Enhanced Reservoir Characterization and Permeability Prediction of Heterogeneous Carbonate Reservoirs from Sonic Velocity and Digital Image Analysis*

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Editor's note: Please view a companion article by these authors, entitled "Prediction of Petrophysical Properties of Trenton-Black River (Ordovician) Reservoirs by Comparing Pore Architecture and Permeability to Sonic Velocity," Search and Discovery Article #50508 (2011)

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Abstract

Heterogeneous pore architecture complicates carbonate reservoir characterization due to the interplay of primary depositional fabrics and diagenetic processes. Ordovician Trenton and Black River carbonates in the Michigan Basin represent one of the classic examples for hydrothermal dolomite reservoirs, with main play strategies being directed by 3-D seismic to identify structural conduits related to flower structures. Recent work has shown, however, that secondary reservoirs exist due to lateral migration of reservoir-forming dolomite that is controlled by facies and stratigraphic architecture.

These secondary reservoirs are highly heterogeneous and have been highly altered by hydrothermal dolomite. Millimeter (thin-section, minipermeameter), centimeter (core plug) and decimeter (whole core) scales of porosity and permeability measurement exhibit considerable variability in these carbonates, in part due to the influence of bioturbation and subsequent diagenetic alteration. Comparison of thin-section porosity, core-plug porosity and permeability and gridded minipermeability measurements on core show that porosity values may range from near zero to 8% and permeabilities may vary by several orders of magnitude within a one-foot core interval.

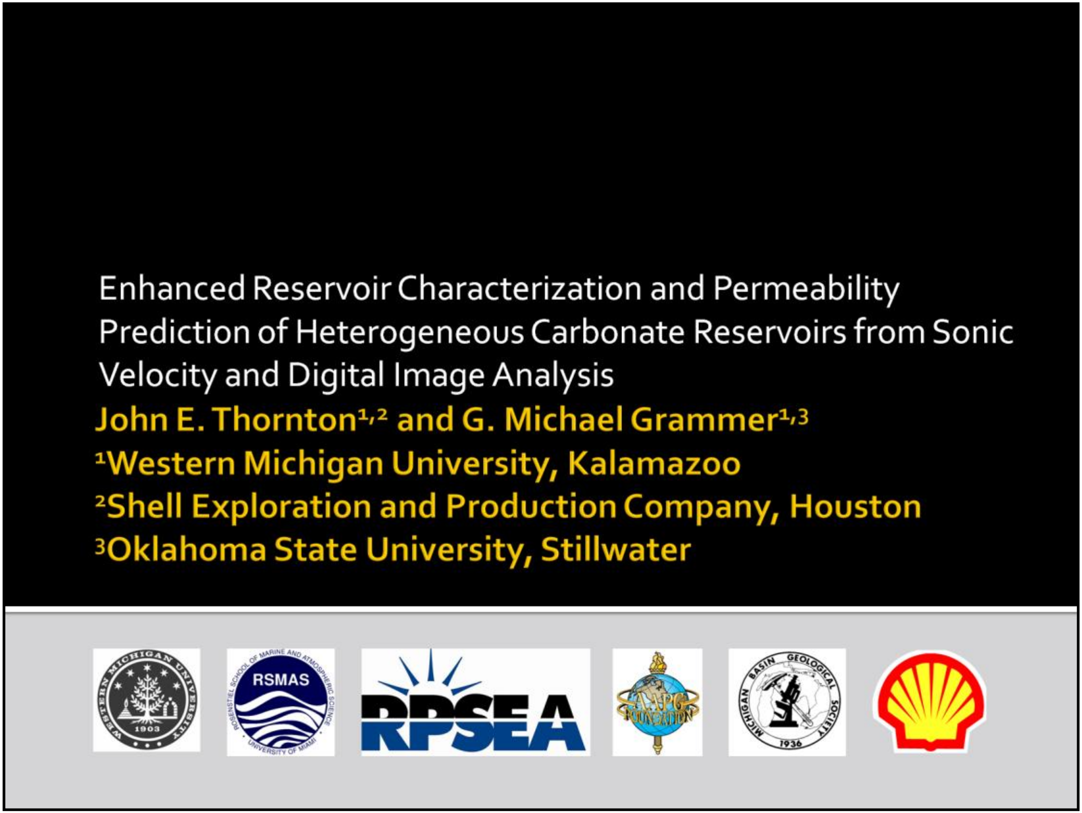
Sonic velocity is a measure of both porosity and pore architecture in three dimensions, and thus may be used as a first-order approximation of permeability. Digital-image analysis measurements of pore architecture predict P-wave velocity of carbonate core plugs to within 5.3%. Permeability of carbonate core plugs is predicted with accuracy of 82% when two- and three-dimensional measures of pore architecture (digital image analysis of thin sections and sonic velocity of core plugs) are integrated with measures of porosity and density.

References

Anselmetti, F.S., and G.P. Eberli, 1997, Sonic velocity in carbonate sediments and rocks: SEPM Geophysical Development Series 6, p. 53-74.

Ehrenberg, S.N., 2007, Whole core versus plugs: Scale dependence of porosity and permeability measurements in platform carbonates: AAPG Bulletin, v. 91/6, p. 835-846.

Weger, R.J., G.P. Eberli, G.T. Baechle, J.L. Massaferro, and Y-F. Sun, 2009, Quantification of pore structure and its effect on sonic velocity and permeability in carbonates: AAPG Bulletin, v. 93/10, p. 1297-1317.



