[PS]Petrophysical Characteristics of Carbonate Drift Deposits in the Maldives*

Emma L. Giddens[1], Gregor P. Eberli[1], Ralf J. Weger[1], Thomas Lüdmann[2], and Angela Slagle[3]

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[1]CSL – Center for Carbonate Research, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL (egiddens01@gmail.com)
[2]CEN, University of Hamburg, Hamburg, Germany
[3]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY

Abstract

In the Maldives, there are two types of drift deposits: (1) flat lying aggradational sheeted drifts and (2) mounded progradational drift deltas. Sheeted drifts lay on top of drift deltas. These deposits accumulate by the action of bottom currents, which pick up large volumes of sediment and flow through inter atoll gateways from the Indian Ocean into the Inner Sea. Drift deposits are hundreds of meters thick, skeletal rich, heavily bioturbated, and contain alternating consolidated to unconsolidated units. The two drift deltas are estimated to cover approx. 350 km^2 each. The coarsest grainstone-rudstone units are found at the apex of drift deposits and consists mostly of large benthic foraminifera. Moving down and off the axis into the more distal portions, the amount of mud increases and only fine-grained wackestone to packstones are found.

Drift deposits have high porosity (15-80%) and do not show the typical trend of decreasing porosity with depth, but in certain intervals porosity increases with depth. Downhole fluctuations in porosity, density, velocity, and resistivity in these pure carbonate successions are controlled by changing depositional textures, grain size, facies, degree of lithification, and pore type. High percentages of microporosity decrease velocity in the deeper, finer-grained drift packages. Some spikes in resistivity are due to the occurrence of chert nodules and the amount of calcite cement. Unconsolidated units have high porosity, low density, and low velocity. Gamma ray values are mostly driven by the amount of organic matter and is generally low. These drift deposits have high macro and micro porosity, relatively high permeability, and their thickness and spatial extent can potentially make them excellent reservoirs.

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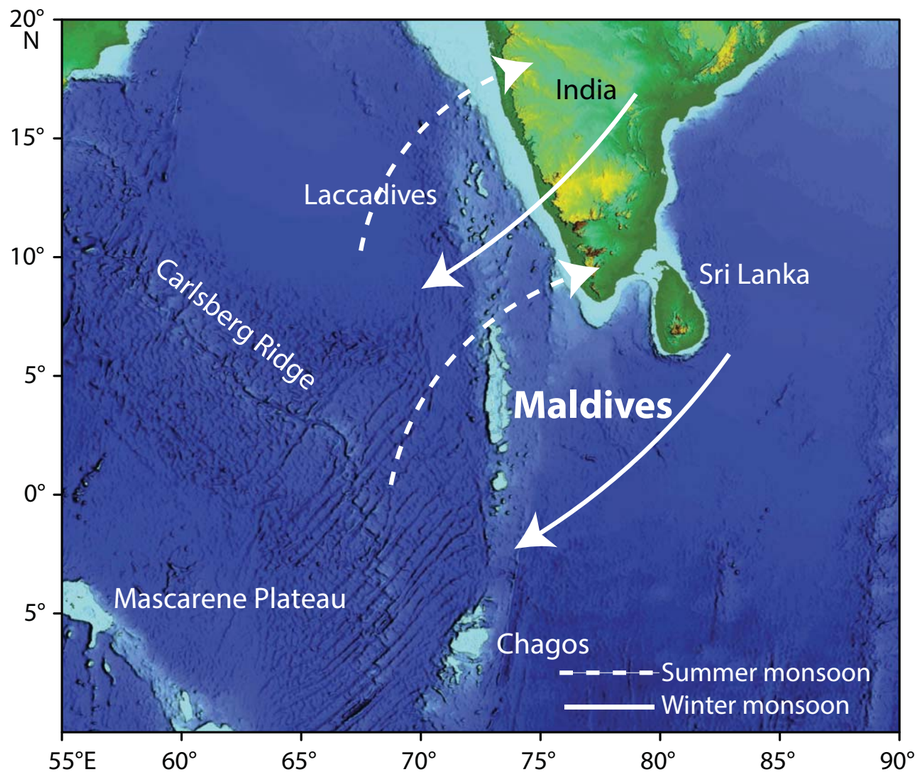
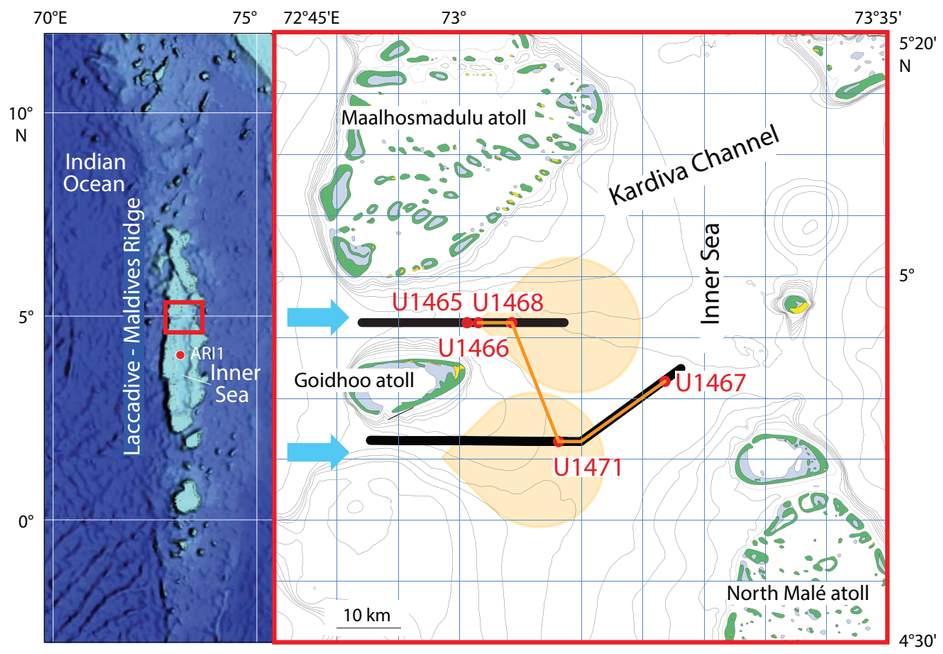
LOCATION





