UT-AUSTIN EDGER FORUM

Rock-physics analysis of composition, fractures, and effective stress

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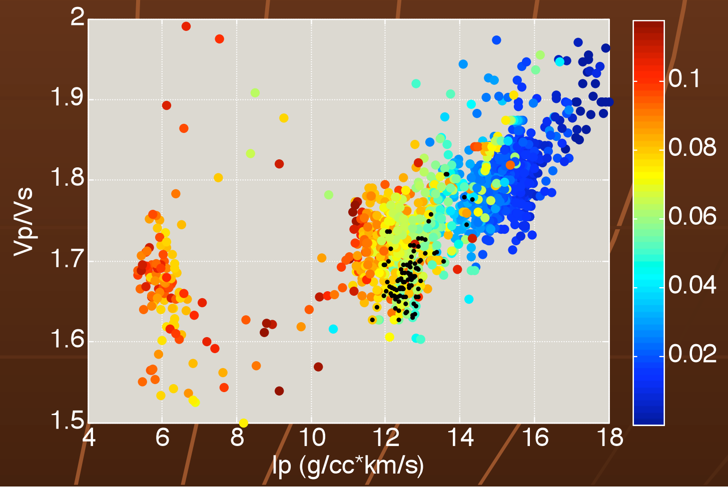
Motivation

The Middle Bakken produces by increased permeability through connected networks of natural fractures and hydraulically induced fracture sets

Rock physics models do not include estimates of elastic properties as a function of both fractures and pores and effective stress

energy.usgs.gov/images/oilgas/section1.jpeg



Outline

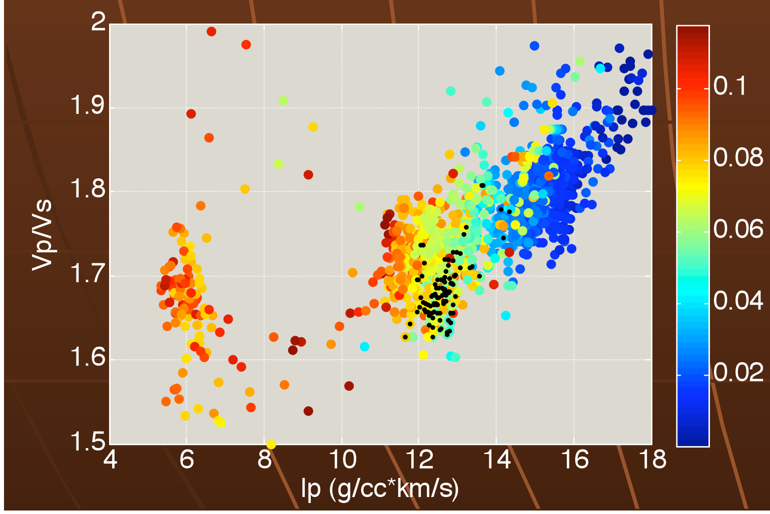
Model density by varying composition

Asses relatively low velocity

Model pore-shape compliances to determine possible pore types

Investigate crack densities and aspect ratios

Address apparent effective stress issues



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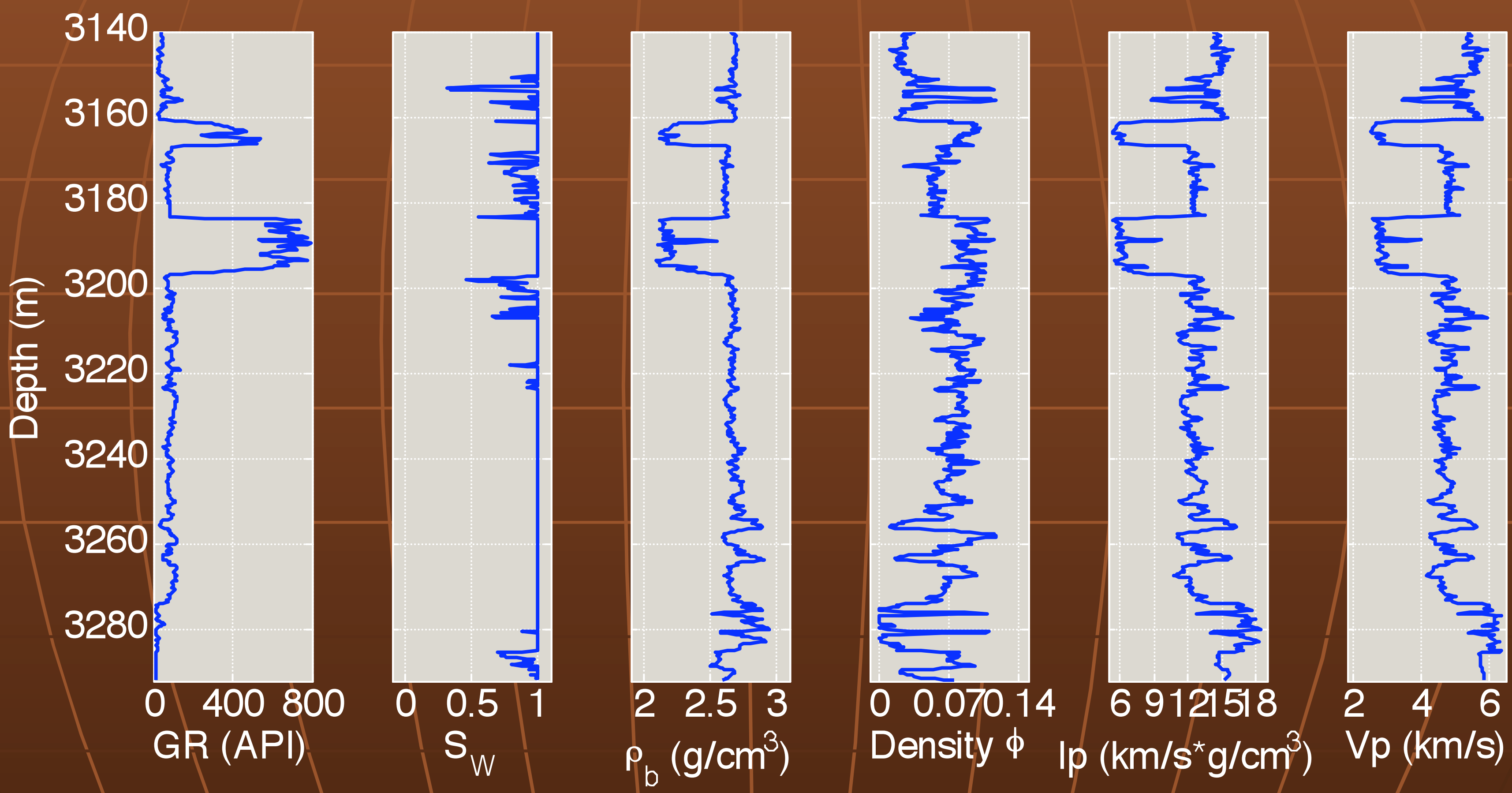
Well data

Annala 11-36H, Sanish Field



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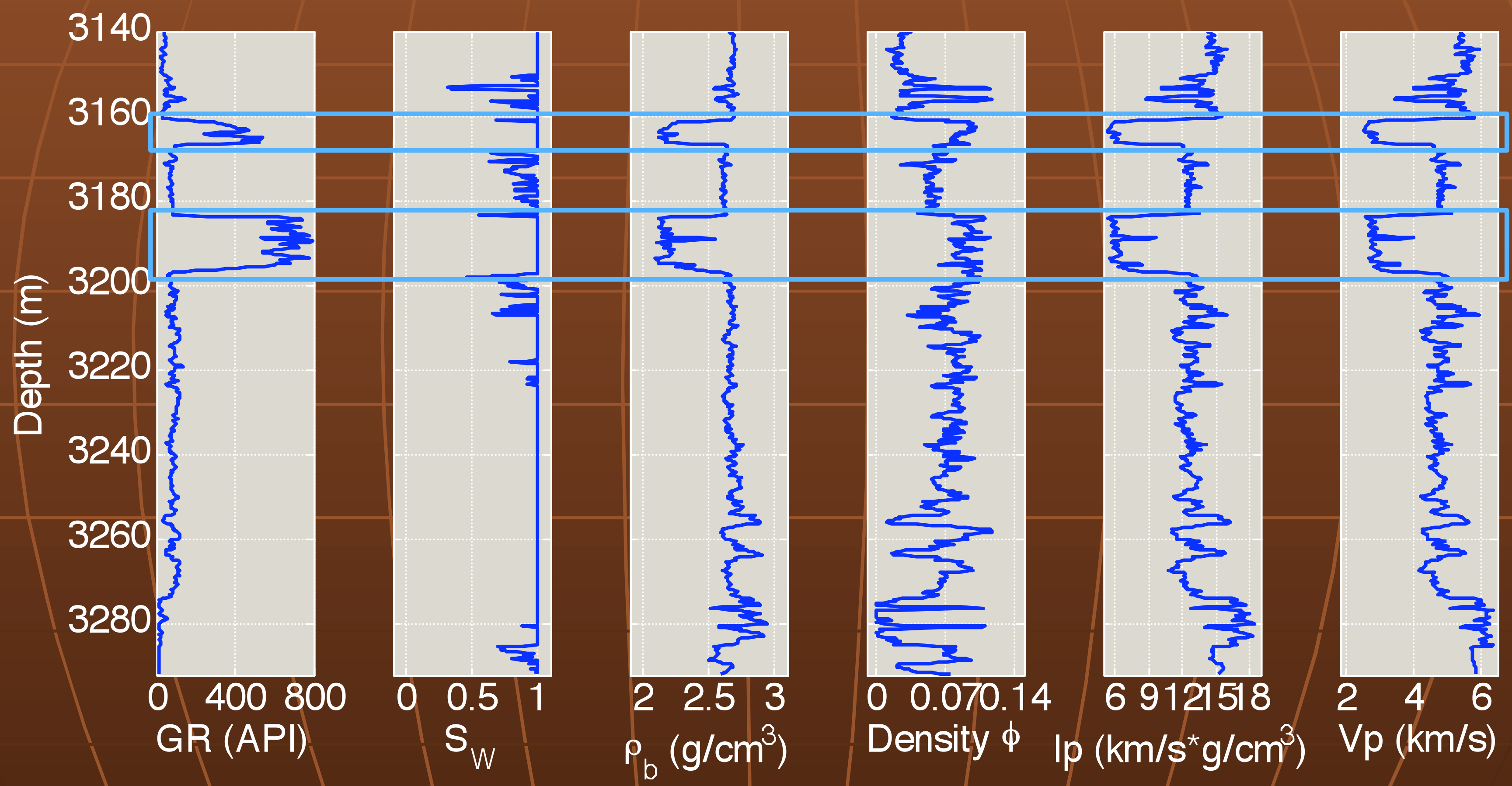

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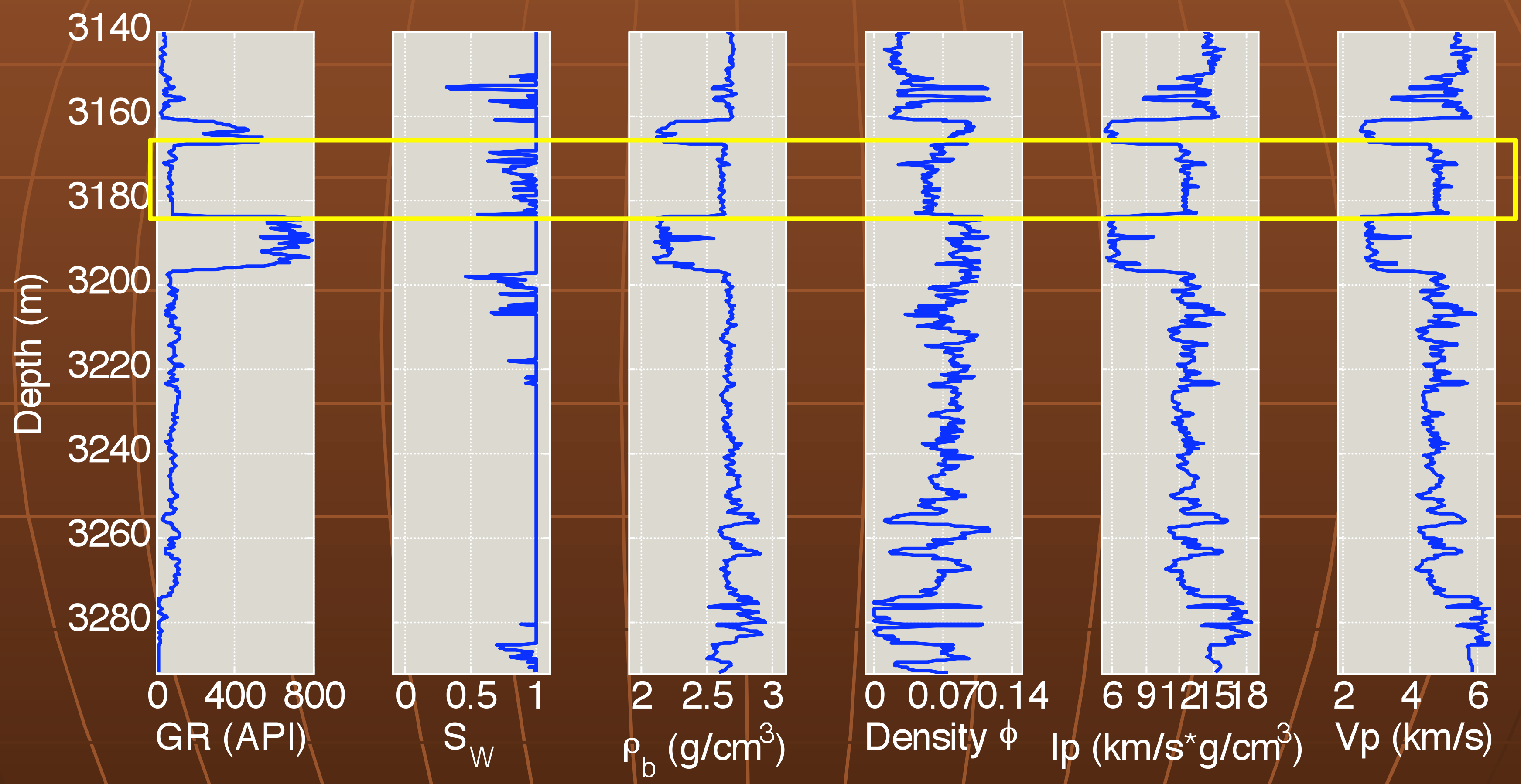
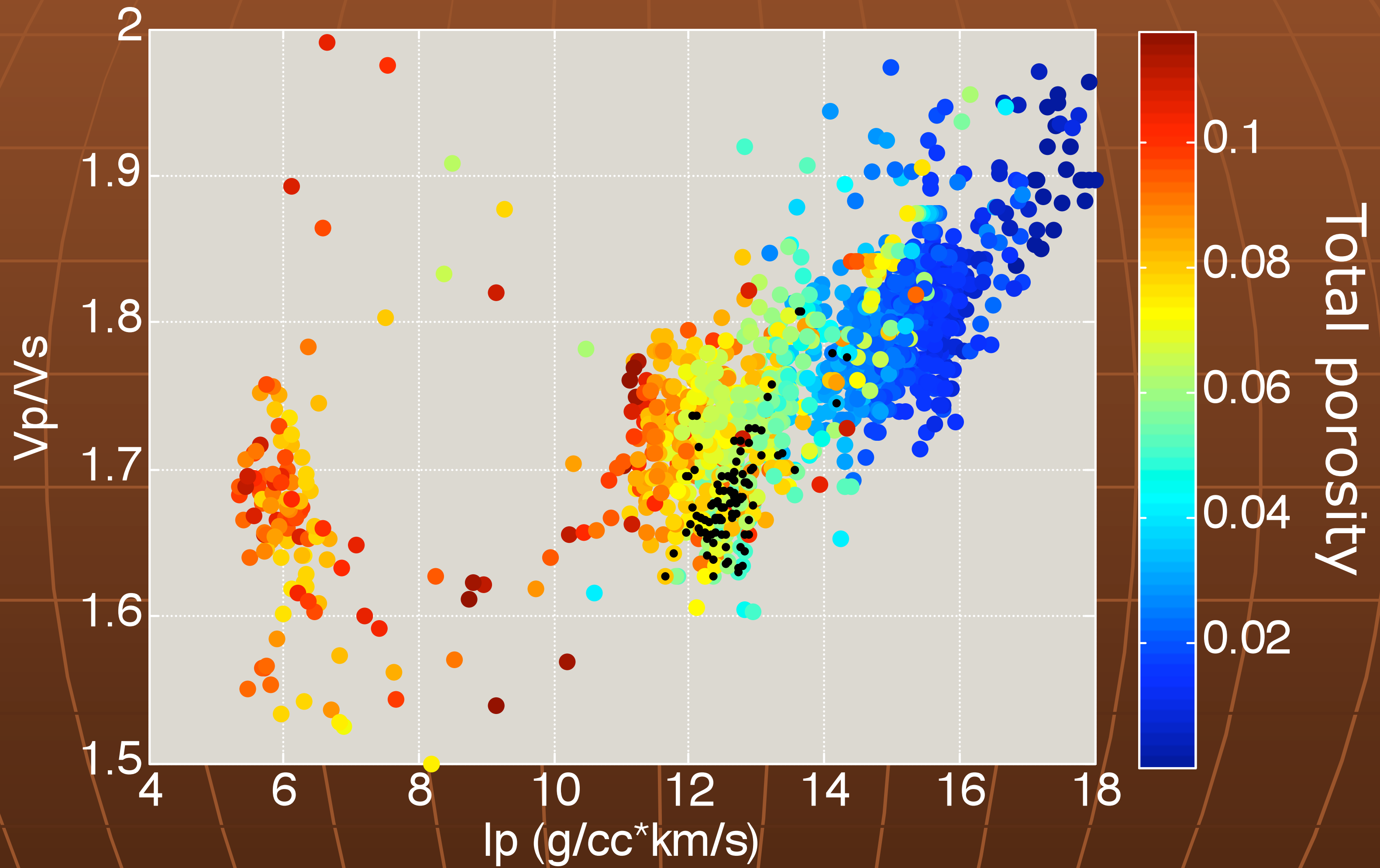
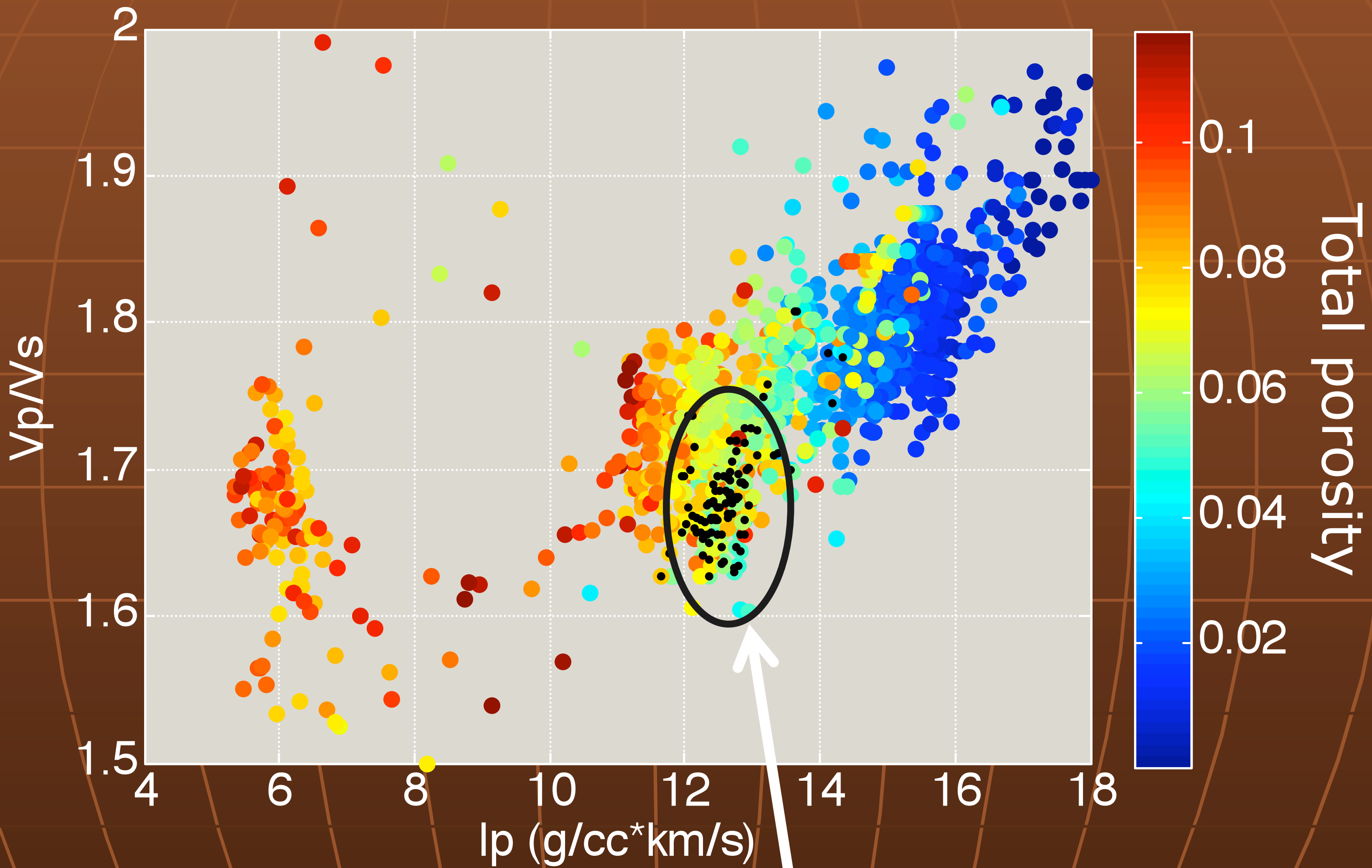


Introduction



Bakken Shale data, Annala 11-36H, Sanish Field

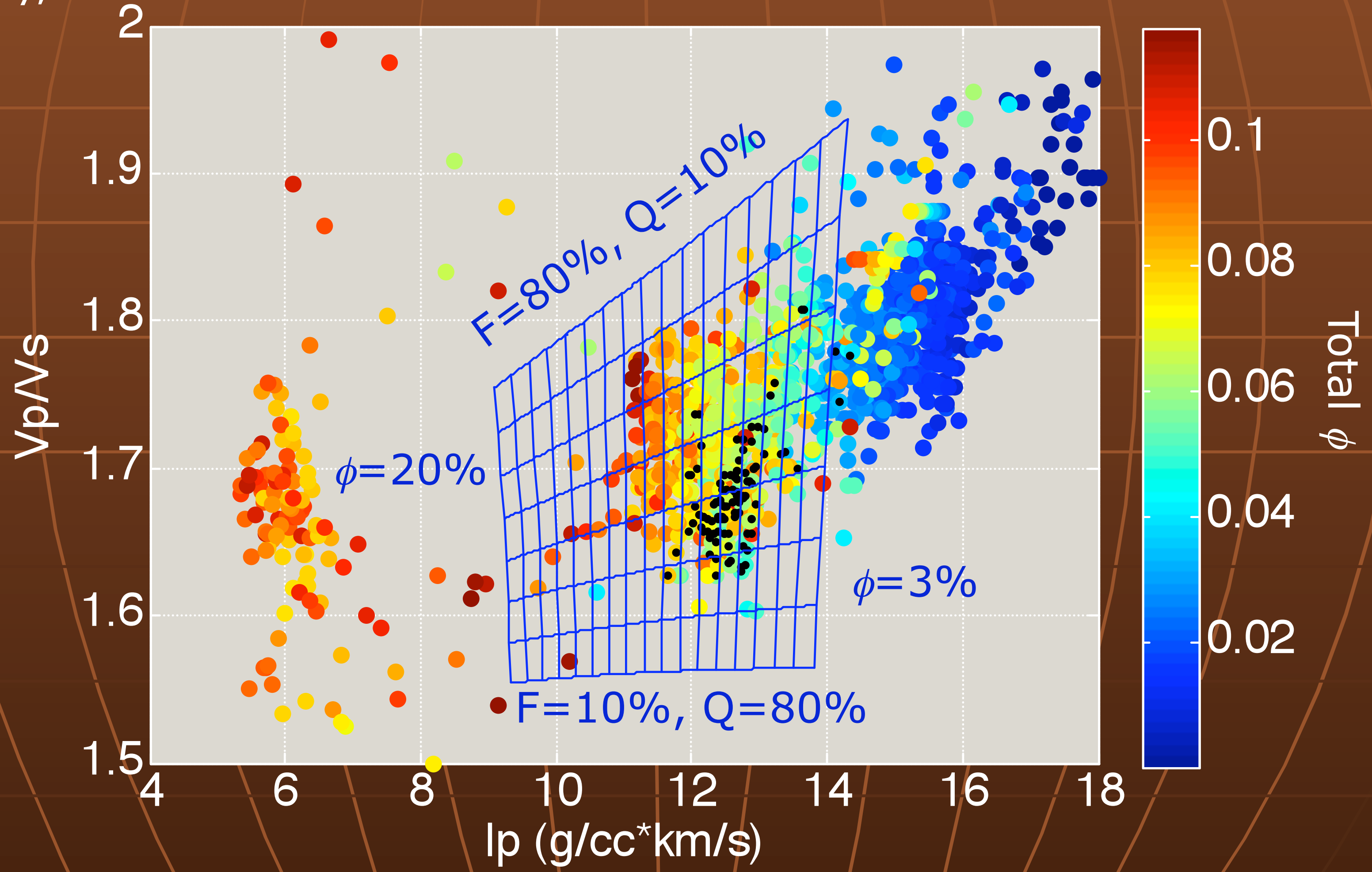
Introduction



Low Vp/Vs in oil-saturated rock.
Why is this ratio low?

Introduction

Contact theory model for a stiff rock
<u>Parameters:</u> Mineralogy, Porosity, Pressure, Critical Porosity, Coordination number.