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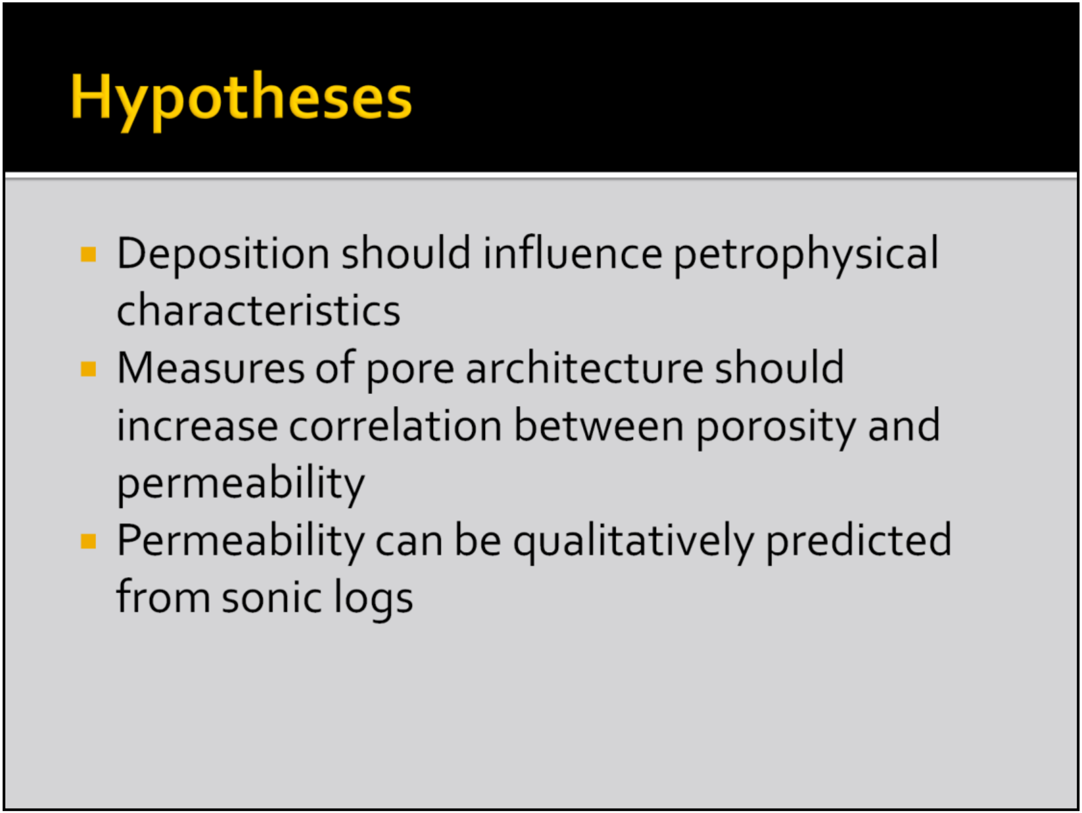
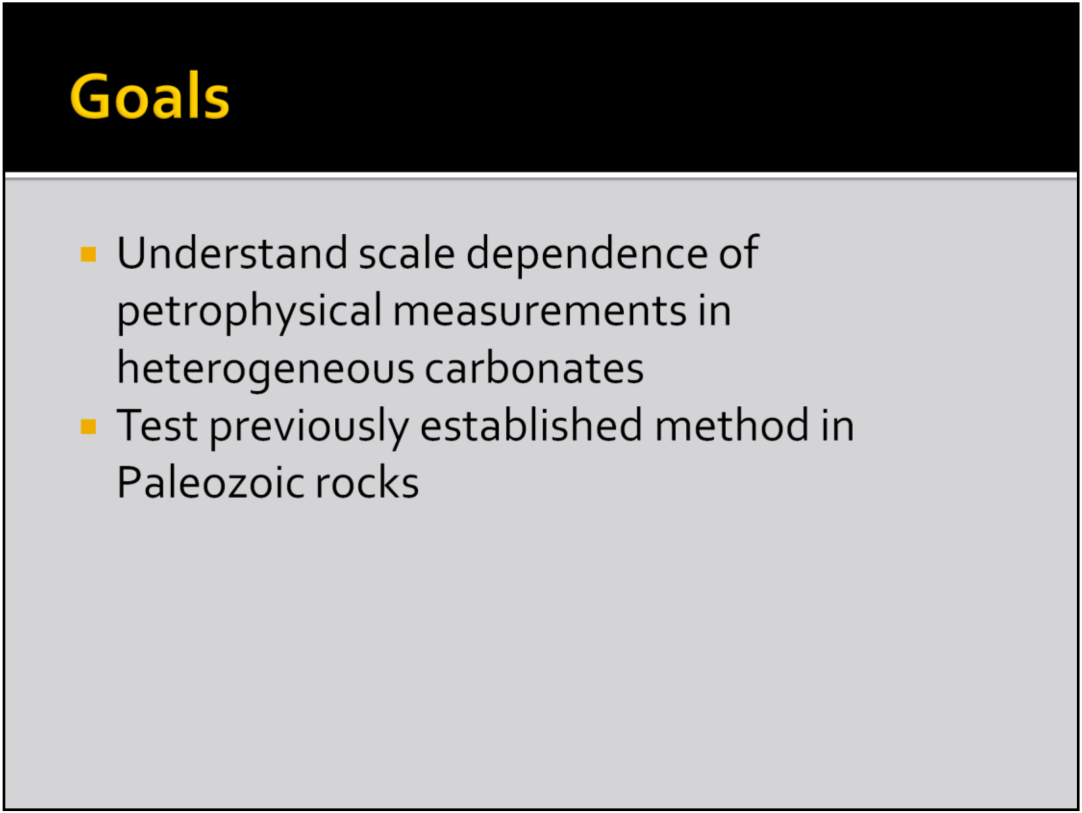
Presenter's notes: If possible, our goal to predict permeability from sonic-velocity data.



Hypotheses

- Deposition should influence petrophysical characteristics
- Measures of pore architecture should increase correlation between porosity and permeability
- Permeability can be qualitatively predicted from sonic logs

Presenter's notes: Depositional fabrics influence primary pore architecture, which influences subsequent diagenetic modification, which, in turn, determines petrophysical expression. Pore architecture: how porosity (phi) is distributed in 3-D-- and methods that measure this, increase predictability. Because sonic velocity (SV) is one measure of pore architecture, it should be possible to increase permeability prediction from logs, using SV over phi alone.



Goals

- Understand scale dependence of petrophysical measurements in heterogeneous carbonates
- Test previously established method in Paleozoic rocks

Presenter’s notes: Determine if petrophysical measurements from core plugs correlate with whole core measurements. Test University of Miami method, previously used in Upper Mesozoic-Cenozoic rocks, in Lower Paleozoic rocks.

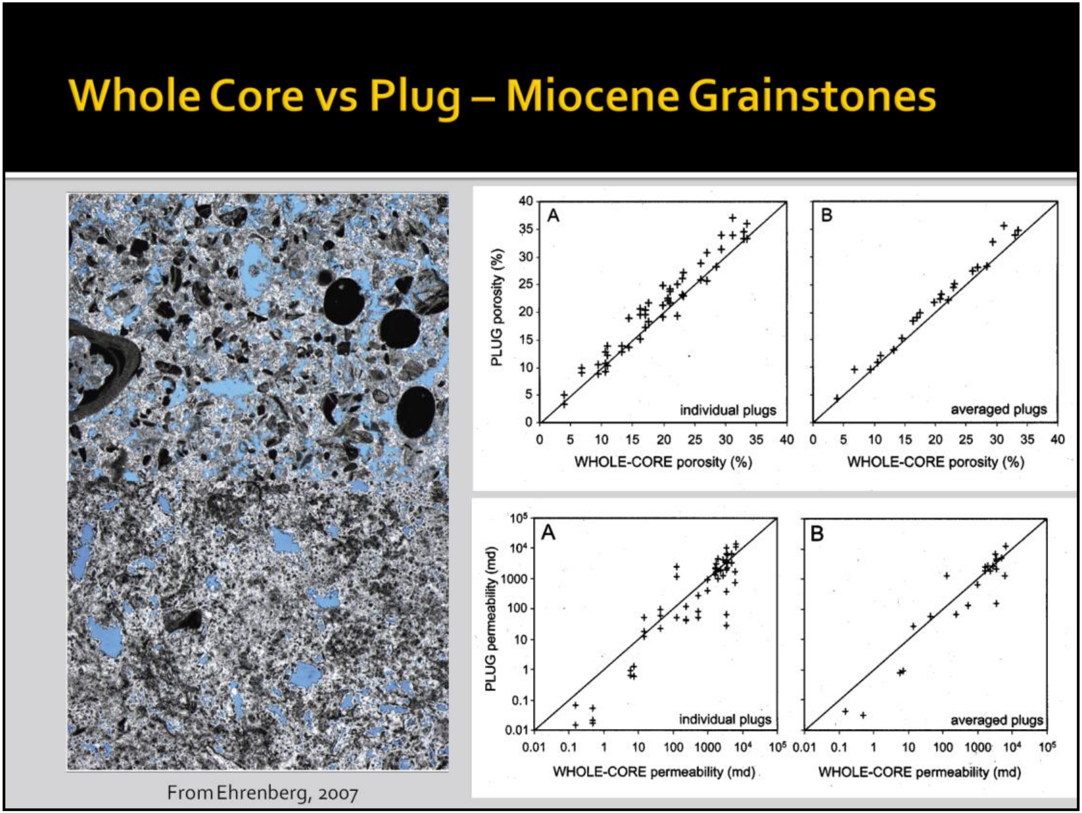
Application

- Understand how rock measurements of different scales relate to one another
- Predict permeable intervals based on elastic properties
- Increase understanding of elastic properties of heterogeneous carbonates

Methods and Materials

- Whole core and core plug analysis
- Computed tomography
- Digital image analysis of thin-sections (DIA)
- Laboratory sonic velocity (University of Miami)
- Minipermeametry
- Multiple variable linear regression (MVLR)

