Click to view presentation slides

Statistical Characterization of Non-Matrix Porosity and Permeability in a Devonian Dolostone Reservoir from Alberta Canada*

John Dunham[1]

Search and Discovery Article #51591 (2019)**
Posted August 5, 2019

*Adapted from extended abstract based on oral presentation given at AAPG 2019 Annual Convention & Exhibition, San Antonio, Texas, May 19-22, 2019
 DOI:10.1306/51591Dunham2019

[1]Dunham Professional Geology, Los Angeles, CA, United States (johndunham76@gmail.com)

Abstract

Middle Devonian relative sea-level rise led to growth of fringing stromatoporoid reefs around Precambrian-granite inselbergs at the edges of the Peace River Arch in northern Alberta. Moldic pores are the only effective pores in these dolostones. Molds up to several cm diameter formed by leaching of fossil fragments. The matrix between the molds is microcrystalline dolomite; core analyses establish that the matrix has less than 0.1 mD permeability. Yet this currently producing reservoir at Slave Field has yielded more than 57 million barrels of oil and water since 1981. Production comes from highly permeable layers where the moldic pores are touching one another. However, not all molds are touching, and core data show that dolostones with porosities over 10% can have permeabilities of less than 1 mD in zones where large open pores are not touching. Thus, there is not a statistically significant correlation between porosity and permeability. None the less, more than 440 porosity and permeability measurements from 8.8-cm diameter core cylinders can be organized to establish details of exploration and development significance. First, the cores are described by original depositional facies which include carbonate mudstone, skeletal-fragment grainstone, Amphipora rudstone-floatstone, and stromatoporoid boundstone. Second, the core data can be grouped into classes with touching vugs and non-touching vugs. Mudstone facies do not contain fossils and as a result, there is no possibility of finding vugs, while facies with fossils always contain vugs but some are touching, and some are not. The probability of encountering touching vugs increases as the number and size of fossil fragments increases in the cores. Although the pores are diagenetic in origin, the distribution of porosity and permeability can be modeled by mapping original depositional facies in the carbonate atolls. Then the data are plotted to show well-defined normal distributions of porosity and log-normal distributions of permeability within each facies type.

Introduction

I am not Robert Dunham, and I did not invent the Dunham Carbonate Classification (Dunham, 1960). But I am interested in carbonates, and also drawn to statistics as applied to carbonate reservoirs. Carbonates are generally classified according to qualities such as textures and structures and fossil assemblages. In situations where a few quantities such as porosity and permeability are available for study, it can be useful to use quantitative methods to test similarities and differences among populations originally discriminated by qualitative methods.

Looking at tables of numbers and "crunching" them through descriptive-statistical routines is useful, but as stated by Chambers et al. (1983), "no single statistical tool is as powerful as a well-chosen graph." Graphical methods convey an enormous amount of quantitative information to the brain in an instant. These graphs contain all the rigor of statistical methods. Graphical methods provide diagnostic tools for confirming assumptions, or where the assumptions are not supported, for suggesting corrective actions.

Theory and Method

Data-analysis software is broadly available for making statistical plots, but these packages may not be readily accessible to people who are not working in academia or for major companies. My presentation will show graphs that are useful for comparing populations and for defining probability distributions. The software used is Microsoft Excel which is widely available at relatively low cost. The following graphs were all created in Excel. Although Excel does not have a built-in option to define a "Probability Scale" it is easy to make one. The graphs presented here are not part of Excel's built in Analysis Tool Pack. There are no 'black-box" buttons to push; the user can see exactly how Excel processes input tables of data into final plots.

The approach presented here follows that outlined by Pyrcz and Deutsch (2014); it starts with a Geological Story as a conceptual model. Lithofacies defined by textures and fossil assemblages can be seen to thicken and thin in certain directions. Statistical graphs are used to test whether populations of data assigned to these different lithofacies are or are similar to one another in terms of porosity and permeability. Statistical graphs test the hypothesis that porosity and permeability follow normal or lognormal probability distributions. If the idea that these distributions are valid is accepted, then probability inputs are defined for Monte Carlo analysis of prospect size and recoverable resource, and prospect risk (Rose, 2007).

The following are graphs made with Excel. The spreadsheet used to make the graphs is available as freeware and can be downloaded by anyone for free use from this link - https://github.com/jdunham76/Excel_Stat_Graphs. Users can put their own data into this workbook to create their own graphs and analyses. I hope people will find this of use.

