PS Capturing Porestructures with Digital Image Analysis for a Quantitative Correlation to Physical Properties*

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Abstract

Porous carbonates typically contain a wide range of pore sizes and shapes that are difficult to capture with existing pore type classifications. These classifications are insufficient to relate complex pore structures to physical properties. The analysis of pores on digital photomicrographs is an objective, repeatable, and quantitative methodology that analyzes the size distribution and describes the shape of the pore system. Pore shape parameters derived using digital image analysis (DIA) capture complicated pore structure and help explain the variability of physical parameters such as acoustic velocity, electrical resistivity (formation factor), and permeability.

The pore size distribution is captured using the parameter Dominant Pore size (DOMsize), a quantitative measure taken from the cumulative size distribution. The complexity of the pore system is measured by the perimeter over area (PoA). PoA (the 2 dimensional equivalent to the specific surface) captures of the overall intricacy of the pore system. Both parameters show high correlation to variations in physical properties.

For example, it has been shown that at a given porosity, samples with simple large pores have higher velocity than samples with an intricate pore network dominated by small pores. This trend is reflected in DIA parameters.

Variations in the formation factor are also related to the pore size and shape. This can be documented in plots of porosity vs. formation factor with DIA parameters superimposed. Samples with a low value of PoA and high DOMsize have relatively high formation factor values, whereas samples with high values of PoA and low DOMsize have low formation factor values. This indicates that for a given porosity samples with simple large pores have higher resistivity than samples with an intricate pore network dominated by small pores.

Theoretically, both pore size and specific surface influence permeability. Samples with low permeability at a given porosity have high values of PoA and low values of DOMSize and vice versa. A caveat, however, are moldic rocks which can have high DOMsize with low permeability due to poor connectivity of the large pores.

Both pore size and pore system intricacy as defined by digital image analysis are highly correlated to acoustic velocity, permeability, and electrical resistivity. A combination of these pore shape parameters with porosity is capable of substantially improving inverting pore structure from down hole logging data.

Capturing Porestructures with Digital Image Analysis for a Quantitative Correlation to Physical Properties

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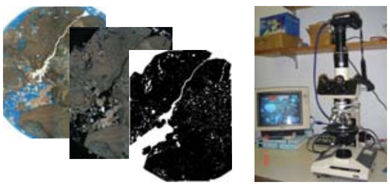
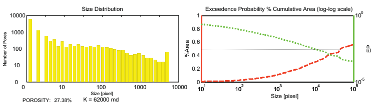
Approach: Integrating elastic, electrical, and geometric measurements to increase the predictability of petrophysical properties

Geometric Attributes





Roundness, PoA, DOMsize, ...

Core Plug

Physical Properties

Velocity, Resistivity, Porosity, Permeability ...

Key Points:

- ➢ Digital Image analysis (DIA) can be used as an objective tool to capture and describe Pore Network Geometry in a repeatable, quantitative way.
- ➢ The DIA parameters Perimeter over Area (POA) and Dominant Size (DOMSize) show excellent correlations to, acoustic velocity, electrical resistivity, and permeability.
- ➢ Integration of these relationships can improve estimation of either physical or pore shape parameters from logging data.

Abstract:

Porous carbonates typically contain a wide range of pore sizes and shapes that are difficult to capture with existing pore type classifications. These classifications are insufficient to relate complex pore structures to physical properties. The analysis of pores on digital photomicrographs is an objective, repeatable, and quantitative methodology that analyzes the size distribution and describes the shape of the pore system. Pore shape parameters derived using digital image analysis (DIA) capture complicated pore structure and help explain the variability of physical parameters such as acoustic velocity, electrical resistivity (formation factor), and permeability.

The pore size distribution is captured using the parameter Dominant Pore size (DOMsize), a quantitative measure taken from the cumulative size distribution. The complexity of the pore system is measured by the perimeter over area (PoA). PoA (the 2 dimensional equivalent to the specific surface) captures of the overall intricacy of the pore system. Both parameters show high correlation to variations in physical properties.

For example, it has been shown that at a given porosity, samples with simple large pores have higher velocity than samples with an intricate pore network dominated by small pores. This trend is reflected in digital image analysis parameters. Low values of PoA and high values of DOMsize occur in samples with relatively high velocities for their given porosity while high values of POA and low values of DOMsize are observed for low velocity samples.

Variations in the formation factor are also related to the pore size and shape. This can be documented in plots of porosity vs formation factor with DIA parameters superimposed. Samples with a low value of PoA and high DOMsize have relatively high formation factor values, whereas samples with high values of PoA and low DOMsize have low formation factor values. This indicates that for a given porosity samples with simple large pores have higher resistivity than samples with an intricate pore network dominated by small pores.

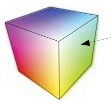
Theoretically, both pore size and specific surface influence permeability. Samples with low permeability at a given porosity have high values of PoA and low values of DOMSize and vice versa. A caveat, however, are typical moldic rocks which can have high DOMsize values but a retarded permeability due to poor connectivity of the large pores.

Both, pore size and pore system intricacy as defined by digital image analysis are highly correlated to acoustic velocity, permeability, and electrical resistivity. A combination of these pore shape parameters with porosity is capable of substantially improving inverting pore structure from down hole logging data.

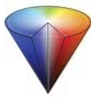
Cross Polarized Light for Accurate Image Segmentation

Images are acquired at 5 mm/pixel resolution and full thin section photomicrographs are constructed from plain-polarized light and XPL at different angles. An XPL variation attribute is calculated and used as additional information during image segmentation to distinguish air bubbles in pore spaces not filled with dyed resin.

RGB vs. HSV: the pros and cons of colorspaces

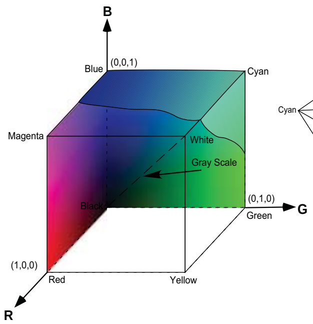


In RGB space, no single band contains a narrow range capable of delineating individual colors (e.g. blue)

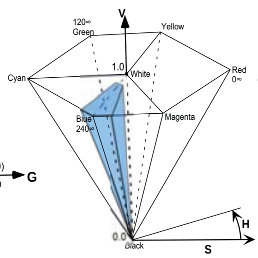


In HSV space, narrow ranges within the hue band are capable of delineating individual colors (e.g. blue)

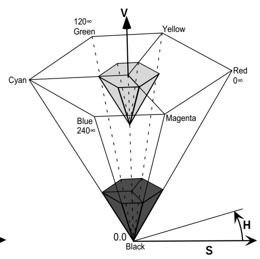
H = Hue : A unit that specifies the "colour" of the colour
S = Saturation : Specifies how much black, white or gray is mixed with the colour.
V = Value : Corresponds to Brightness.



Example of blue color spread over wide range on all three RGB bands.



Comparable blue color is concentrated on narrow range in the hue band in HSV space.