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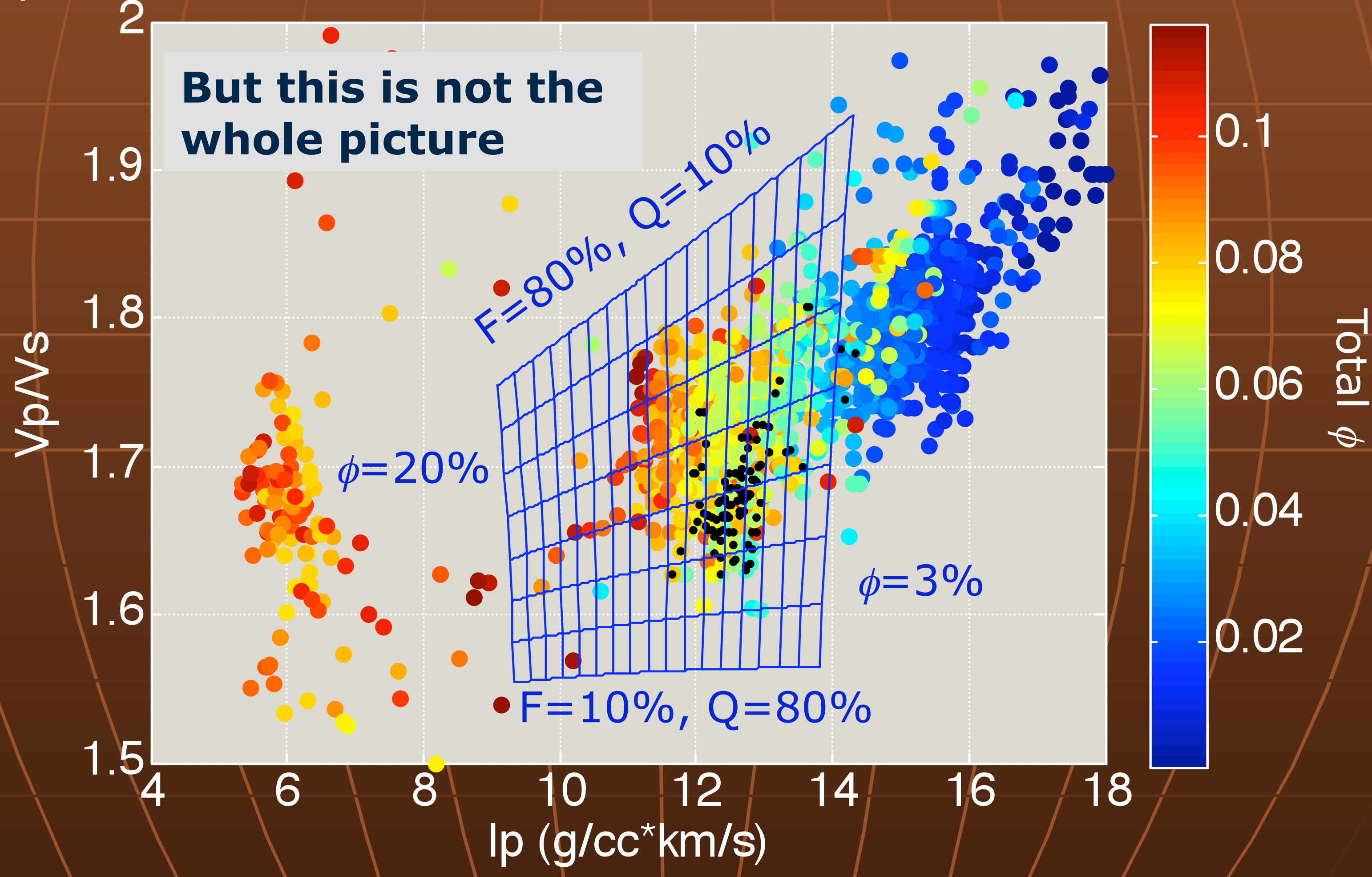

Core and thin section

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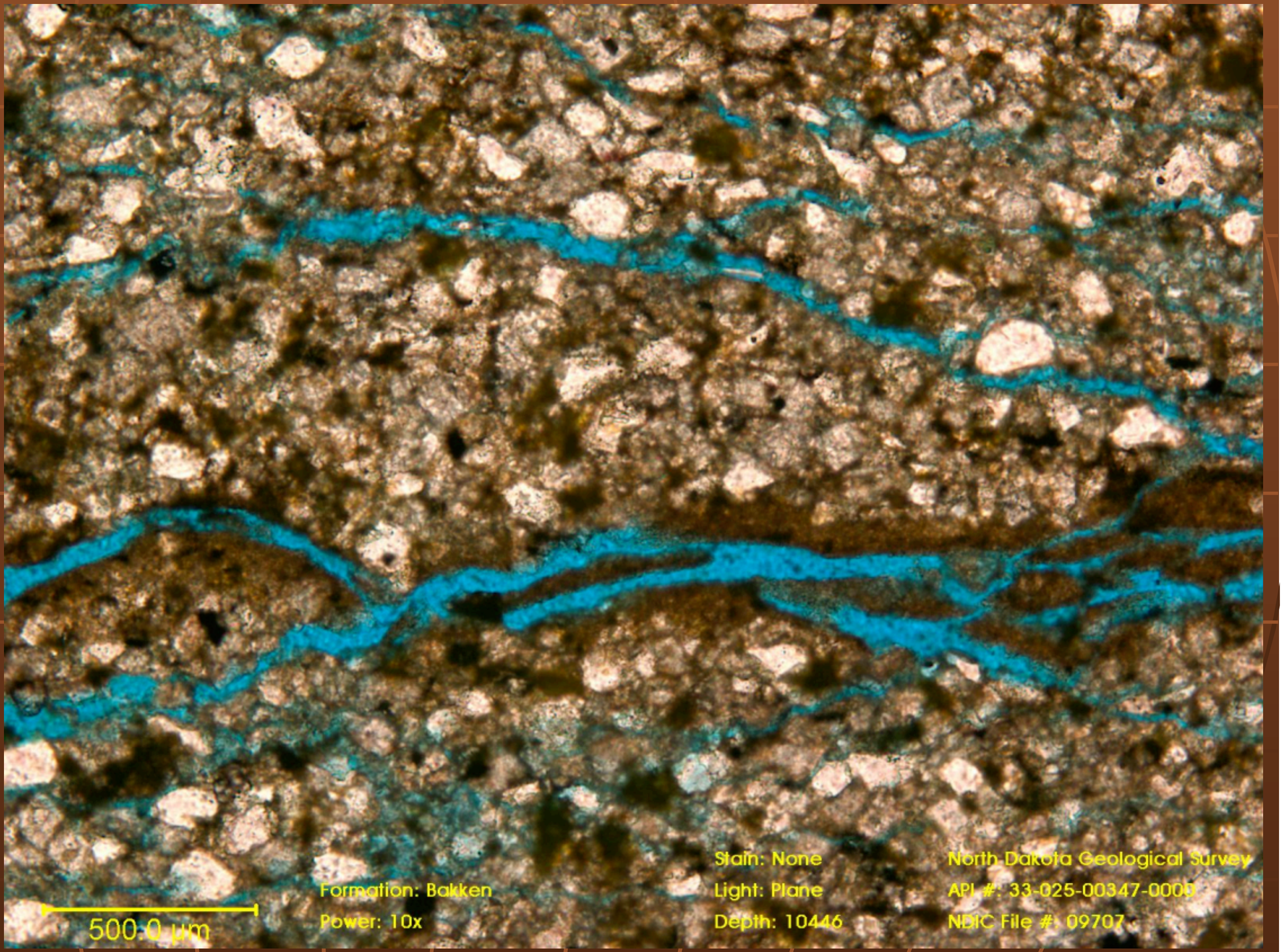
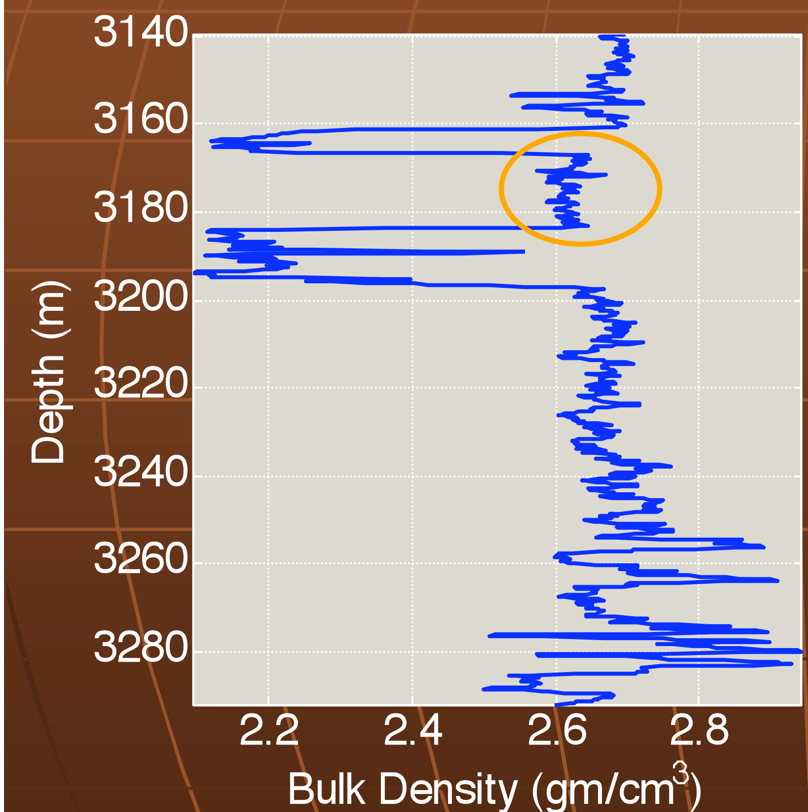
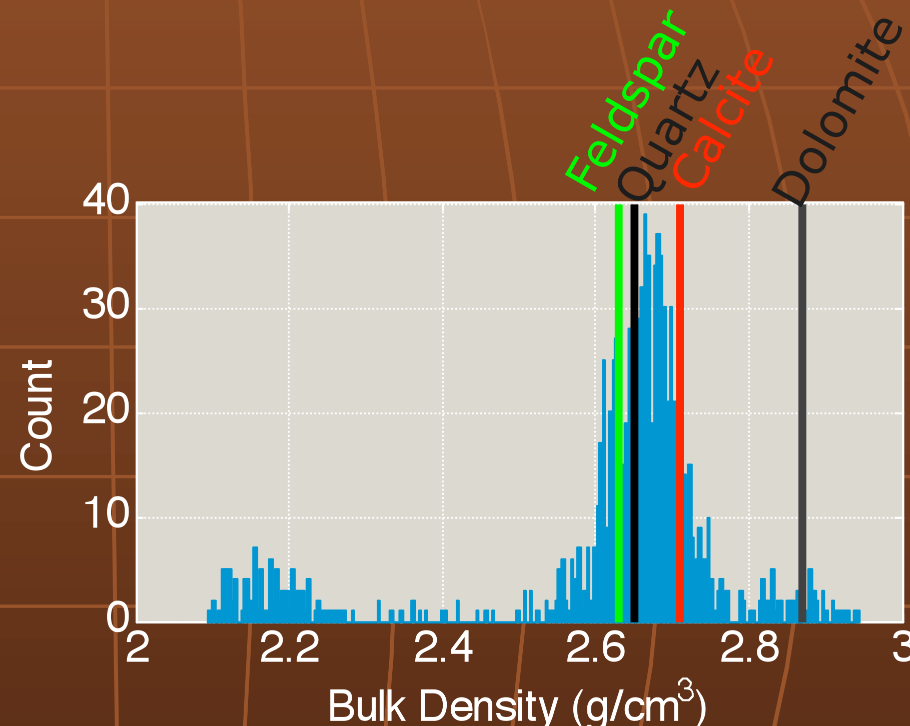
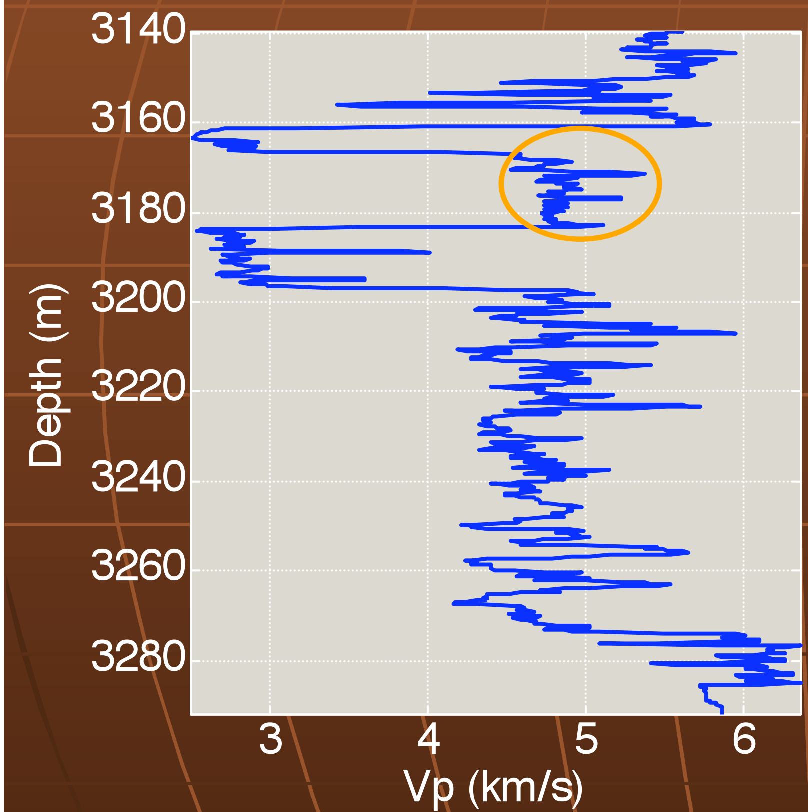


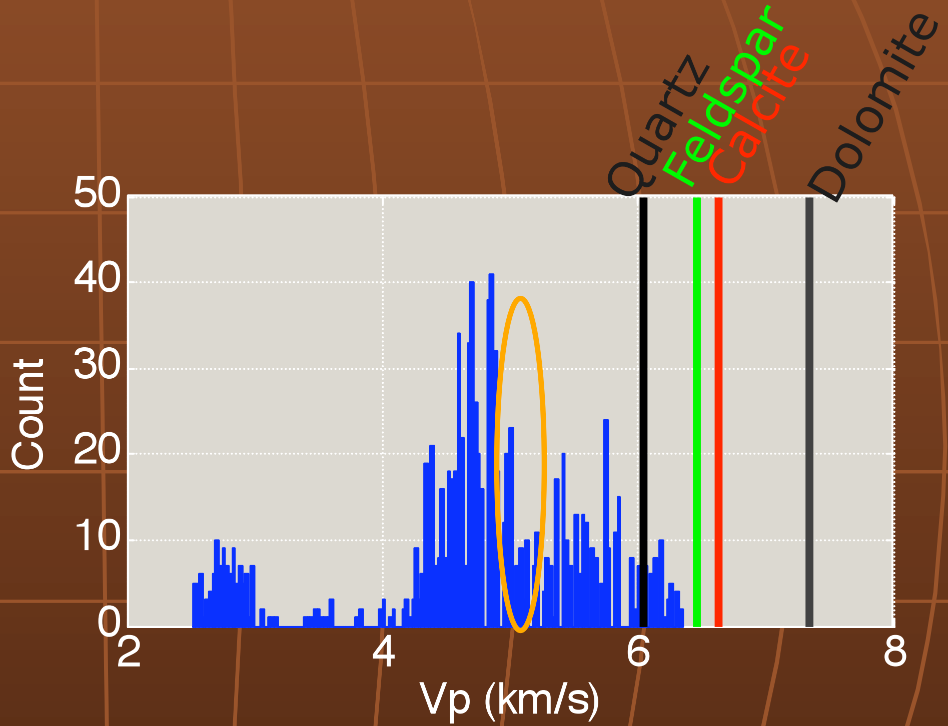
Rock properties—Density



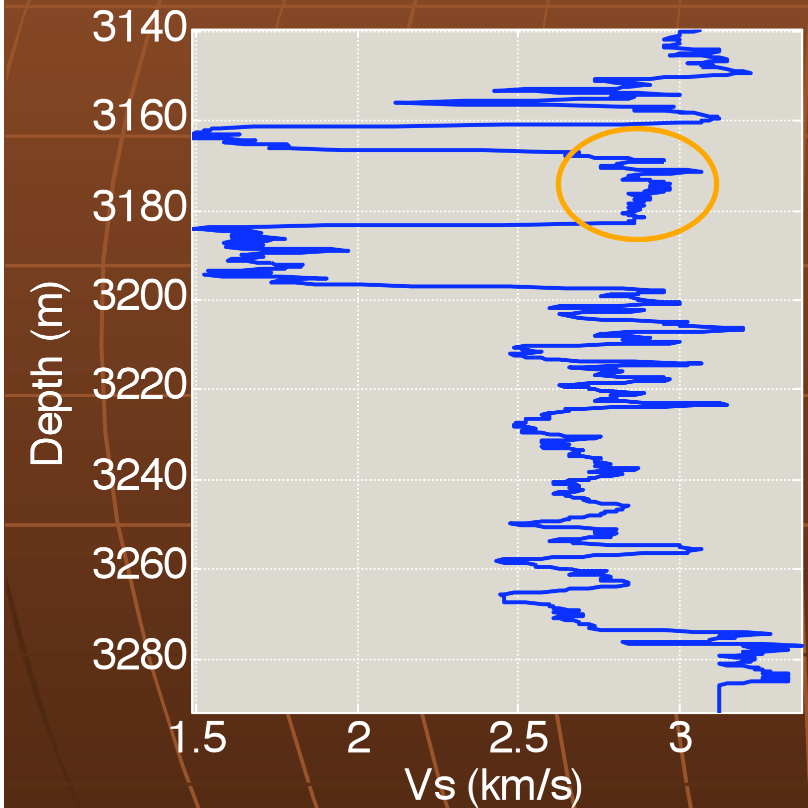


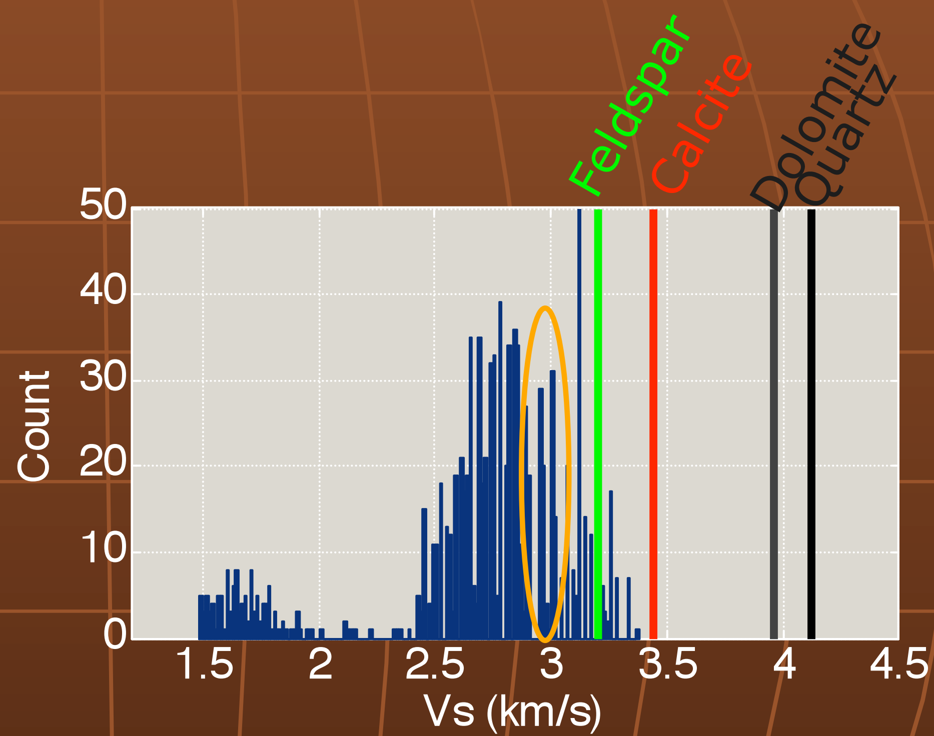
Rock properties—Velocity (P)





Rock properties—Velocity (S)





Rock properties—Bulk modulus

Stress-induced pore-volume change for a saturated case for low frequencies.

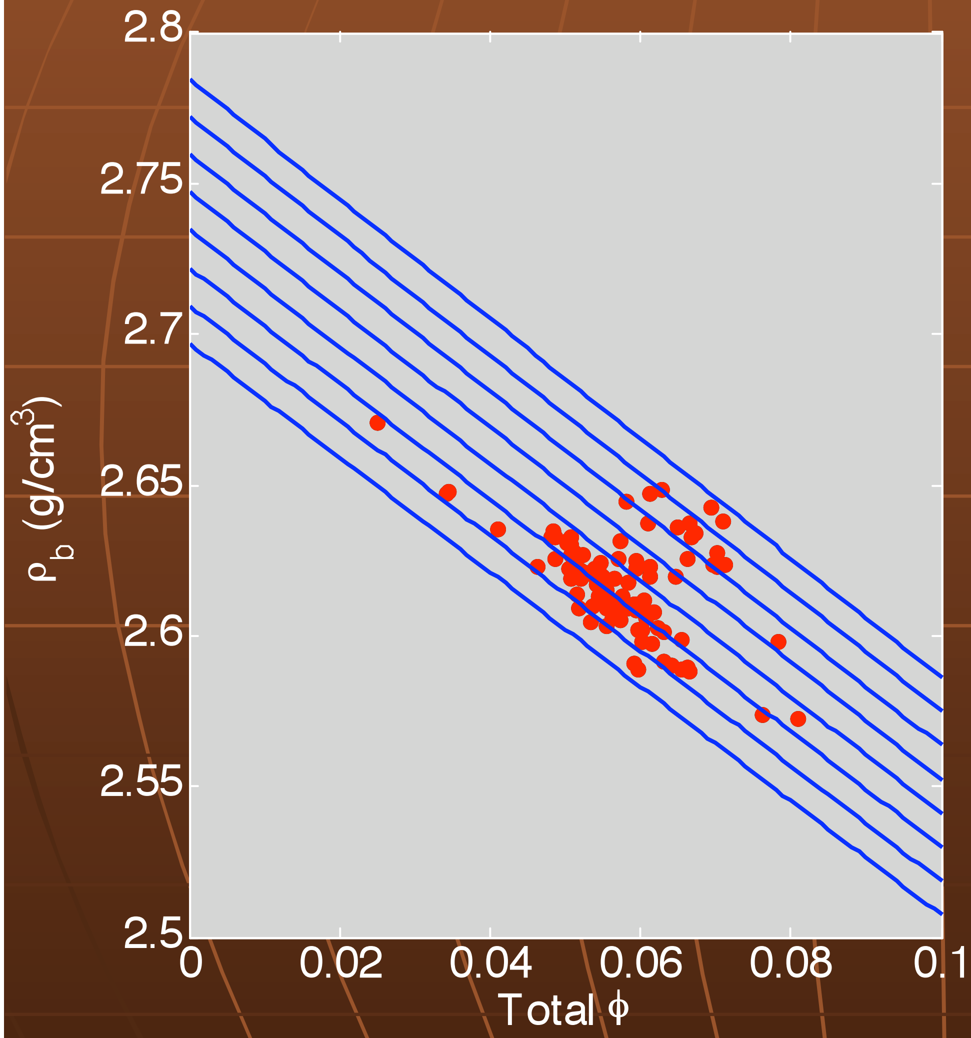
$$K_{Sat} = \frac{1}{K_{solid}} + \frac{\phi}{K_{\phi} + \dfrac{K_{solid}K_f}{K_{solid} - K_f}}$$

$$K_{\phi} = \frac{\phi}{\dfrac{1}{K_{Sat}} - \dfrac{1}{K_{solid}}} - \frac{K_{solid}K_f}{K_{solid} - K_f}$$

Model lines shown previously

From same bounds for a solid

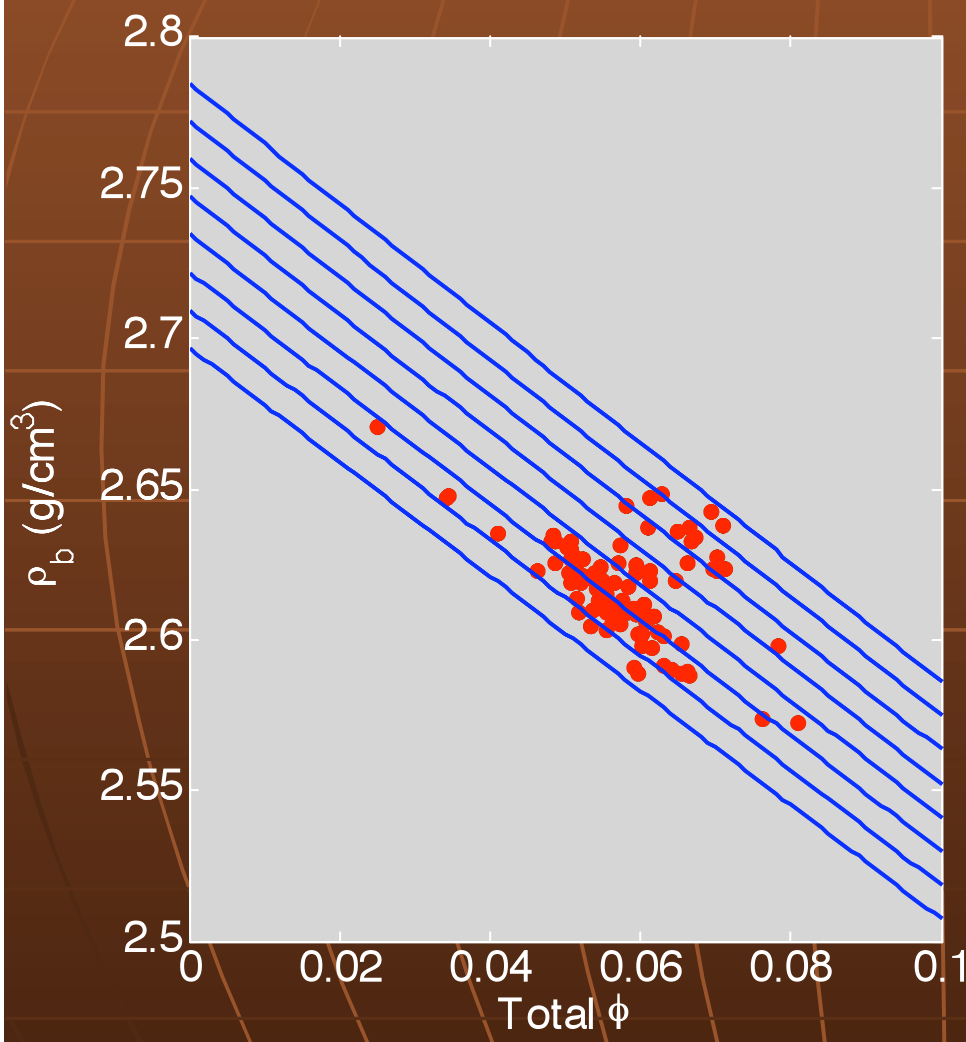
Rock properties—Density



Composition

Quartz content: 20%
Clay content: 10%
Feldspar content: 5 to 40%
Dolomite: 65 to 30%

Rock properties—Density



Significant dolomite fraction necessary

What are the implications?

Low velocities?

Can carbonate component and clastic component be modeled in the same way?

Rock properties—Shear modulus

Hashin-Shtrikman-Walpole bounds

Similar to Hashin-Shtrikman bounds

Incorporate multiple phases

Make no assumptions about grain geometry

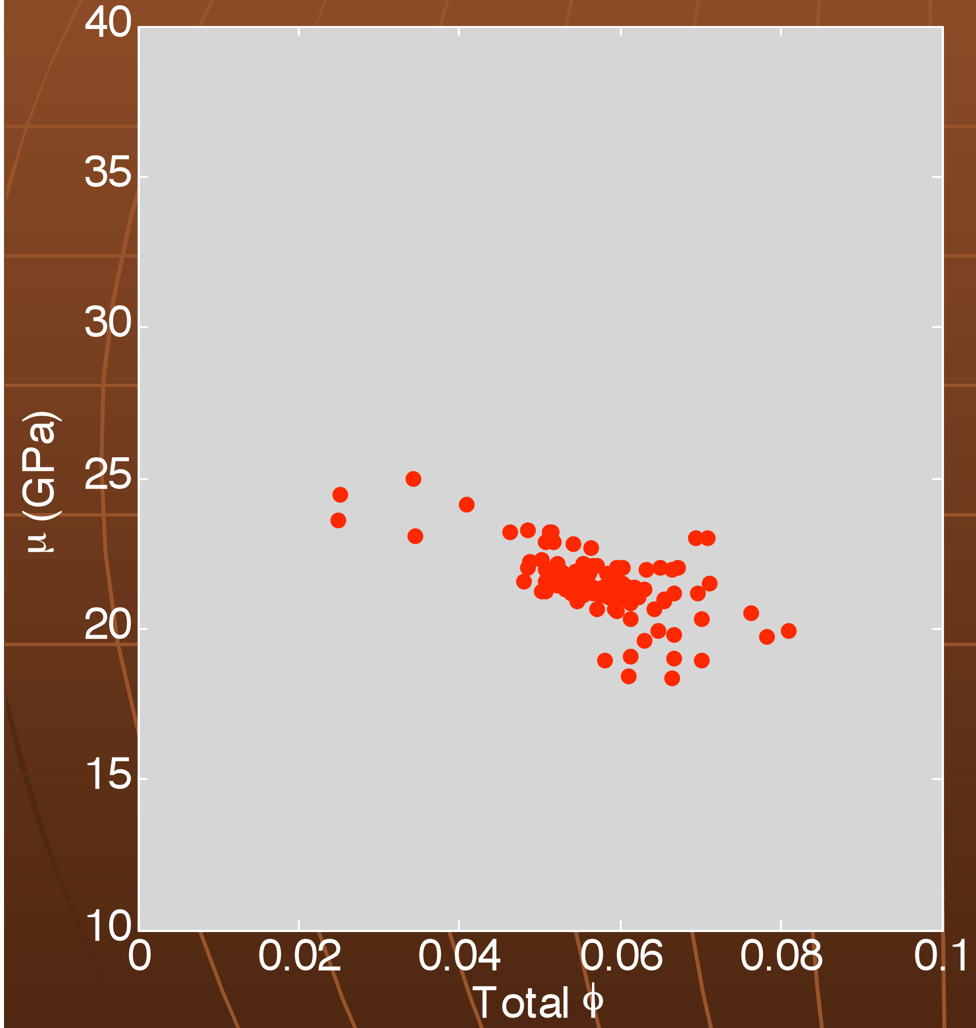
$$\mu^{HSW-} = \left[\frac{\phi}{\mu_f + \Psi} + \sum_{j=1}^{N} \frac{(1-\phi) f_j}{\mu_j + \Psi} \right]^{-1} - \Psi$$

$$\mu^{HSW+} = \left[\frac{\phi}{\mu_f + \mathrm{X}} + \sum_{j=1}^{N} \frac{(1-\phi) f_j}{\mu_j + \mathrm{X}} \right]^{-1} - \mathrm{X}$$

$$\Psi = \frac{\mu_{\min}}{6} \left(\frac{9K_{\min} + 8\mu_{\min}}{K_{\min} + 2\mu_{\min}} \right)$$

$$\mathrm{X} = \frac{\mu_{\max}}{6} \left(\frac{9K_{\max} + 8\mu_{\max}}{K_{\max} + 2\mu_{\max}} \right)$$

Rock properties—Shear modulus



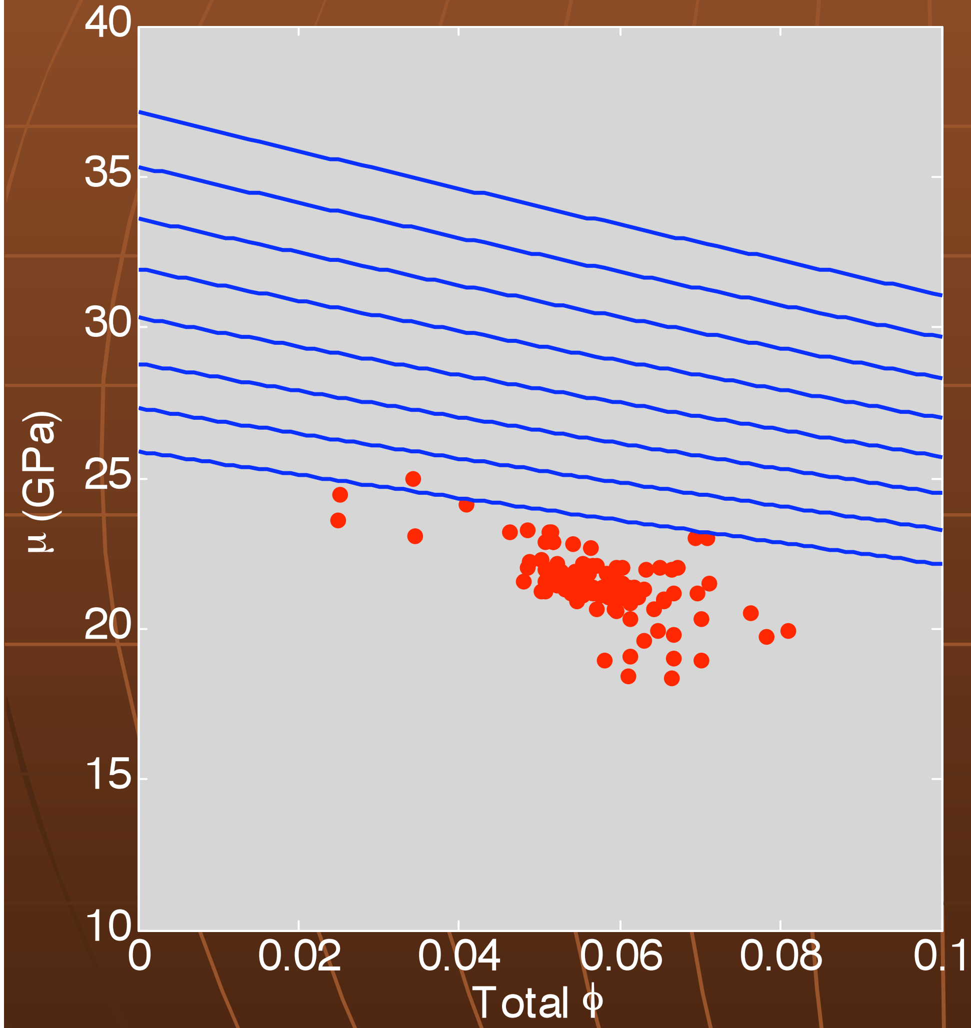
Which rock-physics model is correct to use?

This is difficult to answer.

Have an estimate of mineralogy and confining pressure (from depth).