Northern and Southern seismic lines (black). Proximal to distal transect in orange.

The archipelago in the Maldives is a double row of 22 circular to elongate atolls that enclose the ~550 m deep Inner Sea. The onset of the Indian monsoon (13 Ma) changed the depositional regime in the Maldives from sea level to current-controlled (Betzler et al., 2016). The depositional change caused part of the platform to drown, which gave way to gateways that connect the Inner Sea with the Indian Ocean and allowed the ocean currents to pass through the archipelago. The currents in this part of the Indian Ocean are controlled by the reversing monsoon winds. The currents transport large volumes of sediment from the inter-atoll gateways into the Inner Sea and create stacked prograding convex sigmoidal lobes composed of calcareous, skeletal-rich coarse-grained debris. These current derived debris are from two types of drift deposits: (1) flat lying aggradational sheeted drifts and (2) mounded progradational delta drifts, where sheeted drifts lay on top of delta drifts (Lüdmann, 2018).

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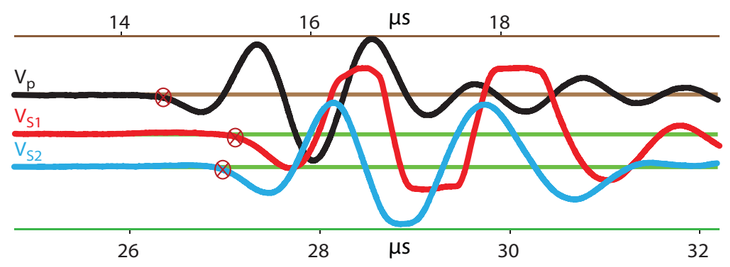
PETROPHYSICAL CHARACTERISTICS

	Sheeted Drift	Delta Drift	Periplatform Sed
Porosity	45-55%	15-55%	21-48%
	20-81%	9.4-63%	no data
Micro Porosity	37-54%	9-52%	16-44%
Permeability	1.8-36 mD	0-22 mD	0.2-95 mD
Velocity	2.3-2.9 km/s	2.3-4.9 km/s	2.4-4.1 km/s
	1.5-5.0 km/s	1.6-5.5 km/s	no data
Gamma (API)	1.5-79	4.8-91	22-74
Density	2.8-2.9 g/cm3	2.4-3.0 g/cm3	2.6-2.8 g/cm3
	1.3-2.1 g/cm3	1.3-2.4	no data
Resistivity (log10(ohm))	1.26-1.28	1.23-2.06	1.26-1.28
	0.7-11	0.8-15	1.1-2.9
Formation Factor (FF)	5.8-13	5.4-140	5-66
Cementation Factor (m)	2.41-2.90	1.98-2.96	2.12-3.06
PoA	63-200	61-227	45-194
DomSize	67-238	24-269	55-364

Downhole well log data is white and core plug data is colored.

