PERMEABILITY ANISOTROPY AND MEANDERING FLUVIAL FACIES ARCHITECTURE OF THE BARTLESVILLE SANDSTONE, NOWATA COUNTY, OKLAHOMA

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Definition of Permeability Anisotropy

Horizontal Well Drainage Pattern Due to Permeability Anisotropy.

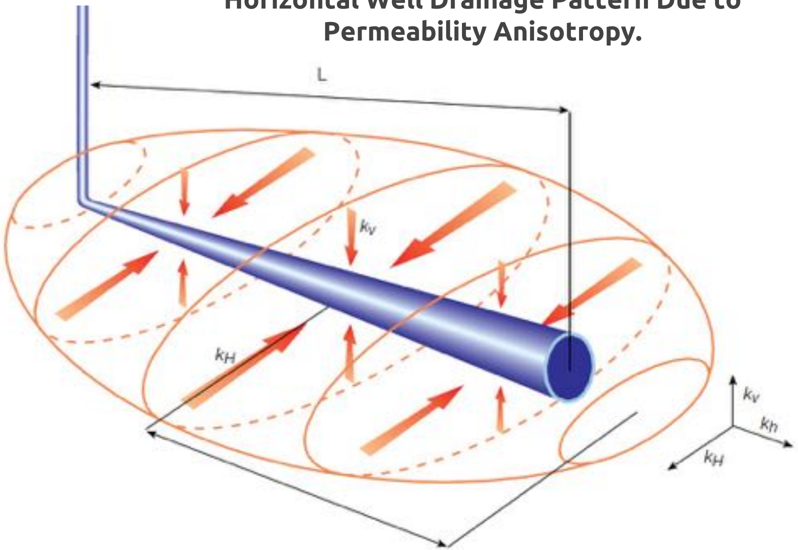


Figure adapted from Economides et al., 2012.

Permeability anisotropy occurs when the permeability of a rock volume changes when measured in different **directions**.

Can be subtle or near isotropic (e.g. a block of clean homogenous sandstone)

Can be prevalent or even an order of magnitude difference in permeability (e.g. alternating sand / shale layers)

Motivation for a Permeability Anisotropy Study Focusing on Finer-Scale Heterogeneity

Reservoir Models

Core-derived petrophysical measurements (*e.g.*, permeability) incorporated in reservoir models are broadly quantified at ft-scale intervals; yet heterogeneity is often observed at inch to millimeter scales.
(Goggin et al., 1988)

Hydrocarbon Recovery

Permeability anisotropy induced by laminated media can hinder hydrocarbon recovery by 50%.
(Ringrose et al., 1993)

Environmental Science

Better understanding of finer-scale permeability variations leads to more accurate contaminant transport models.
(Husmans et al., 2008)

Objectives

Simplified for Presentation

Objective 1

Establish facies architecture of the core.

Objective 2

Characterize permeability anisotropy at core plug scale.

Objective 3

Up-scale permeability anisotropy.

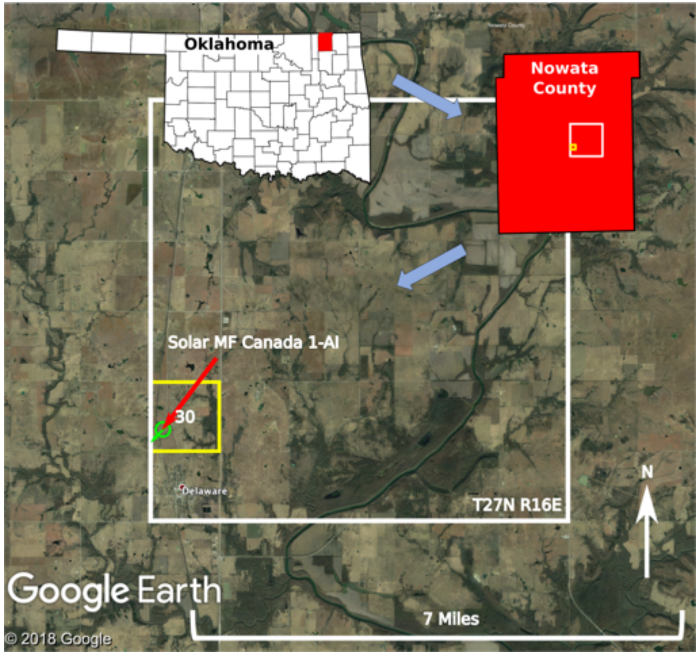
Objective 4

Assess relationships between permeability anisotropy and grain heterogeneities.

Objective 5

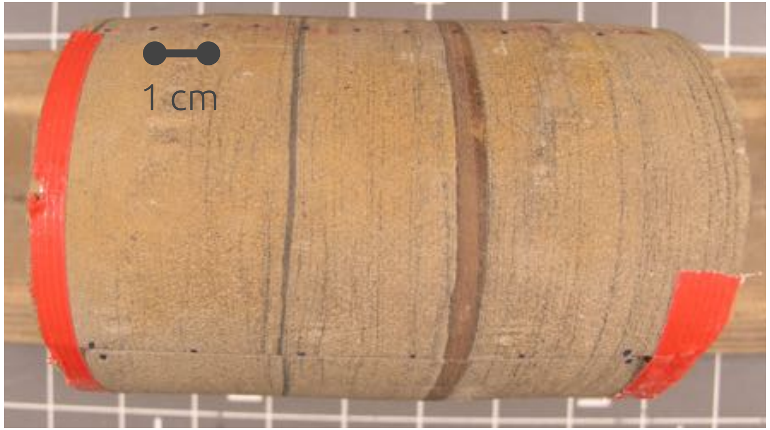
Assess relationships between permeability anisotropy and pore heterogeneities.

Background



Core drilled from Nowata County, OK in 1984.

Core spans 53 ft, depths 795 – 848.5 ft.



Core contains little residual oils / brines. (Obianyor, 2008).

Core never victim of subaerial diagenesis (not outcrop samples). (McCarter, 2017; Yang, 2015)

Background

Regional Stratigraphy

Bartlesville sandstone consists of incised valley fill deposits.