Remaining ambiguity in the wight and black range can be resolved through XPL

Porespace Segmentation using XPL variation

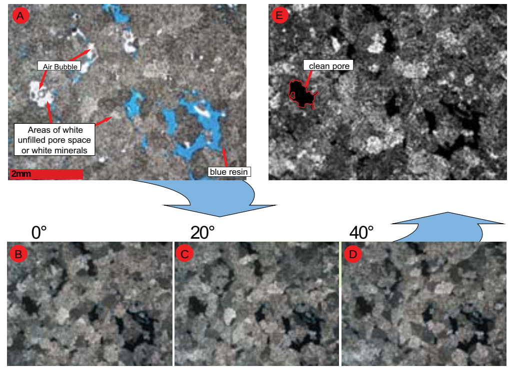
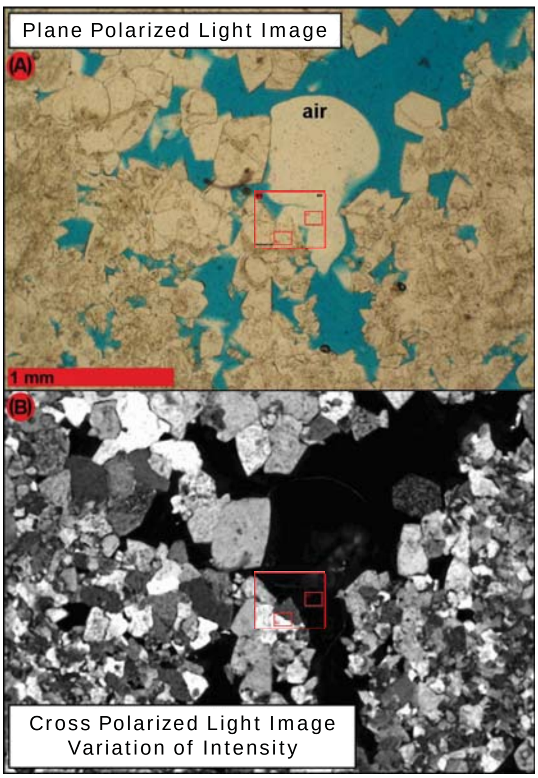
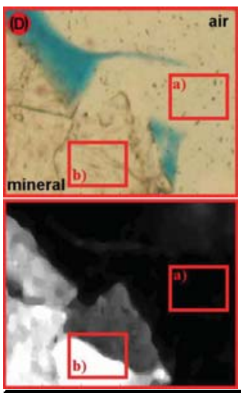


Illustration of the process of determining XPL variation from digital images.
Image (A) was acquired using plain polarized light. Images (B)-(D) were acquired under cross-polarized light (XPL) at different angles (0°-40°). The XPL variation attribute is calculated as the mean absolute variation in light intensity between images (B)-(D). On the resulting XPL variation gray scale image (E), the pore space are predominantly black.

An XPL Image Segmentation Example





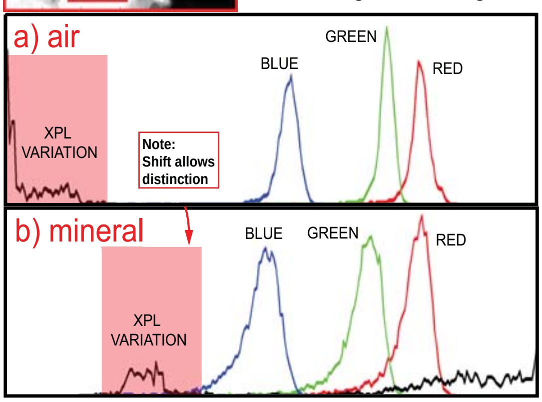
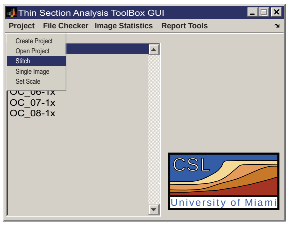
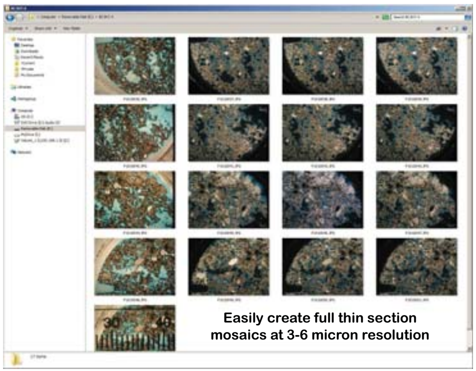


Image (A), acquired using plain polarized light, shows a thin section that is impregnated with blue epoxy resin. Minerals and grains are beige, whereas pore space is blue except for air bubbles that are identical in color to the minerals. The intensity image of XPL variation (B) covers the same area. Histograms of color and XPL distribution from subsections a) and b) illustrate that the RGB color bands of the subsection are almost identical, but the XPL variation of intensity is clearly different in regions of minerals and air.

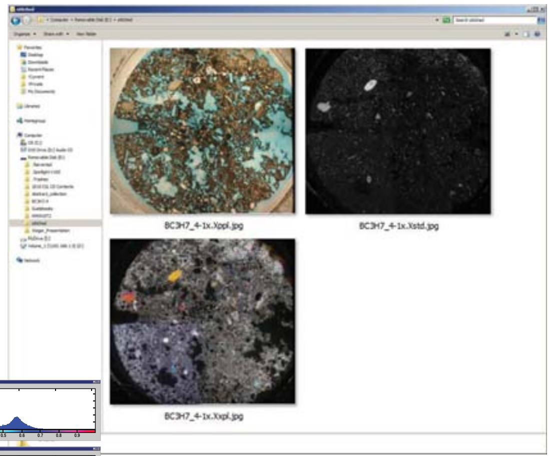
Digital Image Analysis Tool “Erika”

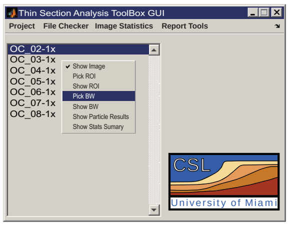
“Erika” is an easy to use tool that provides semi automated batch capability for mosaic creation, image segmentiation, particle analysis and reporting.