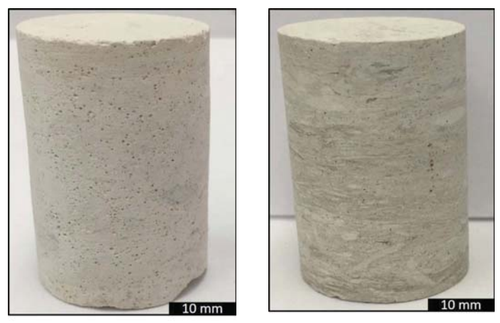
METHODS



Compressional velocity (Vp), shear velocity (S1, S2), and electrical resistivity were measured using a NER Autolab system at effective pressures of 3, 5, and 10 MPa and analyzed at 10 MPa.

IODP Expedition 359 Downhole Well Logs

Logging Tools	U1466	U1468	U1471	U1467
Spectral Gamma (HNGS)	X	X	X	X
Porosity (APS)	X	X	X	X
Density (HLDT)	X	X	X	X
Resistivity (DIT)	X	X	X	X
Sonic (FMS)			X	X



96 core plugs from Expedition 359 sites U1466, U1467, U1468, and U1471 were analyzed at the CSL laboratory from the more distal and deeper portions of the drift deposits where the sediment was lithified. Porosity was measured using a helium pycnometer and samples were sent to Schlumberger to measure permeability.

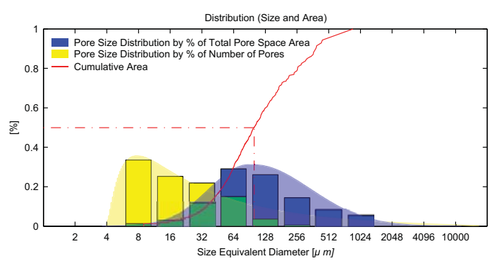
IMAGE ANALYSIS

Digital image analysis (DIA) was preformed on thin sections to quantify pore shape (PoA) and size (DomSize) (Weger, 2009). The thickness of a thin section is about 30µm. Any pore less than that is not imaged; thus, the total helium pycnometer porosity minus porosity quantified by DIA equals the amount of microporosity.

Perimeter over Area (PoA)

PoA is the total perimeter divided by the total area of the pore space. PoA is a measure of pore complexity. In the figures below, all have the same area but different perimeters. The PoA increases from left to right.

DomSize



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(1) CSL – Center for Carbonate Research
Rosenstiel School of Marine and Atmospheric Science - University of Miami
(2) CEN, University of Hamburg (3) Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY

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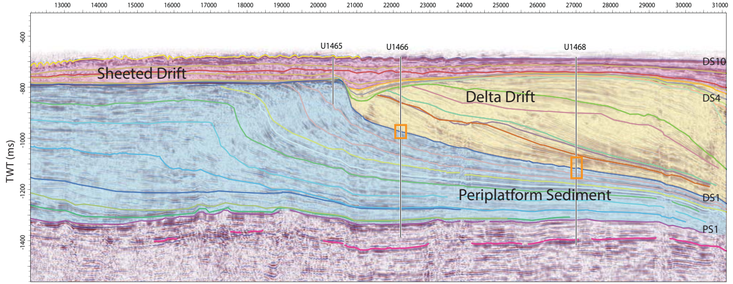
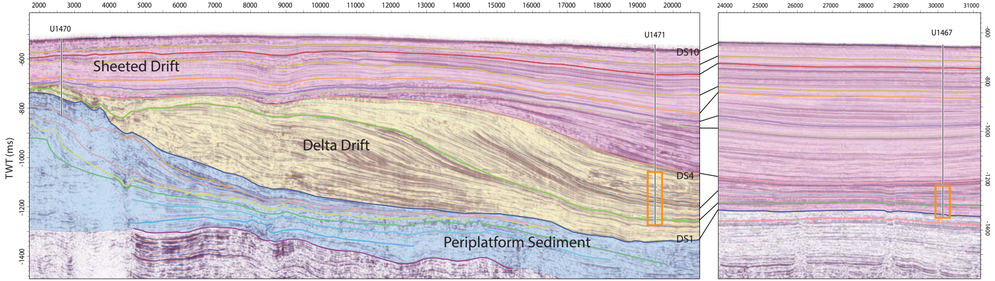
NORTHERN TRANSECT