Upper Bartlesville is **meandering fluvial** deposits.
(Ye and Kerr, 2000)

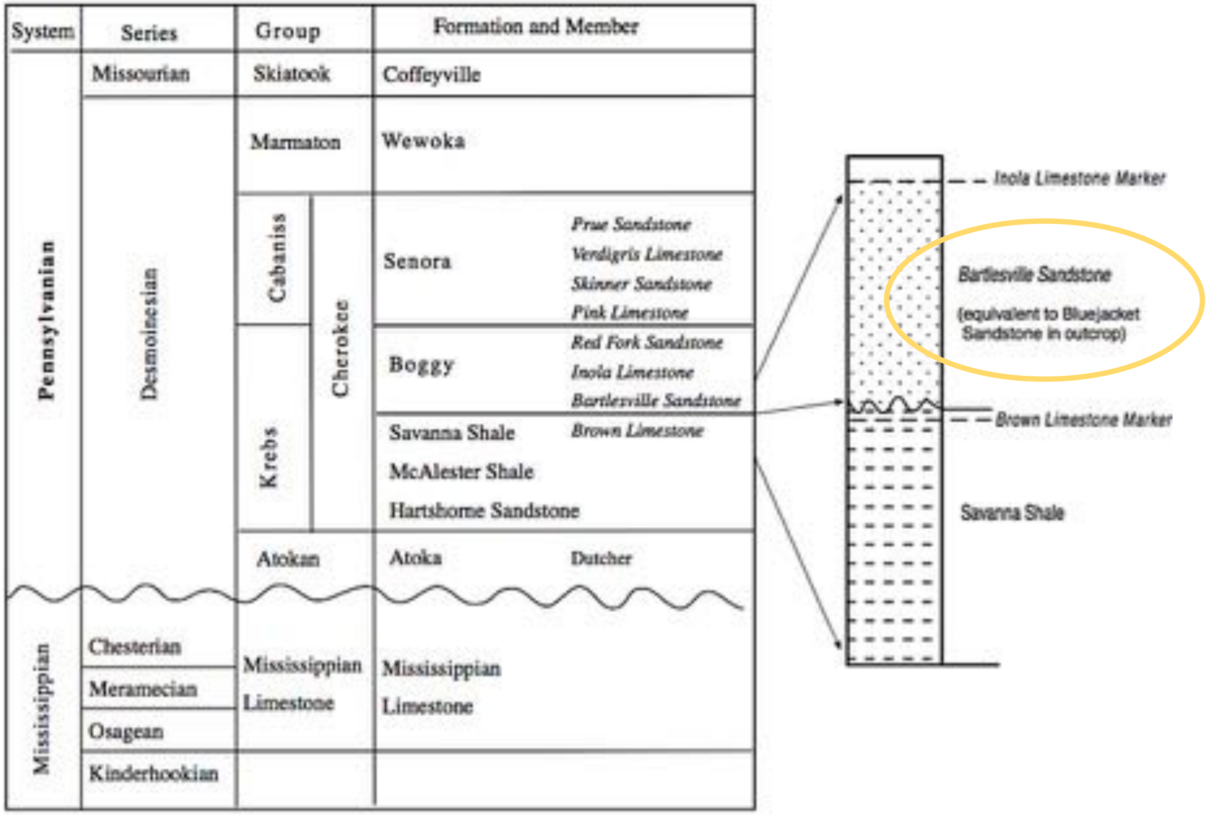
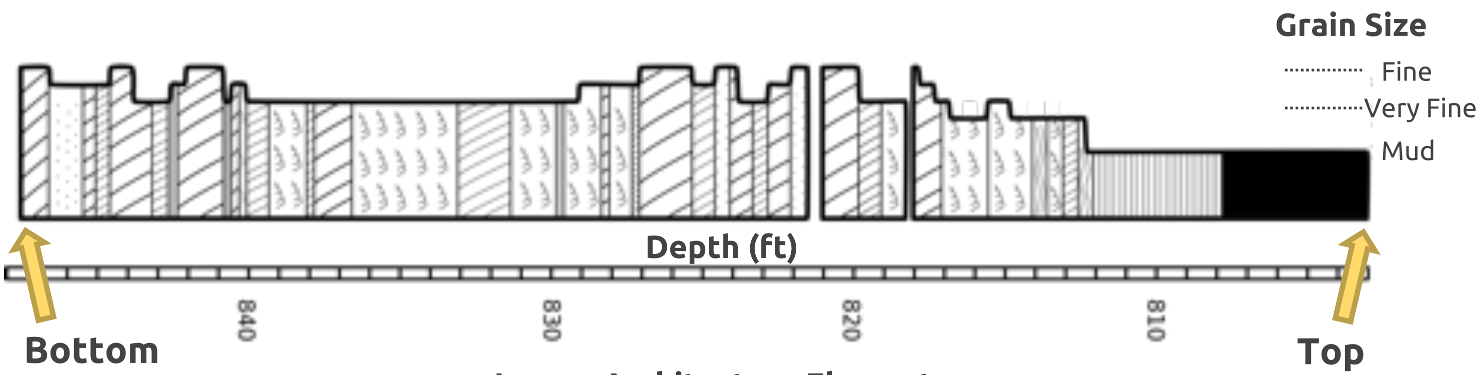


Figure adapted from Ye and Kerr, 2000; modified from Dogan, 1969

Objective 1

Develop the facies architecture of the core.

