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Use of NMR and other logs for study on Texture Characterization of Clastic Rocks

Rituparna Dutta*, B. S. Reddy

Summary

NMR T2 distribution can be inverted also to a grain size distribution into limited classes. The current study pertains to a novel method of doing so against a backdrop of integrated log-data analysis for mineral volumes, voidage and permeability.

Keywords: *NMR T2 Distribution, Permeability, Characteristics Length Scale, Surface-To-Volume Ratio, Pore Size Distribution, Pore Size Classes, Grain Size Classes*

Introduction

NMR data has proven to be a useful tool to understanding pore size distributions amongst other attributes of a rock such as Permeability, Capillary Pressure and so on. With cross-disciplinary studies unlocking hidden relationships between pore size and grain size of a rock which essentially has primary porosity, avenues have opened up for understanding grain size distributions and hence textural attributes of rocks. Clastic rocks are eminently suited for formulation and application of work-flows based on simple models for eliciting textural attributes through inversion of NMR and other log data.

In a natural process of deposition, grains are differentiated into overlapping classes (gradation). So, in reality there exist spatial regimes in a rock which has specific effective grain sizes around which the sizes of grains occurring within these regimes are distributed. A less gradational distribution however has been assumed in the present work as a representation of actual distribution, for simplicity and ease of inversion, without losing the essence of the textural variation encrypted in the actual grain size distribution. The concept of, grains in different size windows occurring within specific spatial regions of rock fabric is central to this work. This allows for a subdivision of total grain size distribution mass (into sets of grain size bins) to be conceptually mappable to a subdivision of rock fabric into regions with a grain belonging to any particular grain size class, having as its nearest neighbors, grains belonging to same class, except for grains which are near boundaries (in spatial sense), between different classes. Thus in this model pores of a particular size class would be surrounded by grains of a particular size class.

It is also assumed that the type of packing is similar for different grain size classes, for un-complicated systematics of pore class population to granulometry mapping (average number of grains neighboring a pore is independent of pore size). The work-flow demonstrates realistic effective grain size computation through inversion of NMR T2 distributions to effective grain size and then extending the techniques to an analysis of the rock as a composite of different grain size classes. The refinements required and the conceptualization and assumptions involved in this part of the computation, that leads to meaningful grain size classification which corresponds to Wentworth Classes already touched upon in the foregoing are further discussed and demonstrated with actual data.

Actual results from Master Logs validate these concepts which are the essential underpinning of the work-flows. The methodology adopted would be best suited for continental riverine, deltaic inter-tidal reworked and redeposited sediments, estuarine depositions, turbidite depositions and some types of shelf slope depositions and so on. (The current study is on a sequence which is part of an estuarine to tidal reworked mouth-bar deposition system).

The work-flows define a new way of achieving the defined goals within the ambit of the conceptual underpinning

A-515, WOB, ONGC Mumbai
dutta_rituparna@ongc.co.in

discussed above, when a rich data-set and desirably actual permeability measurements against rocks are available. The scope of further study would be an inversion assuming distributions of grain size for different grain size classes and a probabilistic analysis of a grain of a particular grain size arising as a part of deposition of detritus belonging to a particular grain size class.

Theory

The following assumptions are made at the outset; a) Nonwetting phase saturation in the zone of investigation of NMR is zero or low so that Transverse Relaxation spectrum does not differ from 100% water saturation case. b) Transverse Relaxation is dominated by Surface (Lattice) Relaxation c) Inter Echo-spacing is small enough for diffusion effects and inter-pore coupling effects are negligible. Under the above circumstances the ***characteristic length scale,*** denoted as **Λ**, relevant to NMR Transverse Relaxation experiments would be the pore dimension representative of the porosity distribution.The T2 log mean T_{2LM} of a T2 relaxation time spectrum would be related to the effective pore radius, r_{eff} as $r_{eff} = \alpha\rho T_{2LM}$where α is a pore shape factor, defined as (α/pore dimension) = specific area of pore, ρ is the NMR Surface Relaxivity of the grain in units of m/sec. The characteristic length scale relevant to models of rock conductivity based on models of assemblages of spherical or near spherical insulating grains coated with a negative charge and immersed in an electrolyte, would be 2/(S/V) where the denominator represents the “surface to volume ratio” measure of interconnected pore space.