The orange boxes mark the locations of core plug samples. They are from the deeper, finer-grained portions of the drift and periplatform deposits. Above these boundaries the sediment was unlithified so no plugs were taken.

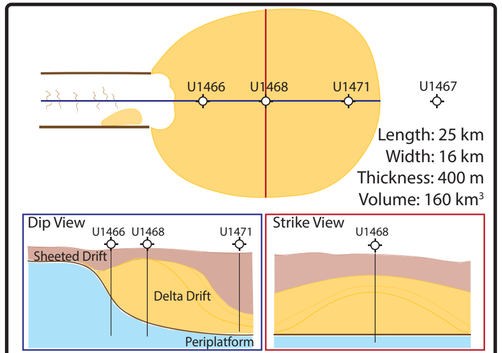
SOUTHERN TRANSECT



Sheeted Drift
- Aggrading flat lying beds
- Low amplitude
- Sediment waves

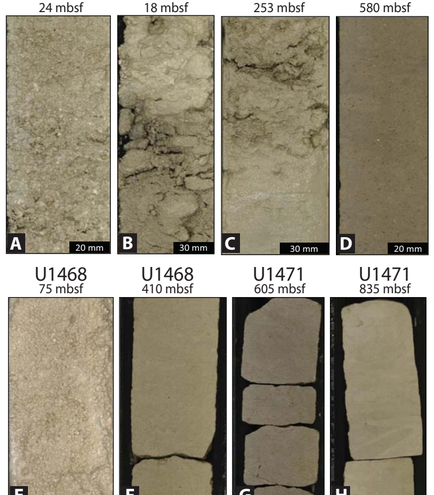
Delta Drift
- Prograding sigmoidal convex clinoforms
- Mounded
- High-low amplitude
- Excavation moat
- Cyclic steps

Periplatform Sediment
- Prograding sigmoidal concave clinoforms
- Medium-low amplitude

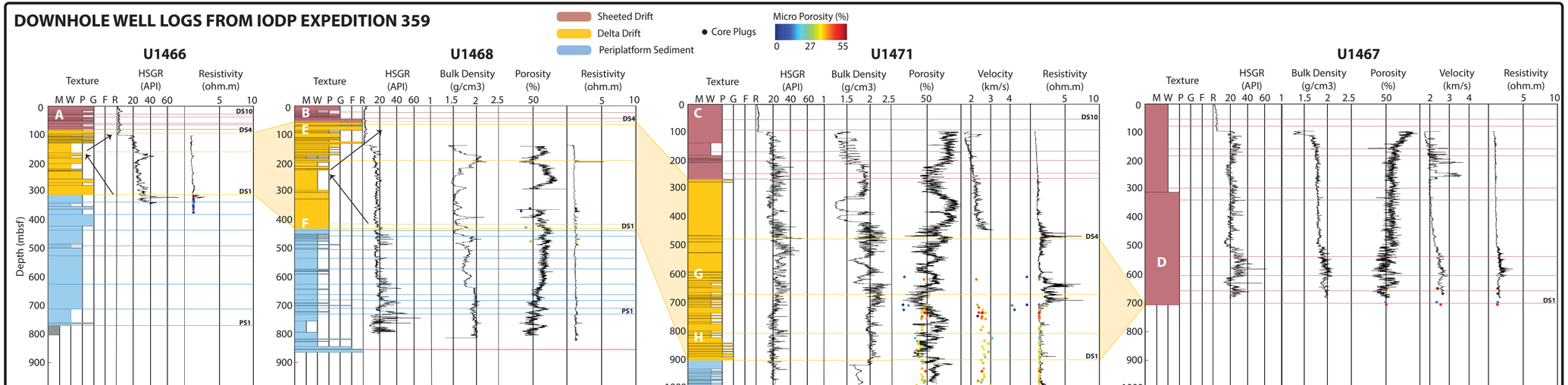


CORE PHOTOGRAPHS

Proximal ⟷ Distal



DOWNHOLE WELL LOGS FROM IODP EXPEDITION 359



Results from core plugs are plotted with the well logs and colored based on the percent micro porosity. The plug and log data correlate well.