Facies Architecture



Larger Architecture Elements

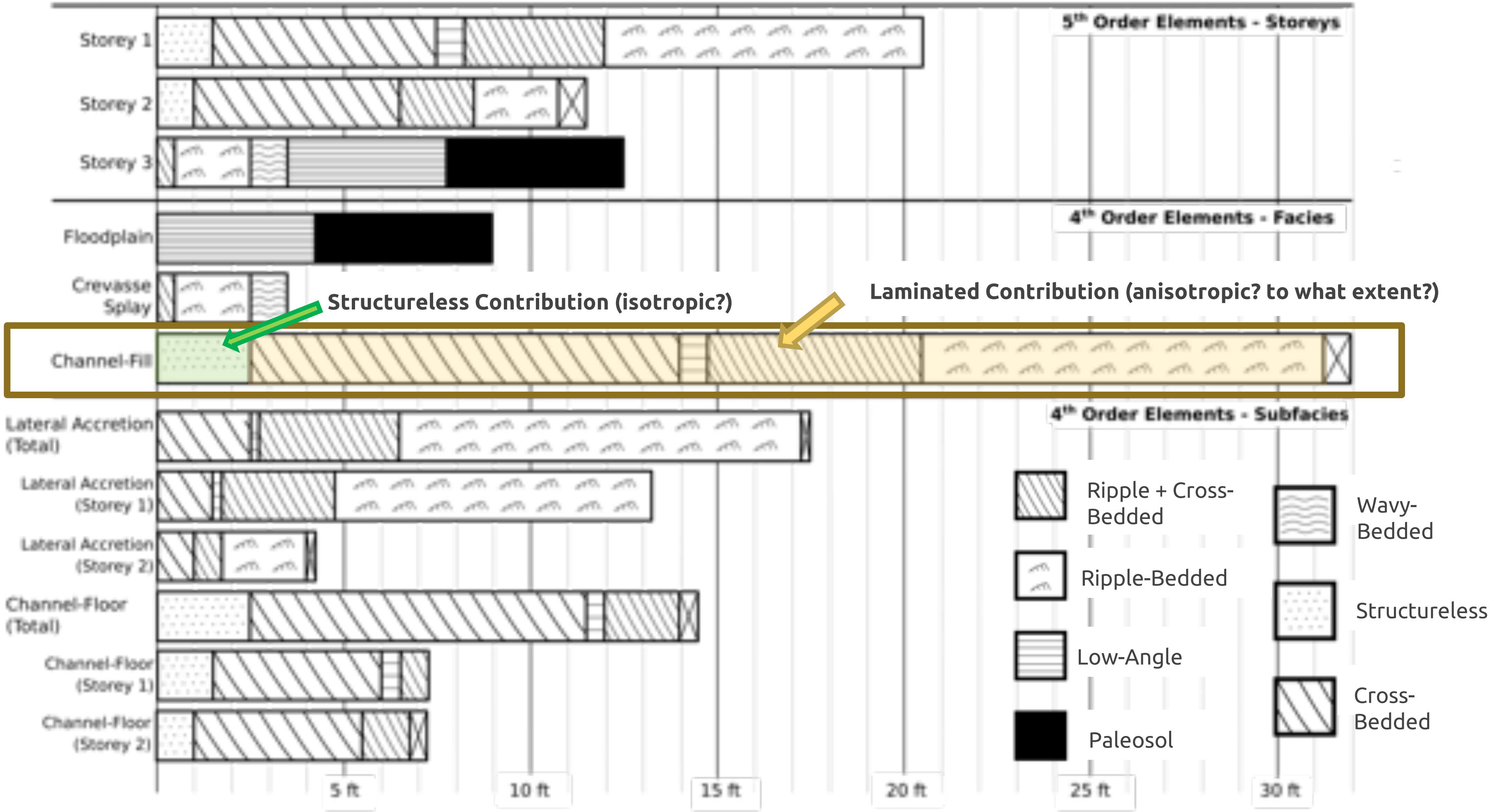
Storey 1		Storey 2		Storey 3	
Channel-Floor	Lateral Accretion	Channel-Floor	Lateral Accretion	Crevasse Splay	Floodplain

There are two vertically stacked channel sandstones (Storey 1 and 2) of possible reservoir quality.

Storey 3 caps off the system with Crevasse Splay sandstone and Floodplain mudstone.

Lithofacies (Sedimentary Structure) Legend

Lithofacies Cumulative Footage Intervals for Architectural Element Hierarchy



Objective 2

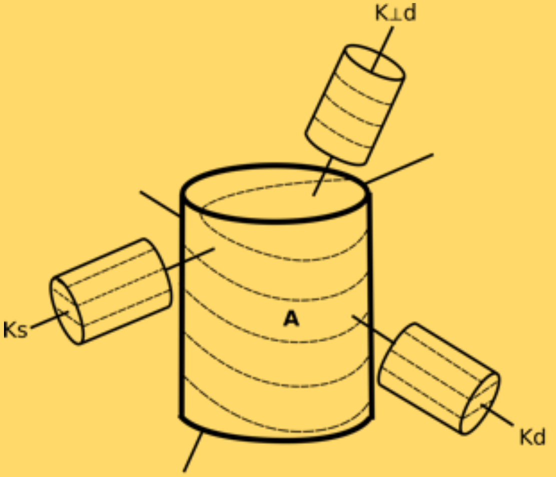
Characterize permeability anisotropy of each lithofacies (sedimentary structure) using core plugs.

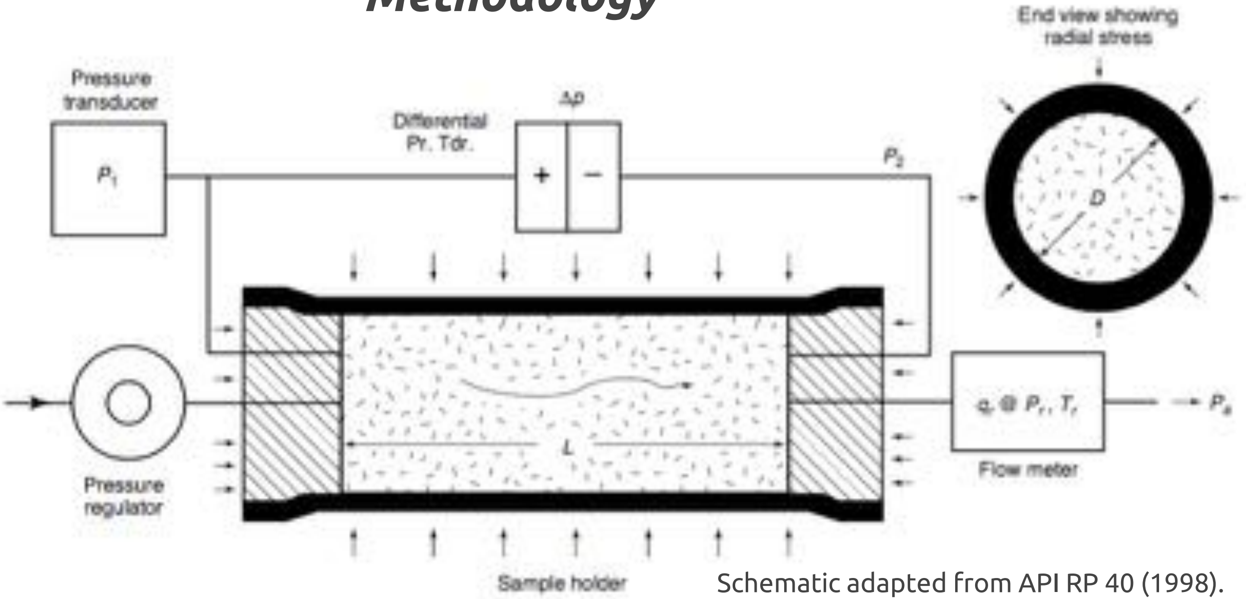
Core Plug Permeatry

Methodology

Core plugs were drilled in three orientations relative to stratal elements.