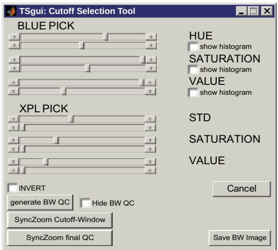


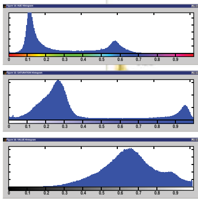
Easily create full thin section mosaics at 3-6 micron resolution

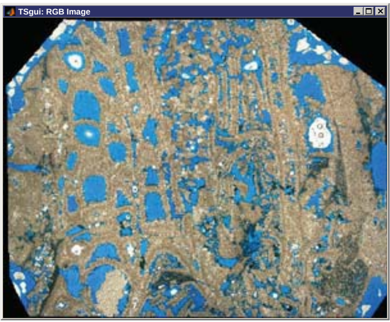


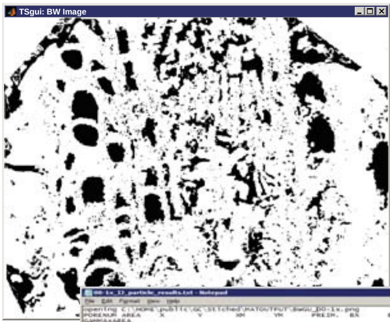


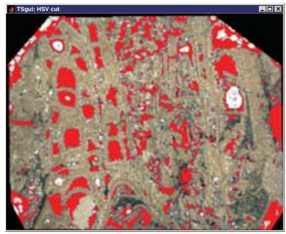
Fast and simple Image segentation based on both color and cross polarized light variation

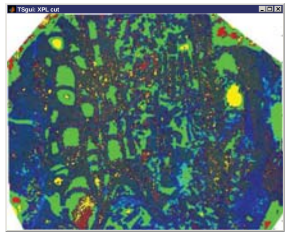


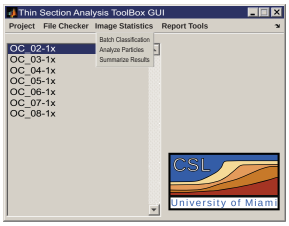




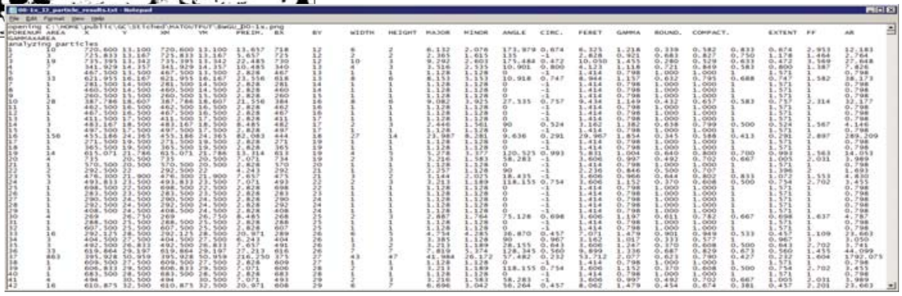




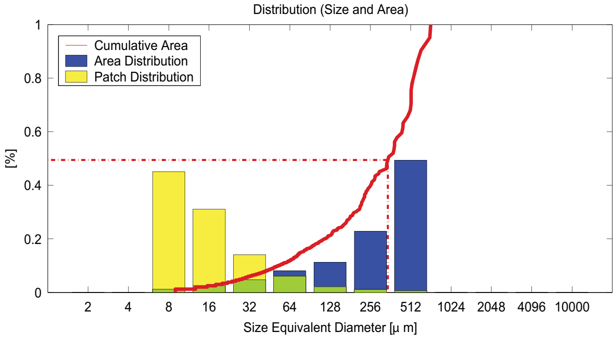


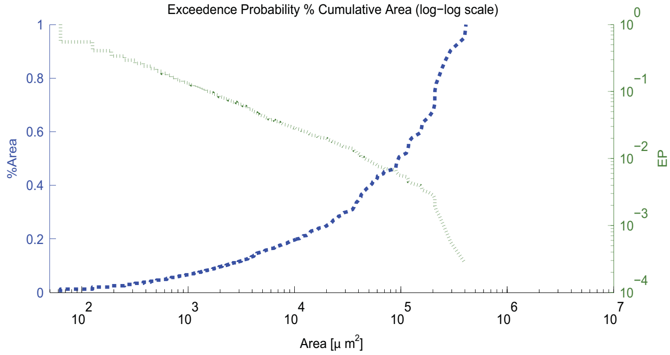


Objective geometry parameters through quantitative particle or pore space analysis



Uniform and Fast Result Reporting



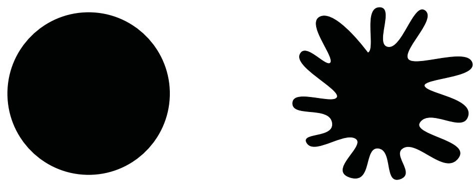


POROSITY:	17.36%	TOTAL NUMBER OF PORES:	3552	log(Area) vs. log(Perimeter):	log(P) = 1.4787 log(A) − 0.21987
AREA WEIGHTED GAMMA:	2.26	NUMBER OF PORES FOR SHAPES:	135	PERIMETER / AREA (TOTAL):	8.7152 mm^{-1}
TOTAL POROSITY AREA:	8.35 mm^2	PATCH DENSITY (TOTAL)	73.8 pores / mm^2	PERIMETER / AREA (POROSITY):	50.2042 mm^{-1}
TOTAL LENGTH OF PERIMETER:	419.22 mm	PATCH DENSITY (POROSITY)	425.4 pores / mm^2		

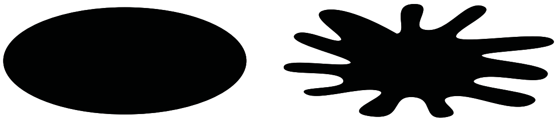
	MAJOR	MINOR	ANGLE	CIRC.	ROUND.	COMPACT.	EXTENT	FORMFACTOR	ASPECTRATIO	GAMMA
MEAN:	38.55	19.63	85.72	0.33	0.52	0.71	0.46	0.33	2.2	1.96
MEDIAN:	29.94	13.63	89.19	0.31	0.51	0.72	0.46	0.31	1.96	1.8
STD:	24.17	14.53	46.41	0.17	0.18	0.13	0.13	0.17	0.98	0.64

Digital Image Parameters Describing Thin Section Geometry

Unique and quantitative description of shapes is a major challenge. No single parameter can unequivocally capture a 2-D shape. A combination is required to distinguish between pores of similar geometric characteristics.



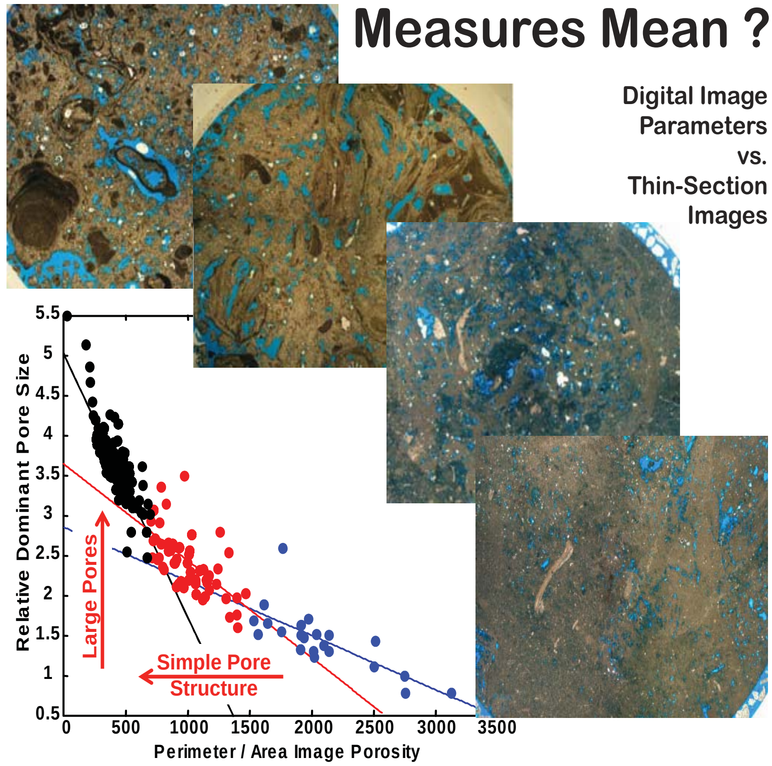
Compactness		γ		PoA		Circularity		AR	
419	349	1.06	2.64	0.89	2.51	0.89	0.14	1.00	1.14
279	241	1.20	3.10	1.01	2.96	0.70	0.10	2.25	2.38