Start with mineralogy by comparing the data to some theoretical bounds.

Rock properties—Shear modulus



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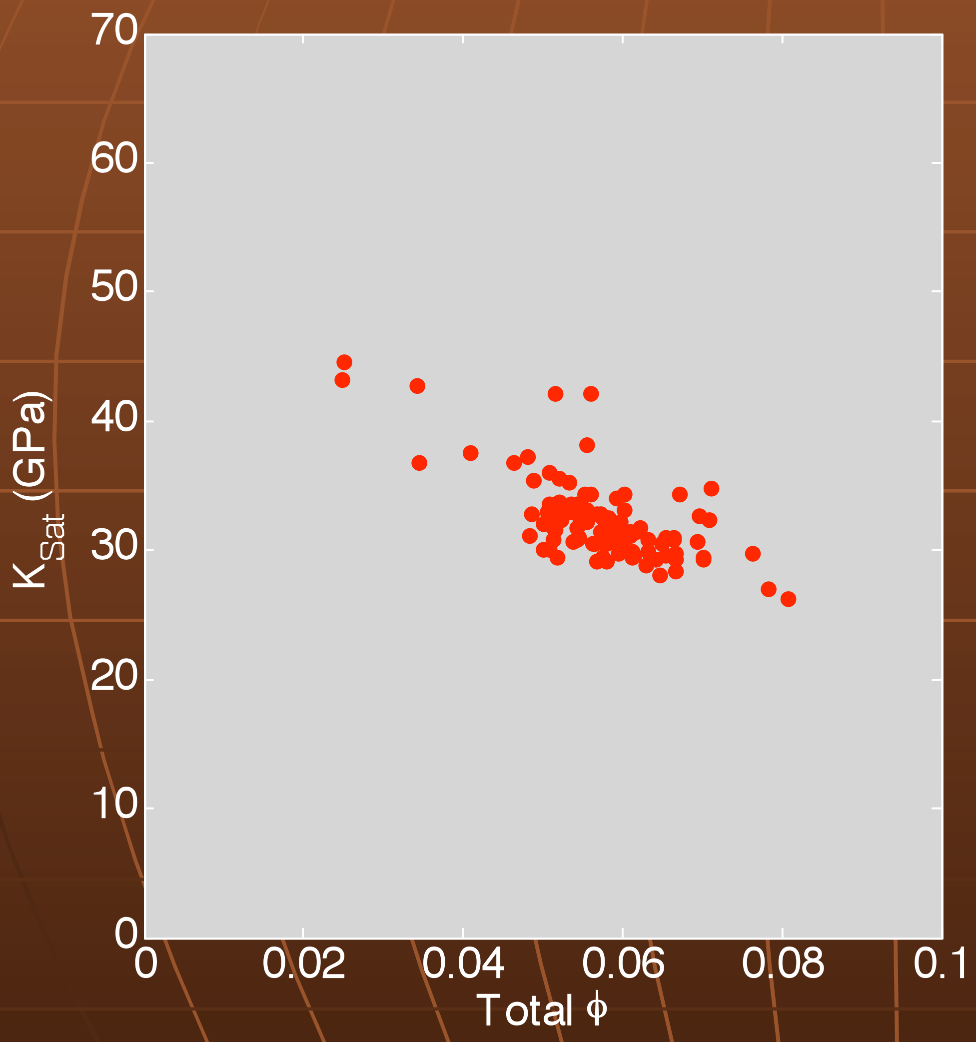
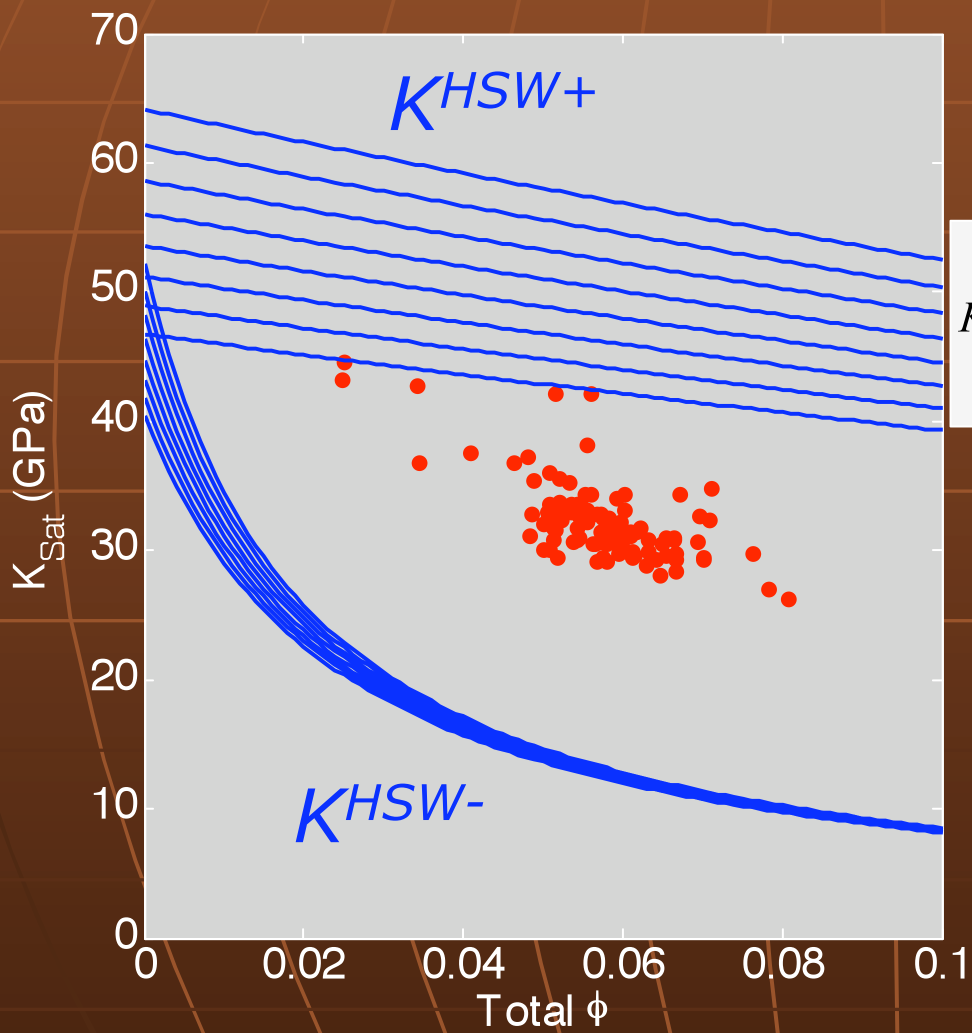
$$K_\phi = \frac{\phi}{\dfrac{1}{K_{Sat}} - \dfrac{1}{K_{solid}}} - \frac{K_{solid} K_f}{K_{solid} - K_f}$$

$$\frac{1}{K_{Dry}} = \frac{1}{K_{solid}} + \frac{\phi}{K_\phi}$$

Rock properties—Bulk modulus



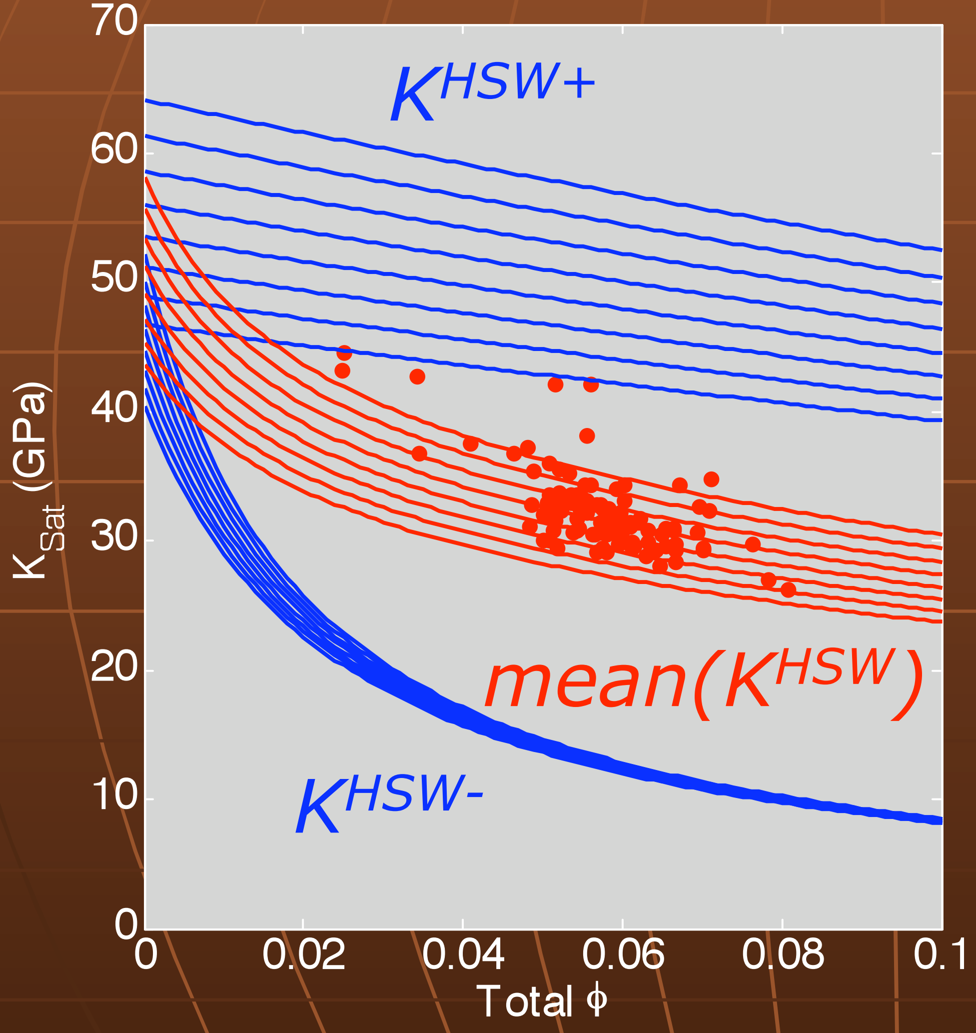
Rock properties—Bulk modulus



$$K^{HSW+} = \left[\frac{\phi}{K_f + \frac{4}{3}\mu_{\max}} + \sum_{j=1}^{N} \frac{(1-\phi) f_j}{K_j + \frac{4}{3}\mu_{\max}} \right]^{-1} - \frac{4}{3}\mu_{\max}$$

$$K^{HSW-} = \left[\frac{\phi}{K_f} + \sum_{j=1}^{N} \frac{(1-\phi) f_j}{K_j} \right]^{-1} - \frac{4}{3}\mu_{\min}$$

Rock properties—Bulk modulus



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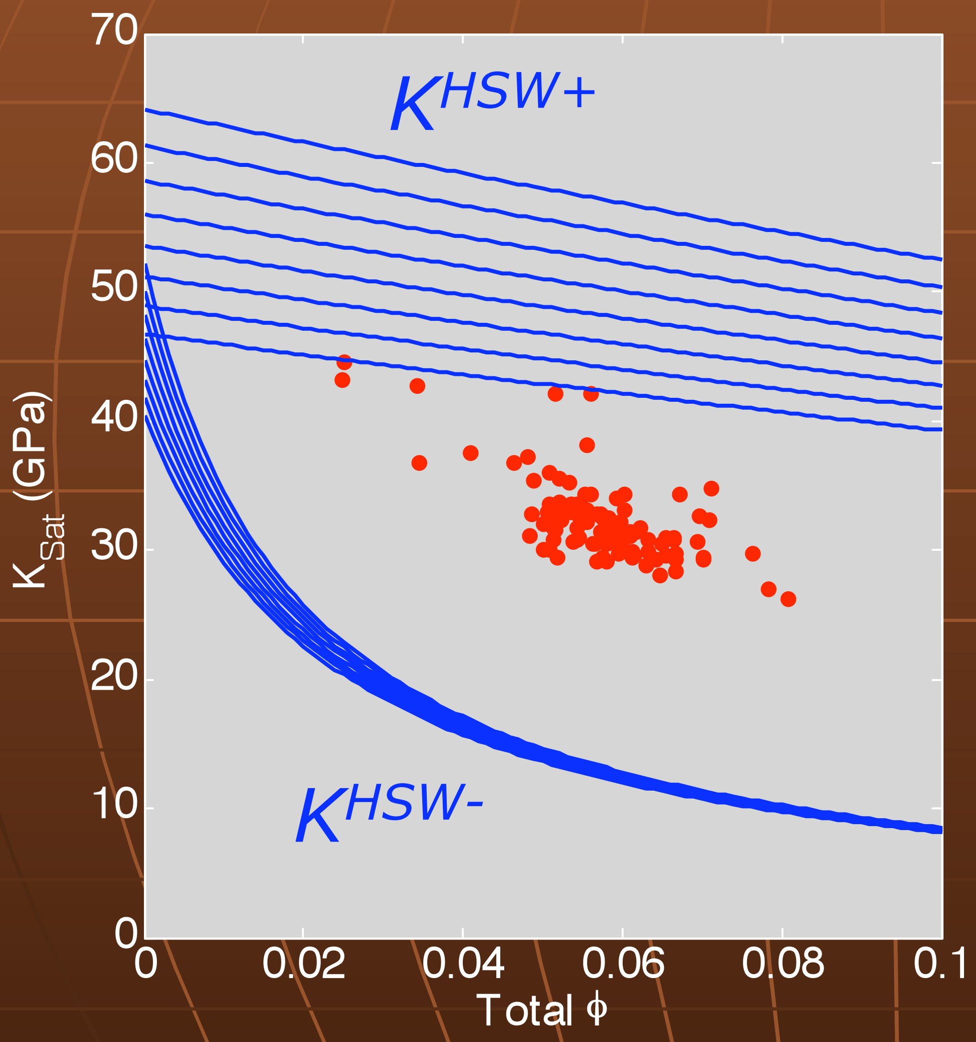

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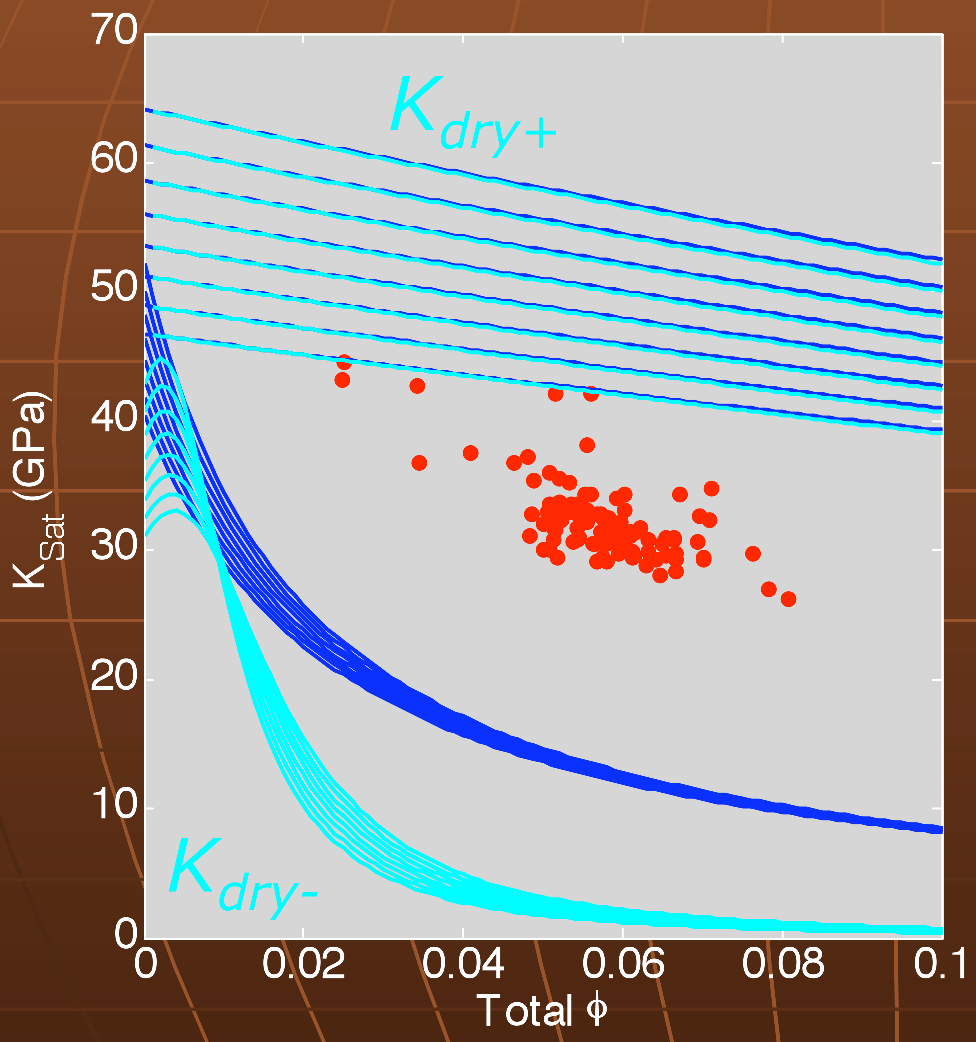

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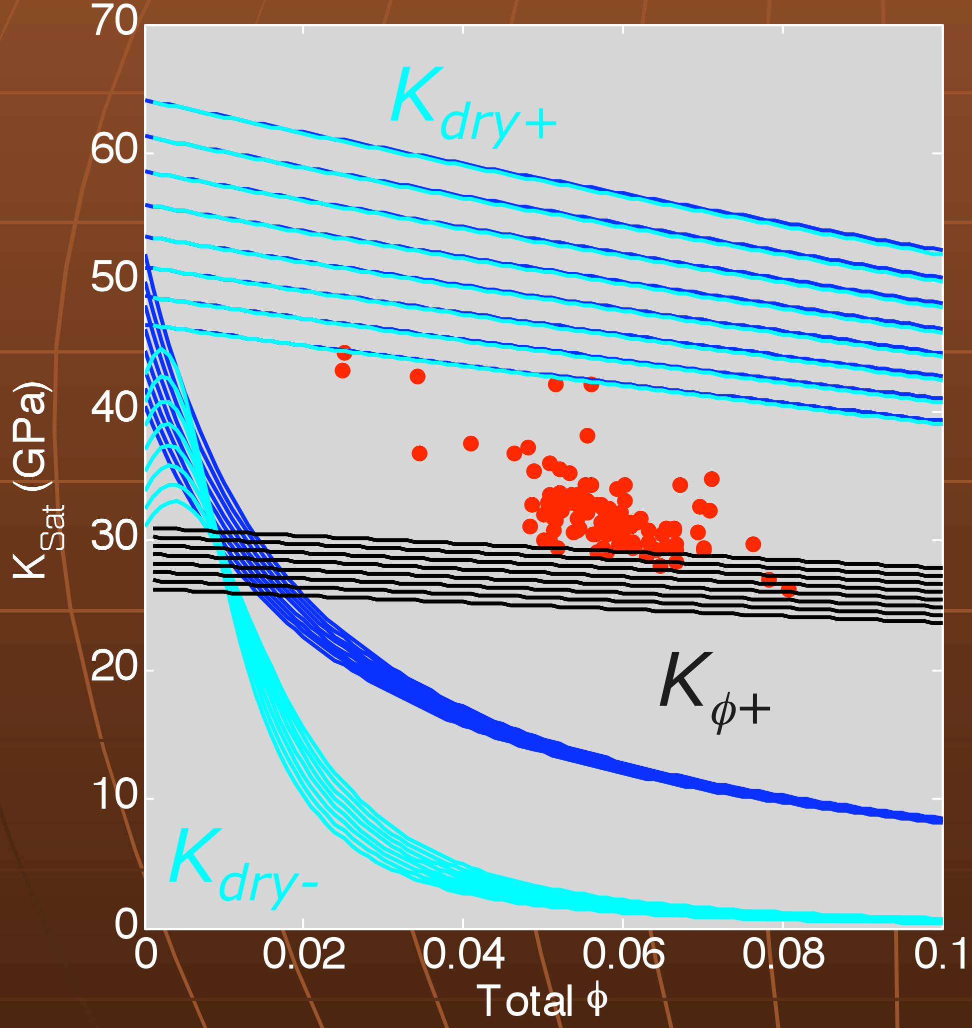

K_ϕ non-negligible

Pore-space compliance needs to be modeled

Porous media?
Fractured media?
Porous and fractured media?

Effective stress coefficients

$$X = f_x(P_C - n_x P_p), n_x \leq 1$$

X is each rock property (e.g., porosity, permeability, elastic moduli, etc.)

n_x is the effective stress coefficient for the property X

$$P_C - nP_p$$

Effective pressure
(Confining minus Pore)

$$\sigma_{ij}^{eff} = \sigma_{ij}^{C} - nP_P\delta_{ij}$$

Effective stress
(general case)

Effective stress coefficients

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X is each rock property (e.g., porosity, permeability, elastic moduli, etc.)

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$$P_C - nP_p$$

Effective pressure

$$\sigma_{ij}^{eff} = \sigma_{ij}^{C} - nP_P\delta_{ij}$$

In general, effective stress

Pressure dependence of each rock property, X, is a linear combination of the effective pressure. Observed and theorized at laboratory scales.

The pressure-induced bulk volume increment δ_{V_T} depends on pore pressure increments

$$\delta PC - n_{V_T}\delta P_p$$

Only in this particular case then is

$$n_{V_T} = n_{BW} = 1 - \frac{K_{dry}}{K_{solid}}$$

n_{BW} is incorrectly used for the effective stress coefficient for other rock properties (Mavko and Vanorio, 2010)

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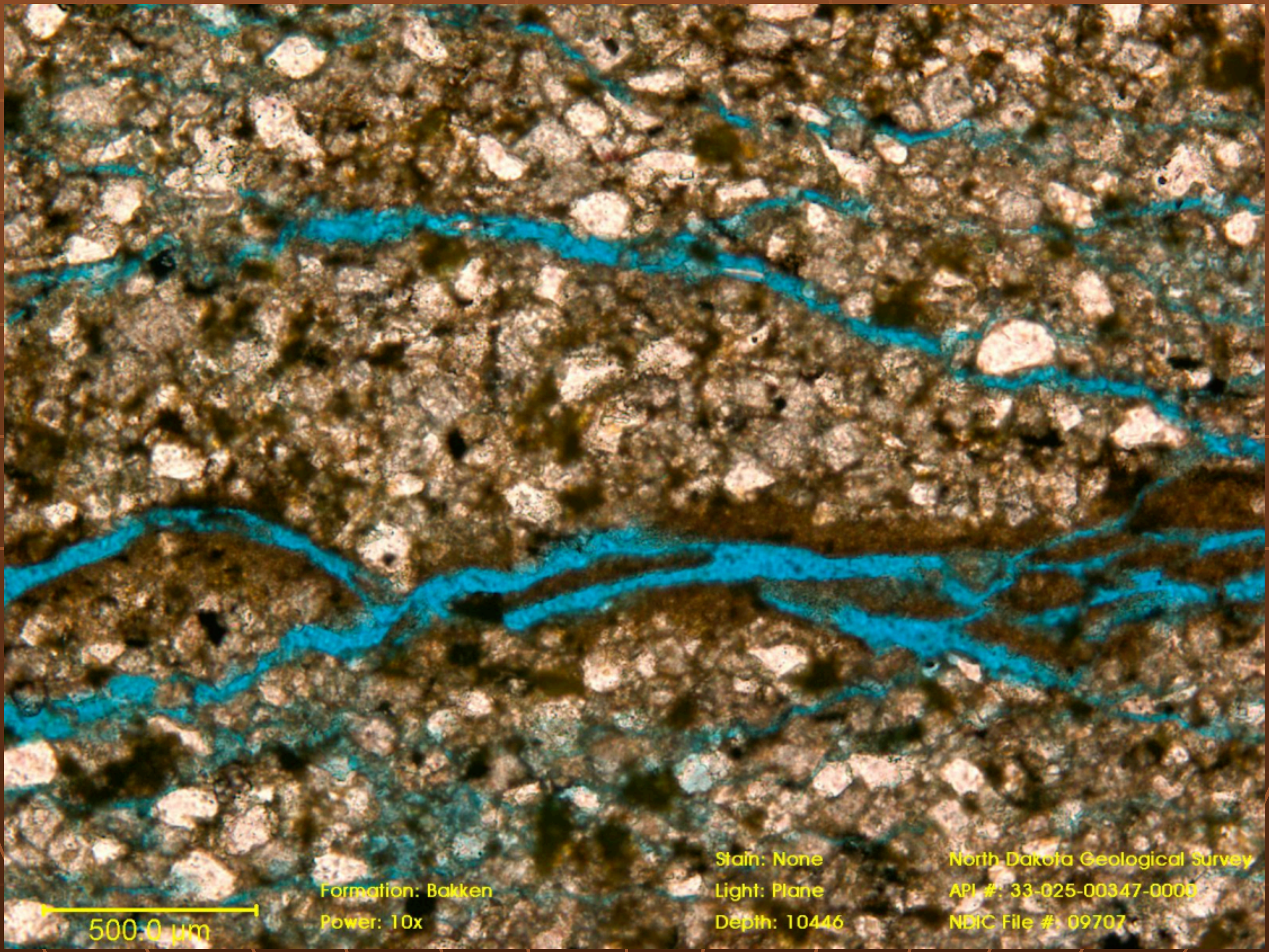
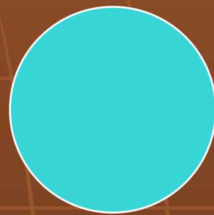


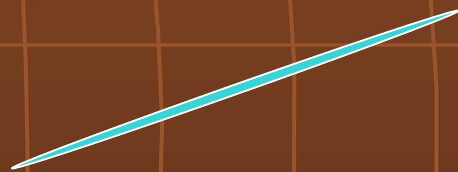
Pore stiffnesses: Ideal shapes

Spherical pores



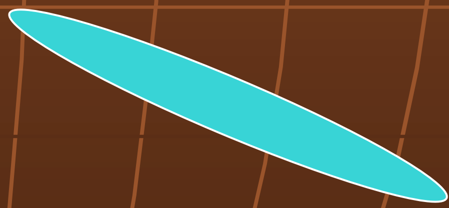
$$\frac{1}{K_\phi} = \frac{1}{K_0}\,\frac{3(1-\nu)}{2(1-2\nu)}$$