- Parallel to strike (**Ks**)
- Parallel to dip (**Kd**)
- Perpendicular to a stratal plane (**K⊥d**)





Schematic adapted from API RP 40 (1998).

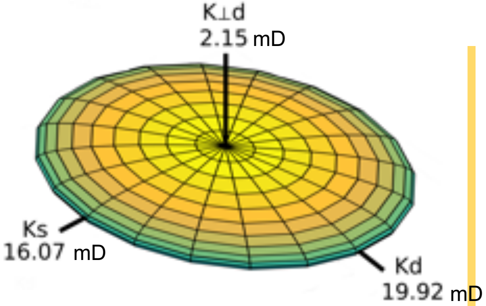
Measurements made using a Hassler-Type chamber apparatus at 100 PSI confining pressure.

Permeability calculated using Darcy's Law.

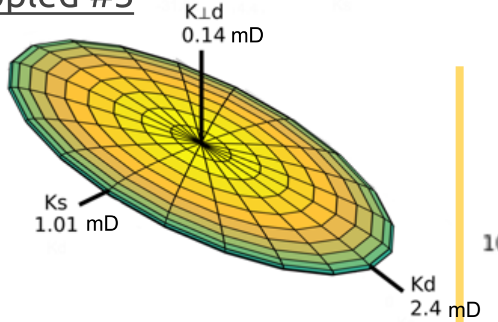
Core Plug Permeability Results

Examples – Permeability Ellipsoids

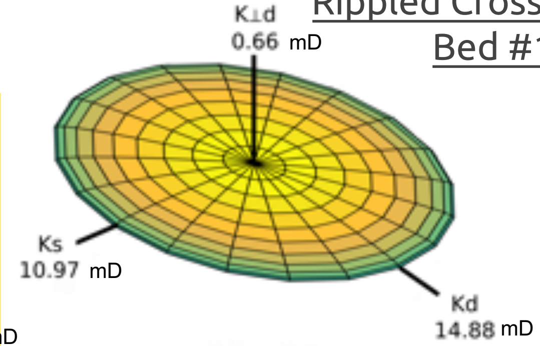
Cross-Bed #3

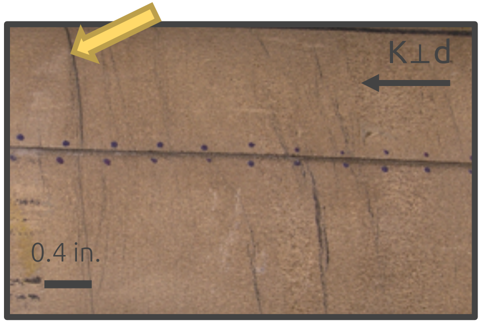


Rippled #3

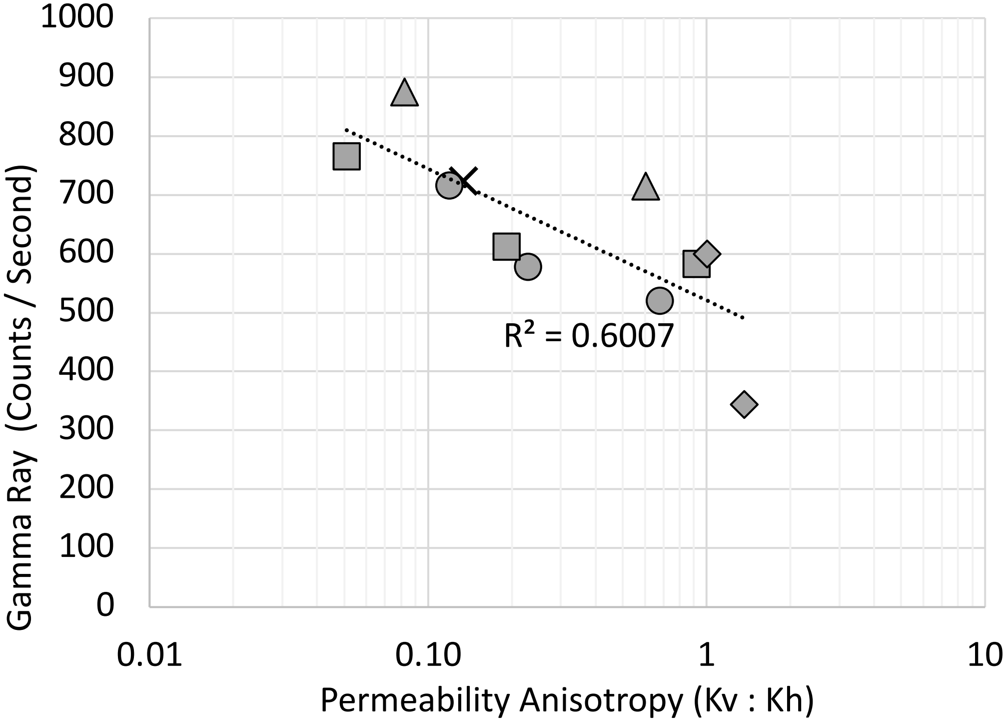


Rippled Cross-Bed #1





Core Plug Permeability Anisotropy and Gamma Ray Count



Gamma ray core scan performed by Monsalve (ca. 1998)

Many laminated samples exhibit permeability anisotropy [vertical / horizontal] approaching or exceeding one order of magnitude.