Texture
- The coarsest sediment is at the apex of the delta drift (U1468), which is a skeletal rich (benthic forams) rudstone
- The delta drift sequences fine then coarsen upward at the proximal sites

Porosity
- Porosity is very high (9-81%) and at places too high for the logging tool to accurately record it

Velocity
- Velocity generally increases with depth - but measurements from core plugs show an inversion with depth
- Spikes in velocity with no change in porosity are due to changes in pore type

Resistivity
- Resistivity is low with respect to other carbonates
- Spikes in resistivity are due to 'chert'-ified intervals and they occur at or near sequence boundaries

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Core Plug Analysis of Distal Delta Drift Deposits

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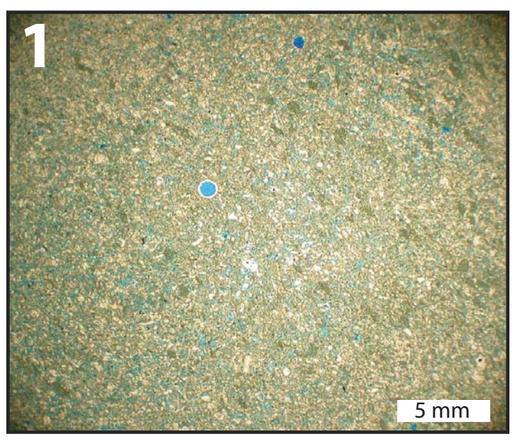
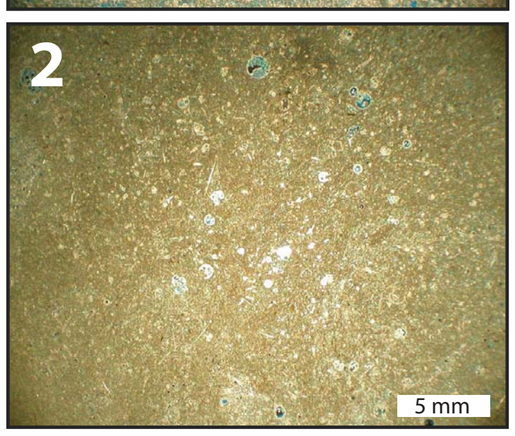
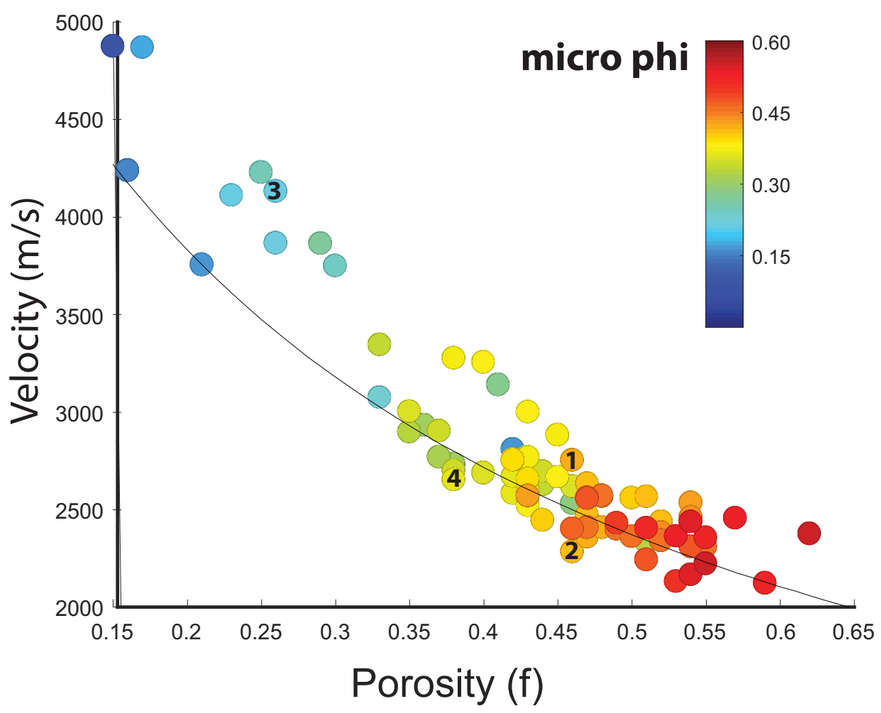
VELOCITY