Needle shaped pores



$$\frac{1}{K_\phi} = \frac{5-4\nu}{3K_0(1-2\nu)}$$

Cracked-shaped pores

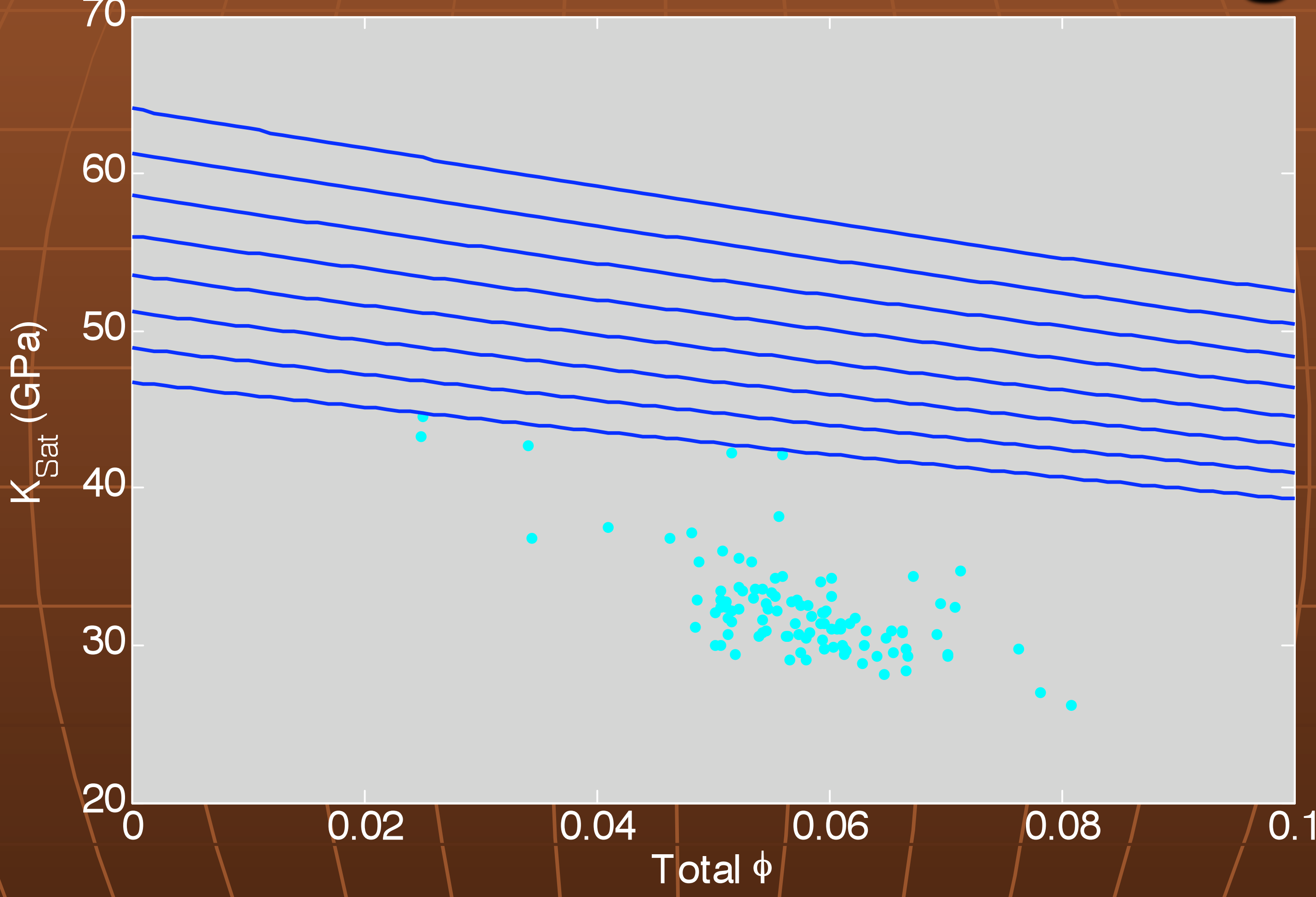


$$\frac{1}{K_\phi} = \frac{4(c/a)}{3\pi K_0}\,\frac{(1-\nu^2)}{(1-2\nu)}$$

$K_0 = K_{solid} = K_{mineral}$

$\alpha = (c/a)$, the aspect ratio

Pore-stiffness modeling



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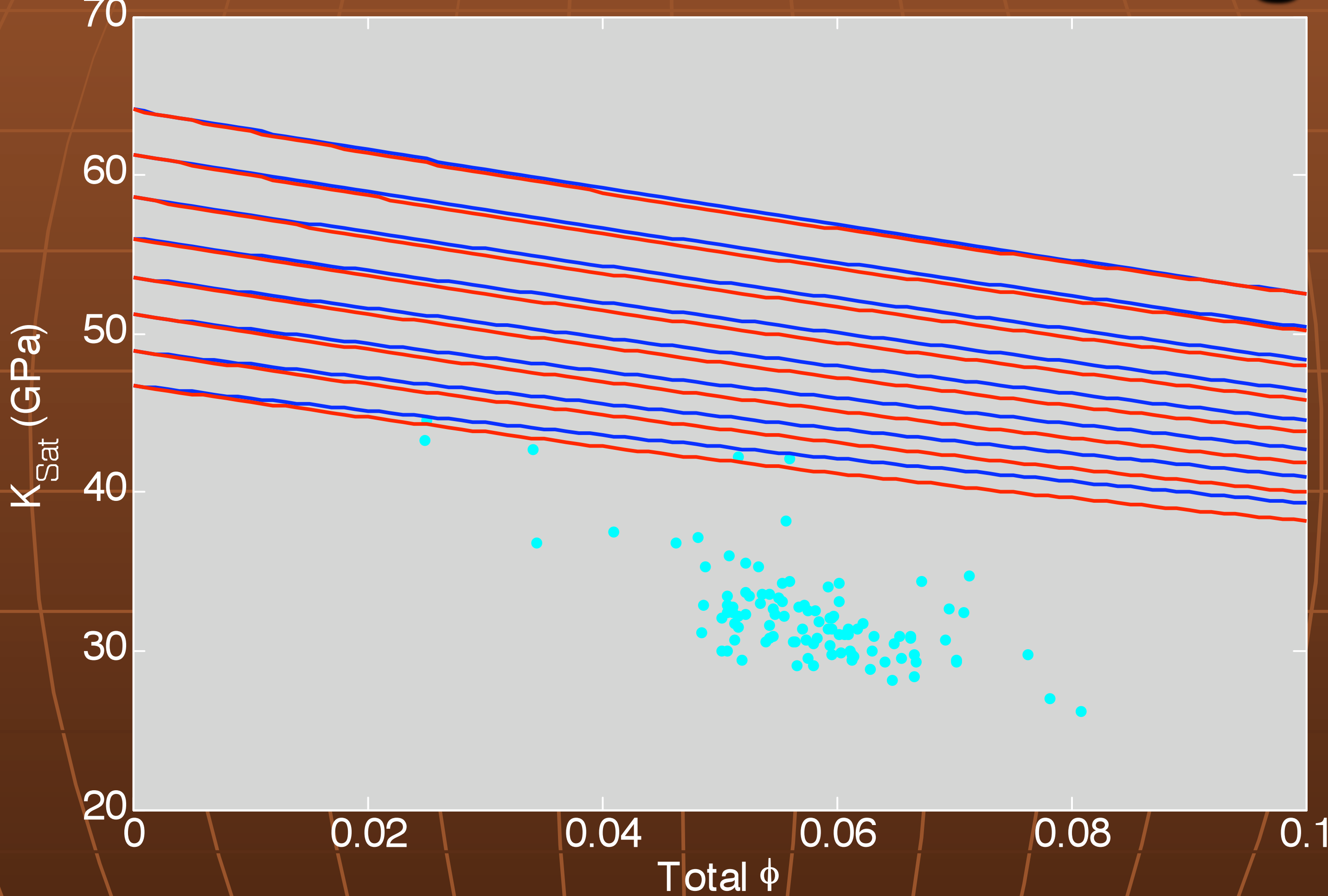
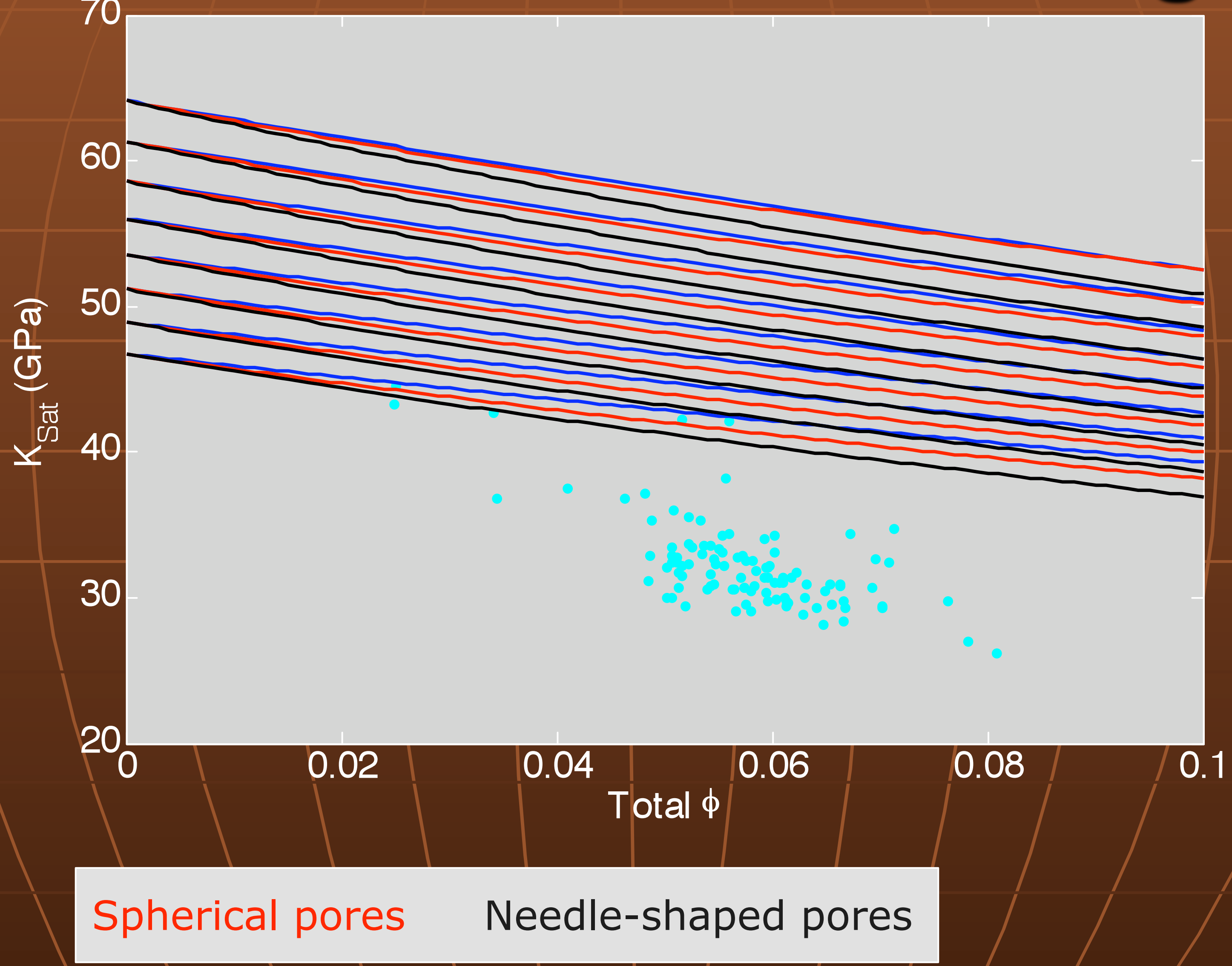


Spherical pores

Pore-stiffness modeling



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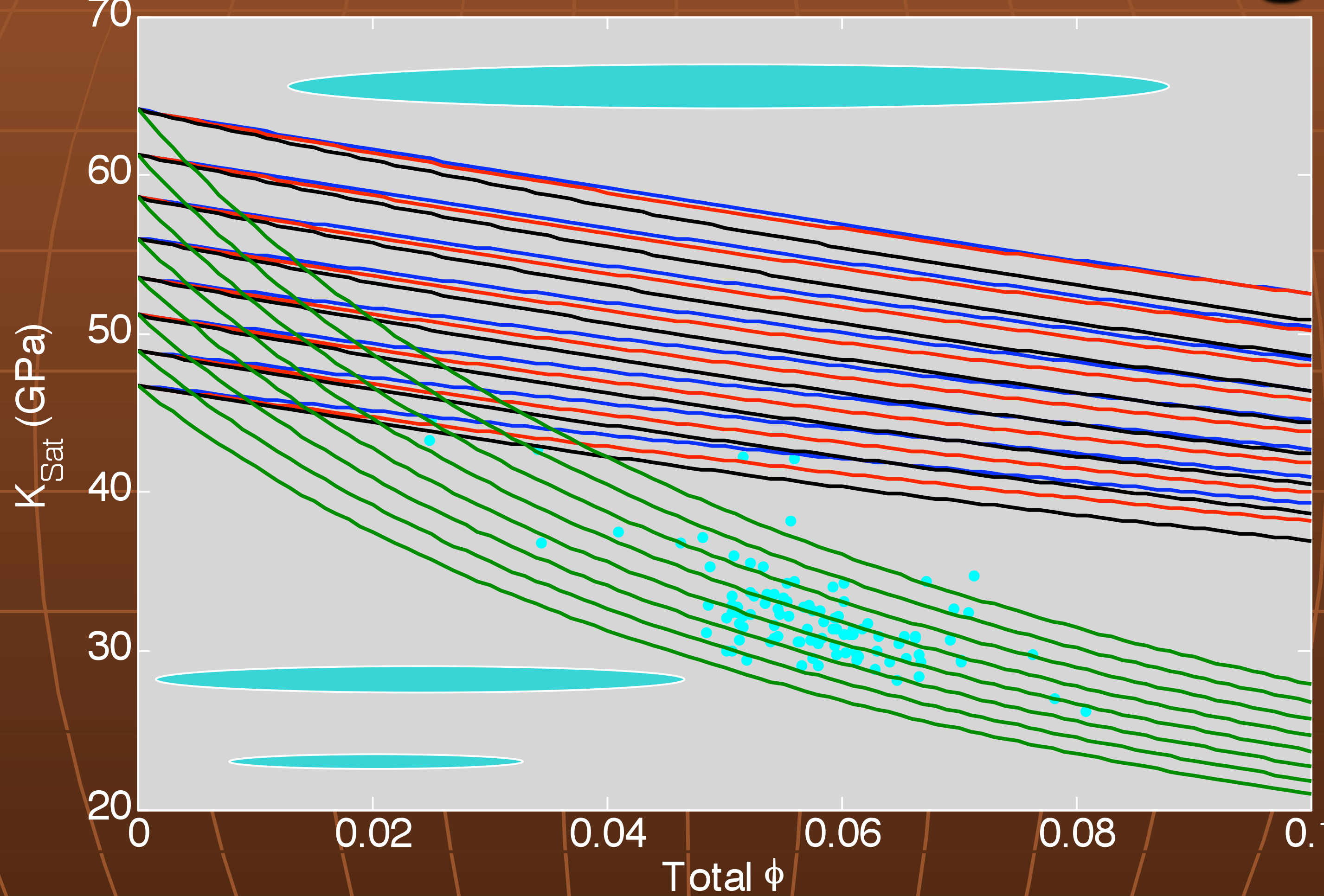


Spherical pores

Needle-shaped pores

Crack-shaped pores
Aspect ratio = 0.05

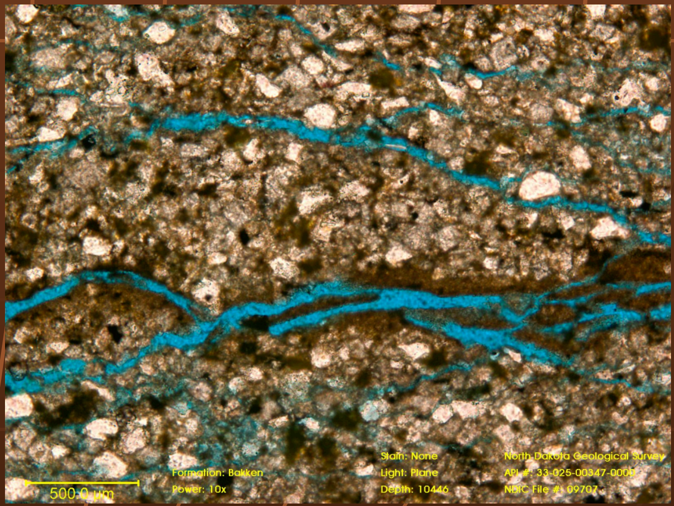
Pore-stiffness modeling

Can model the data reasonably well using

Crack-shaped pores with realistic aspect ratios

Mineralogy remains uncertain

Can fractured media (Hudson’s) model be used?



Pore-stiffness modeling

Can model the data reasonably well using

Crack-shaped pores with realistic aspect ratios

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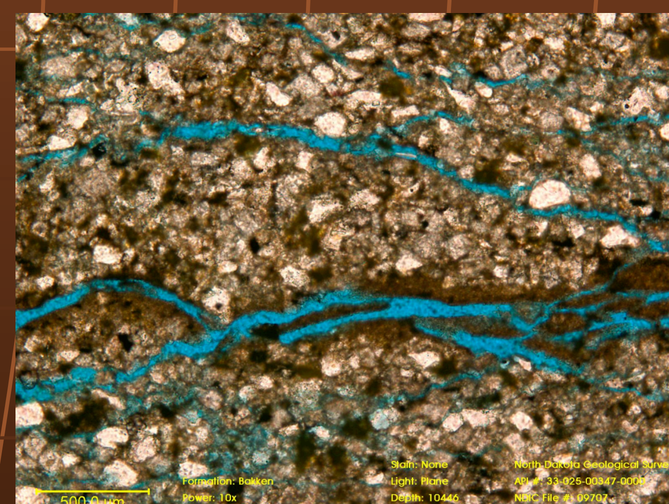
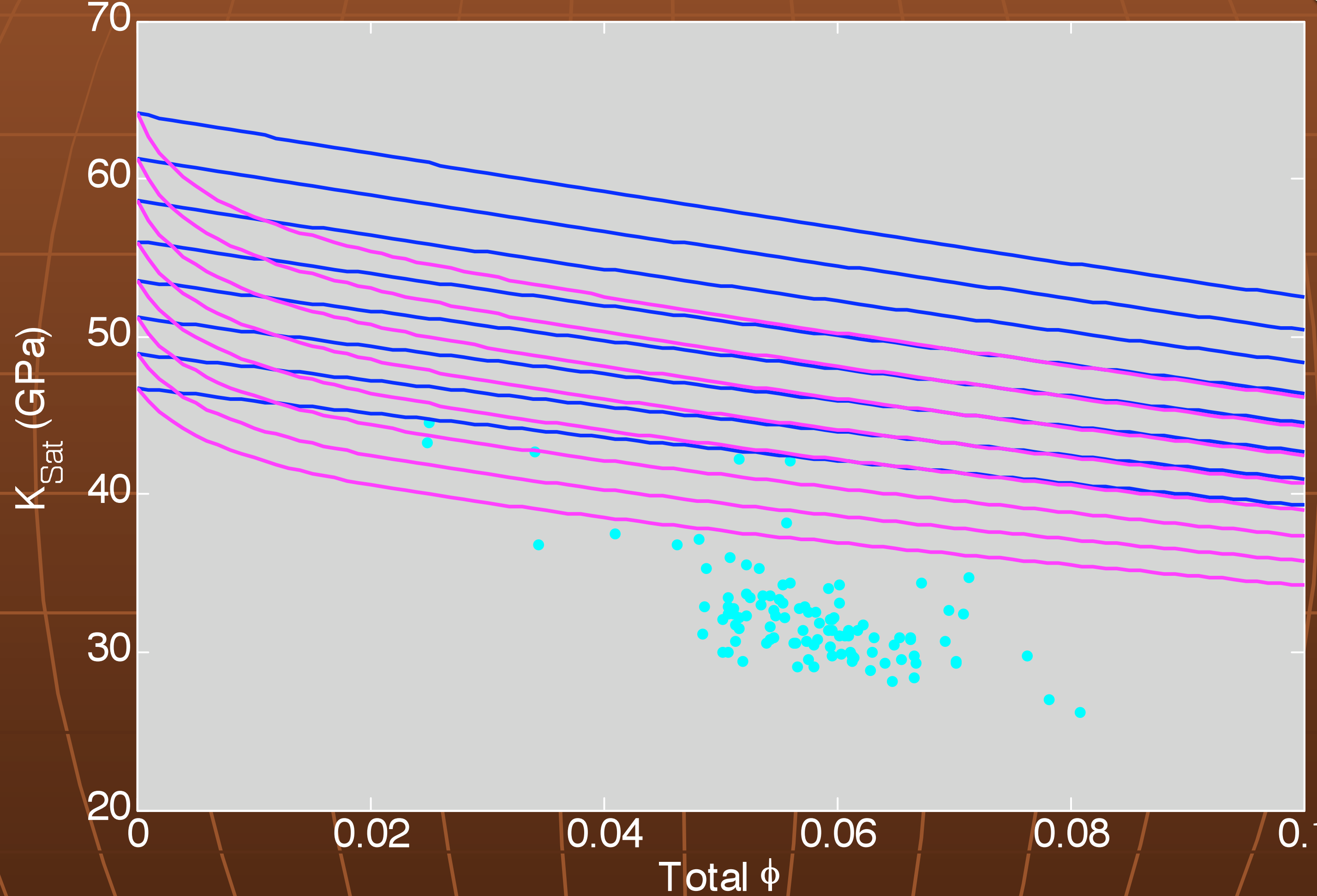
Can fractured media (Hudson's) model be used?

Calculate dry-rock parameters
Fluid substitution: Brown-Korringa for approximate low-frequency saturated-rock parameters



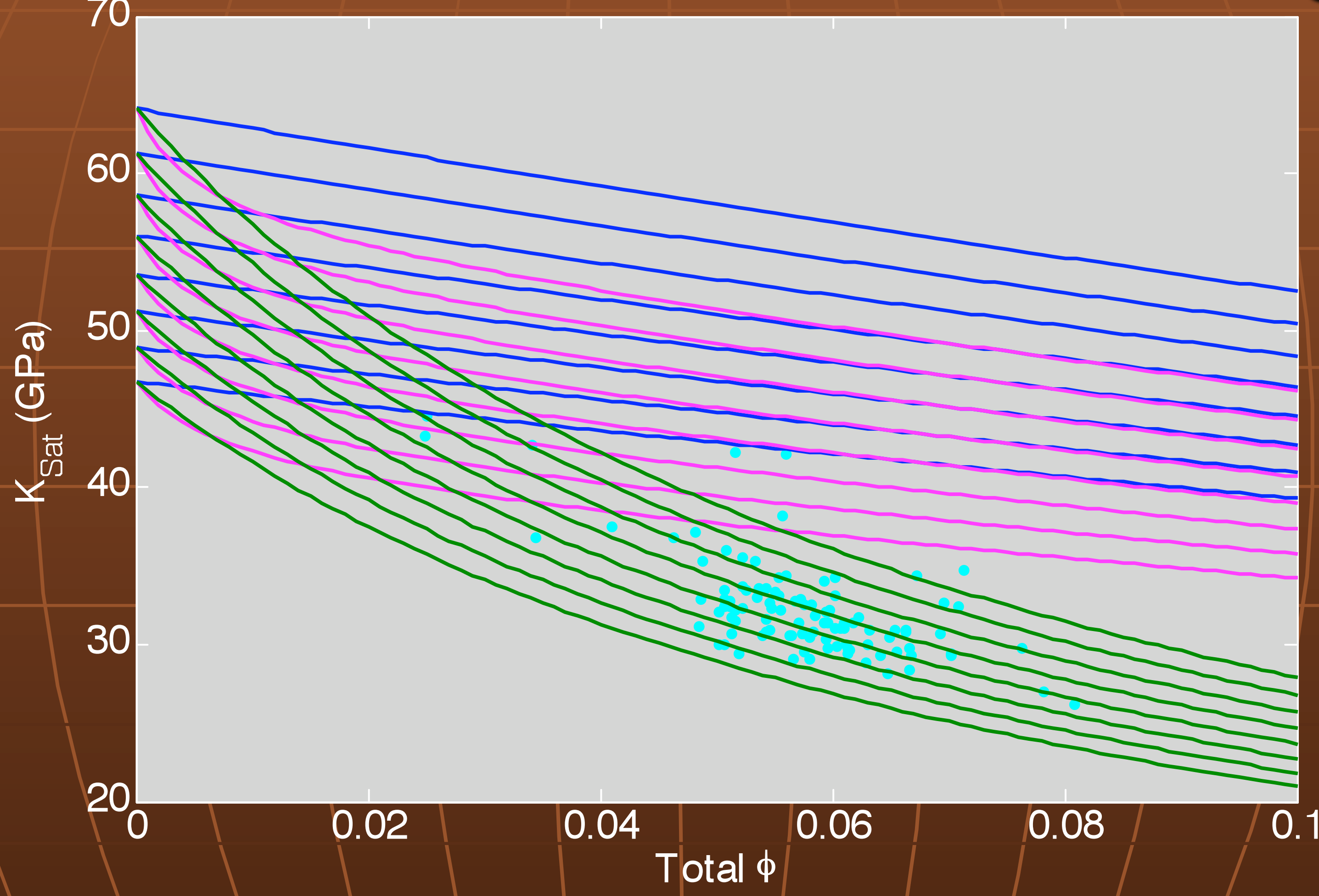
Fractured-media modeling



Fracture model, aspect ratio = 0.005
Crack density = 0.1

Crack-shaped pores
Aspect ratio = 0.1

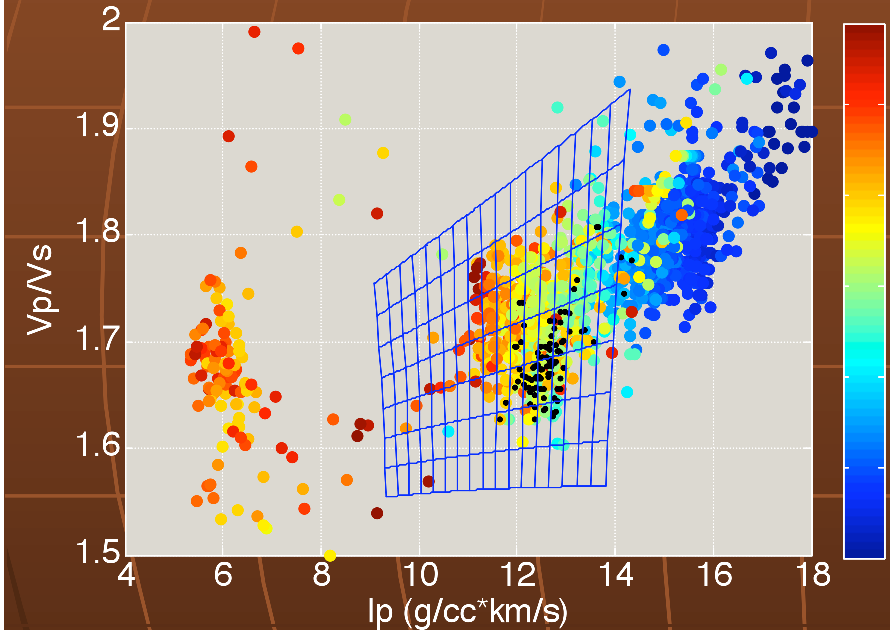
Fractured-media modeling



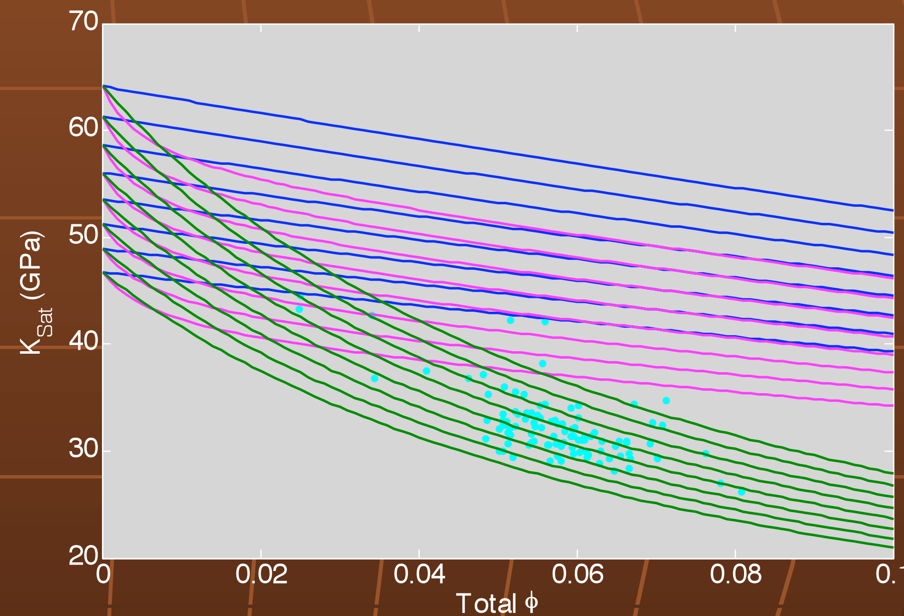
Fracture model, aspect ratio = 0.005
Crack density = 0.1

Crack-shaped pores
Aspect ratio = 0.1

So which one works?



Porous media?



Fractured media?

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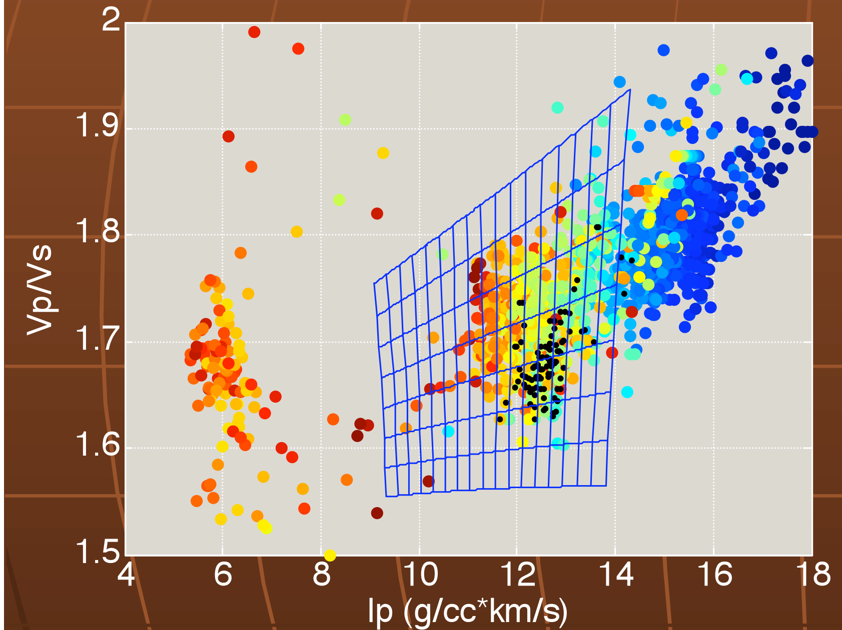
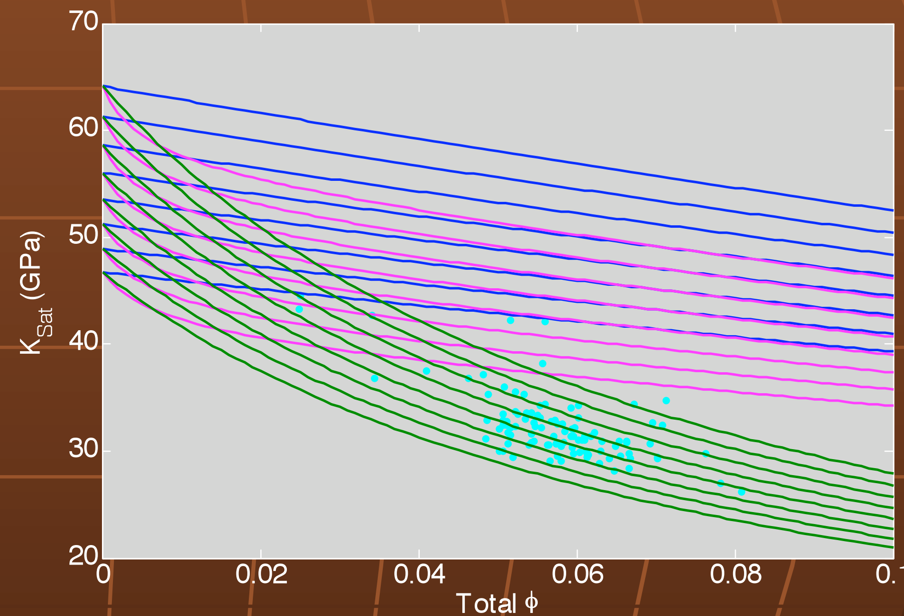




Porous media?

Fractured media?

And then where is effective stress?