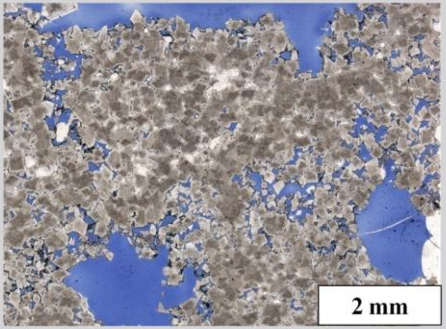
- Thin sections
- Whole cores
- Core plugs
- Wireline logs



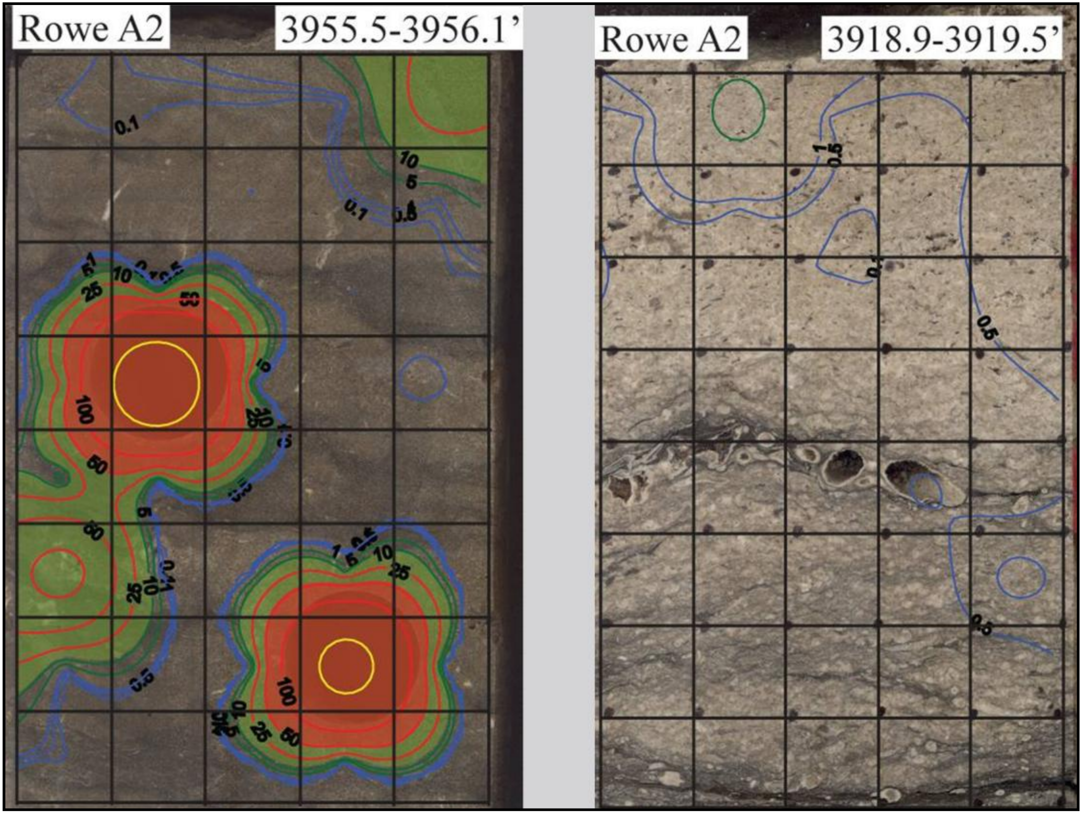
Whole Core vs Plug – Miocene Grainstones

From Ehrenberg, 2007

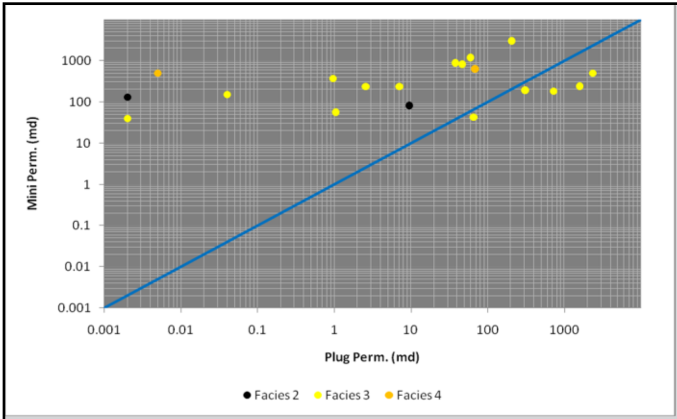
Presenter's notes: Ehrenberg (2007) shows that petrophysical measurements correlate well from core plug to whole core in Miocene platform carbonates (bioclastic with relatively homogenously distributed pores).



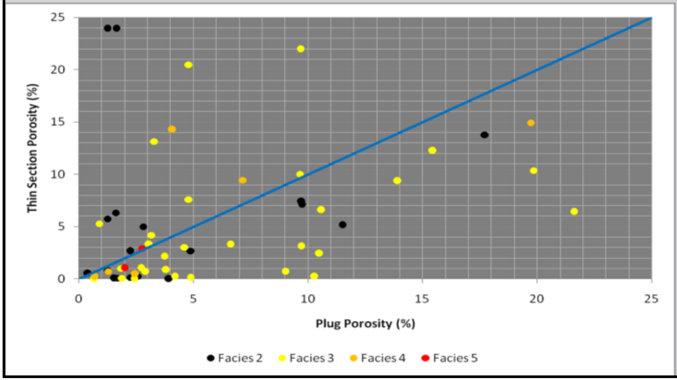
Presenter's notes: The rocks in this study are dolomitized Ordovician platform carbonates from the Michigan basin. Bioturbation has a significant influence on porosity distribution.



Presenter’s notes: Shown here are permeability contour maps as overlays of core butts. Two end members occur: 1) burrowed type → high-permeability variation → permeability highs centered on burrows, due to heterogeneous pore distribution because of preferential dolomitization of burrows. 2) grainstone type → lower permeability variation → lower permeability overall, due to more homogenous pore distribution.