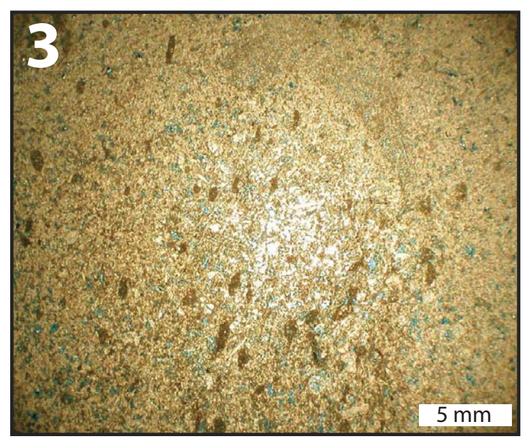
Phi: 45%
microphi: 42%
Perm: 20.8 mD
VP/VS: 1.4
m: 2.68
FF: 8.28
PoA: 189
DomSize: 52
 # Pores: 29,334



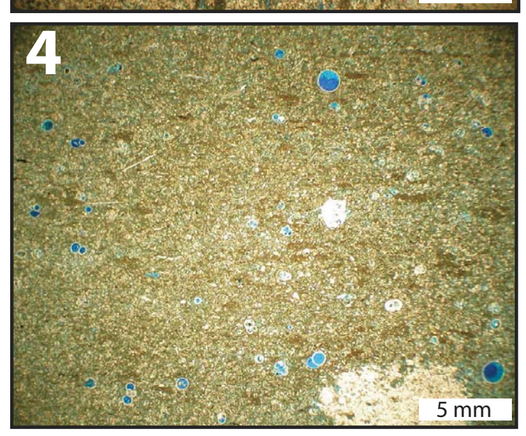
Phi: 46%
microphi: 41%
Perm: 10.9 mD
VP/VS: 2.5
m: 2.35
FF: 6.08
PoA: 121
DomSize: 93
 # Pores: 12,005







Phi: 26%
microphi: 21%
Perm: 20.3 mD
VP/VS: 1.8
m: 2.33
FF: 23.57
PoA: 121
DomSize: 100
 # Pores: 34,660