Geological Setting

During Middle Devonian (Givetian) time, the Peace River Arch existed as a large uplift of Precambrian granite-basement in northwestern Alberta and northeastern British Columbia Canada. Spheroidal-weathered granite outcrops rose several hundred meters above sea level elevation along the axis of the arch, with elevations gradually decreasing from west to east. Cores from Slave Field described in this report are located along the eastern plunging nose of the Arch (Figure 1). Pulses of relative sea-level rise onlapped the edges of granite hills, resulting in progressive transitions from non-marine to marginal marine and fully marine depositional environments. Sedimentation is strongly influenced by paleotopography.

Maps and cross sections through Slave Field show individual granite hills rising 30 to 50 meters above regional elevation, with pronounced thinning of Middle Devonian Slave Point Dolostone against the flanks of granite highs, and commensurate thickening of carbonates and granite-wash sands in the low areas between granite hills (Figure 2). Granite outcrops of the Southern California Batholith at Joshua Tree Park in California are envisioned as analogs to this Devonian paleotopography.

Facies Types at Slave Field

Cores of granite basement show a weathering rind of altered feldspars, with the weathered surface displaying the smooth curve that forms through spheroidal weathering of massive granite. Non-marine granite-wash sands deposited in alluvial fans and channels are present in low areas between granite hills. Initial marine onlap into the region is marked by supratidal to intertidal laminated dolomite mudstone. As onlap continued, laminated muds were overlain by restricted marine burrow-mottled carbonate mud along with fossils with tolerance to restricted conditions including gastropods and the stick-shaped stromatoporoid Amphipora. The 14-14 well (Figure 3) records this upward deepening trend. Eventually, the upper flanks of granite hills become onlapped as regional water depth increased from initial very shallow to water depths that were now several tens of meters deep. As water depth became deeper, conditions changed from restricted-marine to more open-marine which supported the growth of normal- marine fossils like bulbous and massive stromatoporoids.

A final pulse of deepening-upward appears to have exceeded the rate at which stromatoporoid facies could grow upward, resulting in deposition of crinoid-brachiopod mudstone and Waterways Shale atop a maximum flooding surface. These various facies types have combined for production of over 55 million barrels of fluid, both oil and water, from the Slave Point Formation at Slave field, but none of this production comes from primary porosity. Soon after deposition, the fine carbonate mud matrix was replaced by microcrystalline dolomite, while the larger fossil grains remained in calcium carbonate phases. During deeper burial, the fossils were leached away, leaving moldic pores that preserve the shapes of the fossils (Figure 4).

These are moldic pores that are encased in microcrystalline dolostone matrix (Dunham and Watts, 2017). There is no effective porosity within the microcrystalline matrix. As noted by Lucia (1995), the only permeable paths within reservoirs like this are present where the fossil molds touch one another. Individual molds that are surrounded by impermeable matrix do not contribute to effective porosity or permeability. During exploration and development in Slave Field, several cores were recovered, and analyses of these cores allowed testing of the idea that although reservoir quality depended on diagenetic effects, the distribution of better and poorer reservoir quality rocks is controlled by original depositional facies patterns in the reservoir.

Results and Statistical Plots

Porosity and Permeability measurements were made for 451 full-diameter core samples. Each sample was selected from a 3.5-inch (8.8 cm) diameter core that was cut into lengths ranging from 10 to 20 cm long. It would be impossible to measure these properties in a vuggy reservoir like this one with standard 1" diameter (2.5 cm) core plugs. Little is gained from looking at the data table itself; a bit more information is extracted from summary statistics calculated from the table, but the accompanying notched box plot communicates all the summary statistics while showing the shape of the distribution at the same time. This table ignores similarities or differences that might be traced to different facies types (Figure 5).

A better approach to communicating information from porosity and permeability data tables is to divide the data into different populations based on the distinctive facies types identifiable in the cores. Notched box plots (Figure 6) provide a graphic comparison of central tendency and spread of each data distribution. The "notch" shows the 95% confidence interval for the true location of the median of each distribution (Chambers et al. 1983). Where the notches do not overlap, there is a statistically significant difference in the medians of these different populations. The plots convey that porosity and permeability of Facies 2 define better reservoir quality than that of facies 4. However, the plots also show that there is a broad range of porosity and permeability values within Facies 2.