- Vertical permeability (Kv) = K⊥d
- Horizontal permeability (Kh) = arithmetic average of Ks + Kd

Anisotropy ratio greater with increasing gamma ray count (proxy for mud drape abundance).

Lithofacies Legend

- ■ Rippled and Cross-Bedded
- ● Cross-Bedded
- ▲ Rippled
- ◆ Structureless
- ✕ Low Angle Cross-Bedded

Objective 3

Upscale core plug permeability anisotropy to quantify larger-scale facies architecture elements.

Core Plug Permeability Anisotropy Upscaling to Larger Architecture Elements

Methodology

Upscaling technique uses the core plug values of permeability of each lithofacies and the proportion of each lithofacies within the larger facies architecture element.

Ks and Kd

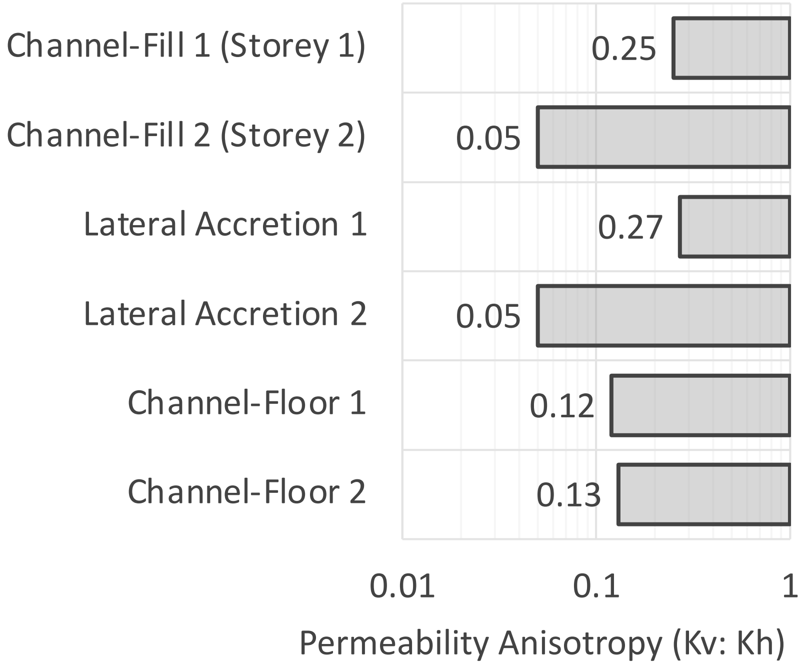
Permeability is generally considered to be distributed geometrically within a heterogenous rock volume.
(Warren and Price, 1961; Selvadurai and Selvadurai, 2014)

A **weighted geometric mean** is used to upscale Ks and Kd.

K⊥d

A **weighted harmonic mean** is suited for upscaling permeability when pore fluid flow is oriented perpendicular to major permeability changes.
(Hollabaugh and Slotboom, 1972)

Permeability Anisotropy of Larger Facies Architecture Elements



Kh is at least 4x greater than Kv for all larger facies architecture elements.

- Vertical permeability (Kv) = K⊥d
- Horizontal permeability (Kh) = arithmetic average of Ks + Kd

The extent of anisotropy primarily reflects the mud drape (carbonaceous drape) abundance of each larger element's unique lithofacies composition.

Objective 4

Use petrographic analyses to investigate relationships between permeability anisotropy and finest-scale heterogeneities (focus on properties of gains).

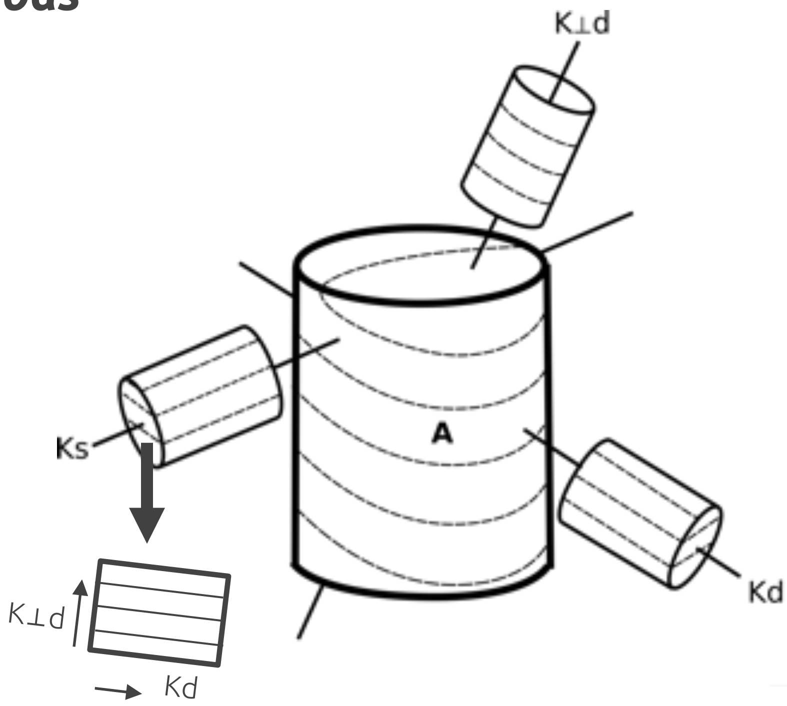
Petrographic Analyses

Methods

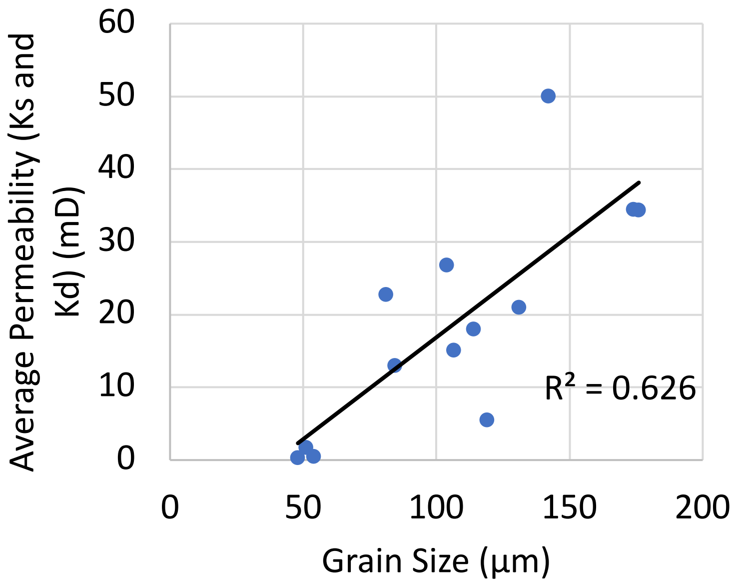
Thin sections were made from the trimmed ends of each oriented core plugs.