Modeling Λ from NMR and Permeability

Λ can be modeled from NMR as

$$\Lambda = (\alpha\rho T_{2LM})/\lambda \qquad \text{……… (1)}$$

(Where λ stands for pore size to throat size ratio; giving Λ in meters when ρ is specified in units of m/sec and T_{2LM} is specified in sec). The generic equation for the RGPZ permeability predictor based on Λ is

$$K = \frac{1}{aF} * \Lambda^2 \qquad \text{……… (2)}$$

Which Relates permeability to characteristic length scale parameter Λ. Parameter ‘**a**’ characterizes the topology of the pore space and has a value near 8/3 for threedimensional arrangements of quasi spherical grains and F is the limiting formation factor.

Computation of effective grain size Integrating Effective Medium Theories and NMR

It was derived by Glover et al.(2006), from comparing the solution of the Bruggeman-Hanai-Sen’sSelf-similarity equation in the high salinity limit to the Effective Medium Theory given by Johnson Koplik and Schwartz (1986) that,

$$\Lambda = R/[m*(1-F)] \approx R/(m*F) = d/(2*m*F)$$

When F >> 1, which is also normally the case,

Relating effective grain radius R to Λ, m, F as

$$R = \Lambda *m*F$$

And effective grain size d, to R to Λ, m, F as

$$d = 2*(\Lambda *m*F) \qquad \text{……….. (3)}$$

Substituting for Λ from the Eq.2 it is seen that effective grain diameter d is given by

$$d = 2*((\alpha\rho T_{2LM})/\lambda)*(mF) \qquad \text{………… (4)}$$

*The value of '**α**'*

For spherical pores the pore shape α is equal to 3.0, while for cylindrical pores it is equal to 2.0. The critical porosity for clastic reservoir rock is of the order of 0.4 and the pore aspect ratio around 0.25. Modeling pore shapes as prolate spheroids with the above aspect ratio, the value of α comes to around 2.4. When grains are angular and / or when grain surfaces are rugose, value of α can be more than 3.0

*The value of '**λ**'*

The Kozeny-Carman Estimator of permeability can be considered as

$$k = \left(\frac{\varepsilon}{F}\right)* (r_{eff})^2*(1/ \alpha^2 \qquad \text{…………(5)}$$

comparing with the Eq.2 which is the base for RGPZ permeability equation, it is seen that

$$[(r_{eff})^2]/ [(\Lambda)^2] = [\alpha^2/(a*\varepsilon)] \qquad \text{…………(6)}$$

Since effective pore throat radius is a good estimator of Λ

$$(r_{eff})/ (\Lambda) = [\alpha^2/ (a\ \varepsilon)]^{1/2} = \lambda \qquad \text{…………(7)}$$

Theoretically (α^2 / 8) would represent value of ‘ε’. For the case of grains which are spherical / quasi spherical in shape, value of ‘a’ applicable is (8/3). The computed value of λ then comes to 1.732 (i.e. $\sqrt{3}$).

Making the substitutions makes it possible to compute effective grain size through modeling characteristic length scale using NMR data.

Computation of effective grain size Integrating the Electro-Kinetic Perspective of Fluid transport through porous medium which has electrically active grain surfaces with Effective Medium Theories and NMR

Following Li et al (Li et al 1995), we note that effective pore radius ‘reff’ is related to effective streaming potential coupling coefficient Cs and electro-osmosotic coupling coefficient Ce as below

$$(r_{eff}^2) = 8*\eta*\sigma_f*(Cs/Ce)$$

Where η is viscosity and σ is conductivity of the pore fluid. Again following Li et al (Li et al 1995), permeability and the ratio (Cs/Ce) are related as

$K = \eta*\sigma_f*(Cs/Ce)*(1/F)$ leading to the equation

$$(Cs/Ce) = k/[\eta*\sigma_f*(1/F)]$$

Which in turn leads to the relation

$$(r_{eff}^2) = [(8*K)/(1/F)]$$

$$K = (1/F)*(r_{eff}^2)/8 \qquad \text{………} (8)$$

Integration of electro-kinetics of the transport of en electrolyte through a porous medium with electrically active grain surfaces, with theories which model permeability in terms of grain size, and porosity, and the topology of interconnected pore space, yields relationships between grain size, porosity and Archie cementation exponent **m** (Glover et al).