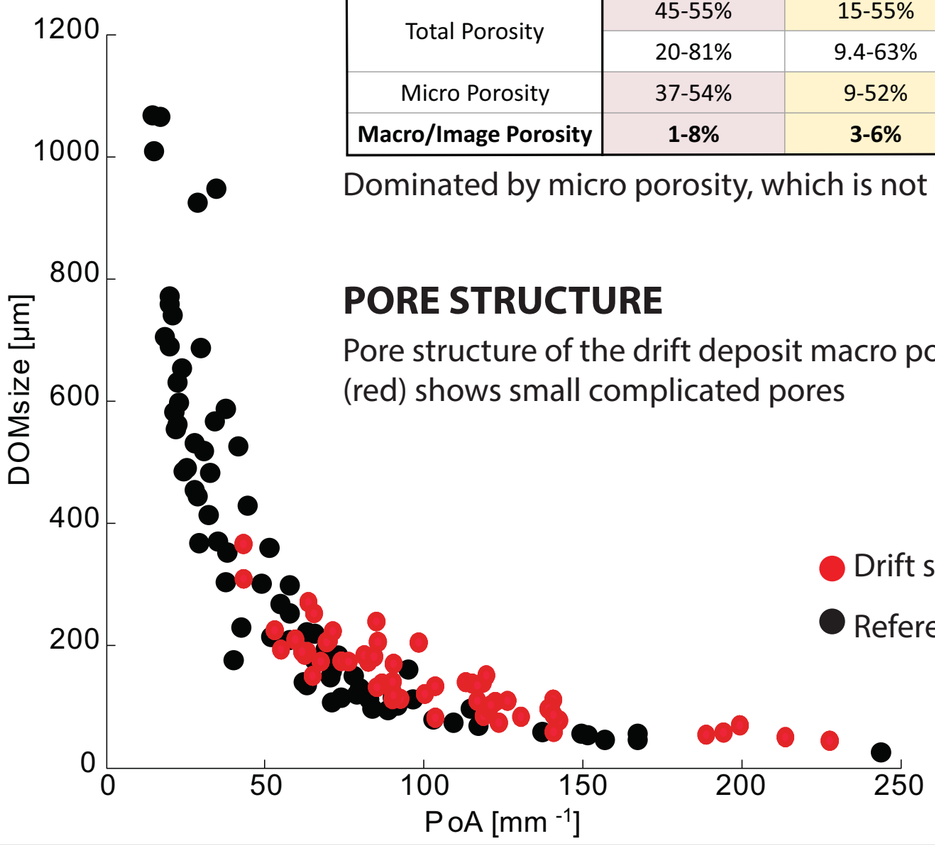


Phi: 38%
microphi: 36%
Perm: 2.58 mD
VP/VS: 1.9
m: 1.99
FF: 6.83
PoA: 131
DomSize: 81
 # Pores: 14,809

POROSITY

	Sheeted Drift	Delta Drift	Periplatform Sed
Total Porosity	45-55%	15-55%	21-48%
	20-81%	9.4-63%	no data
Micro Porosity	37-54%	9-52%	16-44%
Macro/Image Porosity	**1-8%**	**3-6%**	**4-5%**

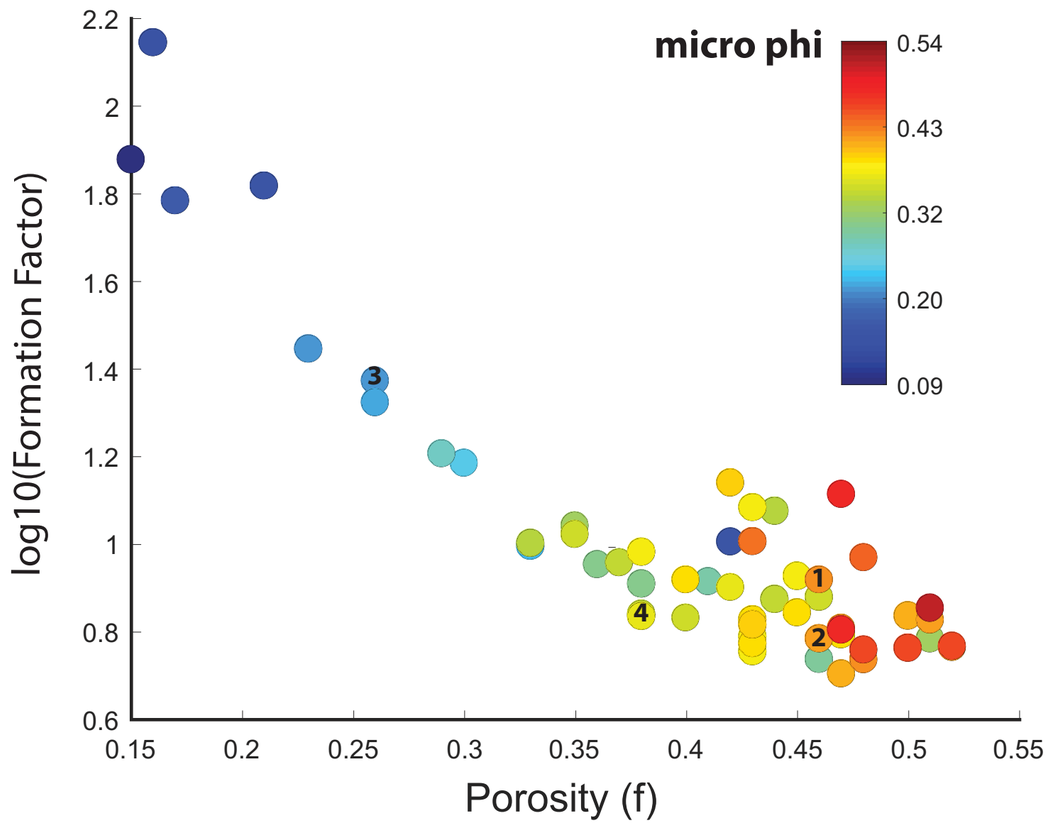
Dominated by micro porosity, which is not captured by DIA