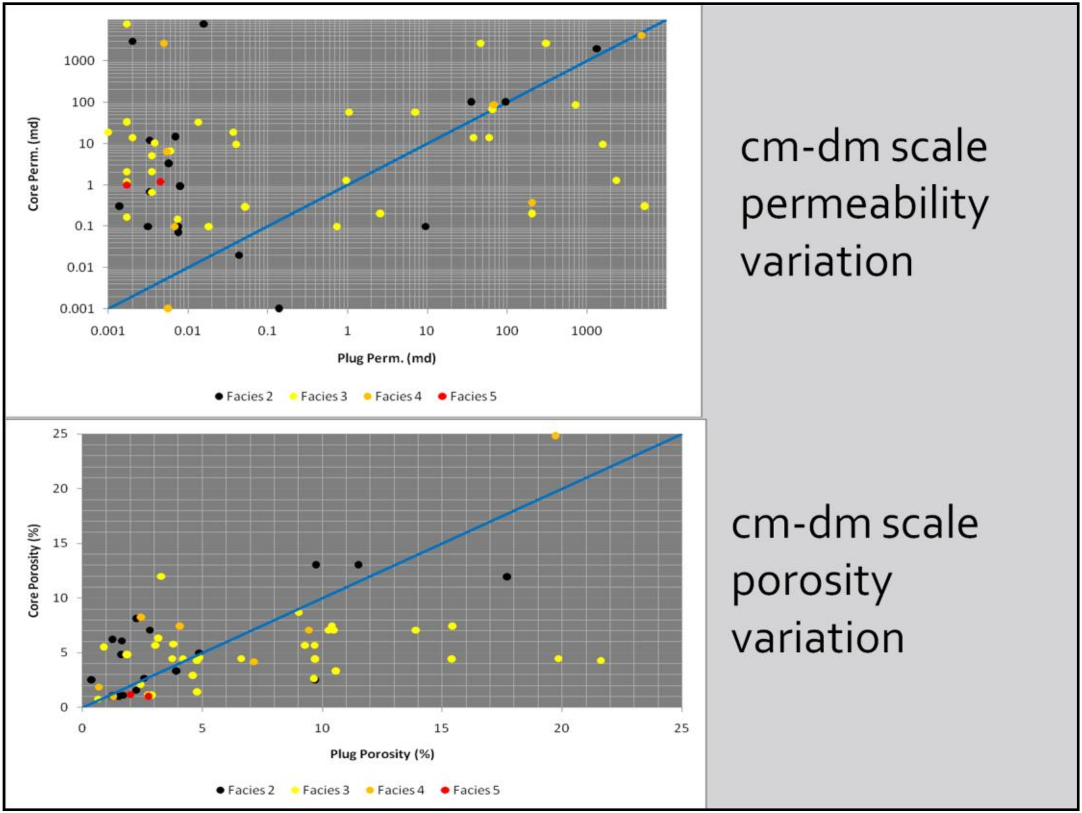


mm-cm scale permeability variation



mm-cm scale porosity variation

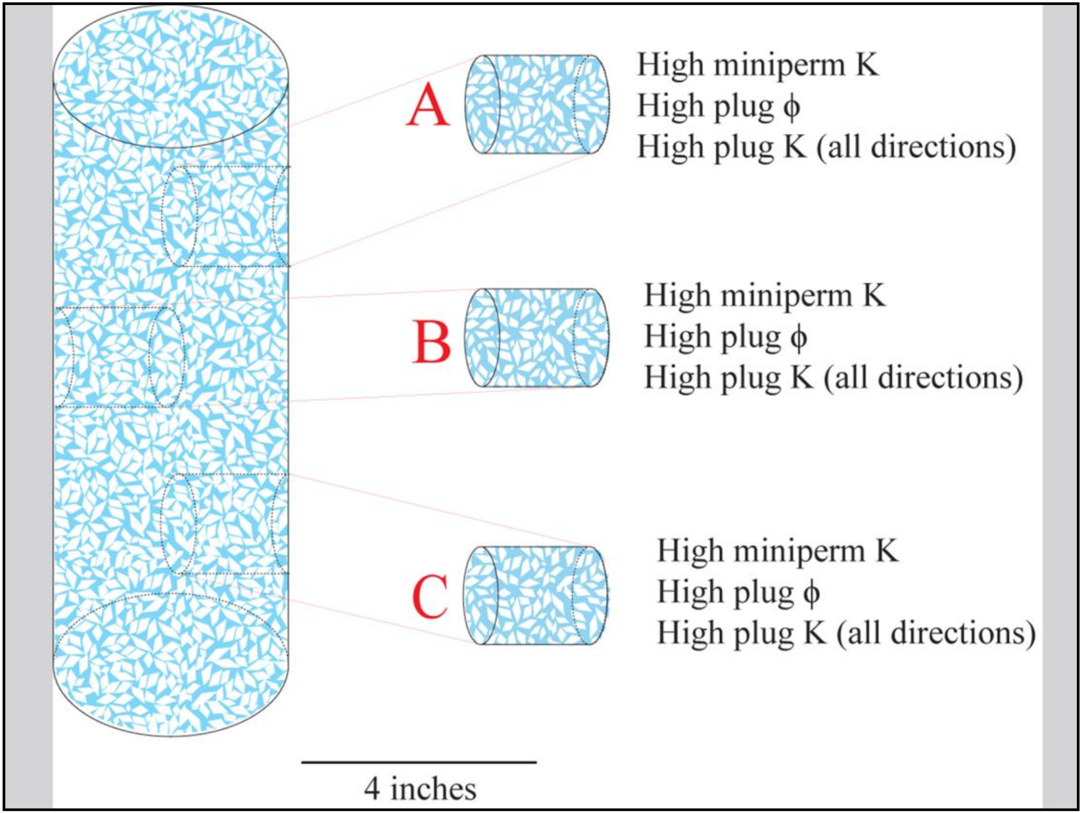
Presenter's notes: Plots show no agreement, due to heterogeneous distribution of porosity.



cm-dm scale permeability variation

cm-dm scale porosity variation

Presenter's notes: Also, little agreement in plots--and heterogeneous porosity distribution.

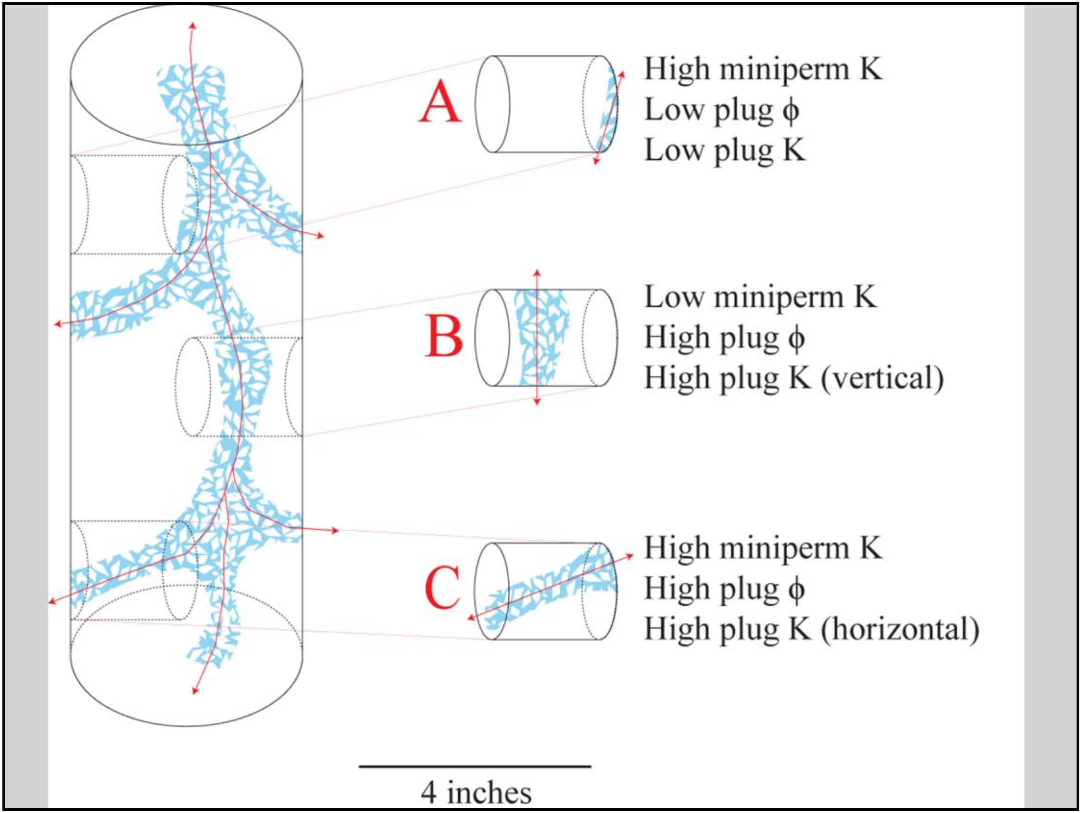


High miniperm K
High plug ϕ
High plug K (all directions)

High miniperm K
High plug ϕ
High plug K (all directions)

High miniperm K
High plug ϕ
High plug K (all directions)

Presenter's notes: Ideal situation → sucrosic dolomite, evenly distributed porosity; core plugs and whole core have similar petrophysical properties—whole core: high porosity/permeability.