The RGPZ equation already discussed, models the fluid permeability of a porous rock in terms of characteristic length scale parameter of connected porosity, volume of the connected porosity per unit rock volume, and the limiting formation factor starting from a base equation (2) we had

$$\Lambda = d/(2*m*F)$$

Hence from eq. (2) we get

$$K = (1/a)*(1/F)*[d/(2*m*F)]^2 \qquad \text{…………} (9)$$

Comparison of the above two equations for k leads to the relation

$$(d/r_{eff}) = [(am^2F^2/2)]^{0.5} \qquad \text{……….} (10)$$

NMR is used to model r_{eff} as

$$reff = \alpha\rho T2LM \qquad \text{……….. } (11)$$

Upon substitution for r_{eff}, modeled from NMR as above, into the L.H.S of the equation (10) and rearranging, we get the relation

$$d= (\alpha\rho T2LM)*[(am2\ F2/2)]0.5 \qquad \text{………..}(12)$$

Computation of Effective Grain Size from Permeability

When a well calibrated permeability curve is available, calibrated with formation tester based permeability station readings, where the source data for permeability can be from NMR permeability data, or can be from mineral volumes data obtained from petro physical processing of logs it is possible to invert permeability to effective grain size using **RGPZ equation for permeability**

The RGPZ Permeability predictor can be written as

$$k = (d^2\varphi^{3m})/(4am^2)$$

Where the relation $F = 1/\varphi^m$ has been used.

The value of the parameter a can be modeled as 8/3 if it is reasonable to assume that grains are spherical or quasi-spherical in shape from SEM photographs if available or from local knowledge. Else a suitable estimate can be made for this parameter and used.For reservoir sands generally m is set to a value of 1.8 or a different value based on local knowledge or laboratory data. For value of 1.8 for '**m**' and value 8/3 for '**a**' the effective grain size is given by

$$d = \{(k*100)/[(2.893)*(\varphi^{5.4})*(d^2)]\}^{0.5}$$

Methodology

Against this background, the current work seeks to extend the analysis of rock as a whole to individual sub-classes in a textural sense, of the rock. To this end we conceive an emulation wherein different pore classes and grain classes are segregated in spatial regions sharing only surfaces which separate them. In this case the pore size distribution from T2 distribution can be uniquely mapped to grain size distribution. The chosen mapping has been the eq. (12) d= (αρT2LM)* [(am2 F2 /2)]0.5

All the parameters have been discussed above. The important parameter of F the formation factor needs internal porosity of different 'spatial regions' mentioned above.

It has been assumed that the grains make-up of the different spatial regions barring those that have a dominance of clay size grains occurring, have a spherical to quasi spherical shape which can give rise to nearly spherical to spheroidal pore shapes. In that case it is reasonable to consider that the internal porosity of individual geographic regions would be independent of the effective grain size which characterizes the grain assemblage in the region. On the other hand, by virtue of the high clay bound water porosity as well as micro porosity characterizing the clay sized grains' assemblages, the internal porosity of around 0.5 can be a reasonable estimate.

As for the non-clay assemblages from the aspect ratio of around 0.2 for the grains as an upper limit the expected internal porosity comes to around 33% which has been assumed. This aspect ratio was arrived at from evaluation of Krief's exponent in reservoir deep water sands from which the aspect ratio had been worked back(This exponent works out in the range 2.5-3.0). There is also support from actual data from logs where it has been an observation from deep water clastic sediments that the porosity values of high energy sandstones are around 33%.

The T2 distribution of NMR is fundamentally a collection of different S/V bins which get converted to pore size bins through eq. (11) i.e., $\mathbf{r_{eff} = \alpha\rho T_{2LM}}$

Here the T2 log mean would stand for that of any particular bin and the T2 left and right margins of T2 bin would convert to the pore size window margins for the pore size window connected with any particular bin. The pore size bins are then grouped into pore size classes whose left (or lower) and right (or upper) range classes are now defined.

Through the mapping mentioned in the foregoing the pore size classes get converted to grain size classes. The grouping has been so made that the grain size classes have bounds which match approximately with the WentworthUdden classification, which enables us to attach textural attributes (or labels) to the grain classes so formed.

We now describe the computation of the fractional representation of the classes in the totality of the grains assemblage to arrive at an understanding of the volumetric representation of the different textures in the total solids regime of the rock.