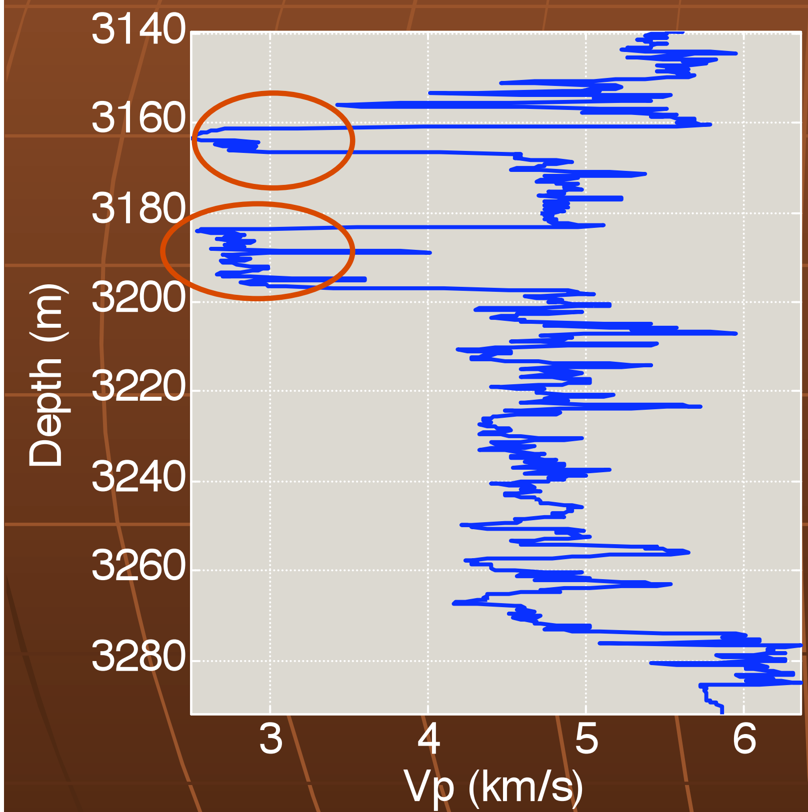
Discussion points

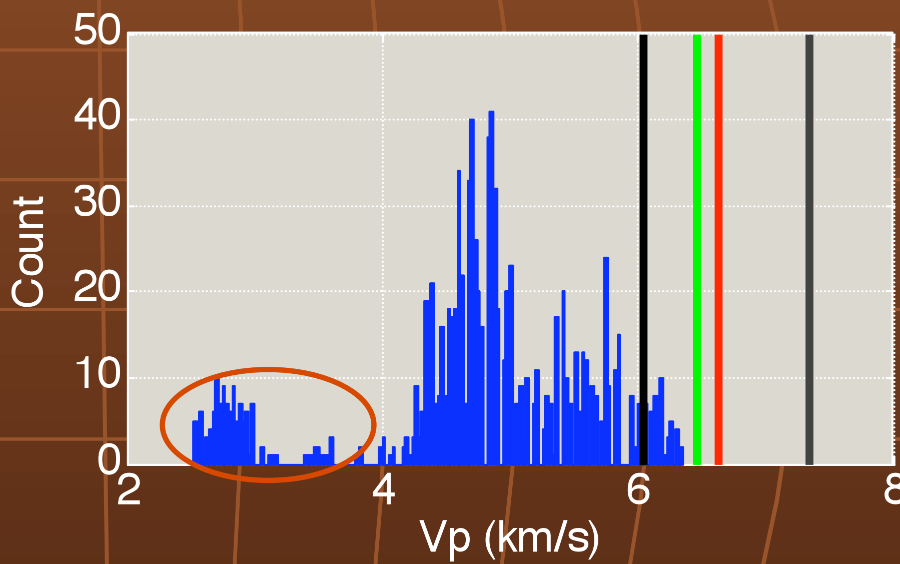
- As with any model, the free parameters can be manipulated to force a fit
- Modeling results obtained with parameters defined within their liits do not point directly to modeling pore stiffness nor to fractured media. with parameters
- A combination of them may provide an answer
- Mixed mineralogy presents some significant challenges
- Carbonate rock physics, influenced significantly by pore type (6 different types) may introduce additional complexities

Areas of future work

- Can model mineralogy and porosity to account for some data scatter
- Need better control on both for fluid substitution
- Need to understand better the effects of pore shape, pore stiffness, and pore fluids on Vp
- For the Middle Bakken, somewhat conventional analysis can be used to an extent
- Must analyze the more subtle parameters that affect the elastic properties
- More work to be done to understand the Upper and Lower Bakken Shales
- Possible that all three intervals will need to be assessed simultaneously to understand the lateral heterogeneity
- Numerical and statistical studies may be necessary to put together a consistent picture of the rocks such as these

Rock properties—Velocity (P)





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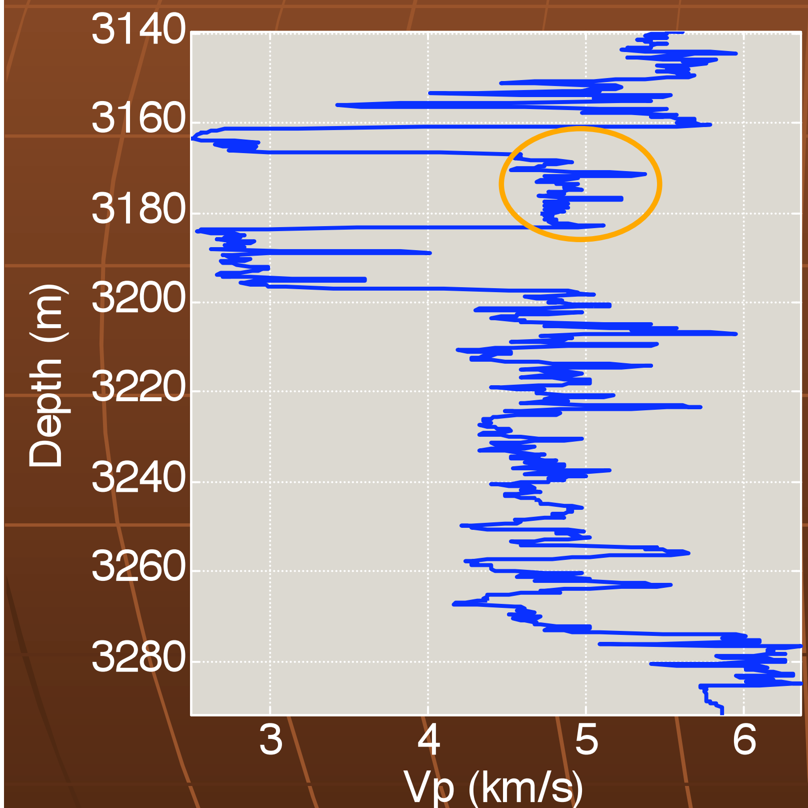

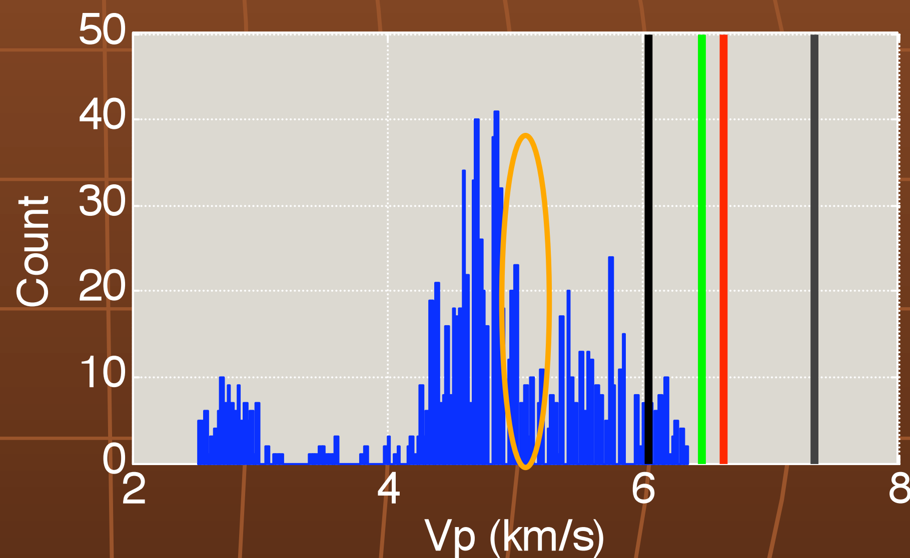

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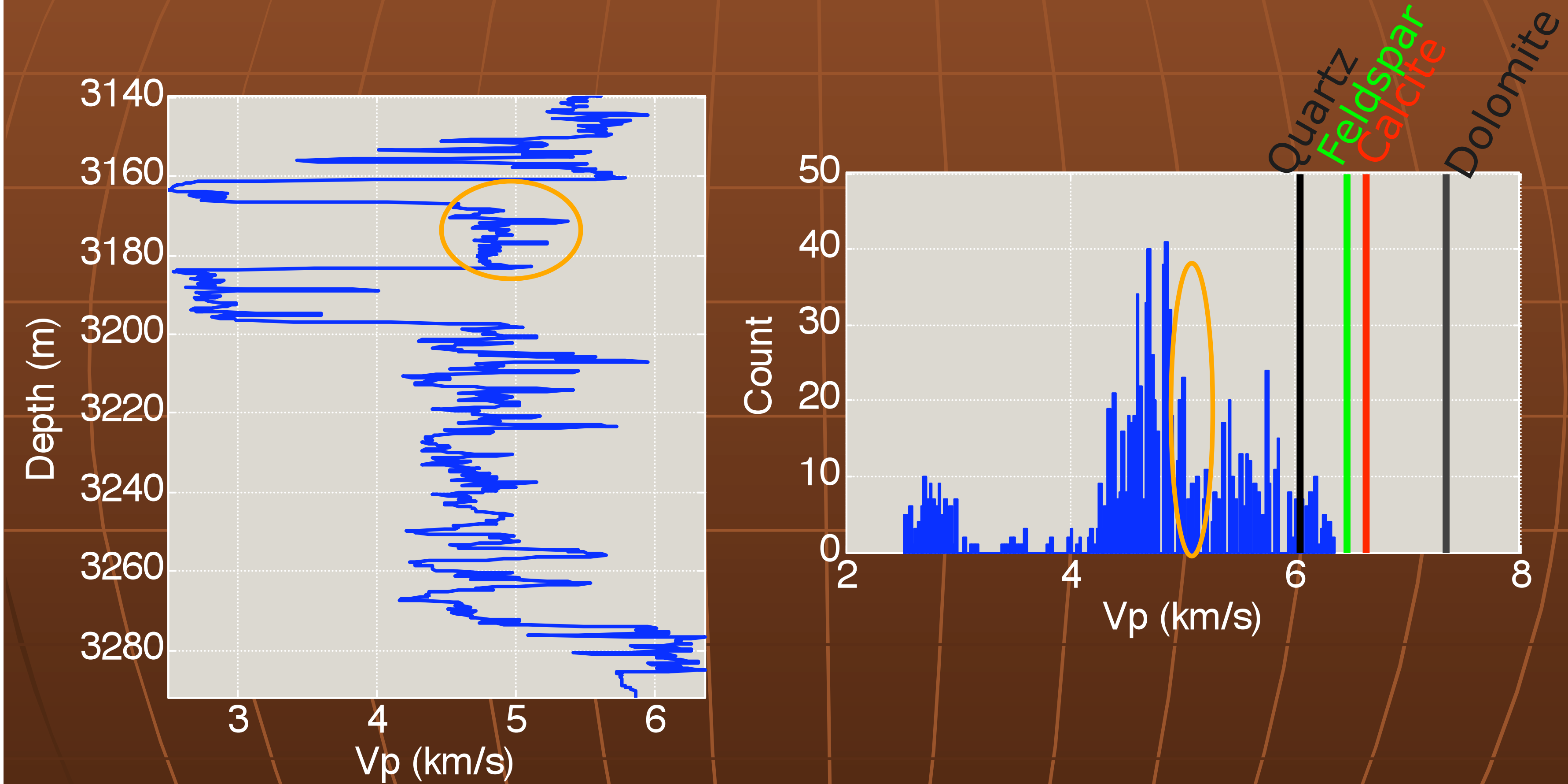

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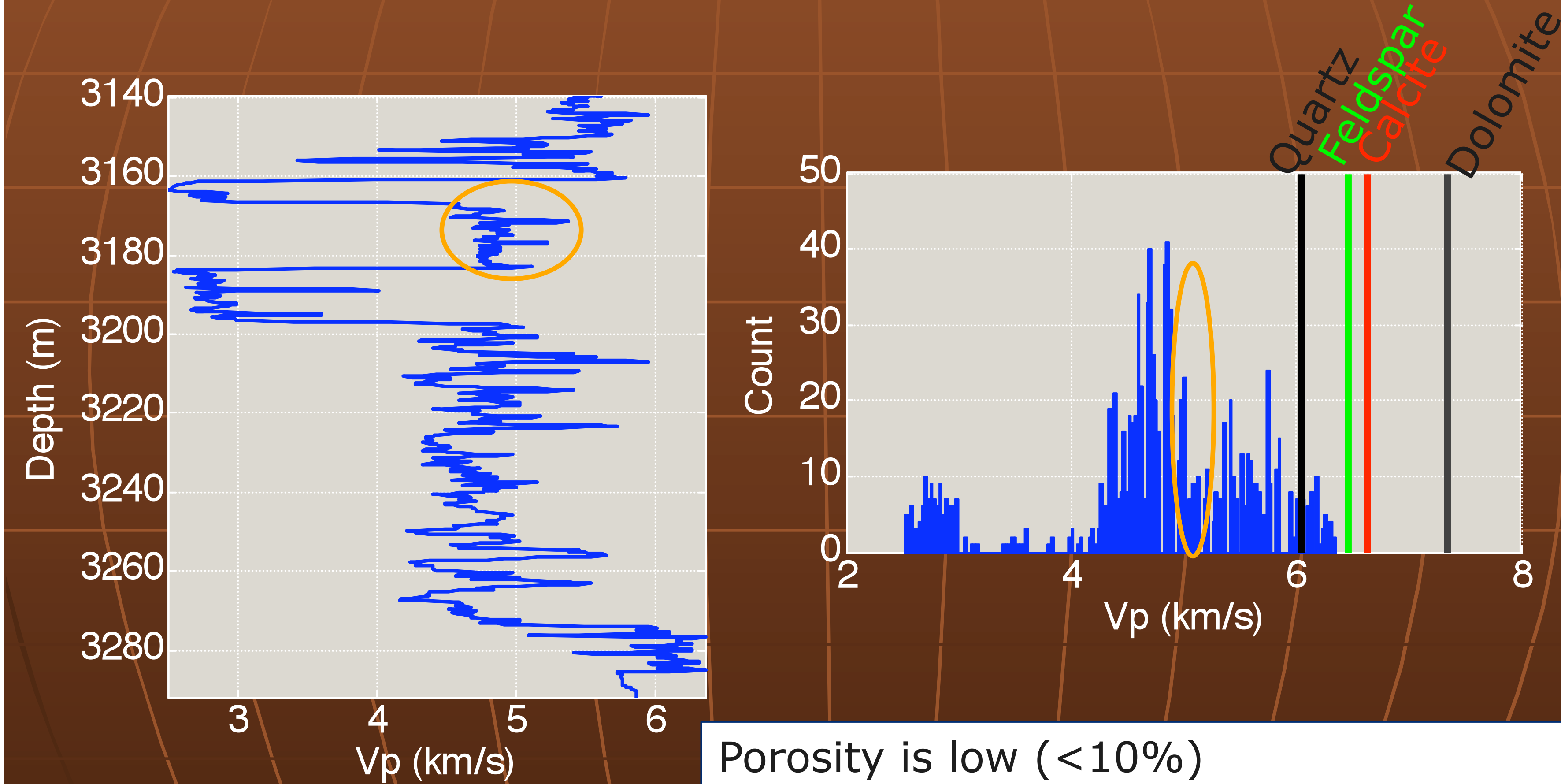
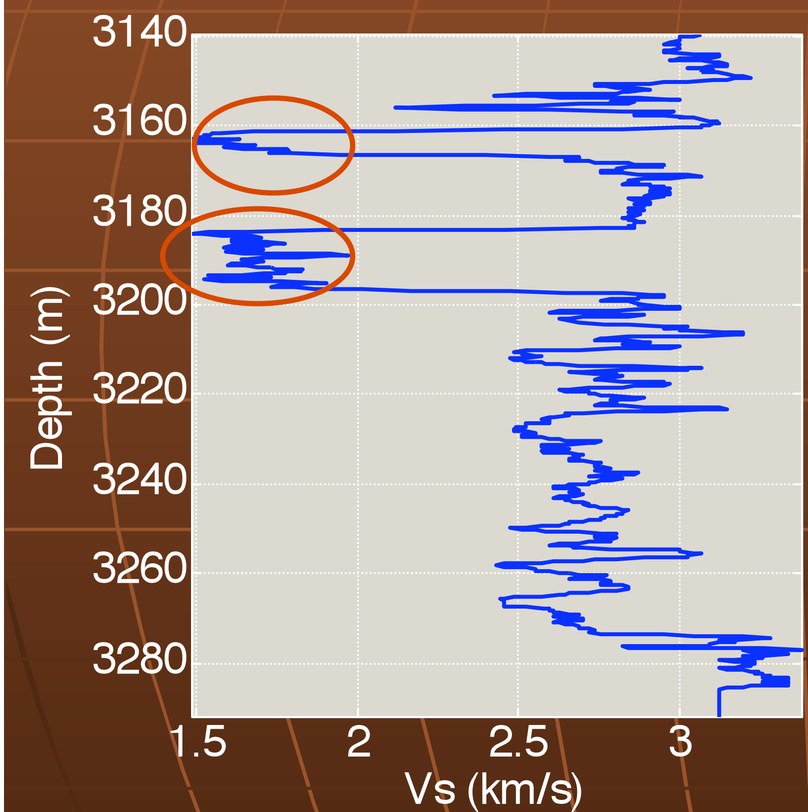
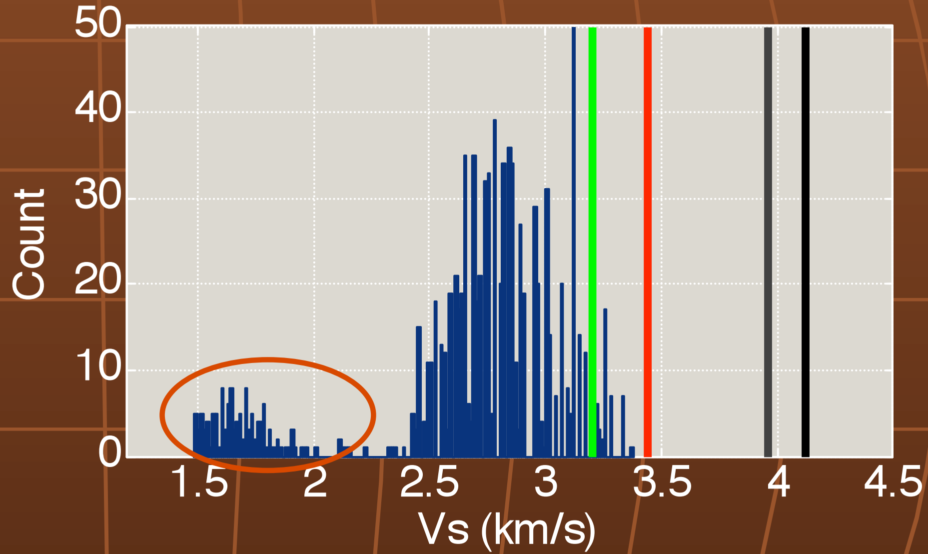


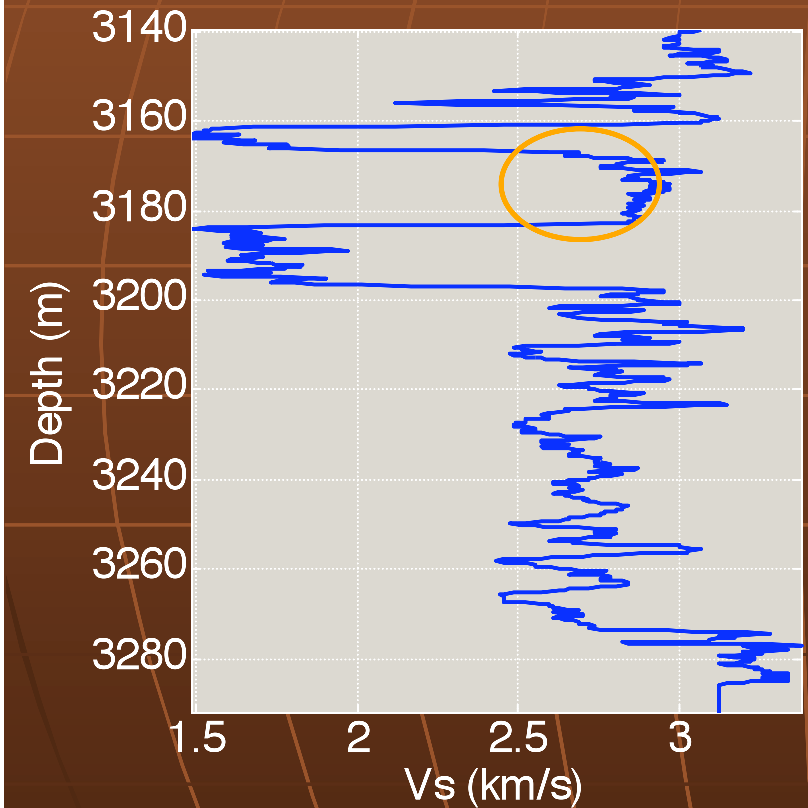
Porosity is low (<10%)
Vp should be close to mineral velocities
Do fluids reduce the velocity?
Which geometric properties cause this?

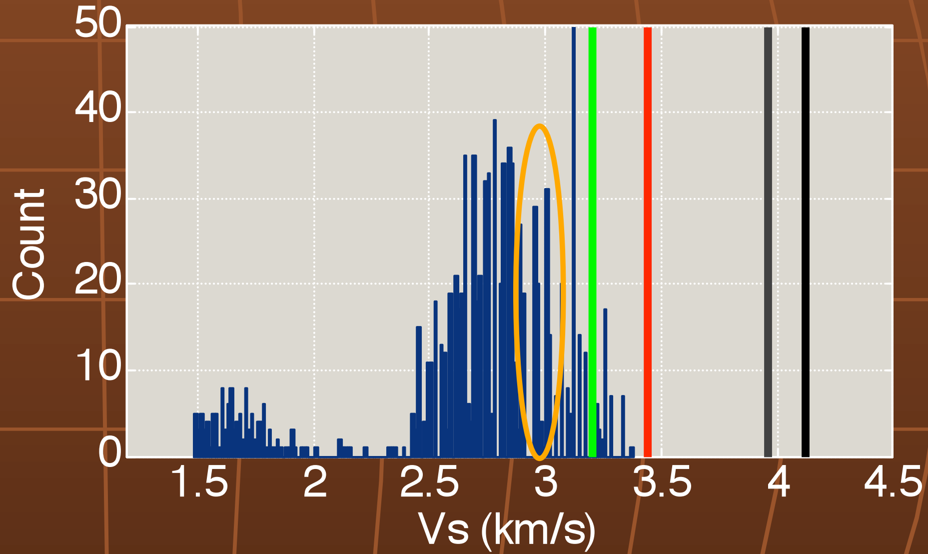
Rock properties—Velocity (S)



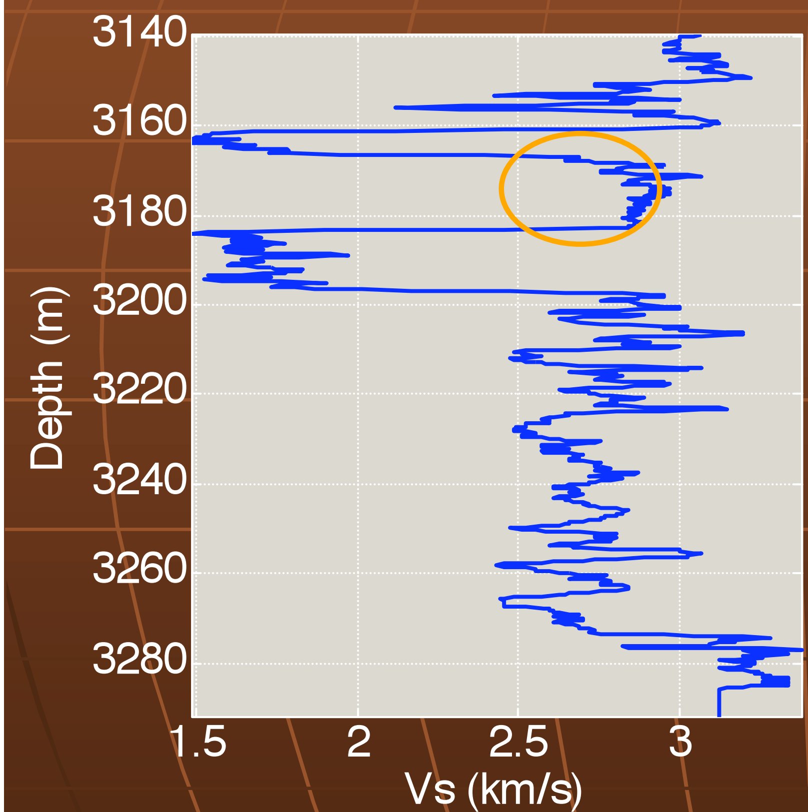


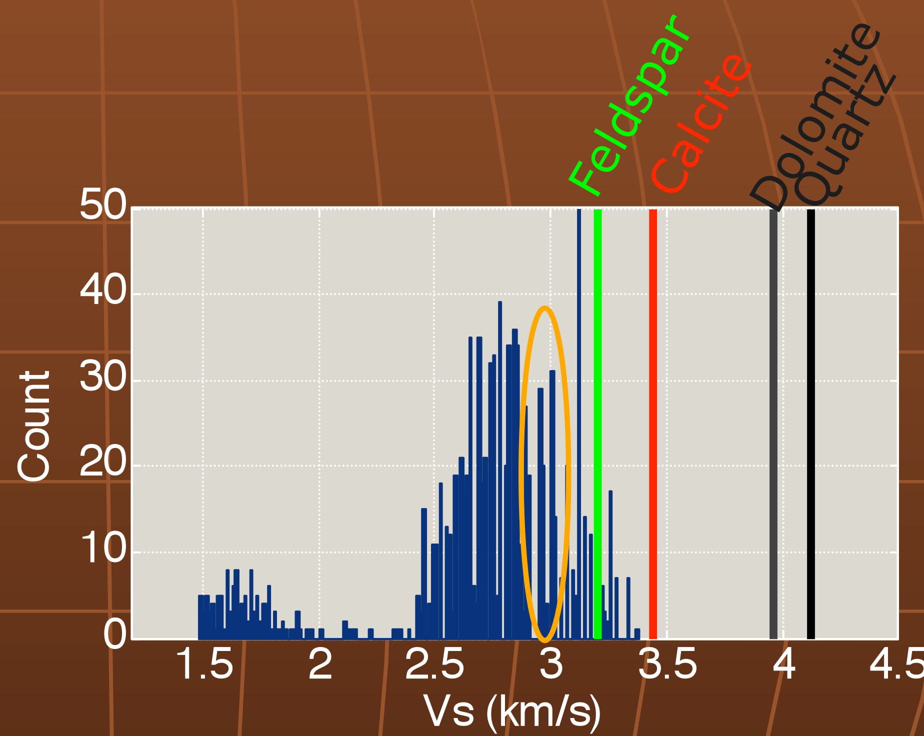
Rock properties—Velocity (S)



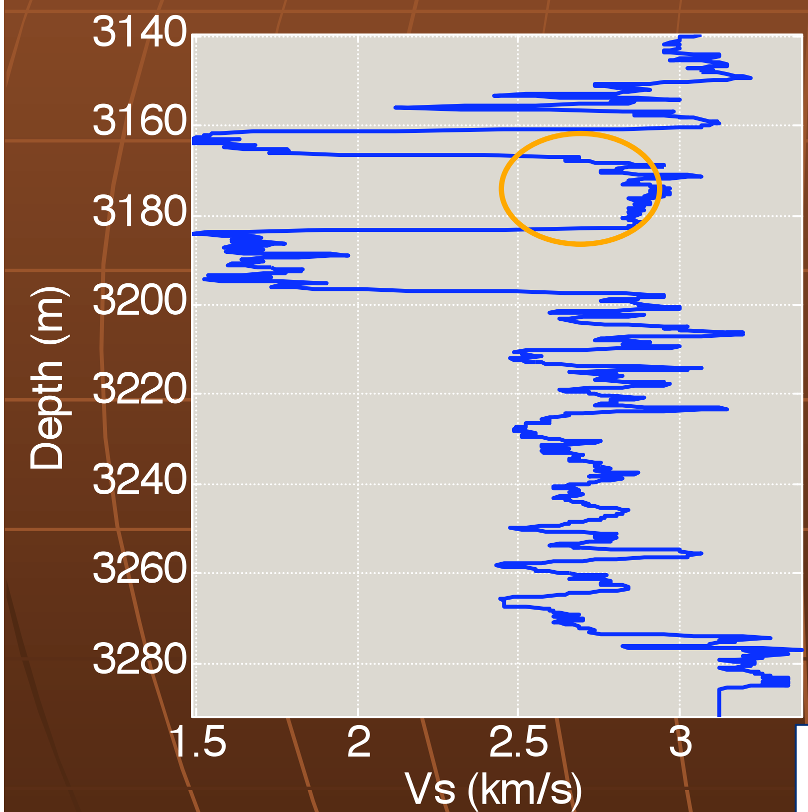


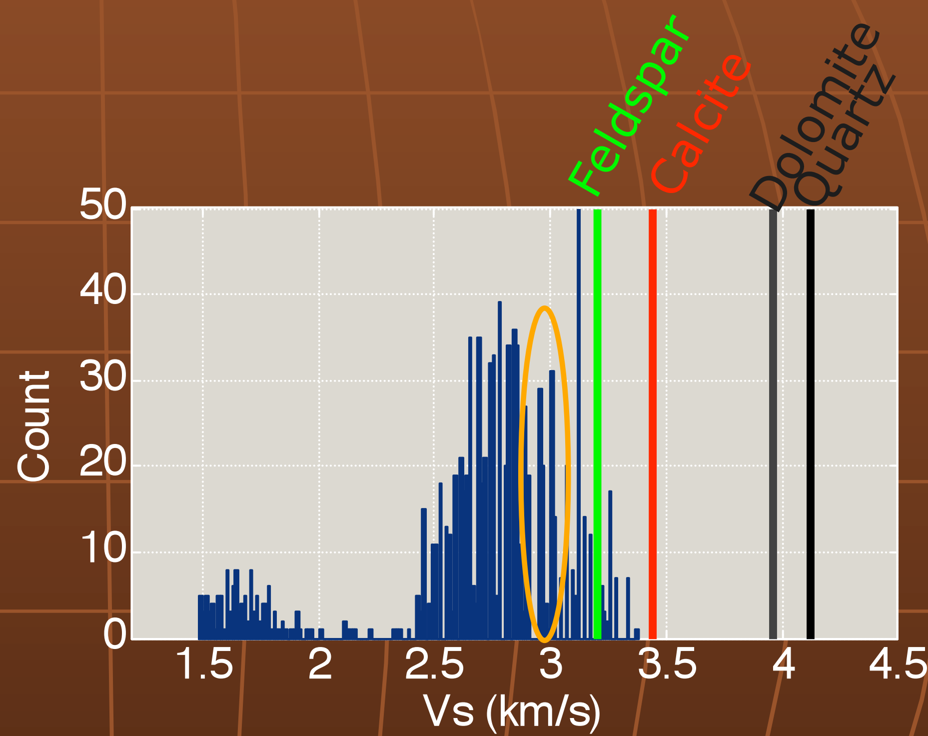
Rock properties—Velocity (S)





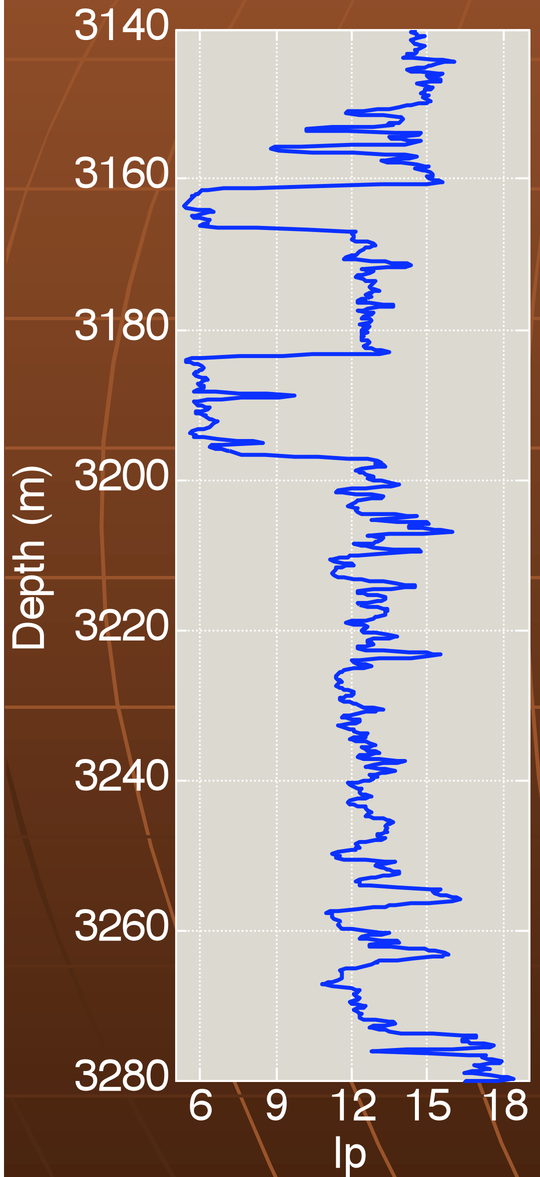
Rock properties—Velocity (S)



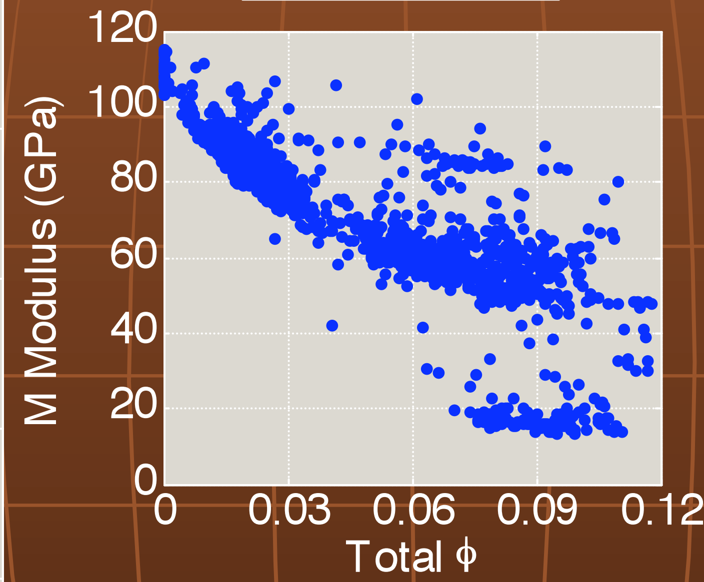


Vs values similar to feldspar velocity
Are fluid effects responsible for Vp?
Can texture account for disparity in Vp and Vs velocity?