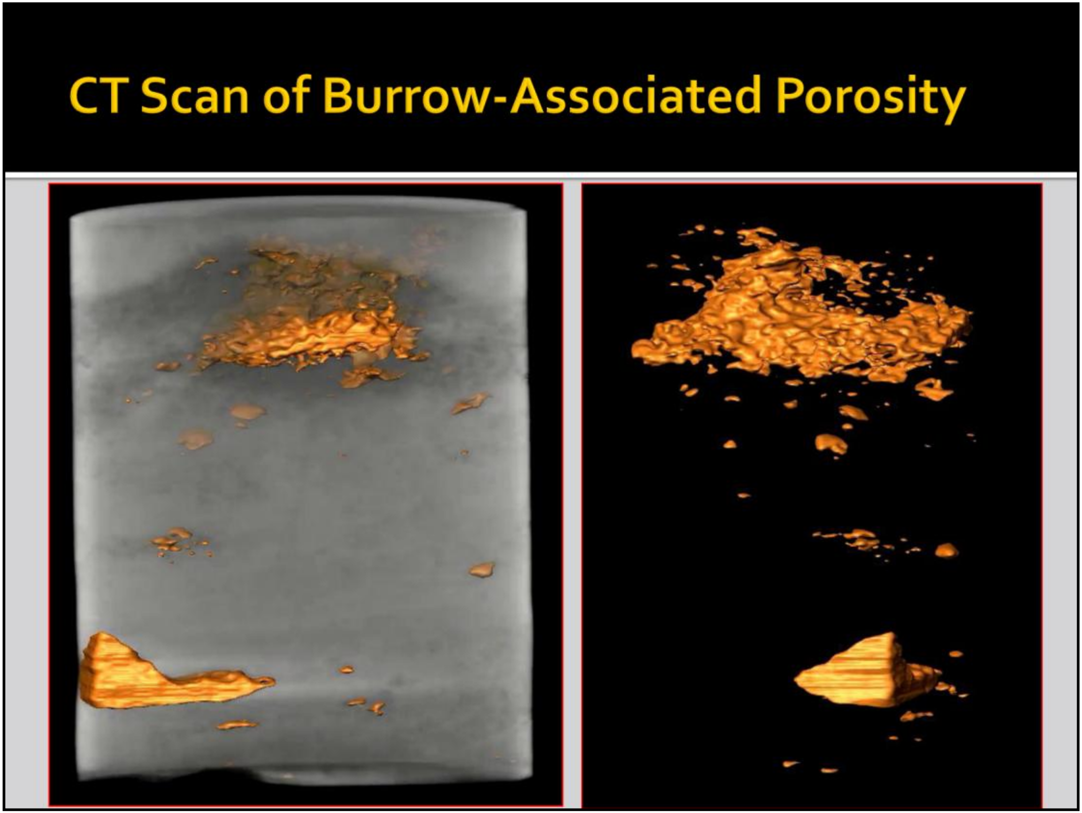


High miniperm K
Low plug ϕ
Low plug K

Low miniperm K
High plug ϕ
High plug K (vertical)

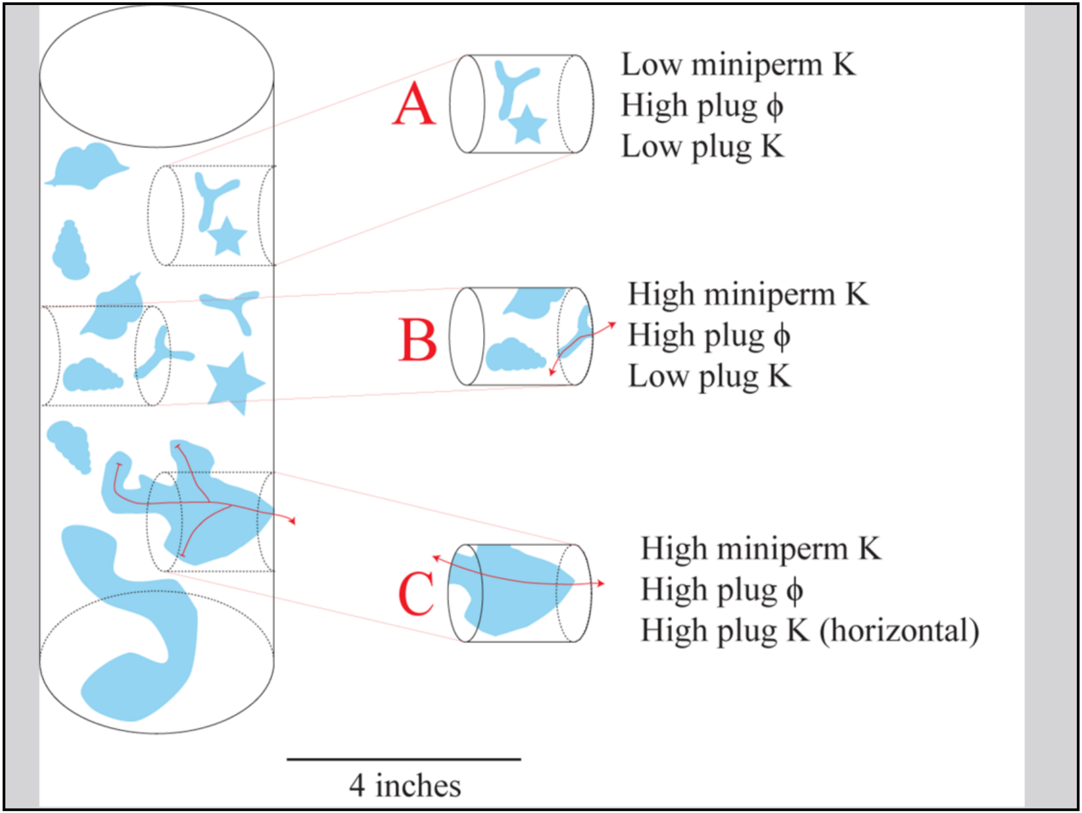
High miniperm K
High plug ϕ
High plug K (horizontal)

Presenter’s notes: The pore architecture shown in the previous image is not the case in Trenton-Black River. In burrowed fabrics, porosity is heterogeneously distributed, controlled by sucrosic dolomite burrows. In whole-core analysis, there is moderate porosity, good permeability. Note the difference in plug measurements from top and bottom of whole core.



CT Scan of Burrow-Associated Porosity

Presenter's notes: CT scans of burrowed facies show similar relationships to those predicted by models. The effect of the position of the plug is clearly demonstrated here.