Compactness		γ		PoA		Circularity		AR	
279	241	1.20	3.10	1.01	2.96	0.70	0.10	2.25	2.38
139	121	1.19	3.01	2.04	5.70	0.70	0.11	2.23	2.39

Geologically, what do these Measures Mean ?

Digital Image Parameters vs. Thin-Section Images

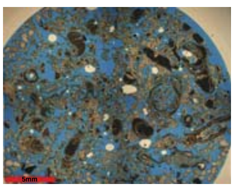


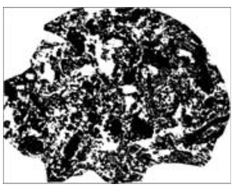
Leg194-176

γ = 5.45 (weighted by area)

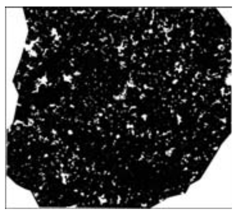
Leg194-203

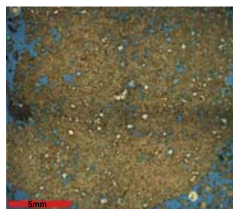
γ = 2.3 (weighted by area)





Comparison of two image analysis summaries from "Erika".

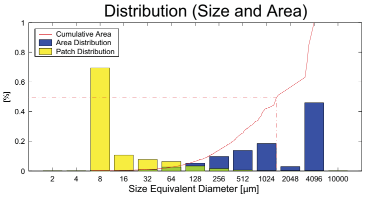




POROSITY: 27.38% K = 62000 md

POROSITY: 7.23% K = 12.2 md

Distribution (Size and Area)



Leg194-176:

	MAJOR	MINOR	ANGLE	CIRC.
MEAN:	48.12	24.16	91.24	0.34
MEDIAN:	29.18	14.47	92.39	0.32
STD:	71.13	37.17	48.22	0.16

	COMPACT	EXTENT	GAMMA	ROUND.
MEAN:	0.72	0.46	1.95	0.54
MEDIAN:	0.73	0.46	1.76	0.53
STD:	0.12	0.11	0.78	0.18

	FORMFACTOR	ASPECT RATIO
MEAN:	0.34	2.1
MEDIAN:	0.32	1.89
STD:	0.16	0.83

PERIMETER / AREA (POROSITY): 23.54 mm^{-1}

Leg194-203:

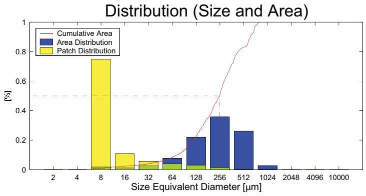
	MAJOR	MINOR	ANGLE	CIRC.
MEAN:	37.05	19.42	90.98	0.35
MEDIAN:	27.97	15.29	93.12	0.34
STD:	26.27	13.24	51.28	0.16

	COMPACT	EXTENT	GAMMA	ROUND.
MEAN:	0.74	0.47	1.84	0.56
MEDIAN:	0.74	0.48	1.73	0.54
STD:	0.11	0.11	0.49	0.17

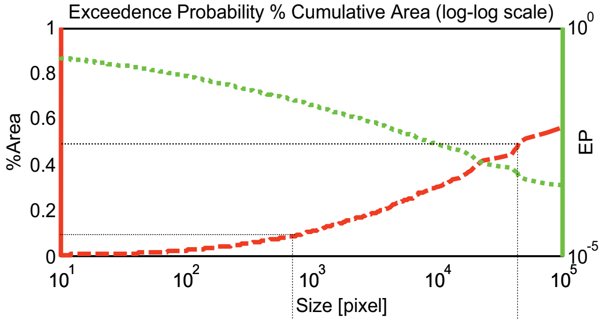
	FORMFACTOR	ASPECT RATIO
MEAN:	0.35	2
MEDIAN:	0.34	1.85
STD:	0.16	0.74

PERIMETER / AREA (POROSITY): 54.5532 mm^{-1}

Distribution (Size and Area)

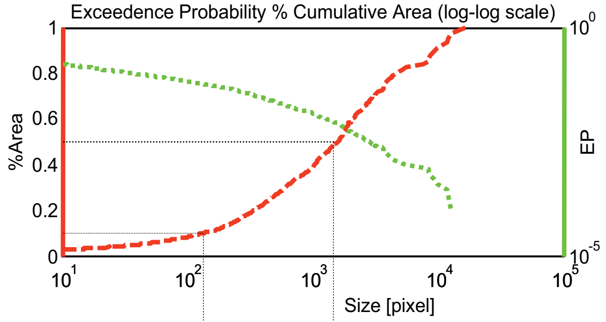


Exceedence Probability % Cumulative Area (log-log scale)



sizeP10 sizeP50 = DOMsize

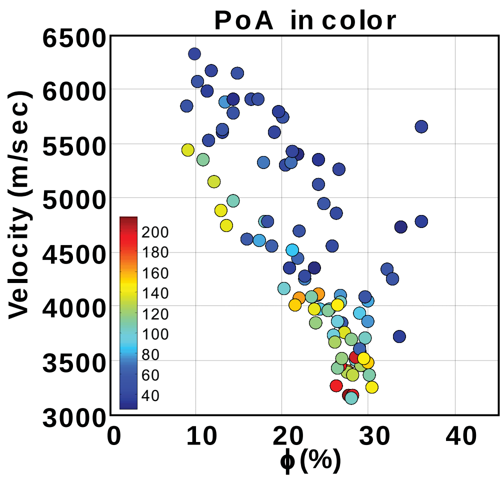
Exceedence Probability % Cumulative Area (log-log scale)