The broad range of values within each facies type demands further explanation. Porosity varies because degree of leaching of fossils varies from partial to complete leaching. Permeability varies because some of the vugs touch one another, while others do not. Permeability depends not on porosity, but rather on whether the moldic pores are touching or not (Lucia, 1995). Also evident on Figure 7 is the observation that permeability can be very different for samples that have similar porosities. Therefore, there is not a good correlation between porosity and permeability in this data set.

The shapes of the porosity box plots appear symmetrical on either side of the median line, indicating that the porosity distributions are not strongly skewed to high or low sides. Numerous studies have observed the tendency for porosity values to follow normal distributions within populations, and this is suggested by the shapes of porosity box plots within different facies populations. Many other workers have observed that estimates of recoverable hydrocarbon volumes from reservoirs are best done through probabilistic methods and have exploited the tendency for porosity to be normally distributed for extracting P10, P50, and P90 porosity values for input into Monte Carlo resource volume estimates. Graphical methods can be used to further investigate porosity distributions within Slave Point Formation facies populations.

Porosity and Permeability Distribution Plots

The Excel workbooks that I have made available with this presentation can make several graphs that are useful for visualizing and analyzing porosity and permeability distributions. Figure 8 presents porosity data from Facies Type 1, crinoid-brachiopod wackestone. Crinoids are never leached and never form moldic pores; brachiopods do become leached and brachiopod valves and fragments do form moldic pores. The histogram shows the number of samples in each porosity bin. The "Bell Curve" shows that a normal distribution would look like for a data set with the mean and standard deviation calculated from this data set. The fact that the curve goes off-scale to the left indicates that this data set isn't exactly following a normal distribution. The plot below the bell curve is a cumulative distribution curve with the solid line tracing the shape of the same normal distribution shown by the bell curve. The next plot below the cumulative curve is a Probability Plot. Probability plots are almost the same as cumulative plots except that the Cumulative Frequency scale is stretched on the low side and the high side such that a normal distribution would plot as a straight line. This type of display is used to determine the equation for the straight line relating cumulative frequency to porosity values. The R2 value indicates the quality of fit of the data to a straight line. The equation for the line is used to extract P10, P25, P50, P75, and P90 values that are used in probabilistic resource volume estimates and in reservoir simulation models. The Notched Box Plot at the bottom is plotted from the same data and shows an easily visualized presentation of this data distribution. Readers are invited to take their own data and plug it into this porosity workbook to see how well their porosity data follow a normal distribution.

Even though we are using 8.8 cm full-diameter cores, it appears that these cores may not be large enough to describe the porosity distribution in Facies Type 2; the leached stromatoporoids form very large moldic pores that exceed several centimeters in diameter. Figure 9 shows graphs of Facies 2 porosity in comparison to Facies 3 porosity. The Amphipora fossils typical of Facies 3 are very uniform in size and when leached, they form molds that are tubular in shape with diameters of 2 to 3 mm and lengths on the order of 10 to 20 mm. In contrast, leached stromatoporoids form molds that vary greatly in size from 1 mm up to almost the full diameter of the cores near 80 mm. Outcrops of similar facies show that molds can exceed 100 mm diameter which of course could not be recovered by cores like these. Figure 9 shows that Facies 3 porosity distribution closely approximates a normal distribution, while Facies 2 does not form a good fit to a normal distribution. A possible interpretation is that a combination of inadequate sample numbers and small core-size is failing to capture the full distribution of pore sizes in Facies 2.

For all facies types, permeability shows a good fit to a lognormal distribution. Figure 10 shows probability plots with permeability set to a logarithmic scale. All facies types show a good fit to a lognormal distribution which facilitates estimation of recoverable resource volumes and reservoir production modeling. The broad range of permeabilities from very low to very high within each facies results from the fact that some vugs are touching and some are not. Samples with high porosity, but where the pores are not touching one another, will have low permeability. Therefore, there is a poor correlation between porosity and permeability in this data set (Figure 11).

Summary

This presentation takes a large data set of 451 full diameter core measurements from a vuggy dolostone reservoir. Graphical methods of data analysis were applied to vuggy dolostones using Excel workbooks that are available as freeware to anyone who wants to use them on their own data. It is hoped that some will find these graphical methods useful for extracting porosity and permeability inputs for probabilistic resource estimation and for construction of quantitative reservoir models.

References Cited

Chambers, J.M., Cleveland, W.S., Kleiner, B., Tukey, P.A. 1983, Graphical Methods of Data analysis: Duxbury Press, Beaumont, CA, 395 p.

Dunham, J.B., Watts, N. 2017. Moldic-pore distribution, basement paleotopography, and oil production from a Devonian Dolostone Reservoir, Peace River Arch, Western Canada: SEPM Special Publication 109, p. 87-105.