Grain size, sorting, shape, etc., were quantified from each lithofacies using >100 grains per thin section.

Detailed analyses of three-dimensional grain fabric performed.



Average Petrographically Determined Grain Size Verses Permeability

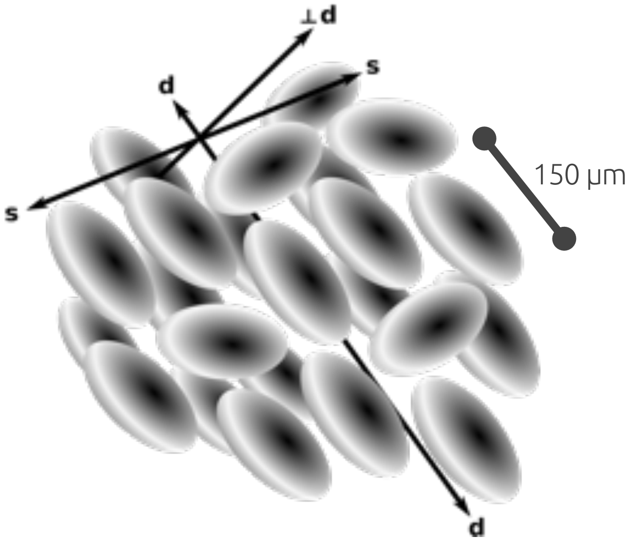


Permeability generally increases with increasing grain size. Some spread in the data suggests other factors (sorting, fabric, diagenesis?) may influence the permeability as well.

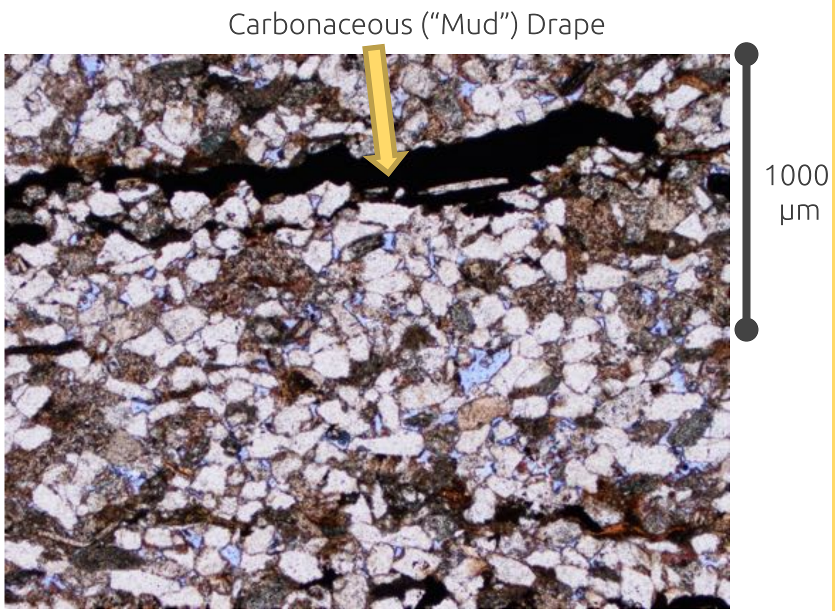
Sorting, grain shape, and roundness were similar between every sample and determined **not** to significantly impact the permeability variations between these samples.

Grains Fabrics and Laminations

All laminated samples exhibit a common grain fabric ranging in the quality of organization.



All laminated samples exhibit some amount of mud drapes.



The extent of permeability anisotropy in the case of every laminated sample can be explained by the prominence of that samples mud drapes. **The extent to which fabric influences permeability anisotropy is uncertain.**

Objective 5

Use micro-CT image volumes to characterize static pore properties and and simulate permeability on small digital rock volumes.

Three-Dimensional Imaging

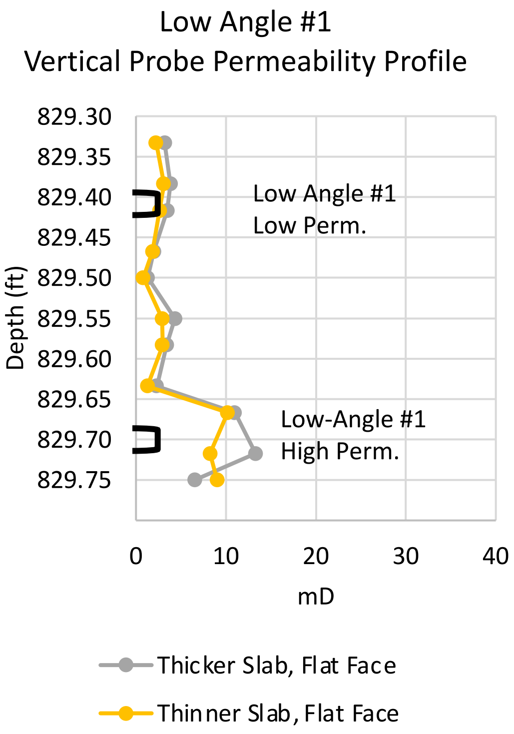
Methodology

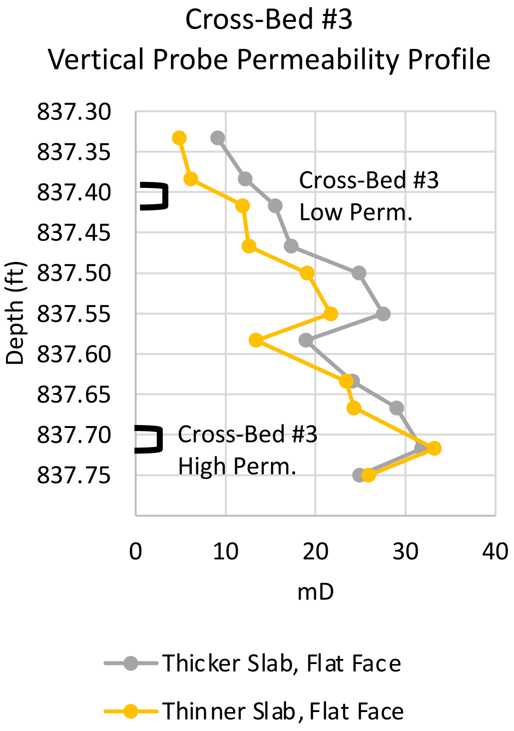
Micro-computed tomography (micro-CT) is used to generate a digital three-dimensional volume of an object.