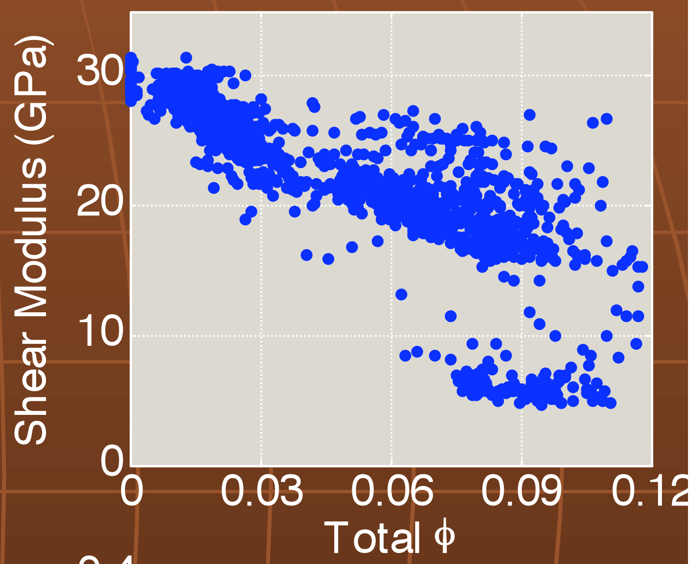
Elastic moduli and Poisson's ratio

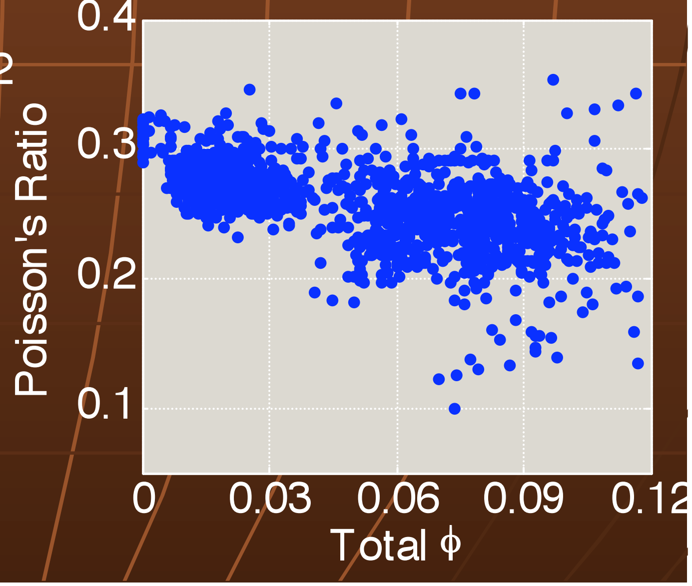


$$M = V_P^2 \rho_b$$

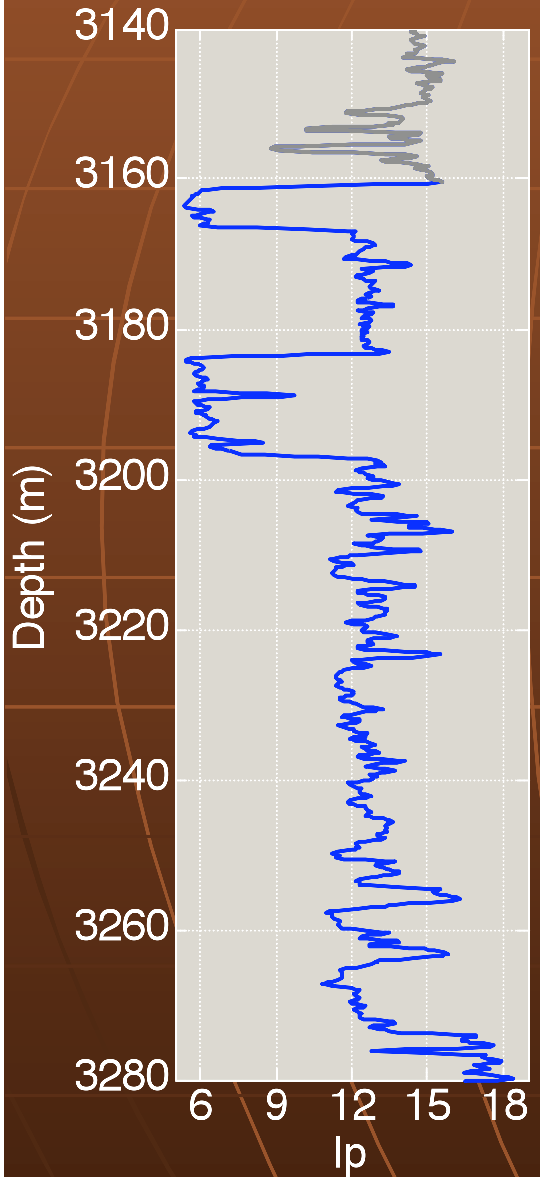


$$\mu = V_S^2 \rho_b$$

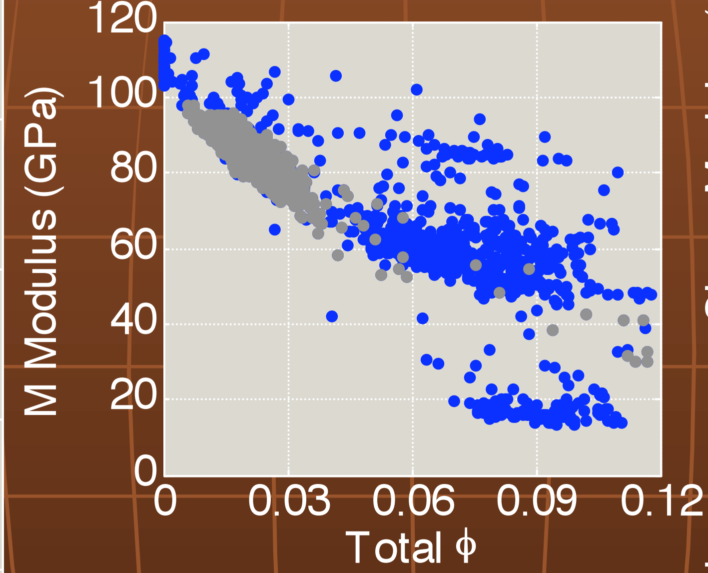




Elastic moduli and Poisson's ratio



$$M = V_P^2 \rho_b$$



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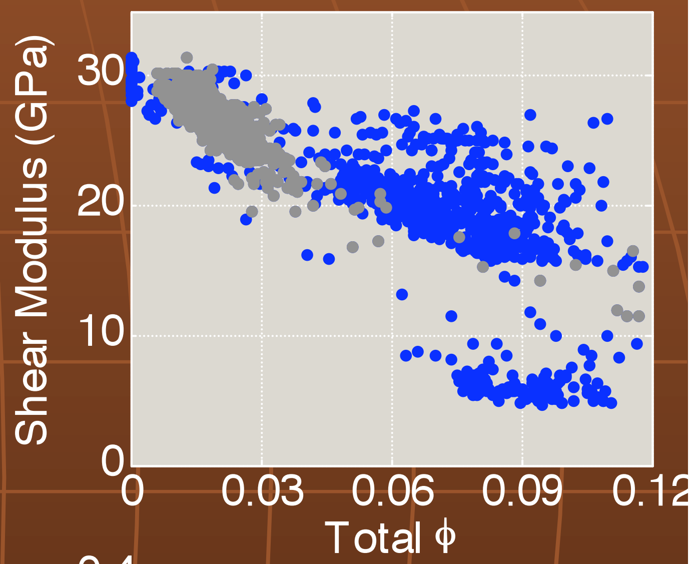

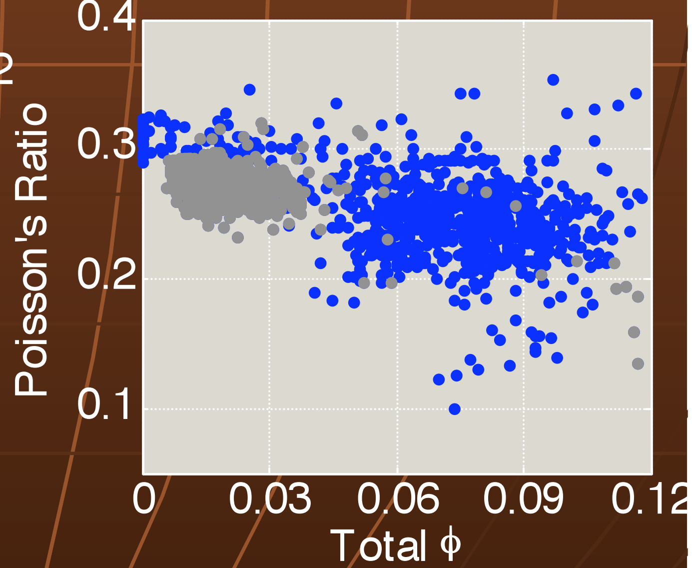

Elastic moduli and Poisson's ratio

$$\mu = V_S^2 \rho_b$$

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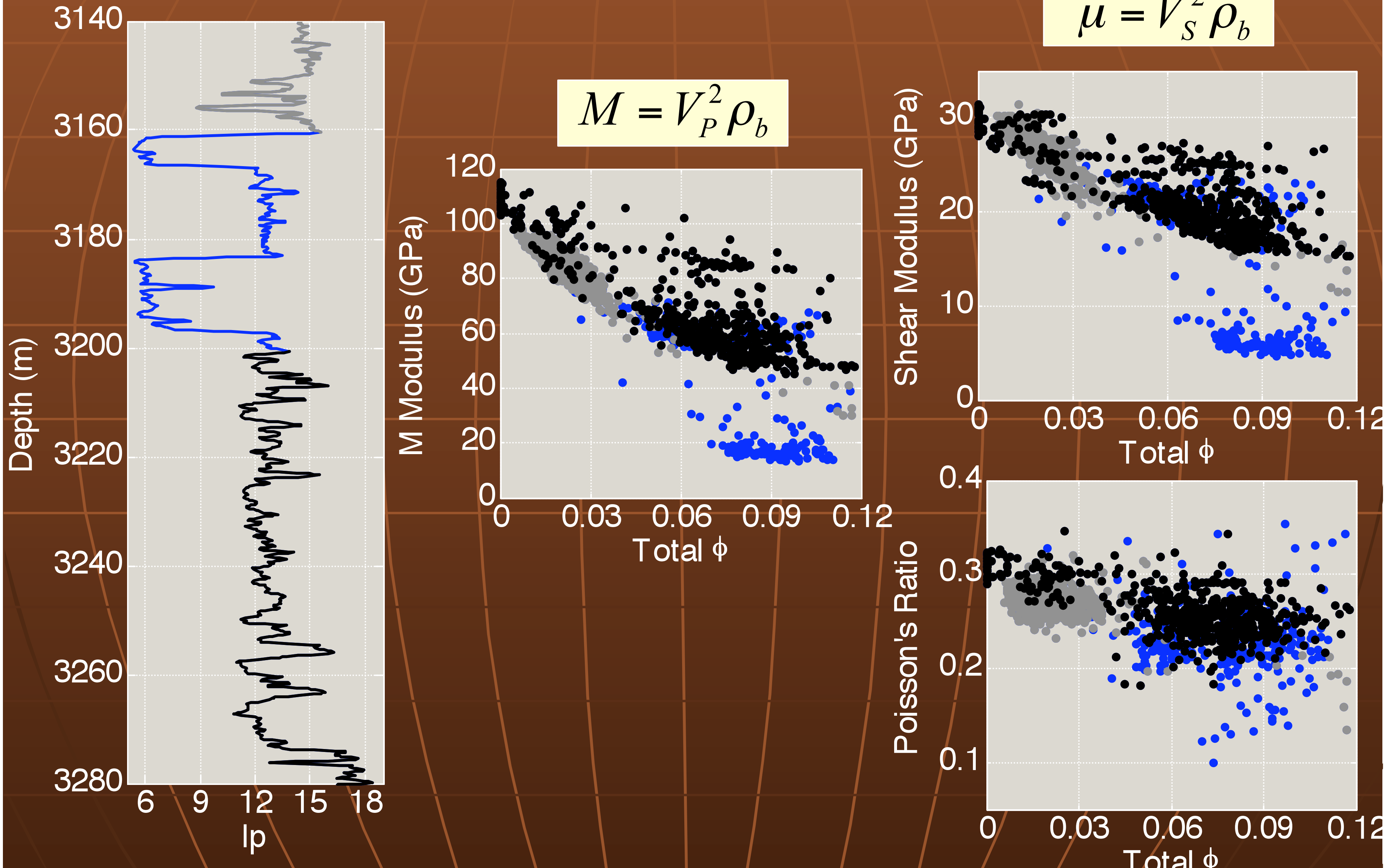

Elastic moduli and Poisson's ratio

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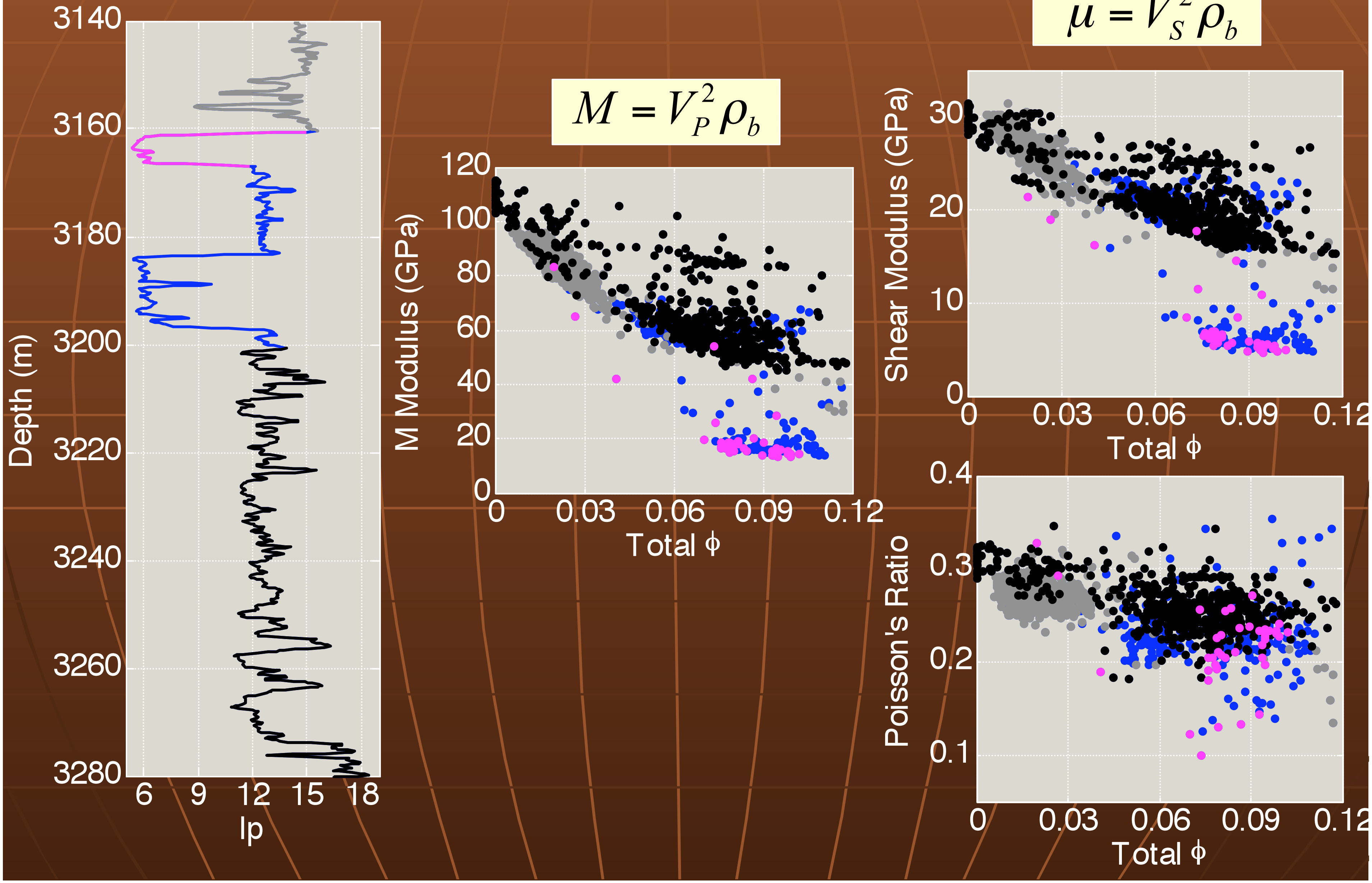
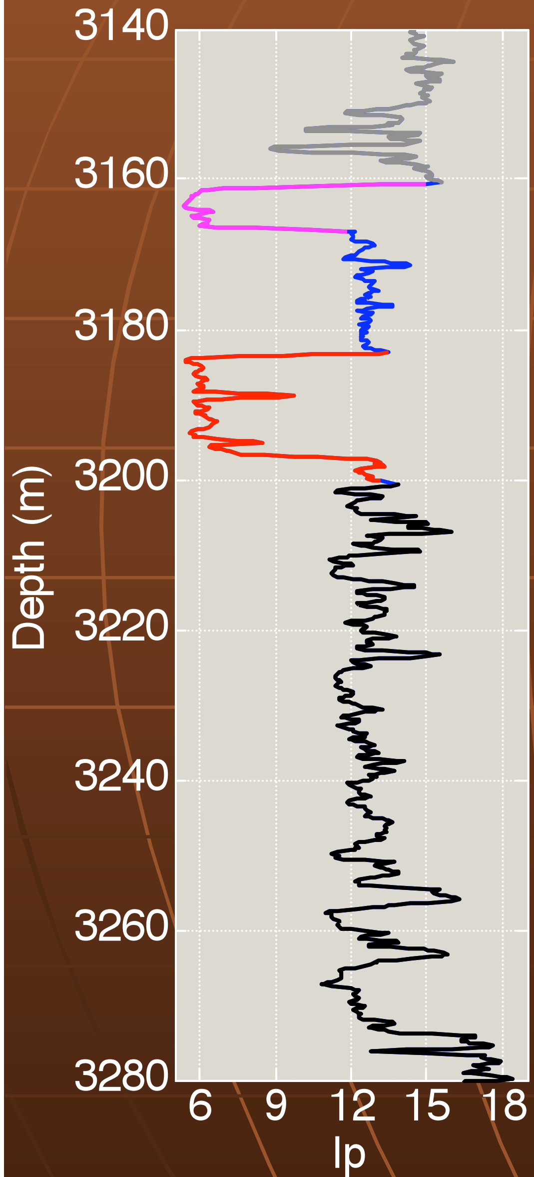
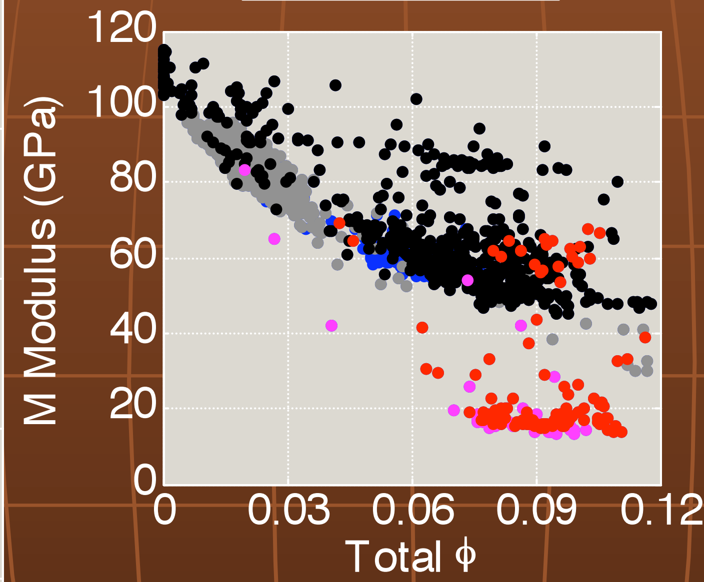


Elastic moduli and Poisson's ratio



$$M = V_P^2 \rho_b$$



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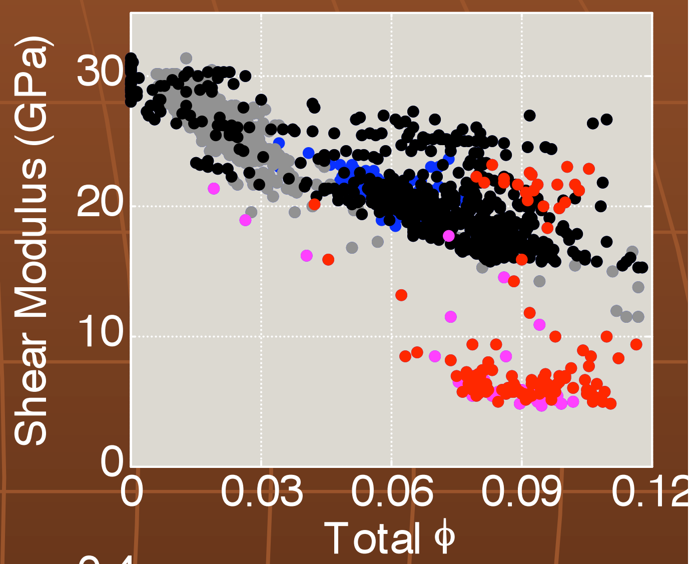
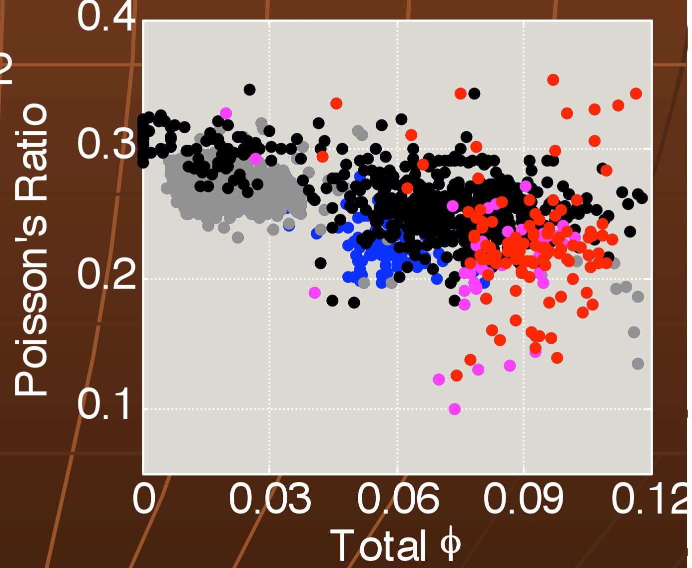
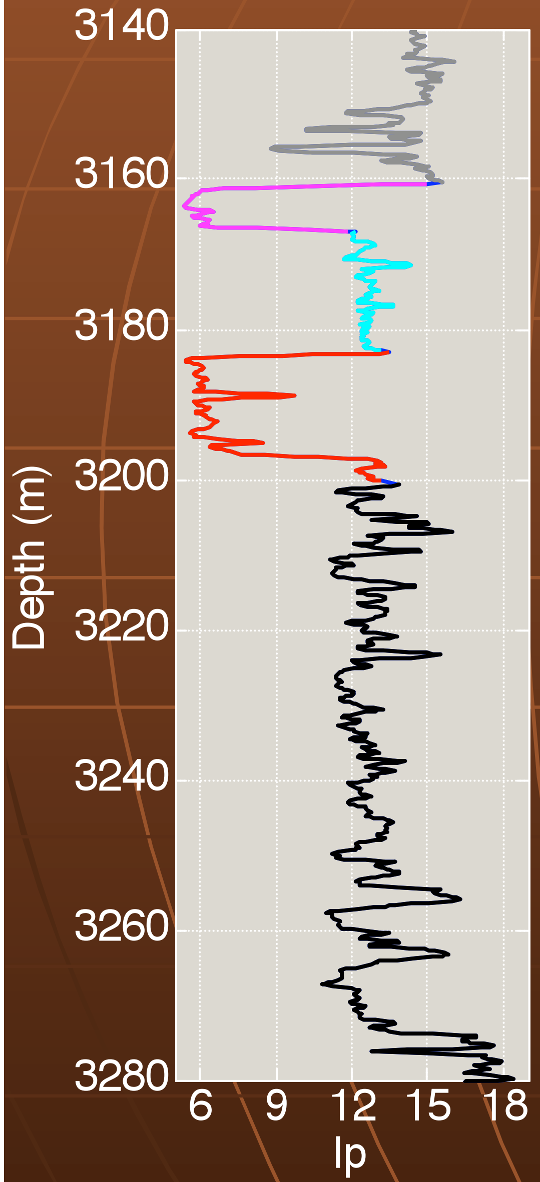




Elastic moduli and Poisson's ratio



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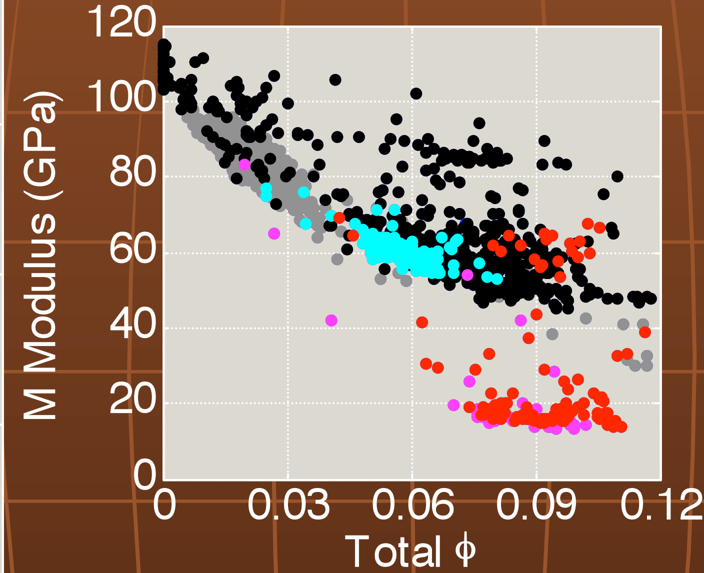