Dunham, R.J. 1962. Classification of carbonate rocks according to depositional texture: American Association of Petroleum Geologists, Memoir 1, p. 108–121.

Lucia, F.J. 1995. Rock-fabric/petrophysical classification of carbonate pore space for reservoir characterization: American Association of Petroleum Geologists Bulletin 79, p. 1275-1300.

Pyrcz, M.J., Deutsch, C.V. 2014, Geostatistical Reservoir Modeling; Oxford University Press, New York, NY, 434 p.

Rose, PR. 2007. Measuring what we think we have found: Advantages of probabilistic over deterministic methods for estimating oil and gas reserves and resources in exploration and production: American Association of Petroleum Geologists Bulletin 91, p. 21-29.

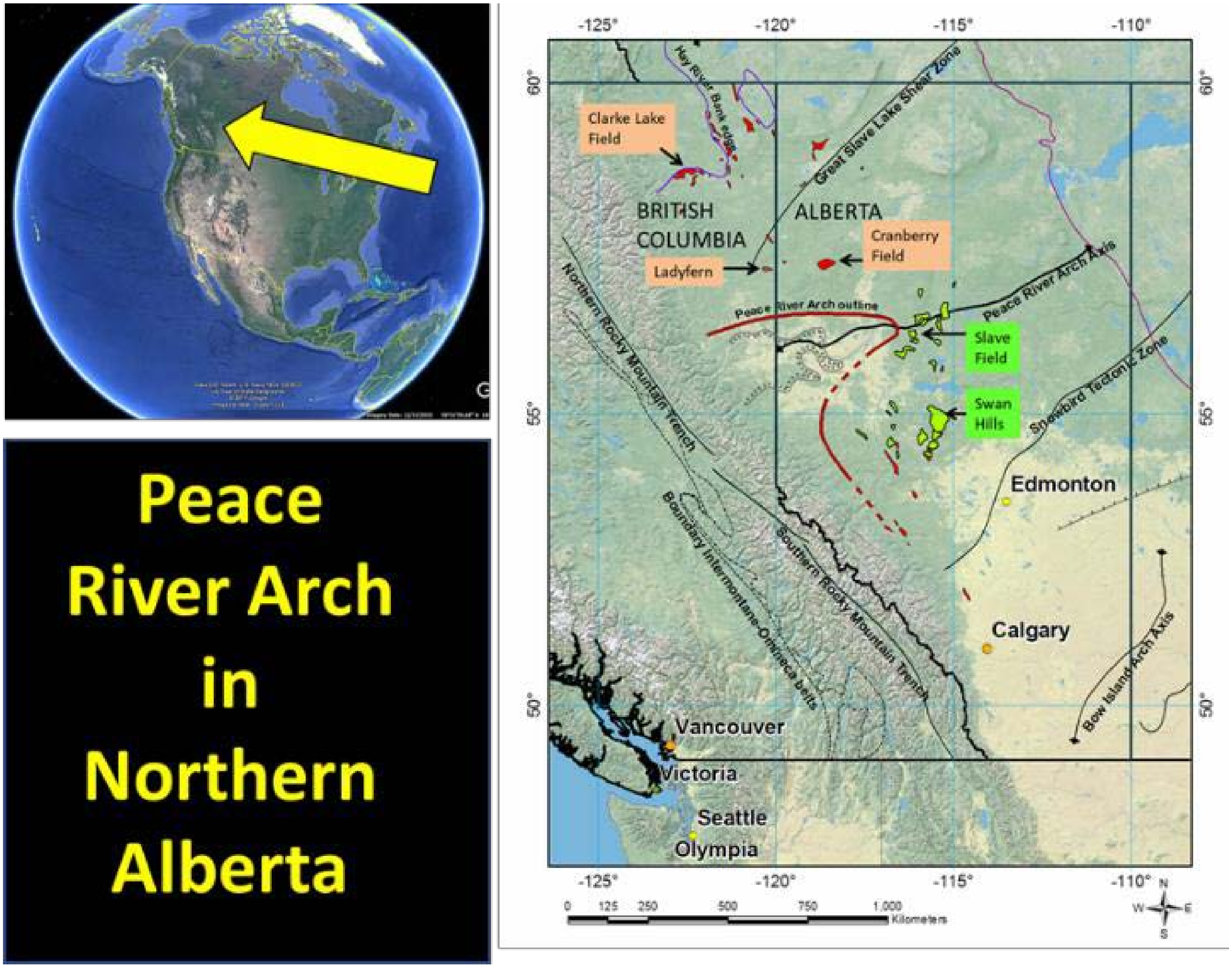

Figure 1. Peace River Arch and Slave Field Locations.