A

Low miniperm K

High plug ϕ

Low plug K

B

High miniperm K

High plug ϕ

Low plug K

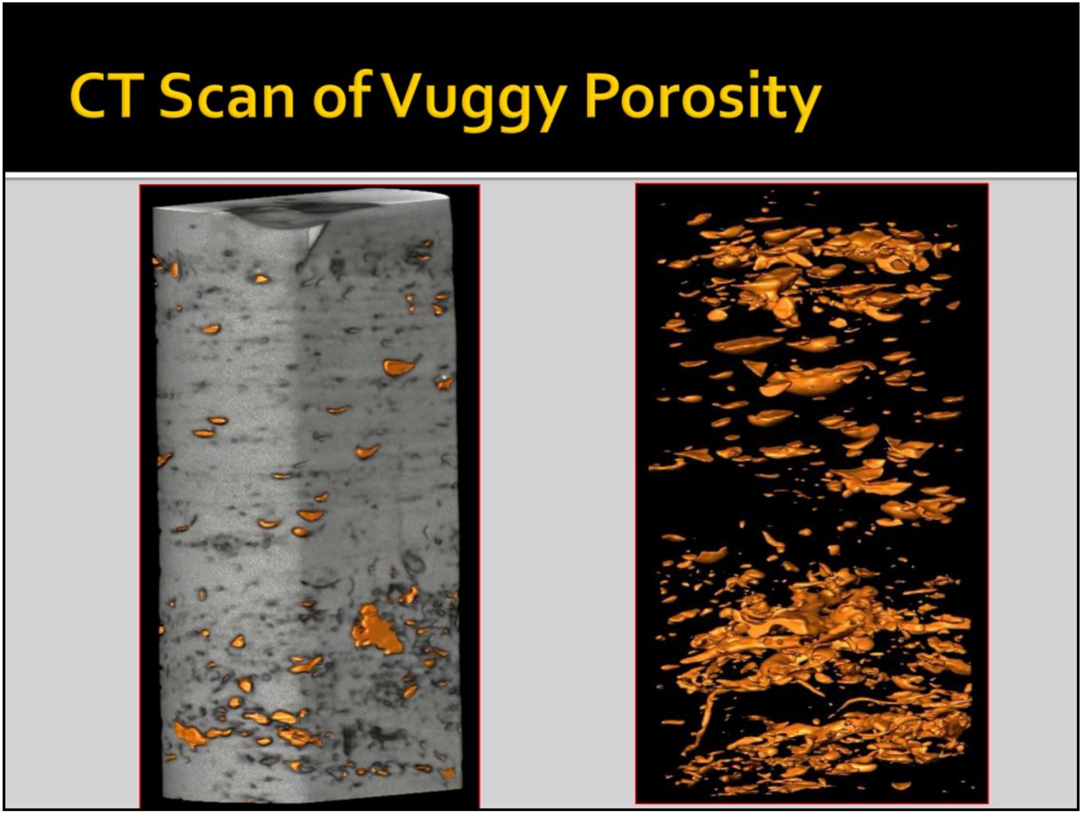
C

High miniperm K

High plug ϕ

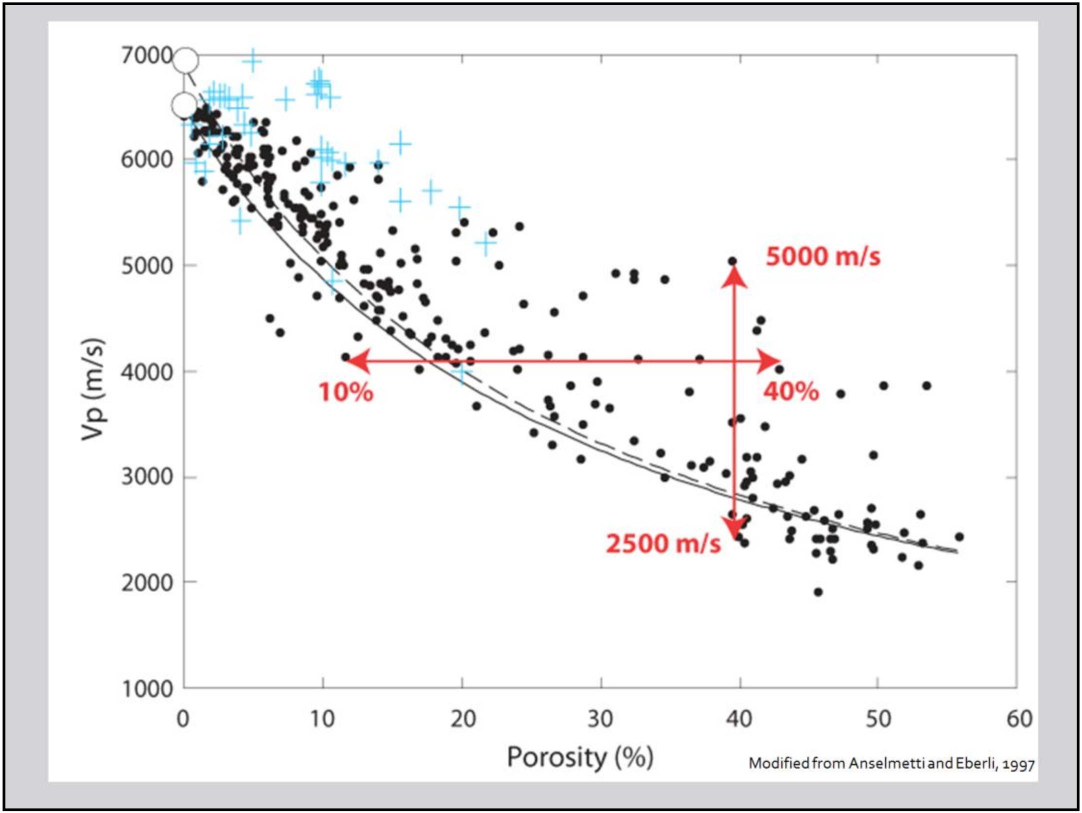
High plug K (horizontal)

Presenter's notes: Moldic/vuggy textures are similar. Whole core has moderate porosity, low permeability. Note the different measurements between top and bottom plugs.



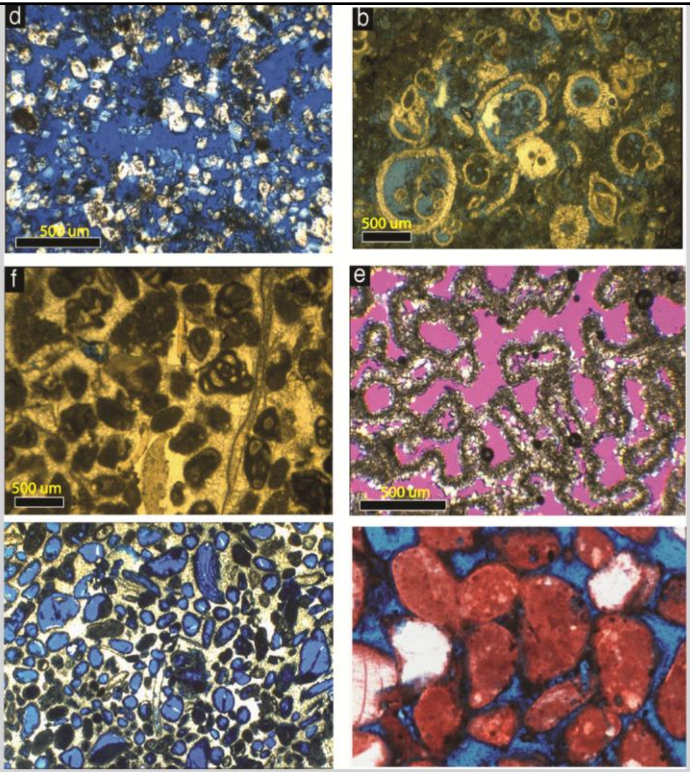
CT Scan of Vuggy Porosity

Presenter’s notes: CT scans shown here are similar to those for burrow-associated porosity.



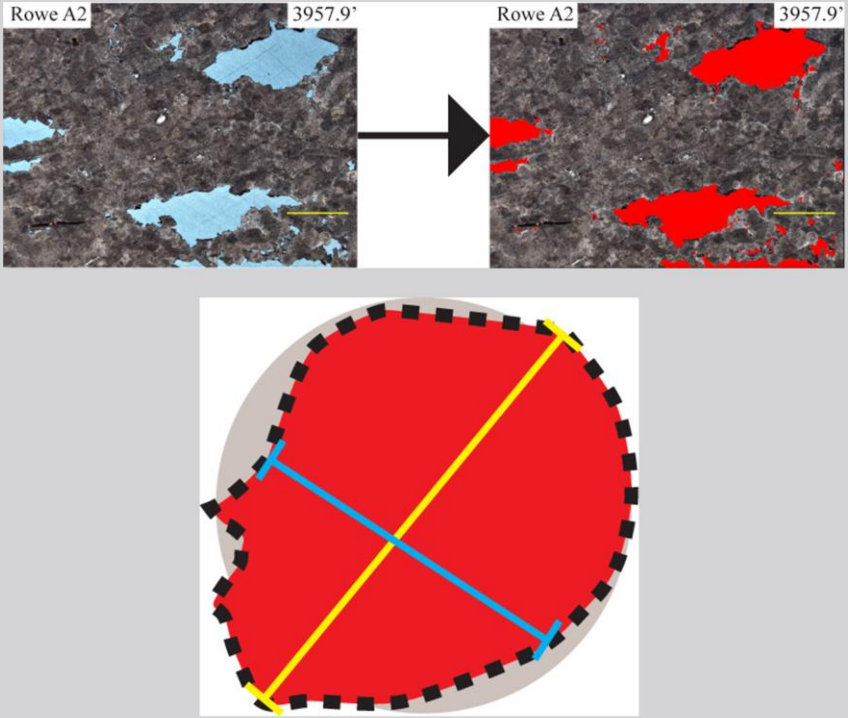
Modified from Anselmetti and Eberli, 1997

Presenter's notes: Variation is due to variable pore architecture.