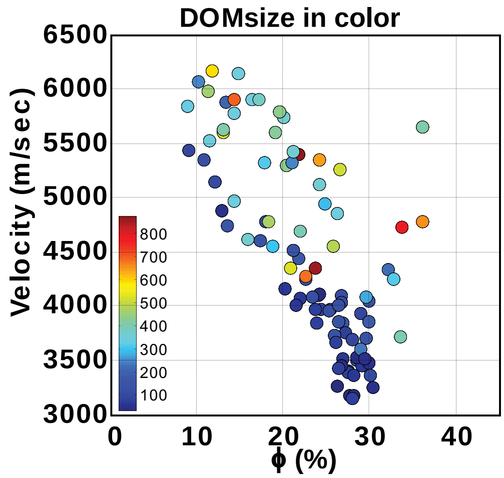


sizeP10 sizeP50 = DOMsize

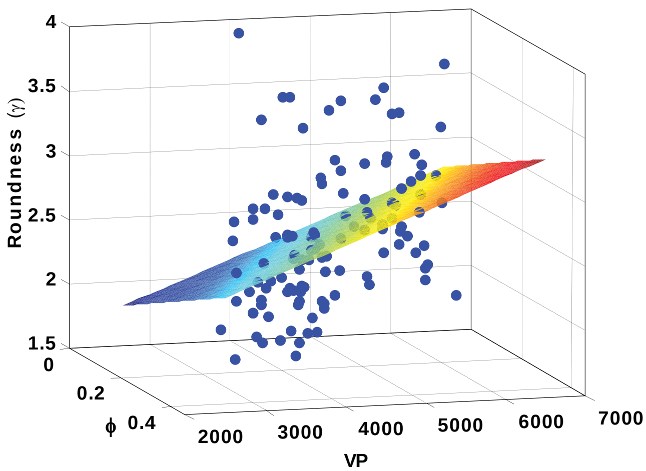
The Relationship between Digital Image Parameters and Acoustic Velocity and Porosity

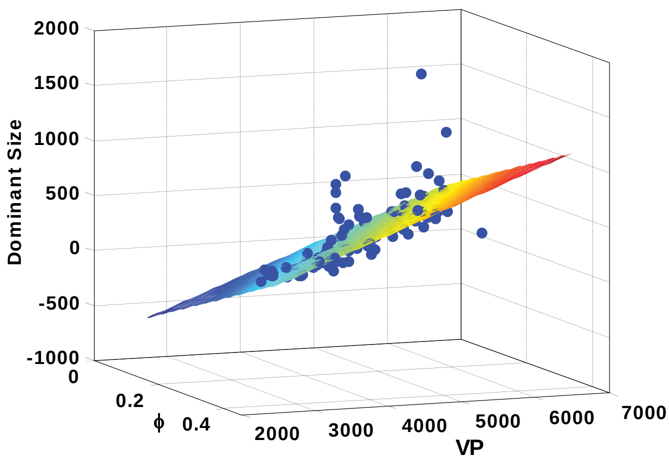
These two crossplots show geometric parameters (superimposed in color) in velocity-porosity space. They are compiled using predominantly limestone samples. Both figures clearly suggest the existance of a relationship between geometric parameters and velocity deviations





Perimeter over Area (PoA) gives most Additional Information to Estimate Porosity from Velocity

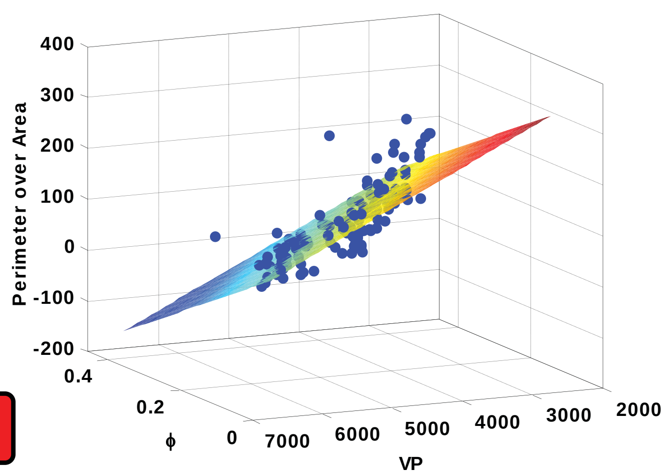




Linear Fits for Geometry-Velocity-Porosity Relationships

Estimators Used for Velocity Prediction	R^2
Porosity (ϕ)	0.490
Porosity & γ	0.524
Porosity & DOMsize	0.684
Porosity & PoA	0.762
ϕ, γ, DOMsize & PoA	0.786

Correlation coefficients from five multivariate linear regressions using different input variables. A combination of three parameters with porosity significantly improves the correlation.



Note: Parameters describing the pore network as a whole (eg. PoA or DOM-size) are more effective then those calculated from individual pores (Gamma)

The Relationship between Extended Biot Theory and Pore Space Geometry in Carbonate Rocks

The simplified EBT model presented by Sun et al. (2001) expresses velocity through the nine equations listed below (for detailed derivations of these equations see Sun, 1994)

$$V_p = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \qquad V_s = \sqrt{\frac{\mu}{\rho}}$$

$$F_k = \frac{1-(1-\phi)f_k}{[1-(1-\phi)f_k]\frac{K_f}{K_s} + (1-\frac{K_f}{K_s})\phi}$$

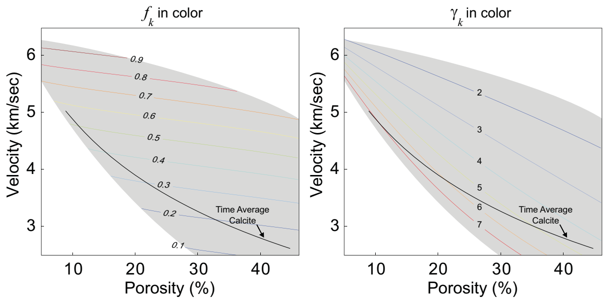
$$\rho = (1-\phi)\rho_s + \phi\rho_f \qquad \mu = \mu_s(1-\phi)f_\mu$$

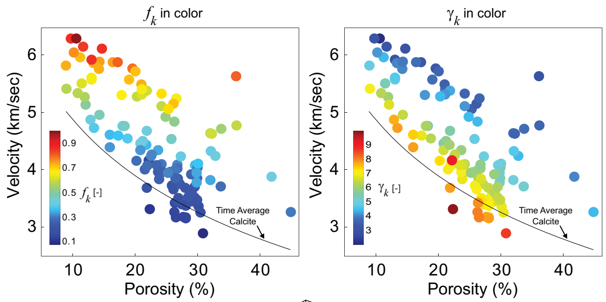
$$K = (1-\phi_k)K_s + \phi_k K_f \qquad f_k = (1-\phi)^{\gamma_k - 1}$$