X-rays are sensitive to the density of the material, thus micro-CT is a great tool to differentiate between **pores** and **grains**. (e.g., Mees et al., 2003; Andra et al., 2013; Howard et al., 2019)

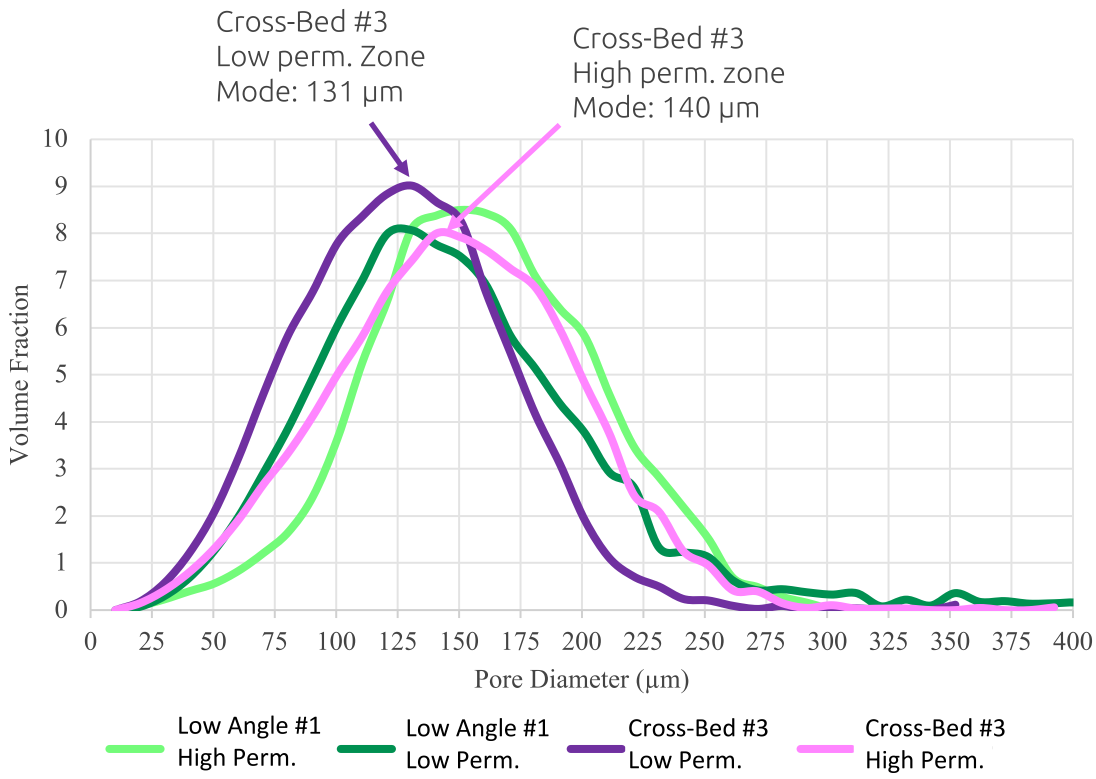
Two miniplugs (2.5 cm length x 1 cm diameter) were each cut from two lithofacies targeting a low and high permeability zone. Each were drilled **parallel to the stratal dip.**

A **10.06 µm** scan resolution was achieved.





Pore Volume Fraction Distribution of Miniplugs



Larger mode of pore diameter correlates with higher permeability zone.

Digital rock volumes are ~0.2 – 0.5 cm^3. Probe permeameter thought to sample ~1.7 cm^3.
(Goggin et al., 1988)

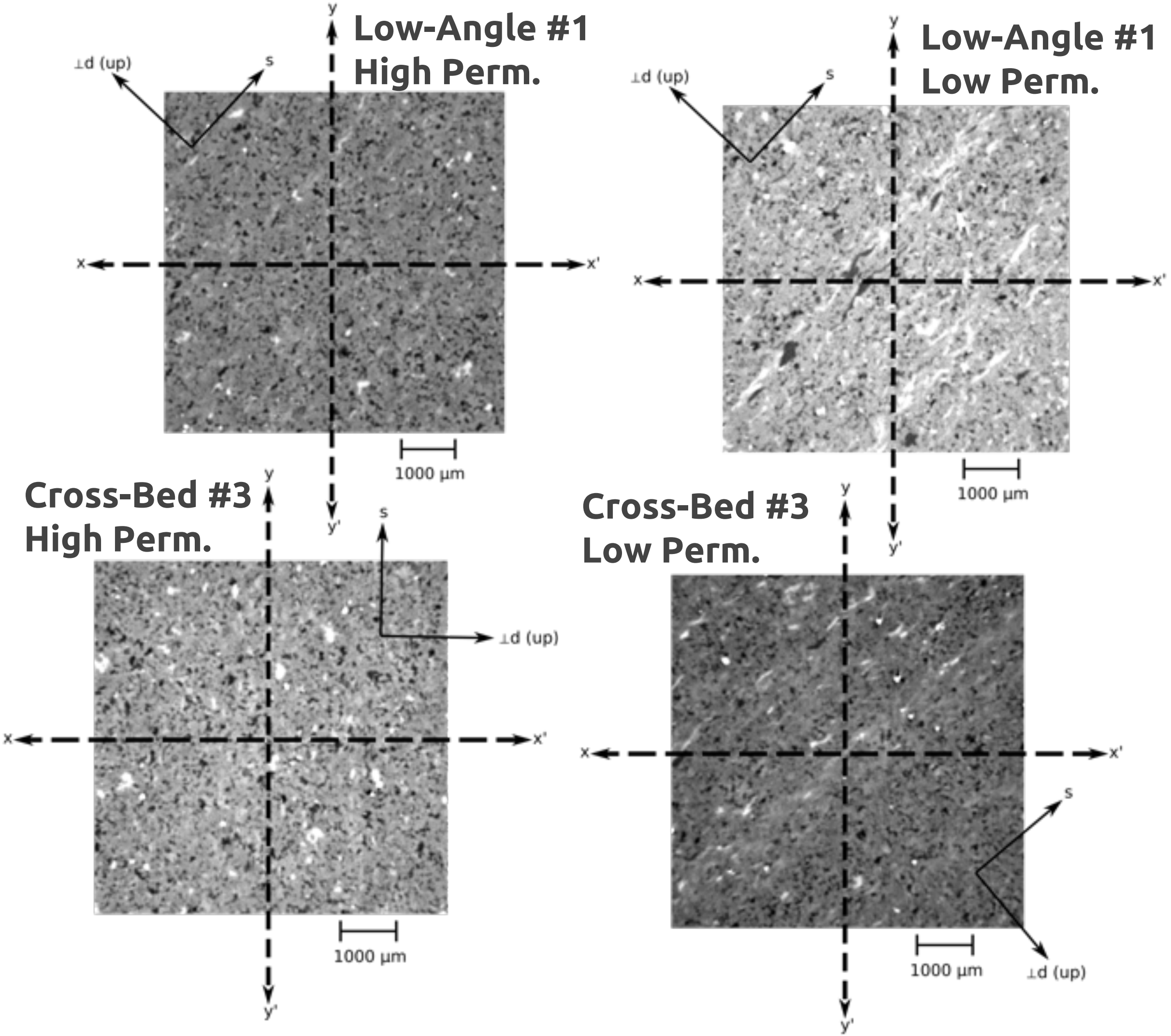
Sample size >100,000 pore bodies.