As per Wentworth Grain Size Classification:
<4 µm = Clay
<62.5 µm= Silt
<125.0 µm= Very Fine Sand
<250µm= Fine Sand
<500µm= Medium Sand
< 1000 µm= Coarse Sand
<2000µm= Very Coarse Sand

T2 bins CBP1, CBP2, CBP3 are considered to represent S/V of pores bounded by prolate spheroidal grains (i.e. high aspect ratio spheroids). The αis assumed to be 1.4 for this case, whereas, for the case of bin CBP4, αof 2.4 is assumed. For the case of CBP5, CBP6 and CBP7 pores are assumed to copy cylindrical beads with very small length constrictions separating them. Hence α assumed to be 2.0. Internal porosities of regions dominated by pores falling in the classes CBP1, CBP2, CBP3 is assumed to be 0.50 while for the regions dominated by rest of the classes, Internal Porosity is taken in accordance with the PIGN-T2LM cross-plot values as illustrated in Figure 2 and Figure 3 in **Example** section.

Uniform cementation exponent of 1.8 has been assumed. Quasi-spherical pores, (and hence value of 'a'=8/3)used for the case of CBP classes CBP4 and beyond.

The logic that, the ratio (number of grains)/(number of pores) is a function of packing, and that local variation in packing type, in the rock is absent, which ensures the validity of (no. of grains)/(no. of pores) being constant has been assumed. This simplification entails a certain uniformity of grain shapes and asperity which has been adhered in our work flow.

Effective grain dimension for grains making for pores in the class CBP3 is 4.106µm and CBP2 is 1.06µm. CBP3 has been interpreted to be the product of compaction of fine silt-clay size grains and CBP2, CBP1 are interpreted to be product of clay-sized grains compaction. CBP4, CBP5, CBP6, CBP7 relate grains representing silt, very fine sand, fine to medium sand and medium-coarse grained sand respectively. Inspection of the aforementioned bin porosities versus Lithology supports the same.

In light of the forgoing logic, if we consider Grain supported rock and if say that CBP4, CBP5 and CBP6 are well represented, for instance, then

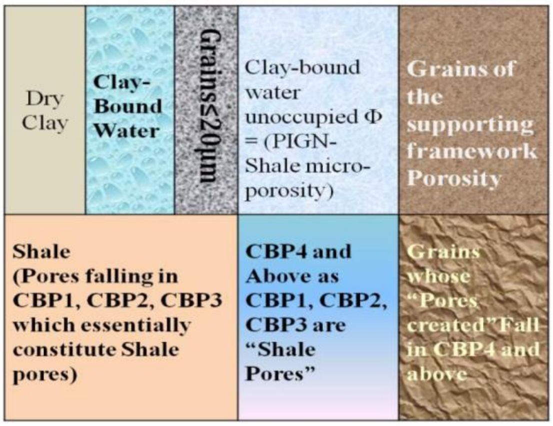
$$\frac{nPi}{\sum_{i=a}^{b} nPi} = \frac{nGi}{\sum_{i=a}^{b} nGi} \qquad \ldots\ldots\ldots\ldots..\ (13)$$

Where, nPi=no. of Pores in CBPi and nGi= no. of Grains making for those pores and hence this is the basis of the grain classes classification in the present workflow.

Bin Classes	T2 ms	T2 lm	Phi. internal	reff µ	F. Internal	RAT=(d/reff)	Grn. Dia (µm)
CBP1	0.3-1.0	0.54	0.5	0.027	3.48	7.237621	0.106
CBP2	1.0-3.0	1.73	0.5	0.084	3.48	7.237621	0.354
CBP3	3.0-10.0	5.48	0.5	0.269	3.48	7.237621	1.064
CBP4	10.0-30.0	17.32	0.28	1.417	9.88	20.55216	21.58
CBP5	30.0-100.0	54.80	0.30	4.022	8.73	18.15196	38.12
CBP6	100.0-300.0	173.20	0.33	12.125	7.36	15.29033	107.03
CBP7	300.0-1000	547.70	0.33	38.340	7.36	15.29033	321.1

The rock model

In this model the volume of grains in the supporting Framework, denoted by Vsup.grain is given by Vsup.grain= (1-Vsh-PIGN)



Since shale micro-porosity is not clay-bound-water porosity, but is still believed to fall in 0.3-3ms range, CMR_3ms should strictly be (PIGN-Shale Micro Porosity). But in reality when CMR data quality is good CMR_3ms matches very well with PIGN when fluid effects are absent. This indicates that shale micro-porosity is under called by
CMR.