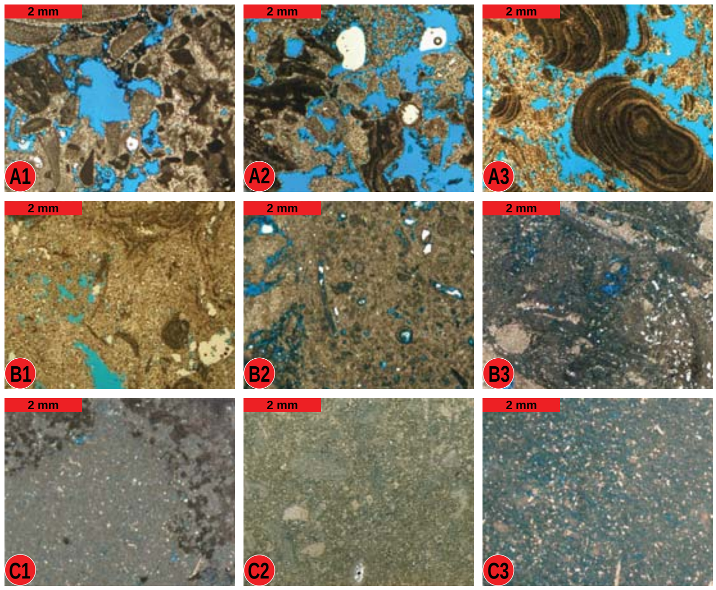
$$\phi_k = F_k\phi \qquad f_\mu = (1-\phi)^{\gamma_\mu - 1}$$

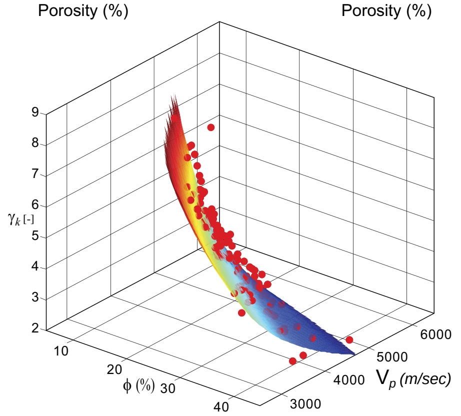
where

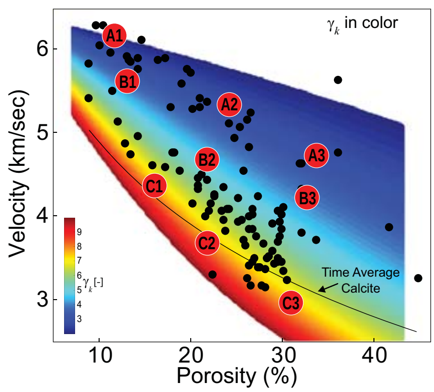
V_p = compressional velocity
V_s = shear velocity
K = bulk modulus
μ = shear modulus
ρ = bulk density
ρ_s = bulk density of the solid
ρ_f = bulk density of the fluid
K_s = bulk modulus of the solid
K_f = bulk modulus of the fluid
μ_s = shear modulus of the solid
ϕ = porosity
ϕ_k = effective porosity
F_k = effective coupling factor
$f_k, f_\mu, \gamma_k, \gamma_\mu$ = frame flexibility factors