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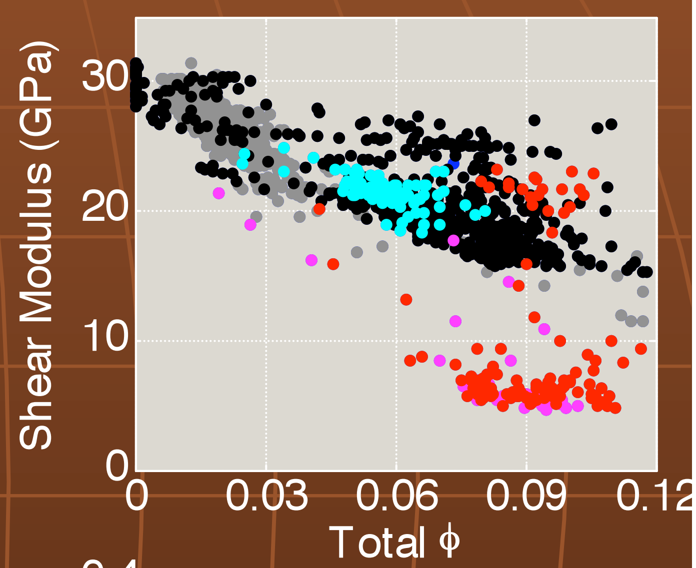
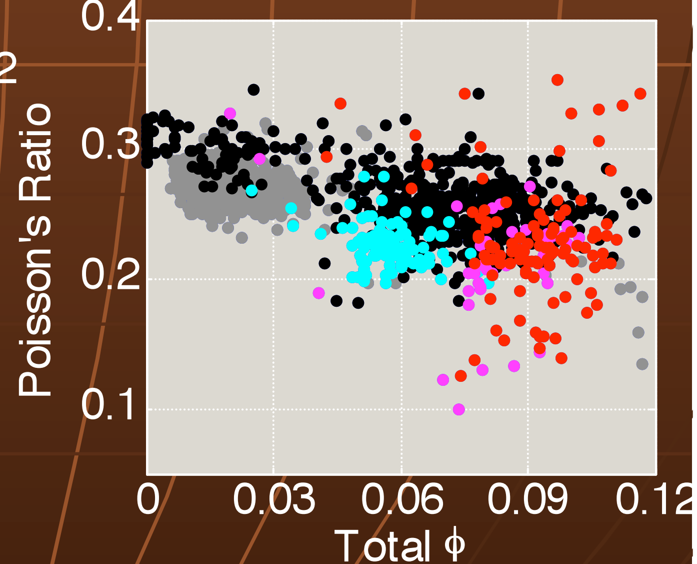
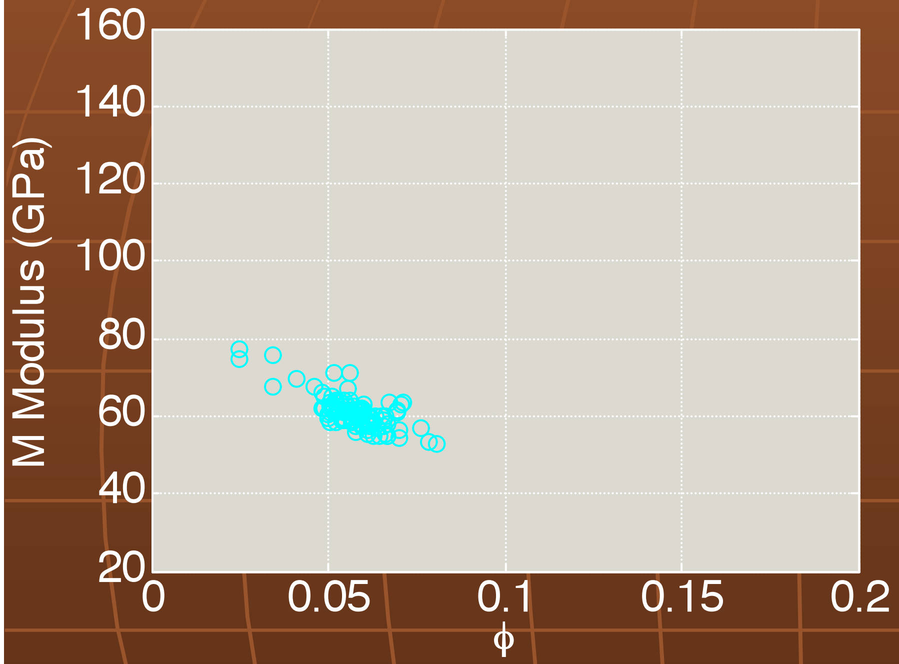


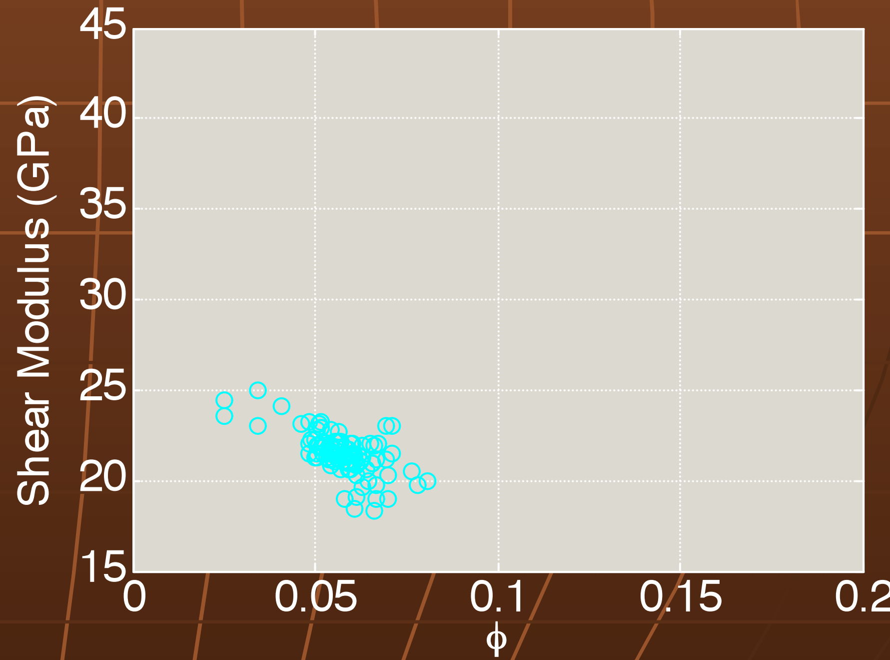


Elastic bounds

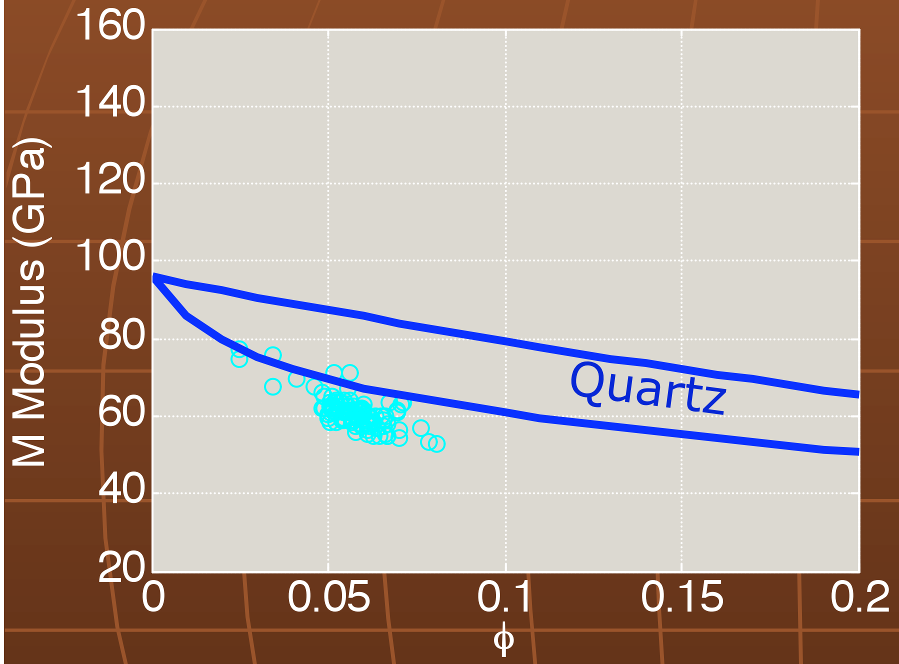


o Middle Bakken

How does the mineralogy vary laterally?



Elastic bounds



o Middle Bakken

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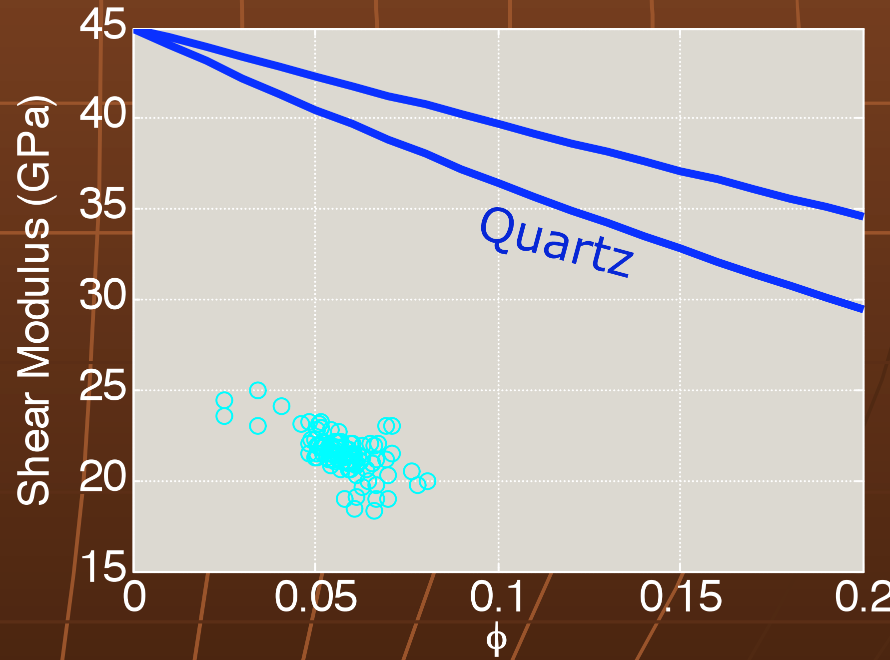
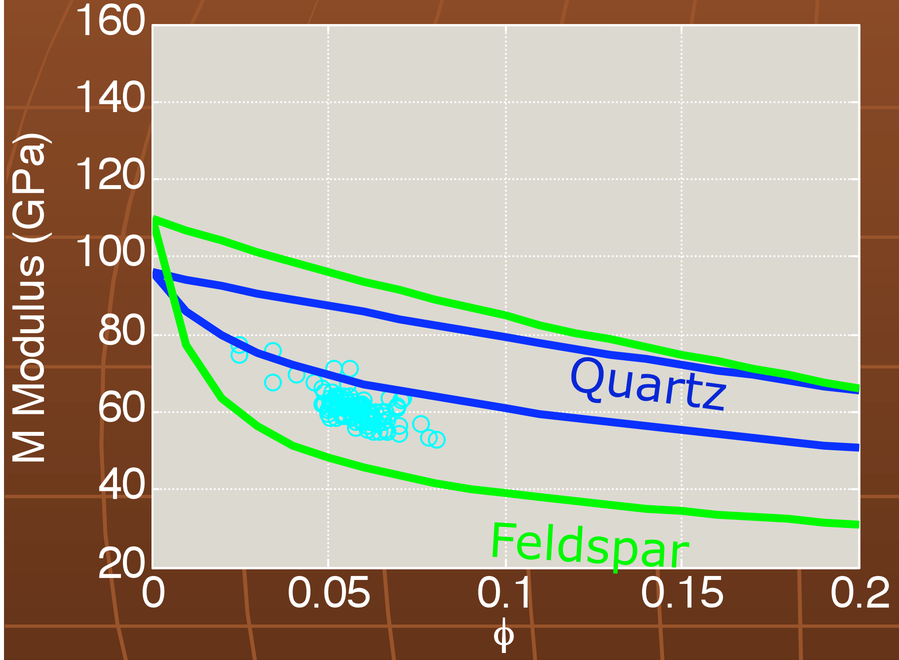


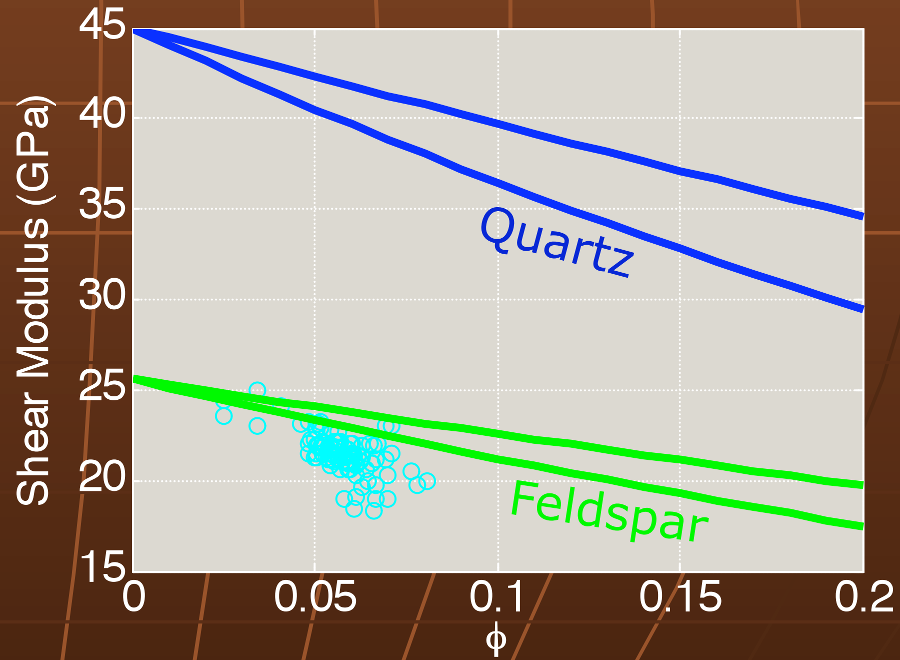
Upper and lower
Hashin-Shtrikman bounds

Elastic bounds



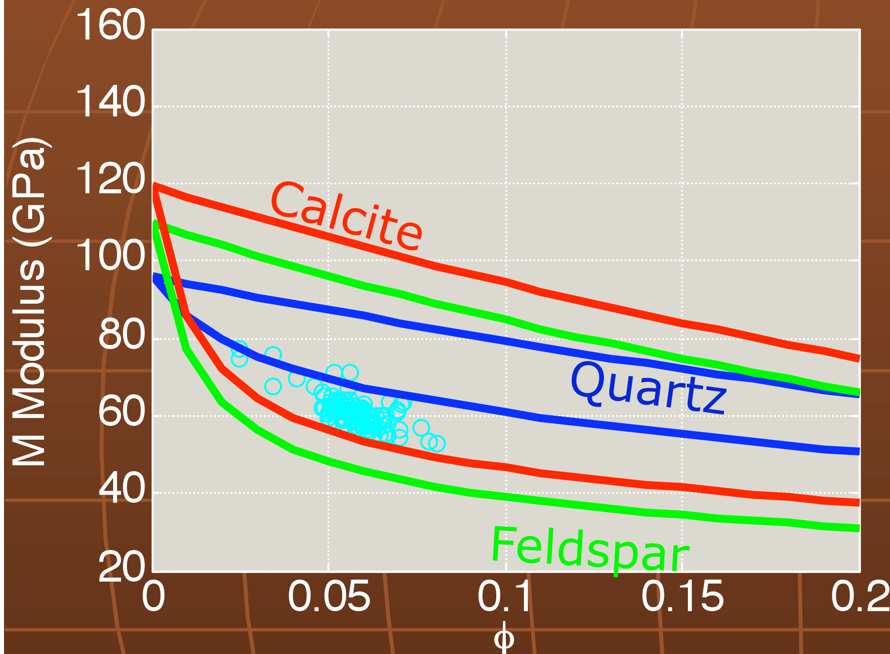
o Middle Bakken

How does the mineralogy vary laterally?



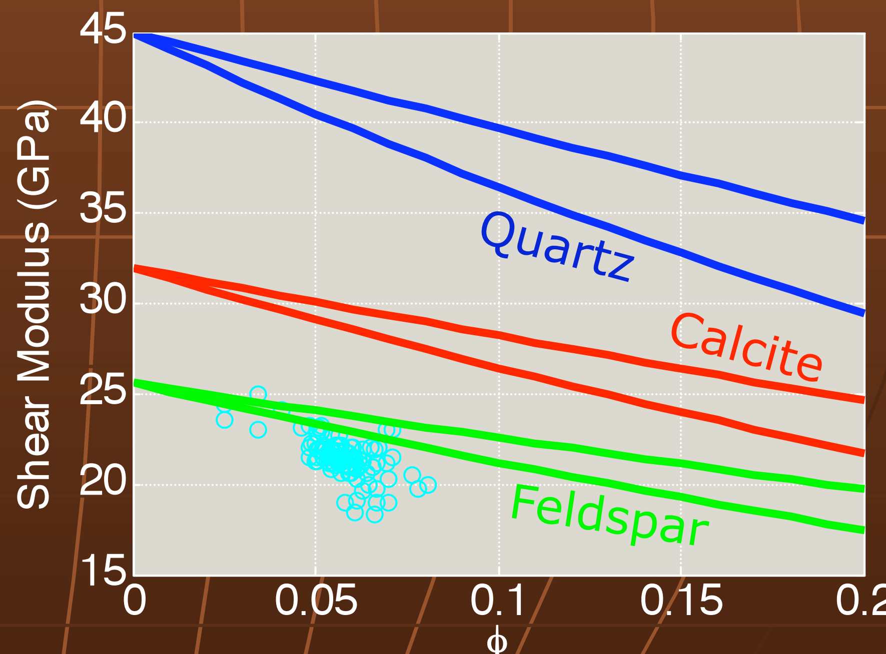
Upper and lower Hashin-Shtrikman bounds

Elastic bounds



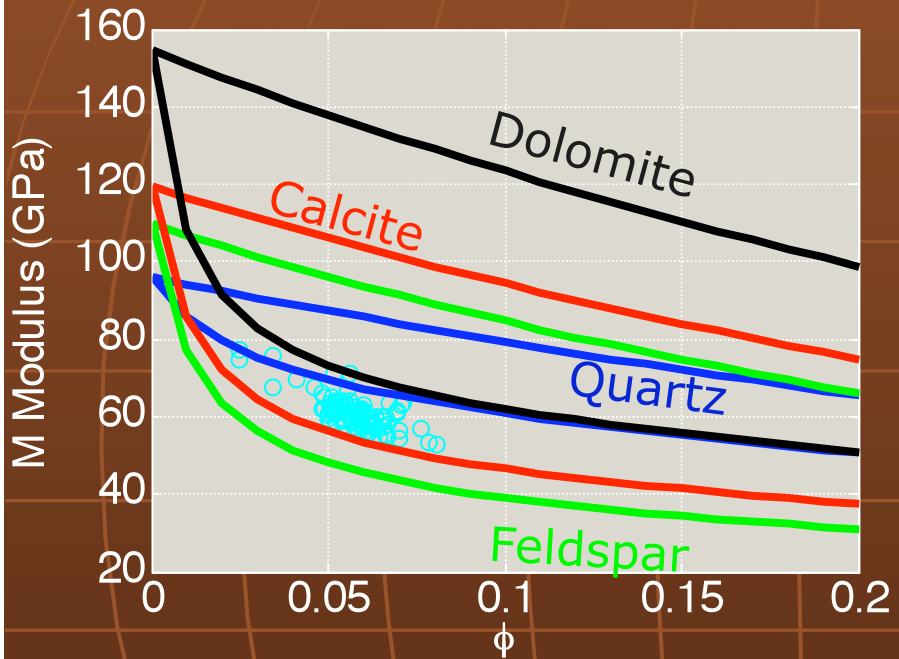
o Middle Bakken

How does the mineralogy vary laterally?



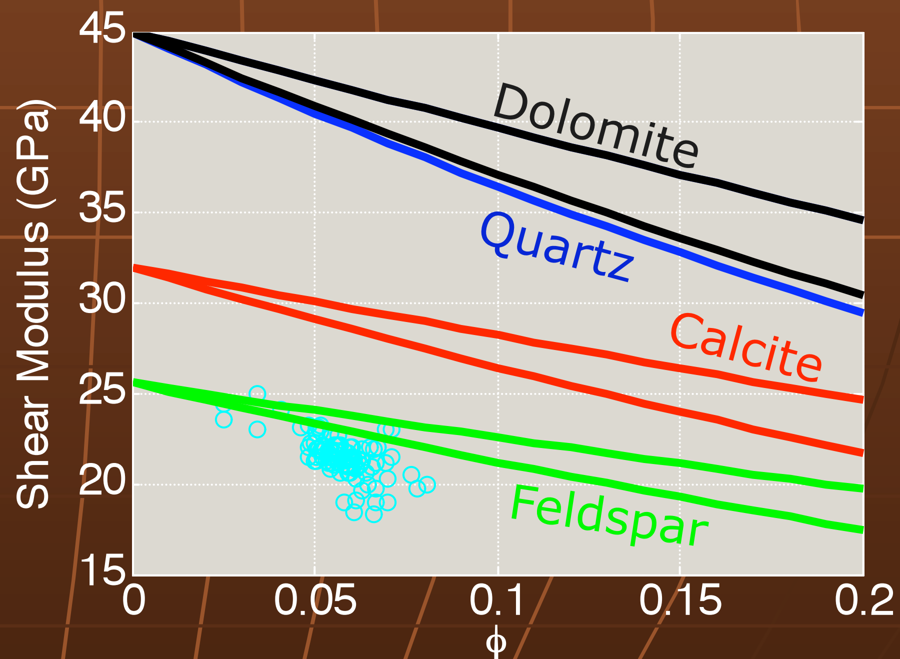
Upper and lower Hashin-Shtrikman bounds

Elastic bounds



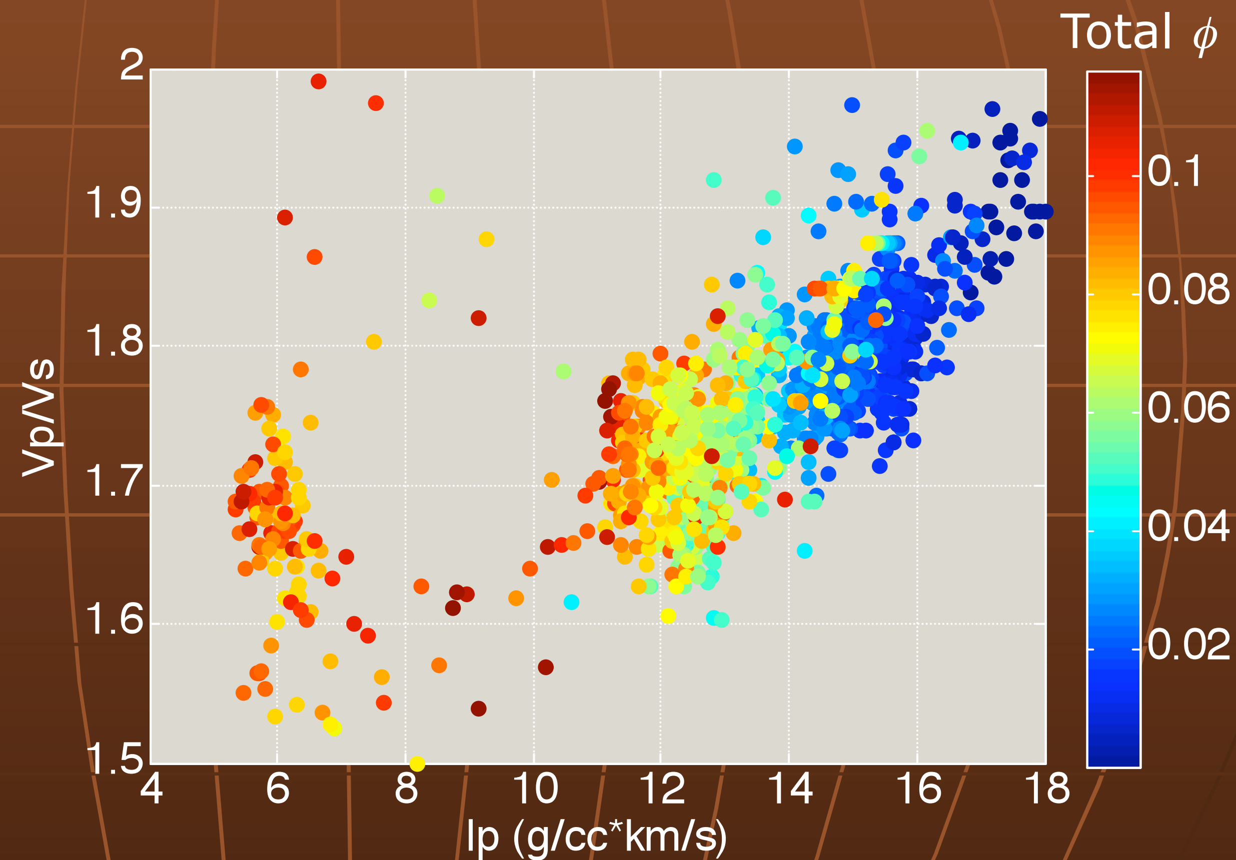
o Middle Bakken

How does the mineralogy vary laterally?
How much dolomite is present?
Middle Bakken appears to be feldspathic.

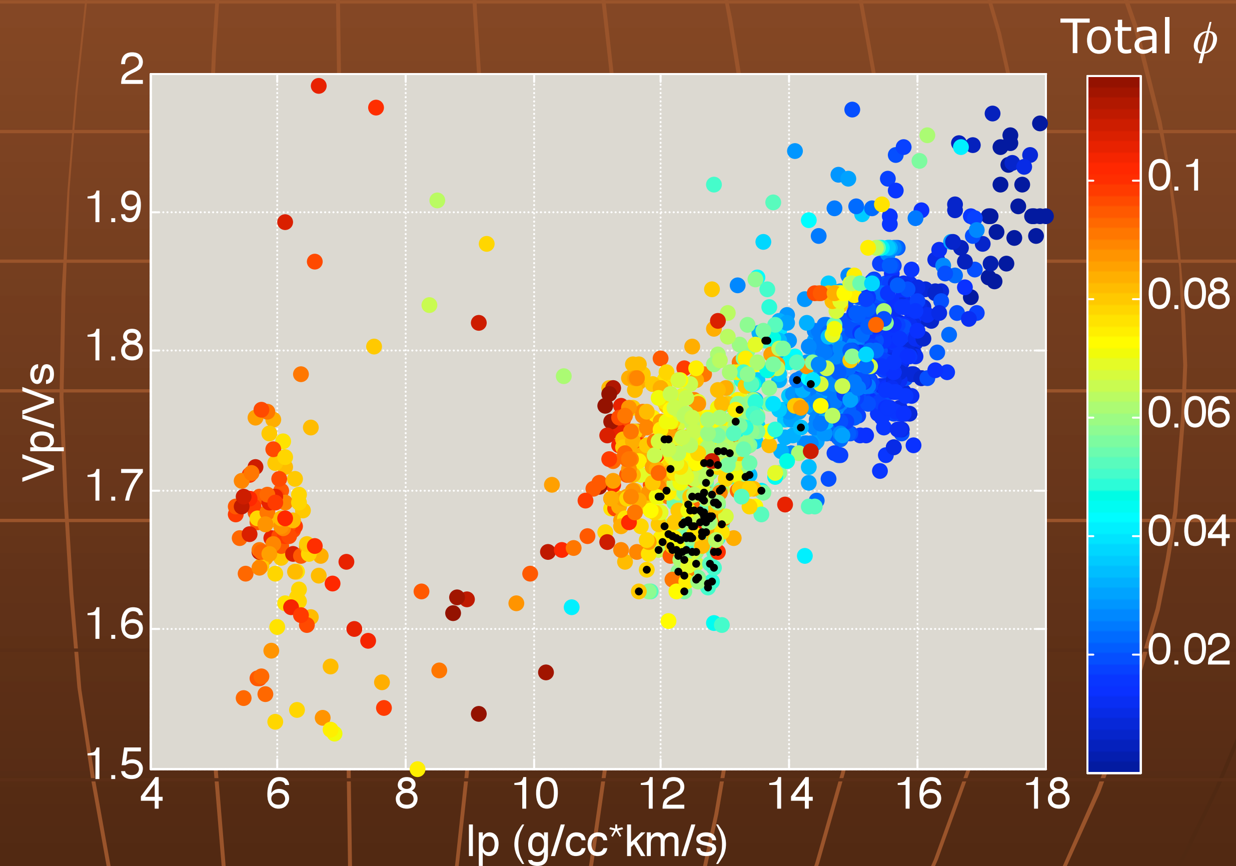


Upper and lower
Hashin-Shtrikman bounds

Rock physics model



Rock physics model



Rock physics model

Contact theory model for a stiff rock

Parameters

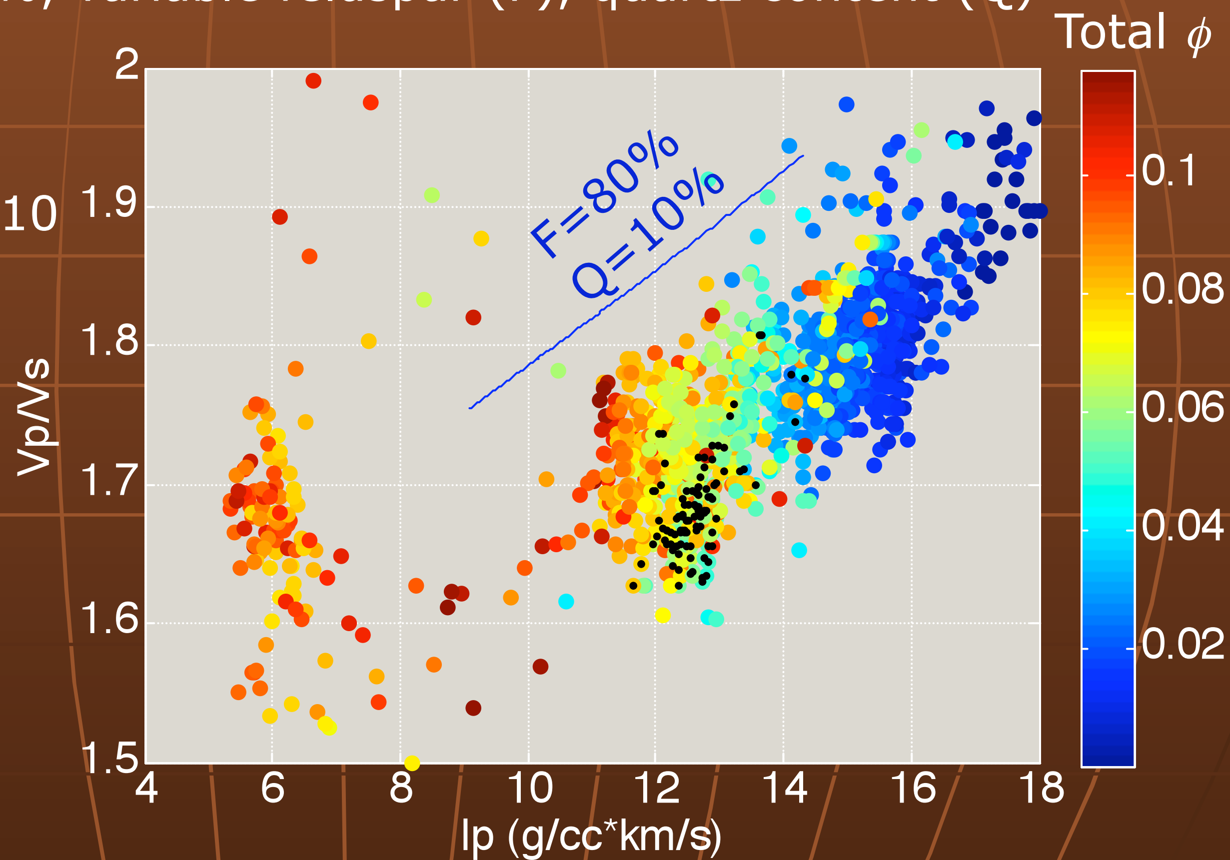
Mineralogy: Clay = 10%, variable feldspar (F), quartz content (Q)