PORE STRUCTURE

Pore structure of the drift deposit macro pores (red) shows small complicated pores

RESISTIVITY

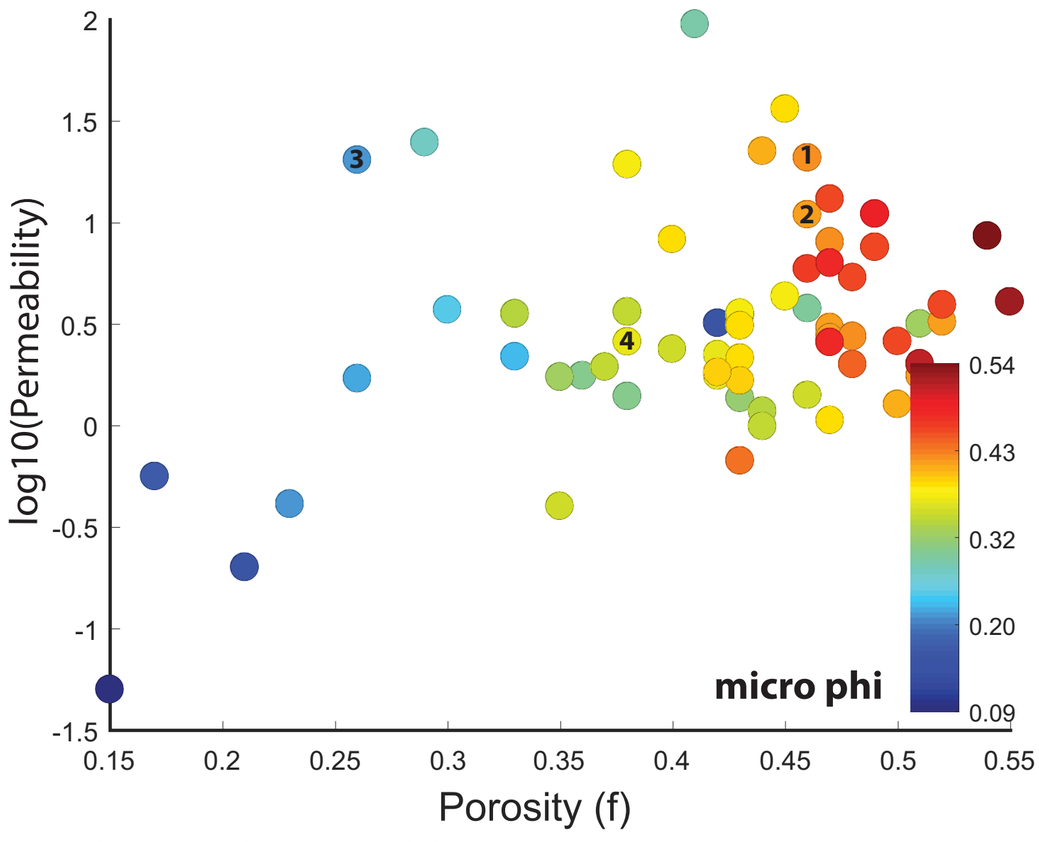


$$FF = \Phi^{-m} = \frac{Ro}{Rw}$$

FF = Formation Factor
Φ = Porosity
m = Cementation Factor
Ro = Resistivity of the solid
Rw = Resistivity of the fluid

High micro and total porosity, low resistivity

PERMEABILITY



(1) High porosity low permeability
(2) Permeability increases as porosity increases
(3) Above 30% porosity, there are large variations in permeability

PLUG ANALYSIS CONCLUSIONS

1. The fine-grained sheeted drift and delta drifts have extremely high porosity (15-55%) that is dominated by micro porosity (9-54%)
2. Drift deposits have smaller and more complicated pores when compared to other carbonate deposits
3. Given their high porosity, permeability is low (0-36 mD)
4. At any given porosity, there is a relatively small range in velocity (max 650 m/s)