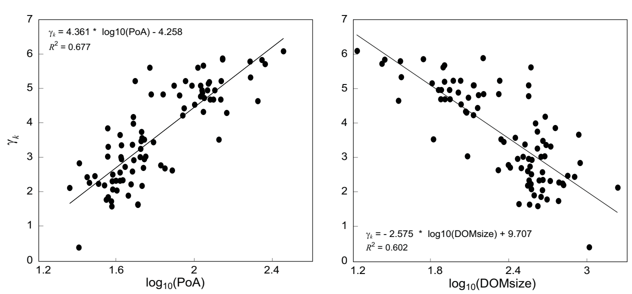


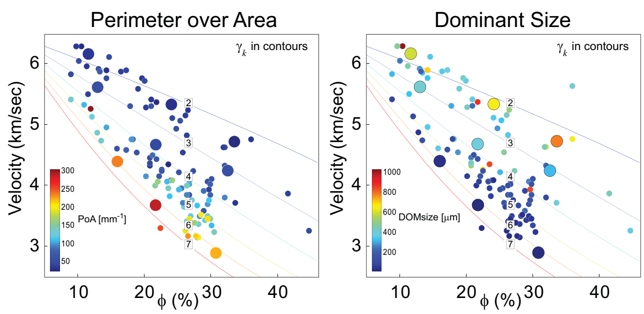




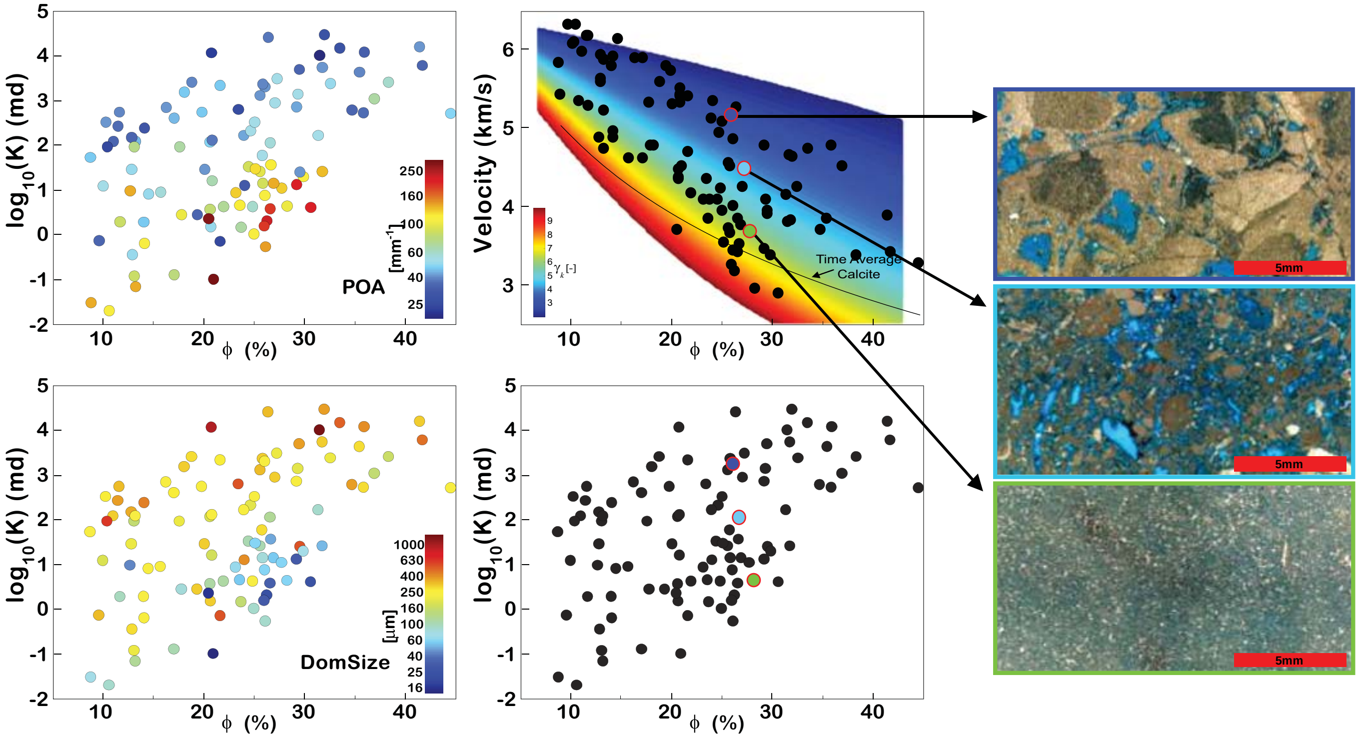


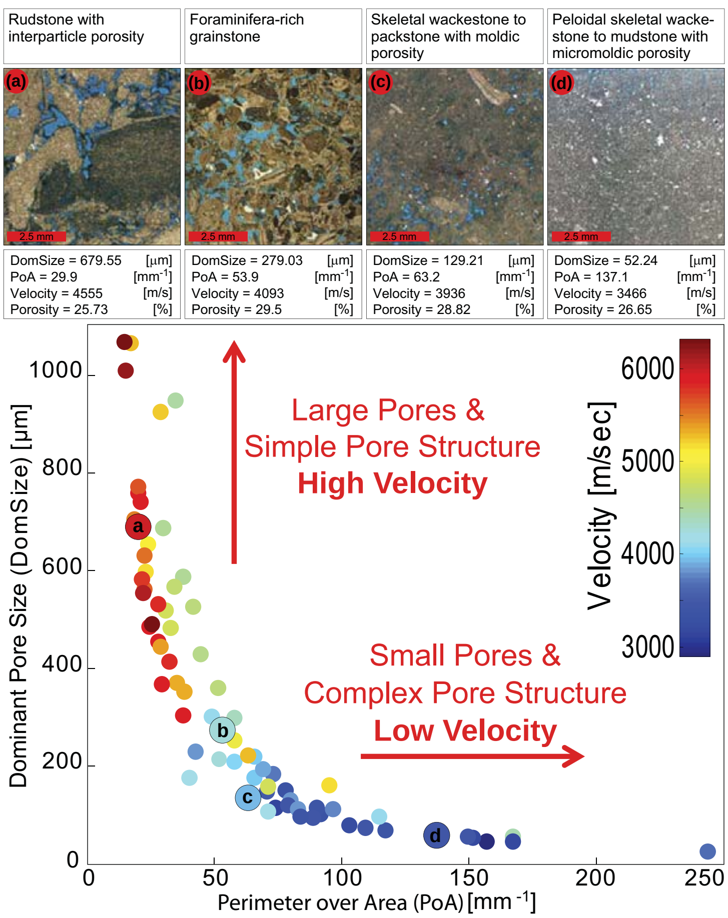






Estimating Permeability from Velocity and Pore Space Geometry in Carbonate Rocks





The Challange:

Separate Rocks with Simple Pore Space Geometries (stiff rocks) that have connected pore networks from those with unconnected pore networks

Both of these types of rocks have low PoA and high DOMSize. They show high velocities for their given porosity and have low γ_k

Almost all rocks fitting this description have excelent flow properties, but some oomoldic rocks have little Permeability.

Effects of Pore Space Geometry on Electrical Resistivity in Carbonate Rocks

Electrical Resistivity & Archie's Law

$F=\varphi^{-m}$ ⟸ cementation factor

Where,

$F=R_o/R_w$

ϕ = porosity

F = formation resistivity factor

R_o = resistivity of fully saturated rock (100% saturation)

R_w = resistivity of pore fluid

Electrical Resistivity & Pore Structure

The cementation factor ranges from 1.7 to 4.1.

Samples with larger pore sizes (e.g. grainstones) have higher electrical resistivity and cementation factor than samples dominated by smaller pore sizes (e.g. wackestone).

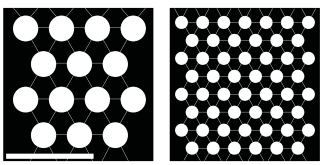
Samples with high dominant pore size and low perimeter over area have a high cementalion factor for a given porosity.

Samples wilth low dominant pore size and high perimeter over area have low cementation factor values.

Explanation:

In natural rocks many more pores (and pore connections) need to exist in rocks with smaller pore sizes than in rocks with larger pores in order to maintain equal porosity (see synthetic example on pannel 2).

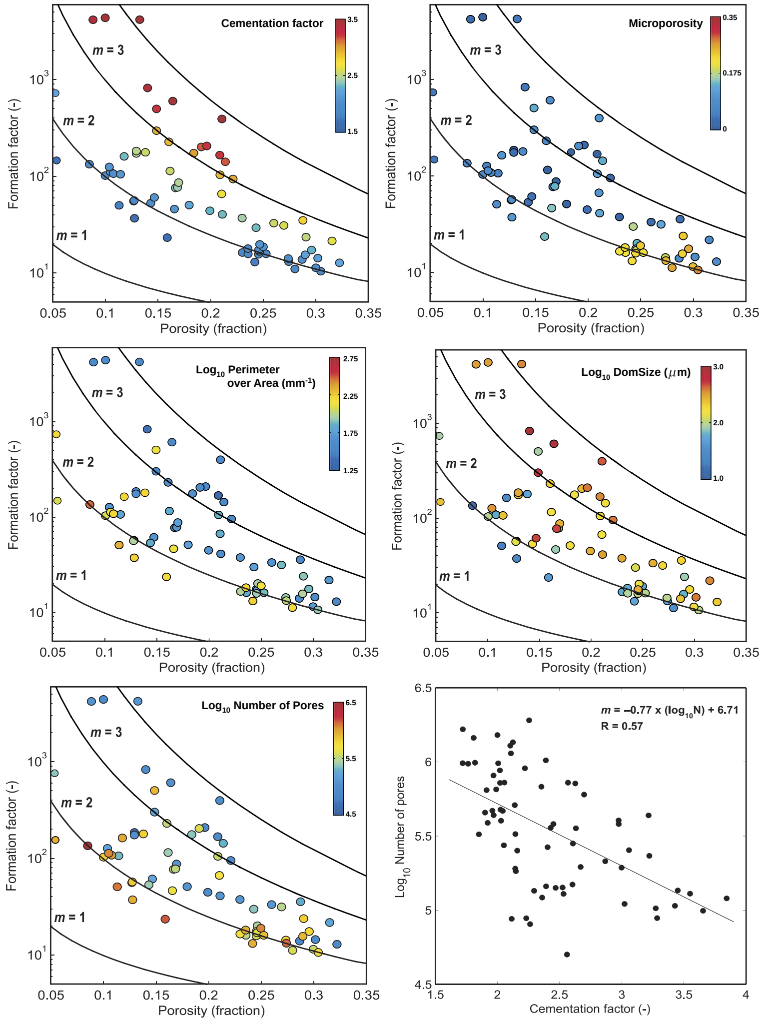
This results in fewer pore conetions for rocks dominated by larger pores and hence conduction of electric current is retarded. For samples dominated by many small pores the low of electrical charge is facilitated by the dense pore network.