Qualitative Characteristics of the Miniplugs

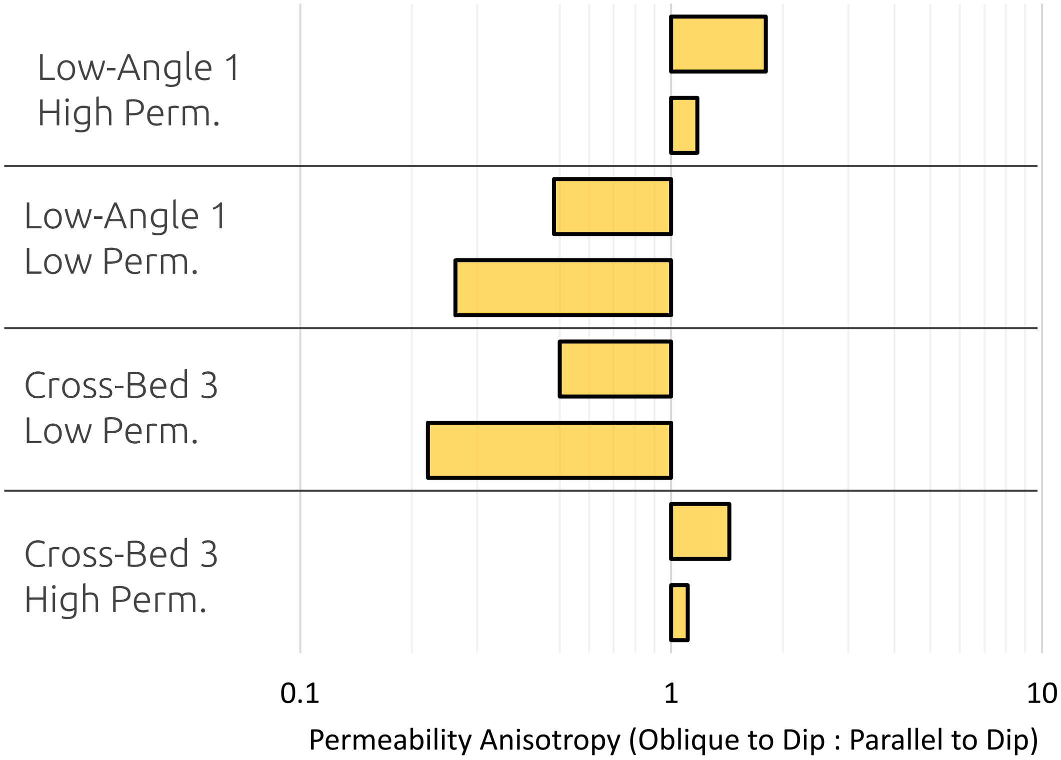
Parallel to dip direction is into and out of the screen.

Lower permeability miniplugs from Low-Angle #1 and Cross-Bed #3 lithofacies contain more prominent **laminations.**

Higher permeability miniplugs are more **homogenous.**



Permeability Anisotropy Simulations



Two smaller volumes (0.127 cm^3) were used from each miniplug to simulate permeability.

Laminated miniplugs show permeability anisotropy where parallel to dip is 2 – 4x greater than oblique to dip directions.

More homogenous miniplugs drilled from high permeability zones show isotropic permeability or slightly >1. No laminations / mud drapes to baffle flow.

Simulations generally agree with measurements made at the core plug scale (~18 cm^3)! **Two orders of magnitude difference in scale.**

Conclusions

1. Core-plug derived permeability anisotropy up to and exceeding one order of magnitude was observed in laminated lithofacies characterized by mud drapes.

2. Upscaled permeability anisotropy (Kv/Kh) of larger facies architecture elements approaches and exceeds one order of magnitude and reflects the mud drape abundance of each larger sand bodies unique lithofacies composition.

3. Petrographic analyses of the finest-scale heterogeneities (sorting, grain shape, fabric) ultimately suggests mud drape abundance is the primary influence on permeability anisotropy.

4. Permeability simulations on small digital rock volumes reveal permeability anisotropy (oblique to dip : parallel to dip) in image volume characterized by laminations and mud drapes. These results agree with much larger core-plug scale results.

Finer-scale heterogeneities (ex. mm-scale mud drapes) play an important role in shaping macroscopic rock properties.

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