For CBP3, range of Reff =0,147-1.05 microns and is same as micro-pores assigned to shale, exclusively
Total grain supported porosity = $\sum_{i\geq4} CBPi$
Equivalent grain size for this is $\sqrt[3]{\sum_{i\geq4} CBPidi}$ where di stands for grain size of i-th CBP class.

If nGi = no. of grains/unit volume of rock for CBPi, volumetric fraction of cumulative volume of nGi grains vs. total grains volume $\sum_{i\geq4} nGi$ for i≥4

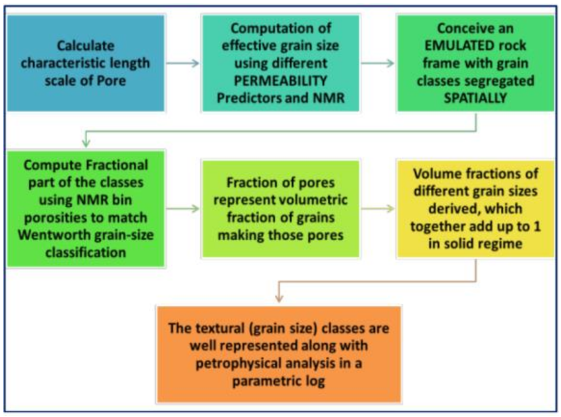
$$\text{Vgi} = \left(nGi.\frac{di3}{8} * \frac{4\pi}{3}\right) / \left(\sum_{i\geq4} nGi * \frac{di3}{8} * \frac{4\pi}{3}\right)$$

$$\equiv \left(\frac{nGi}{\sum_{i\geq4} nGi}\right).\frac{di3}{d3} = \left(\frac{nPi}{\sum_{i\geq4} nPi}\right).\frac{di3}{d3}$$

The R.H.S. part of this equation had been already evaluated and if we assume that shale fraction is not too high in the reservoir section of our interest, the R.H.S. part for *i=3,4,5…* is equivalent to the same for *i=4,5…*

Then the volume fraction **Vgi** $= \frac{nGi}{\sum_{i\geq4} nGi}.\frac{di3}{d3}$ on the L.H.S of the above-mentioned equation is known and they add up to 1.0 while {1-(PIGN-CBP3)-Vshale} can be divided up in the above ratios, to get the volumetric fraction of grains and particular size in the grain-supported framework make-up.

The essence of the complete workflow is imbibed in the flowchart below:



Example

The presentation below captures the multi-mineral model analysis using log data of a clastic sequence, with resistivity and porosity log-curves in track 1 and track 2, Formation Fluid volume, Density-CMR derived gascorrected porosity DMRP, Total Porosity (PHIT) and intergranular porosity PIGN curves in track 3, Multi-mineral volumetrics at track4, Grain concentrations w.r.t. total grain population on trcak5, NMR-derived and formation-testing derived Permeability'sat track 6 and finally grain classes at track 7 have been plotted.

Permeability, computed from NMR, as both KTIM and KSDR, with the gas corrected total porosity used as the inter-granular porosity in the Timur-Coates and SDR computation of permeability. The permeability computed from MDT draw down mobility as discrete data plotted as K_Gas on track 7, establishes that the permeability computed from NMR, using the gas corrected total porosity DMRP is a robust permeability. This permeability estimator has been used in the work-flows employed in the current work.

The last track brings up the results of volumetric fractions of different grain classes with respect to the total grain volume. The naming of the classes corresponds to the Wentwoth-Udden scheme. Different classes have been denoted by different back ground coloration and fill which suggest the normally understood representation of the sedimentary grain classes.

