Sandstone	172.806835142	21.8	21.9	11.7	17.3	OK	OK	26.4039782273	0.237490643891	20.2348690154	3.27112740665	57.9333190327	2.01	21.
19	LE	Leapord	Sandstone	250.596455419	20.5	20.2	17.9	1610.0	OK	OK	2.93365624546	0.0961810815258		9.69601745597	26.5171838965	1.78	16.
20	NU	Nugget	Sandstone	144.187506415	10.8	10.3	7.8	8.61	OK	OK	27.4924583593	0.389392274457	38.956023421	1.58995737847	31.7847985254	1.76	50.
21	SG	Sister Gray Berea	Sandstone	214.161146205	20.8	21.0	15.7	149.0	OK	OK	44.5392460637	0.202730230576	15.817171457	3.94444392861	106.90376259	1.97	22.

12

SPE International Brazil Section

LAR Laboratório para Aplicações da RMN e Petrofísica
Universidade Federal Fluminense

2 - AUTOMATION

NMIP imports all input data from Excel spreadsheets:

- NMR T2 distributions
- MICP Rt distributions
- Routine Core Analysis (porosity, absolute permeability, etc...)
- Any other petrophysical input.

NMIP automatically tries to calculate:

- All Pythagorian means (harmonic, geometric or "logarithmic", arithmetic).
- Saturations cutoffs from 5% to 95%, with a 5% step
- sHg matches with all possible combinations
- NMR-MICP direct matching (Cross-Correlation)

Create arbitrary cutoffs from NMR or MICP data.

Run Custom Python Scripts.

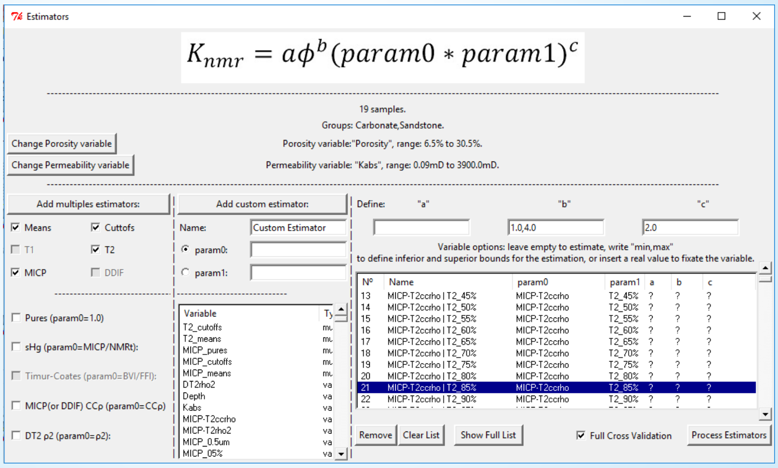
Possibility to edit the NMR-MICP match.

13

SPE International Brazil Section

UFF LAR **Laboratório para Aplicações da RMN e Petrofísica**
Universidade Federal Fluminense

3 – PERMEABILITY ESTIMATION

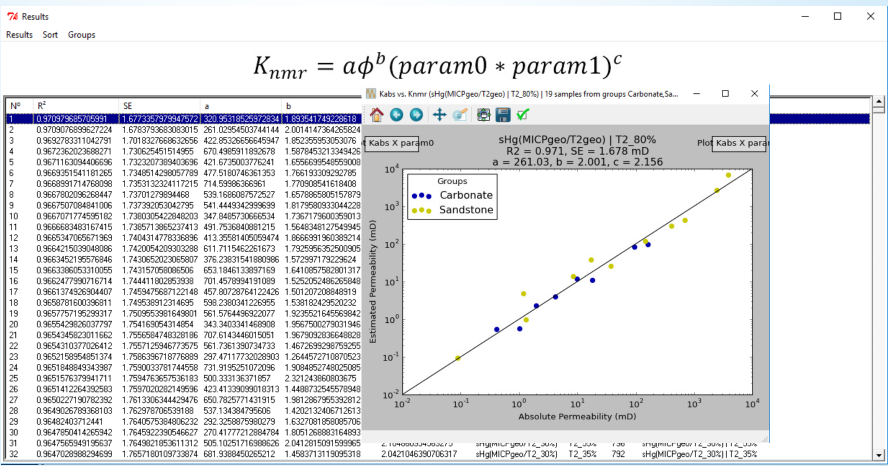


14

SPE International Brazil Section

UFF LAR **Laboratório para Aplicações da RMN e Petrofísica**
Universidade Federal Fluminense

4 - RESULTS



15

SPE International Brazil Section

UFFLAR *Laboratório para Aplicações da RMN e Petrofísica* Universidade Federal Fluminense

CONCLUSION

- Positive feedback from pilot users.
- It never ends!!
- Project is open for ideas and suggestions.
- UFFLAR will register it as a free software.

16

SPE International Brazil Section

UFFLAR *Laboratório para Aplicações da RMN e Petrofísica* Universidade Federal Fluminense

Acknowledgments

- **UFFLAR – UFF**
- **SCHLUMBERGER**
- Sponsored by **Shell**, registered as "Aplicação de técnicas avançadas de Ressonância Magnética Nuclear (RMN) assistidas por ferramentas computacionais na avaliação petrofísica de rochas carbonáticas" (**ANP** 18999-3) under the **ANP** R&D levy as "Compromisso de Investimentos com Pesquisa e Desenvolvimento"

17

Brazil Section

Laboratório para Aplicações da RMN e Petrofísica
Universidade Federal Fluminense

Thank you!

NMIP

Email: pedroviannamesquita@gmail.com