From Anselmetti and Eberli, 1997

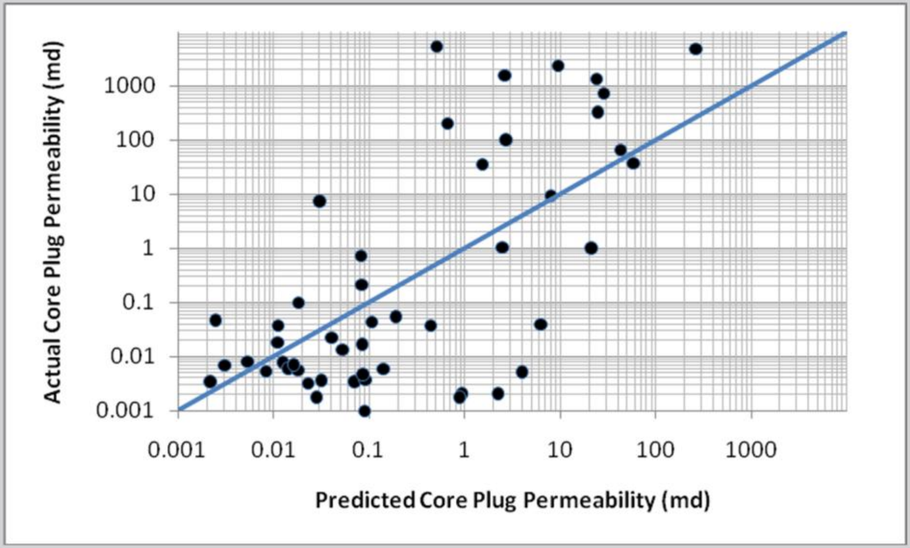
Presenter's notes: Carbonate rocks have various pore architectures with differing relationships to petrophysical properties; e.g., upper left and lower left.



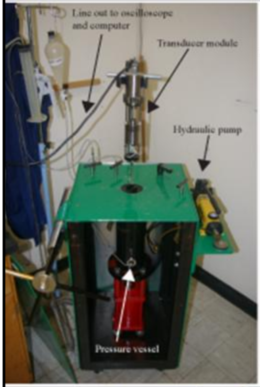
Presenter's notes: Digital-image analysis was performed in ImagePro Plus; pore parameters were calculated based on previous work done by Weger et al. (2009).

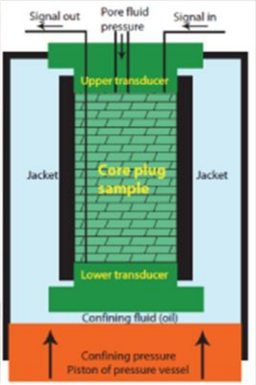
$$\ln K = 0.909\ln\Phi + 9.724\ln A_{ds} + 3.028\ln {}^{L}/_{W} + 1.222\ln {}^{P}/_{A} - 2.955\ln\lambda - 38.887$$

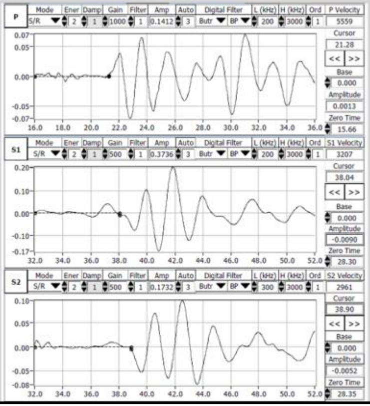
$R^2 = 0.446$



Presenter's notes: MVLR of these paramaters increases prediction of permeability over porosity alone--but not to a great degree; this is thought to be due mostly to DIA being a 2-D measure of pore architecture.







P	Mode	Ener	Damp	Gain	Filter	Amp	Auto	Digital Filter		L (kHz)	H (kHz)	Ord	P Velocity
	S/R	2	1	1000	1	0.1412	3	Butr	BP	200	3000	1	5559

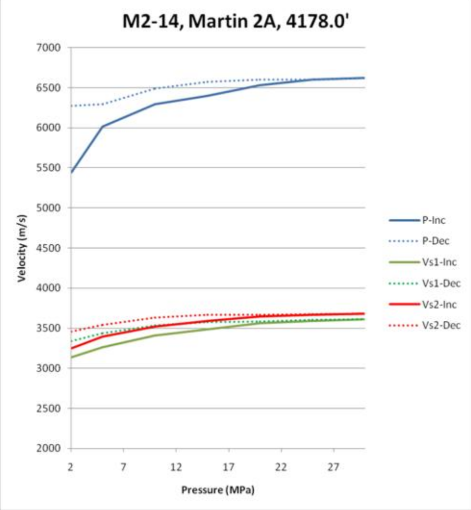
Cursor 21.28
Base 0.000
Amplitude 0.0013
Zero Time 15.66

S1	Mode	Ener	Damp	Gain	Filter	Amp	Auto	Digital Filter		L (kHz)	H (kHz)	Ord	S1 Velocity
	S/R	2	1	500	1	0.3736	3	Butr	BP	200	3000	1	3207

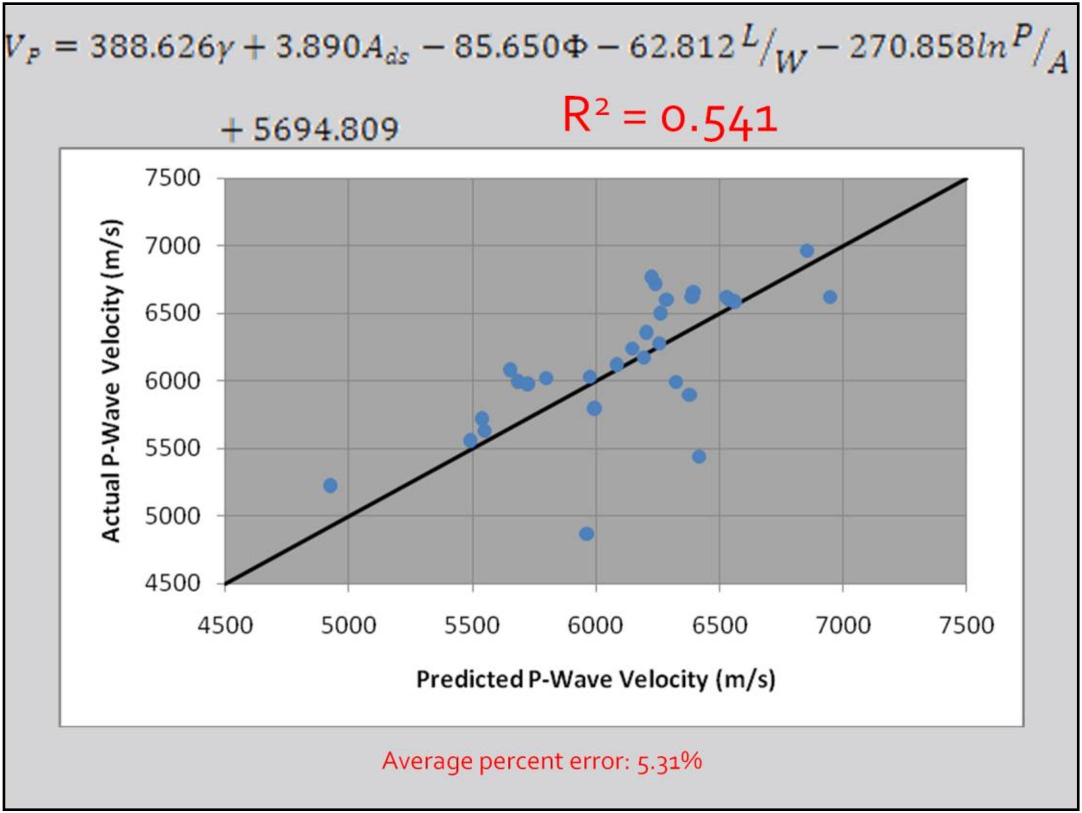
Cursor 38.04
Base 0.000
Amplitude -0.0090
Zero Time 28.30

S2	Mode	Ener	Damp	Gain	Filter	Amp	Auto	Digital Filter		L (kHz)	H (kHz)	Ord	S2 Velocity
	S/R	2	1	500	1	0.1732	3	Butr	BP	300	3000	1	2961

Cursor 38.90
Base 0.000
Amplitude -0.0052
Zero Time 28.35



Presenter's notes: Pressure steps so accurate that in situ reservoir conditions can be obtained.