Porosity: 3 to 20%

Pressure: 30 MPa

Critical porosity: 0.4

Coordination number: 10



Rock physics model

Contact theory model for a stiff rock

Parameters

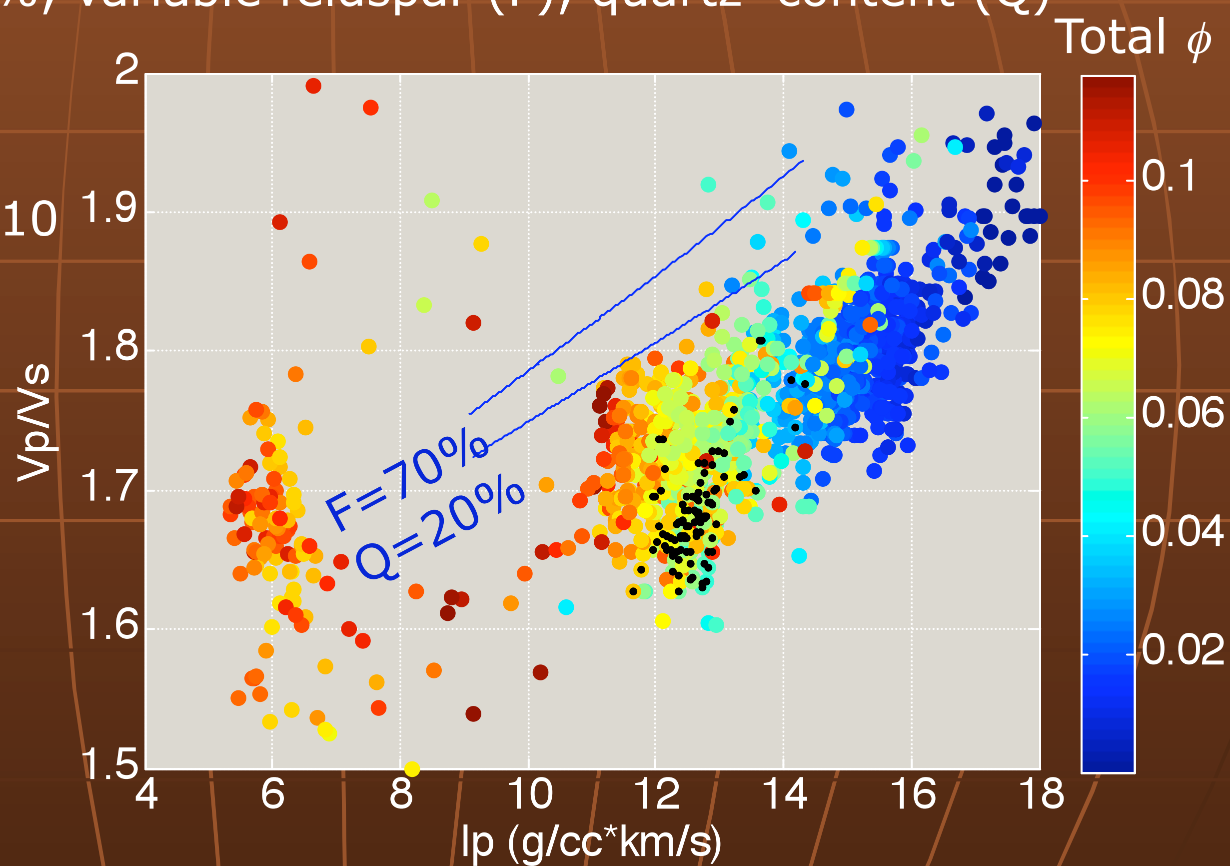
Mineralogy: Clay = 10%, variable feldspar (F), quartz content (Q)

Porosity: 3 to 20%

Pressure: 30 MPa

Critical porosity: 0.4

Coordination number: 10



Rock physics model

Contact theory model for a stiff rock

<u>Parameters</u>

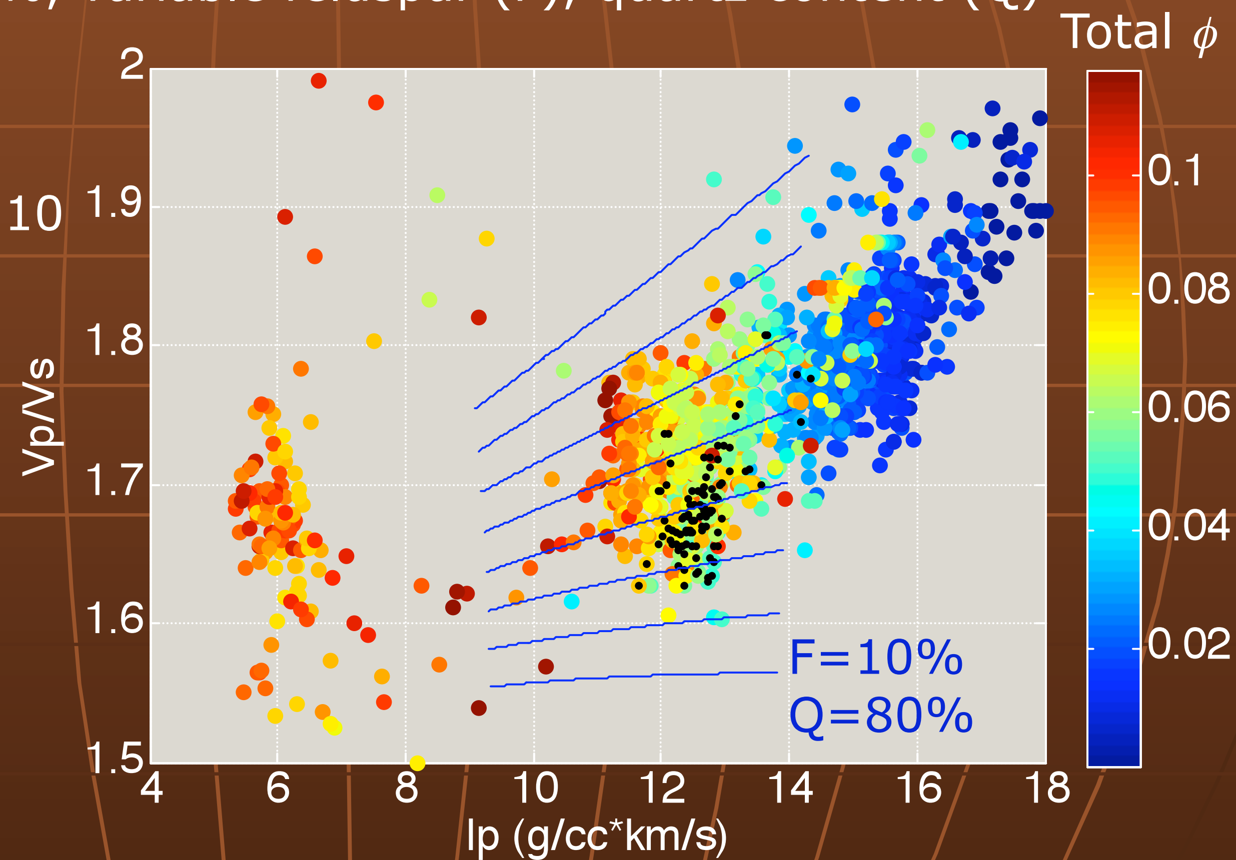
Mineralogy: Clay = 10%, variable feldspar (F), quartz content (Q)

Porosity: 3 to 20%

Pressure: 30 MPa

Critical porosity: 0.4

Coordination number: 10



Rock physics model

Contact theory model for a stiff rock

<u>Parameters</u>

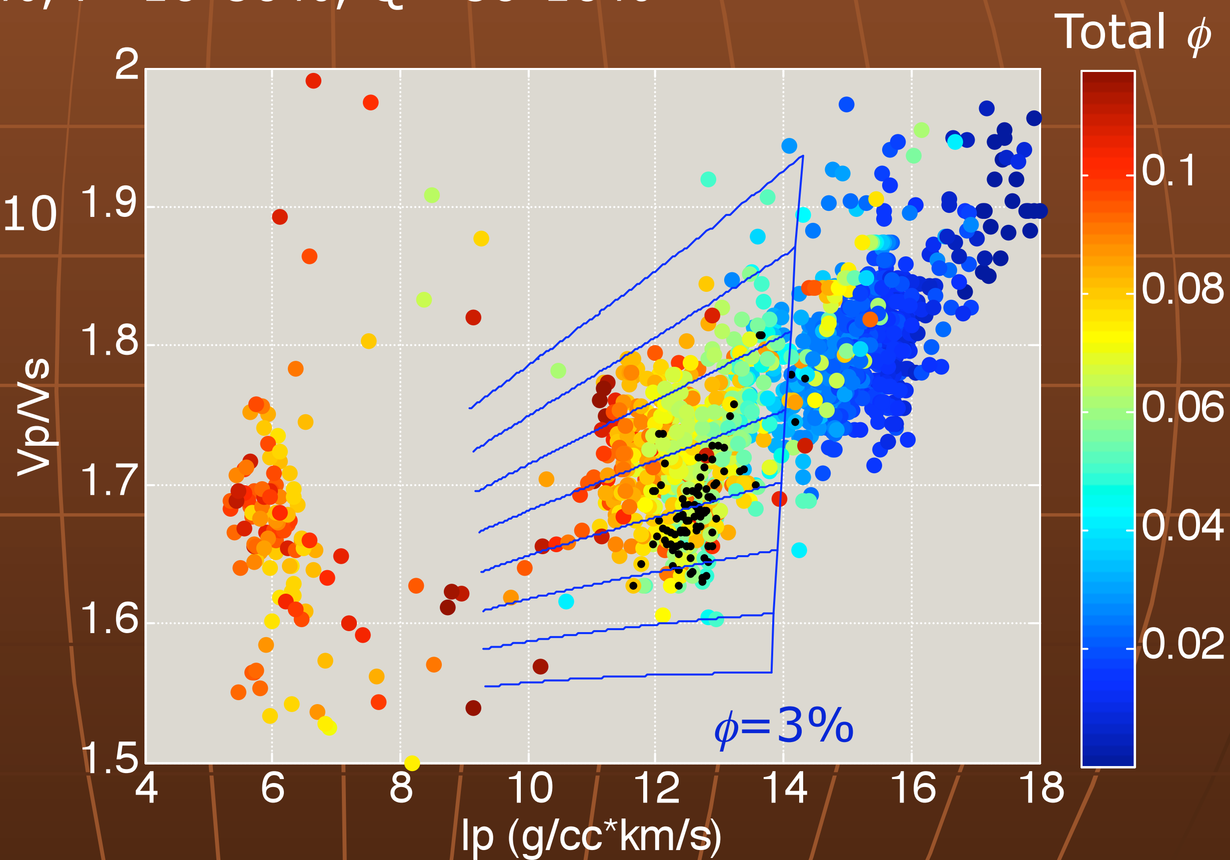
Mineralogy: Clay = 10%, F=10-80%, Q =80-10%

Porosity: 3%

Pressure: 30 MPa

Critical porosity: 0.4

Coordination number: 10



Rock physics model

Contact theory model for a stiff rock

Parameters

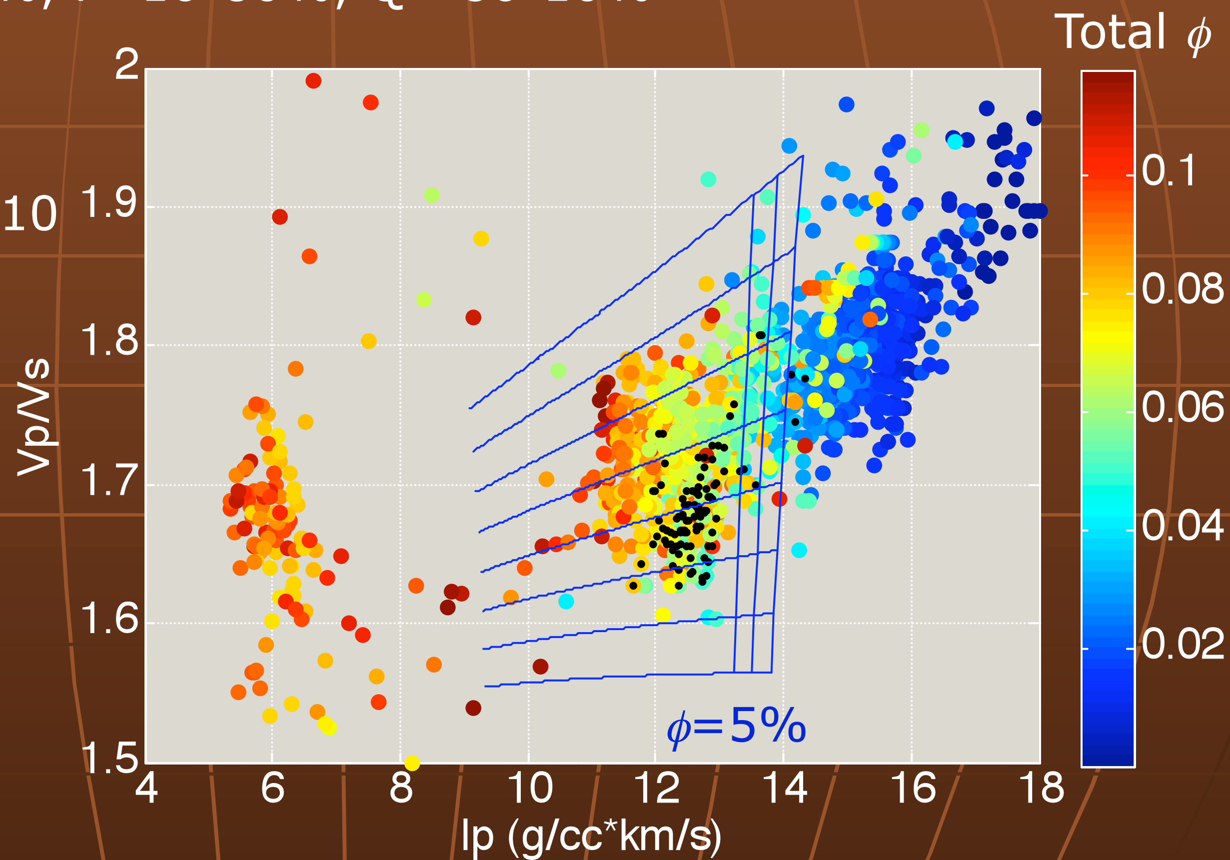
Mineralogy: Clay = 10%, F=10-80%, Q =80-10%

Porosity: 5%

Pressure: 30 MPa

Critical porosity: 0.4

Coordination number: 10



Rock physics model

Contact theory model for a stiff rock

<u>Parameters</u>

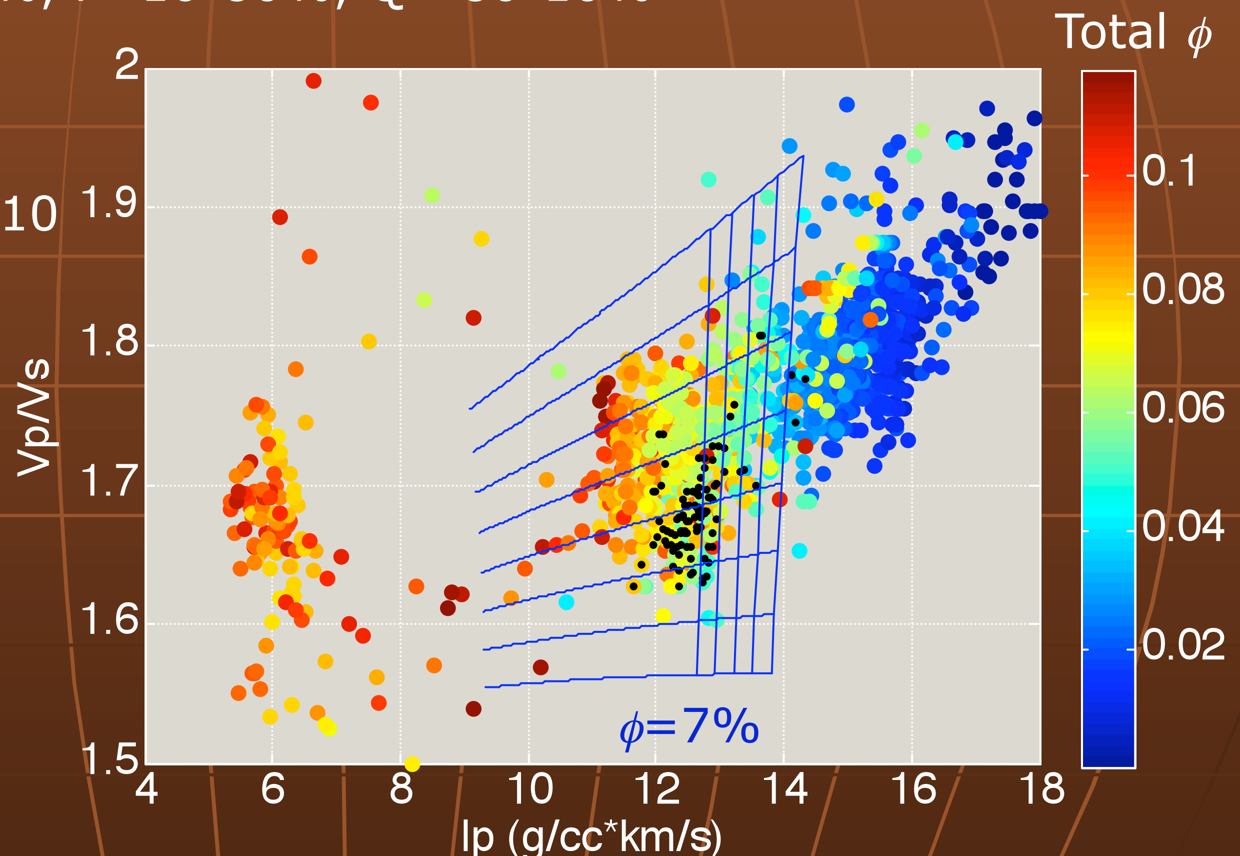
Mineralogy: Clay = 10%, F=10-80%, Q =80-10%

Porosity: 7%

Pressure: 30 MPa

Critical porosity: 0.4

Coordination number: 10



Rock physics model

Contact theory model for a stiff rock

Parameters

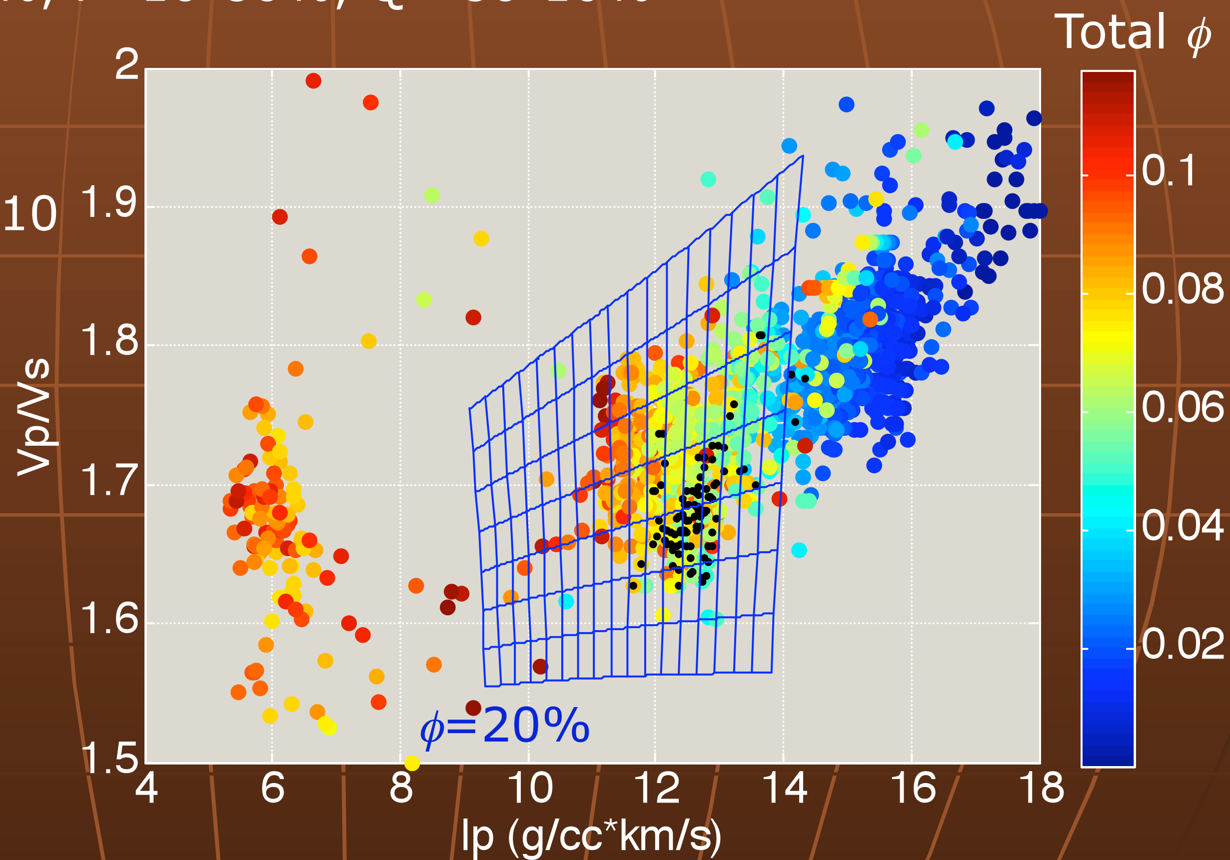
Mineralogy: Clay = 10%, F=10-80%, Q =80-10%

Porosity: 20%

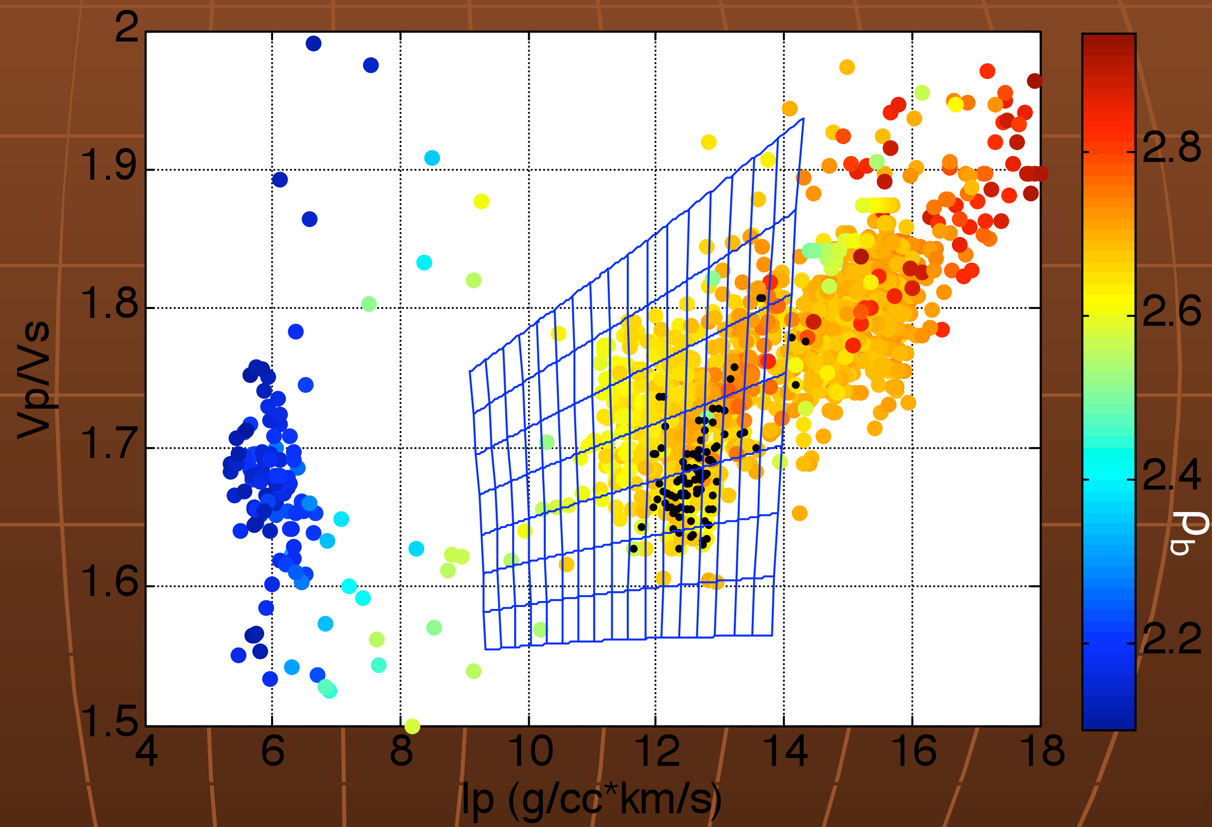
Pressure: 30 MPa

Critical porosity: 0.4

Coordination number: 10

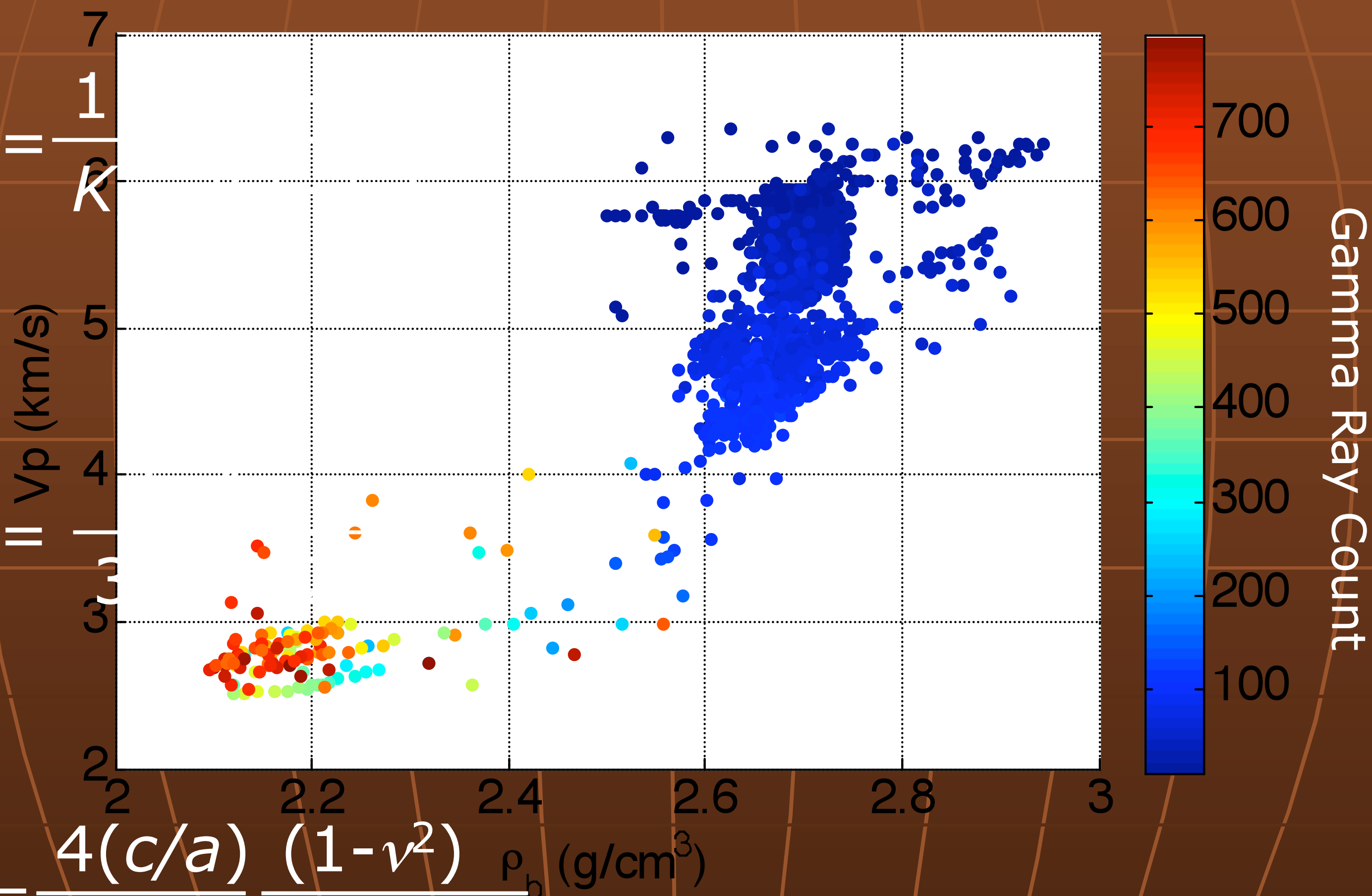


Rock physics model



Rock properties

$$\frac{1}{K_\phi} = \frac{1}{K}$$



$$\frac{1}{K_\phi} =$$

$$\frac{1}{K_\phi} = \frac{4(c/a)}{3\pi K_0} \frac{(1-\nu^2)}{(1-2\nu)}$$

Rock properties

$$\frac{1}{K_\phi} = \frac{1}{K_0} \frac{3(1-\nu)}{2(1-2\nu)}$$

$$\frac{1}{K_\phi} = \frac{5-4\nu}{3K_0(1-2\nu)}$$

$$\frac{1}{K_\phi} = \frac{4(c/a)}{3\pi K_0} \frac{(1-\nu^2)}{(1-2\nu)}$$