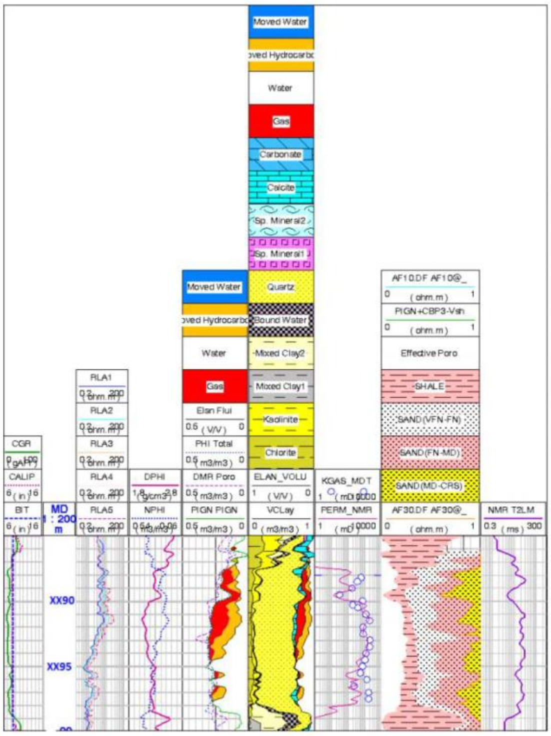


Figure 1: Results of Minerological Textural and Petrophysical analysis of an interval of the well section studied

Cross-plots PIGN-T2LM - A discussion towards choosing Internal Porosity:

In fig.1, when the CBP1+CBP2+CBP3<0.1, porosity PIGN is 0.3-0.33. The internal porosity of the bins CBP4, CBP5, CBP6 can be therefore assumed to be in the range 0.3-0.32. T2LM is around 100ms. This indicates that CBP5 and CBP6 are active contributors to porosity.

In fig.3, another reservoir interval of the same well, the upper sandstone section having T2LM value 15-30ms and PIGN is 0.20-0.25. The T2LM indicates CBP4 is active contributor. While in lower section, T2LM is around 20ms and PIGN is 0.26-0.28. The T2LM indicates that CBP4 is active.

From the foregoing, we could ascribe Internal porosity of 0.26-0.28 for CBP4 and 0.3-0.33 to CBP5 and CBP6.

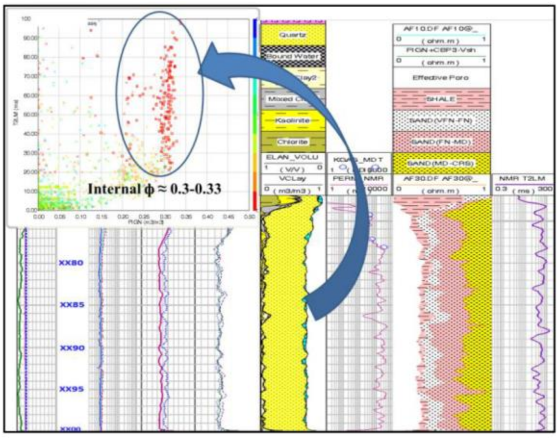


Figure 2: PIGN-T2LM plot of a clastic section with internal porosity ~0.3-0.33pu

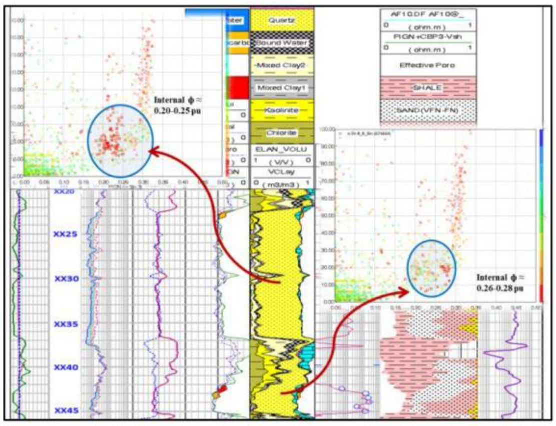


Figure 3: PIGN-T2LM plot of two clastic sections with internal porosity ~0.2-0.25pu and 0.26-0.28pu respectively

Conclusions

- Inversion of log data including NMR data to quantitative grain size classification demonstrated.
- Results in agreement with Master logs generated on the basis of on-site analysis of drill cuttings.
- Petro-physical analysis fully validated by NMR results.
- Robust permeability estimator generated using geochemical permeability and NMR based permeability data amply validated by Formation tester data derived permeability.
- The textural classification demonstrated adds immense value to the mineralogical characterization of rock fabric and pore space characterization.
- Useful input for lithological definition and characterization of sedimentary depositional sequences.
- Valuable input,(hitherto unavailable), of grain size distribution, critical for sand control engineering design for successful well testing of clastic sequences.
- Valuable input for modeling mechanical properties of sedimentary rock and understanding the interrelationship between mechanical properties and texture.
- Textural characterization and thereby evolution of texture in a sequence of deposition, important input for decoding environmental conditions of deposition.

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