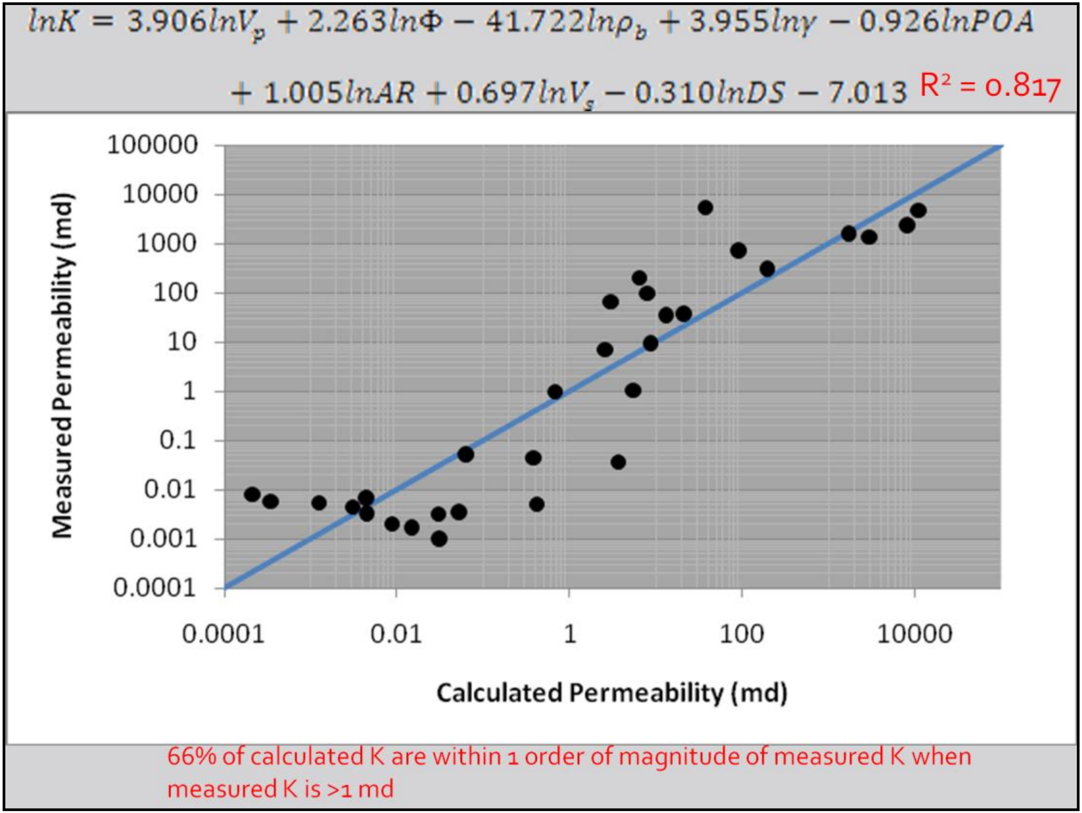


$$V_P = 388.626\gamma + 3.890A_{ds} - 85.650\Phi - 62.812\,{}^{L}/_{W} - 270.858\ln{}^{P}/_{A} + 5694.809$$

$R^2 = 0.541$

Average percent error: 5.31%

Presenter’s notes: MVLR was used to predict Vp from phi and DIA; it predicts Vp better than phi (about 10% greater). This indicates that Vp is measuring pore parameters.

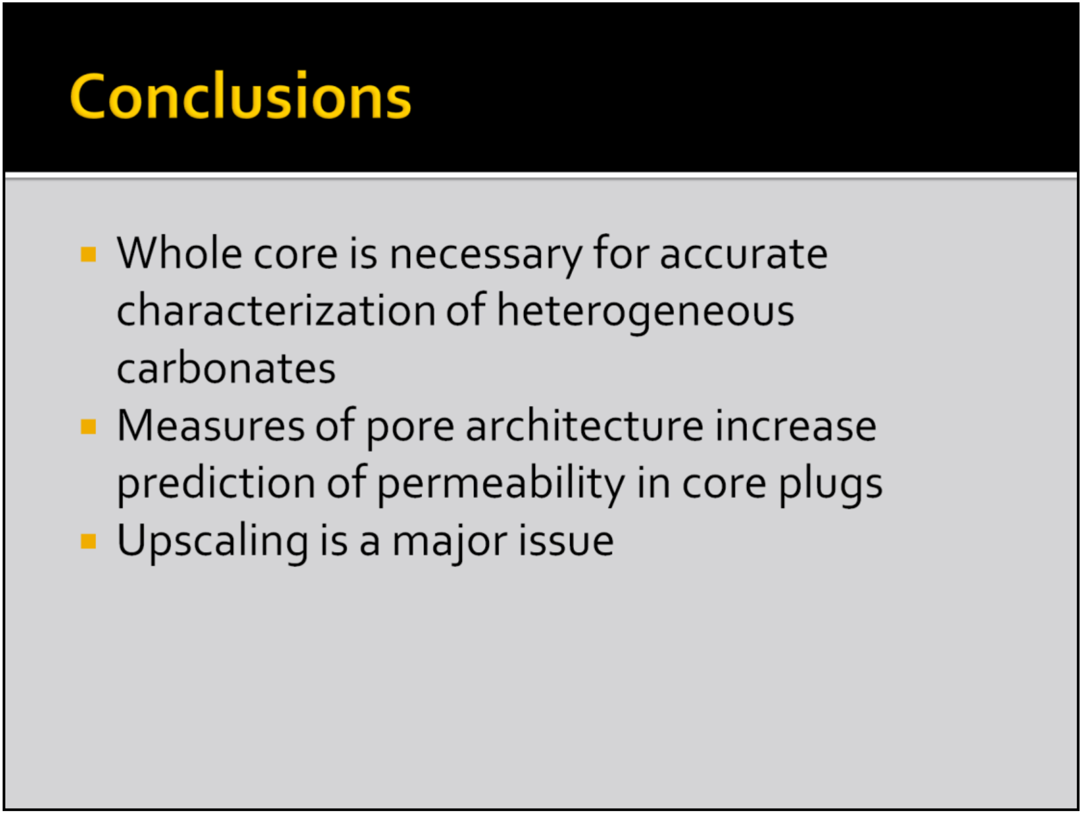


$$lnK = 3.906 lnV_p + 2.263 ln\Phi - 41.722 ln\rho_b + 3.955 ln\gamma - 0.926 lnPOA + 1.005 lnAR + 0.697 lnV_s - 0.310 lnDS - 7.013$$

$R^2 = 0.817$

66% of calculated K are within 1 order of magnitude of measured K when measured K is >1 md

Presenter's notes: MVLR predicts K--resultant equation with accurate R2. Vp is measuring pore architecture.



Conclusions

- Whole core is necessary for accurate characterization of heterogeneous carbonates
- Measures of pore architecture increase prediction of permeability in core plugs
- Upscaling is a major issue

Presenter's notes: Textures are very heterogeneous in Trenton – Black River, and as such, care must be taken when trying to characterize porosity/permeability measures of pore architecture; SV and DIA increased prediction of K in core plugs. Upscaling is difficult due to high degree of heterogeneity.