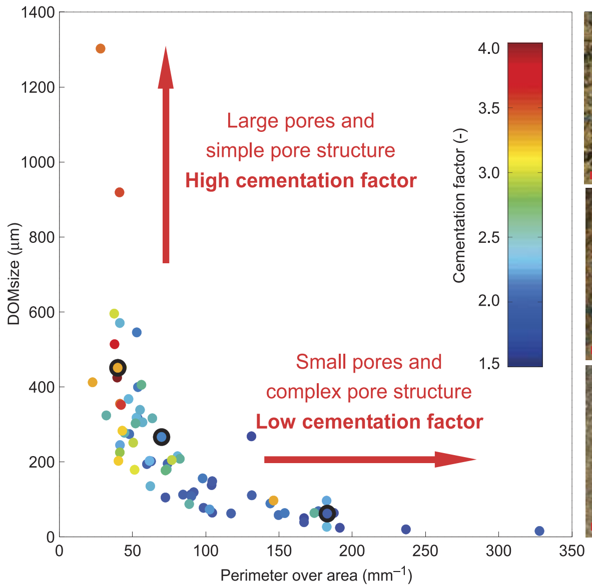


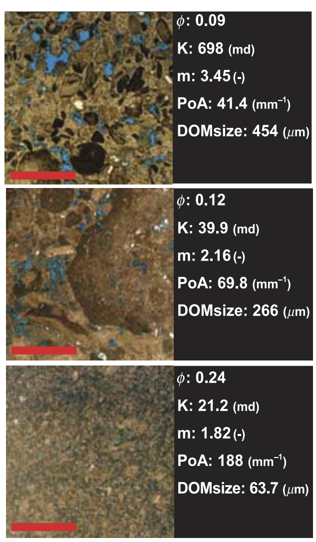
Porosity	34%
Number of pores	14
Number of throats	39
Dominant pore size	1500 μm
Perimeter over area	3 mm^{-1}

Porosity	31%
Number of pores	52
Number of throats	154
Dominant pore size	730 μm
Perimeter over area	5.8 mm^{-1}

Formation Factor and Pore Geometry



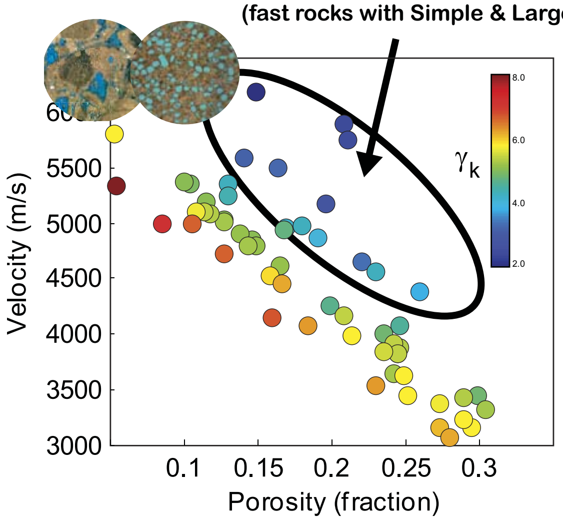




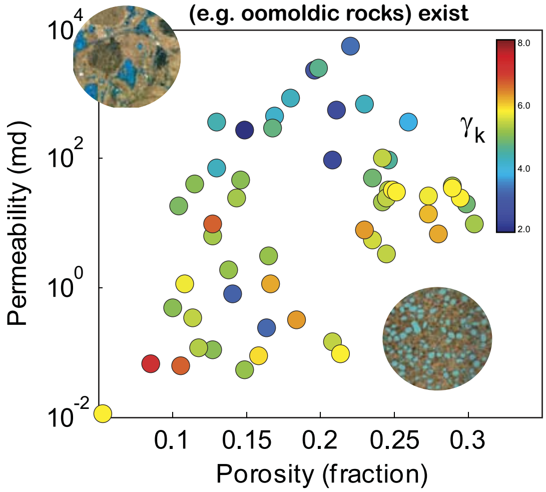
Electrical resistivity in carbonate rocks is not dependent on pore throat diameter or turtuosity but rather on pore structure and number of pore connections

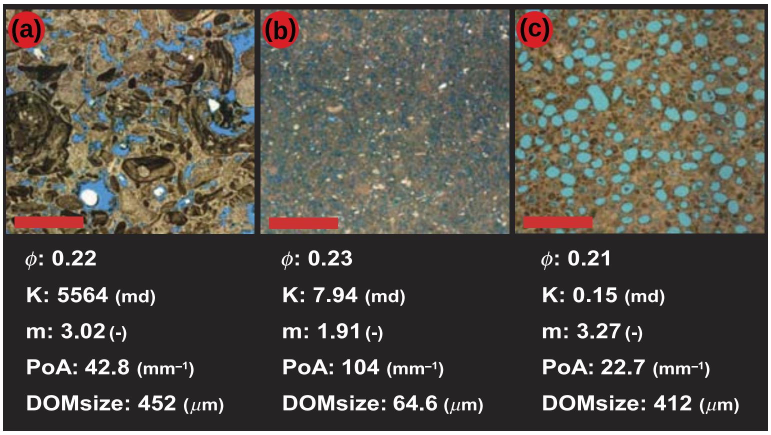
Use Electrical Resistivity to eliminate unconnected stiff Pore Space Geometries

Samples with low frame flexibility
(fast rocks with Simple & Large Pores)

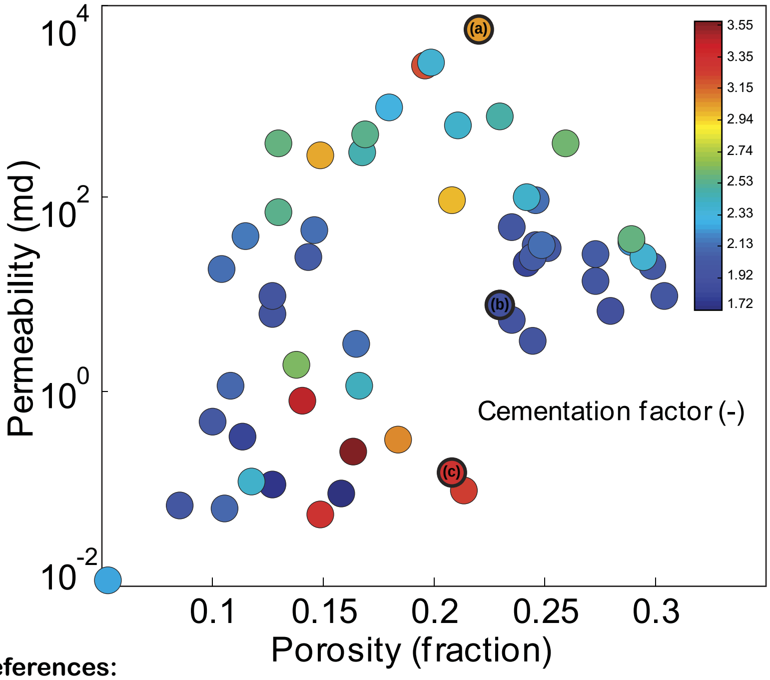


Most low frame flexibility samples
have high permeability, but exceptions
(e.g. oomoldic rocks) exist





Electrical resistivity measurements and resulting cementation factors can be used to destinguish those rocks with low frame flexibility factor and connected pore network from those with unconnected pore network.



Three DIA parameters are able to identify high permeability samples

Rocks with low PoA, high DOMSize, and large number of pores are those of high permeability for their porosity

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