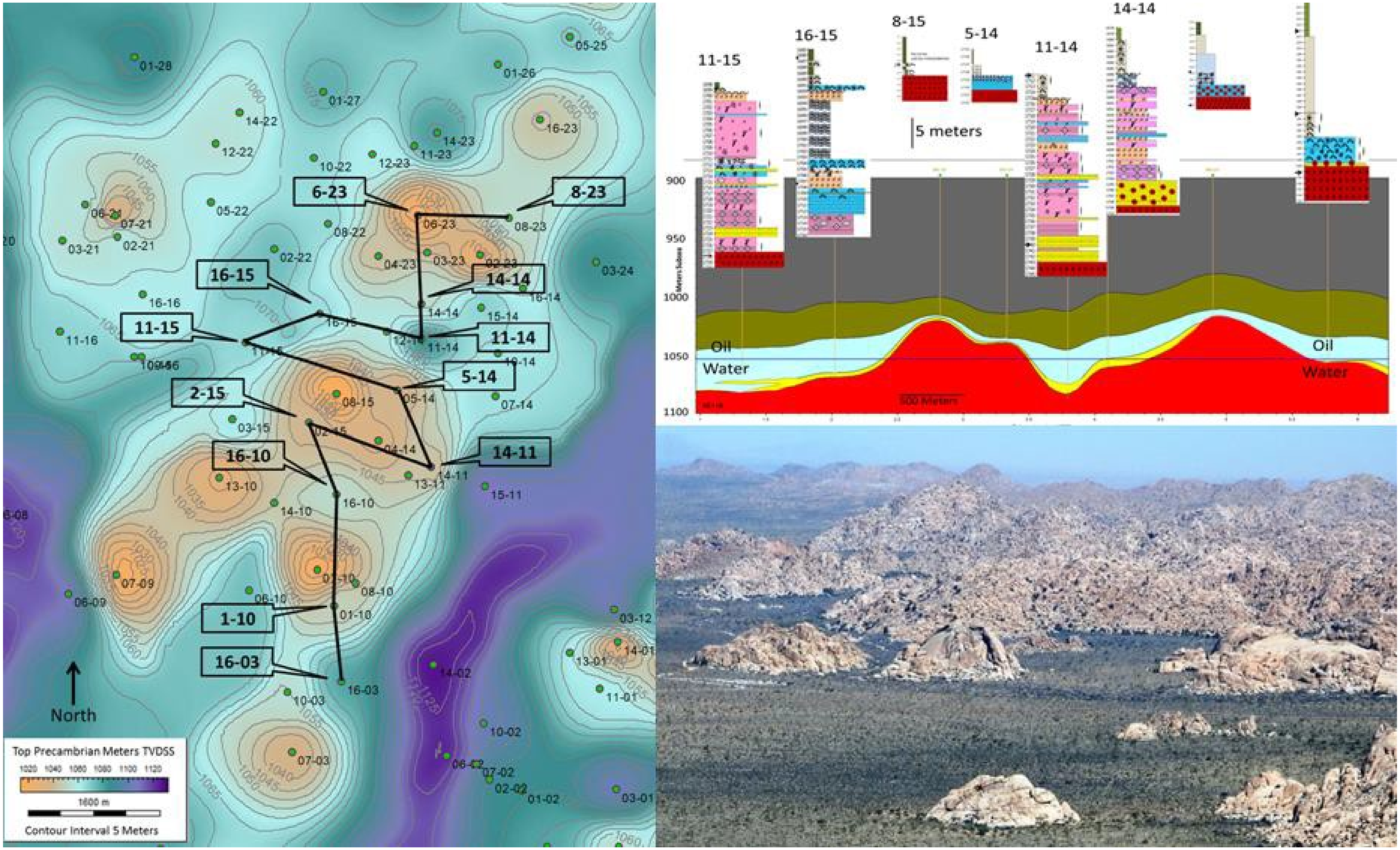

Figure 2. Structure contour map on top Precambrian Granite surface from wells at Slave Field; cross section showing thickening and thinning of Middle Devonian aged sediments above the Precambrian Granite surface. Granite outcrops at Joshua Tree Park are similar in size and shape.

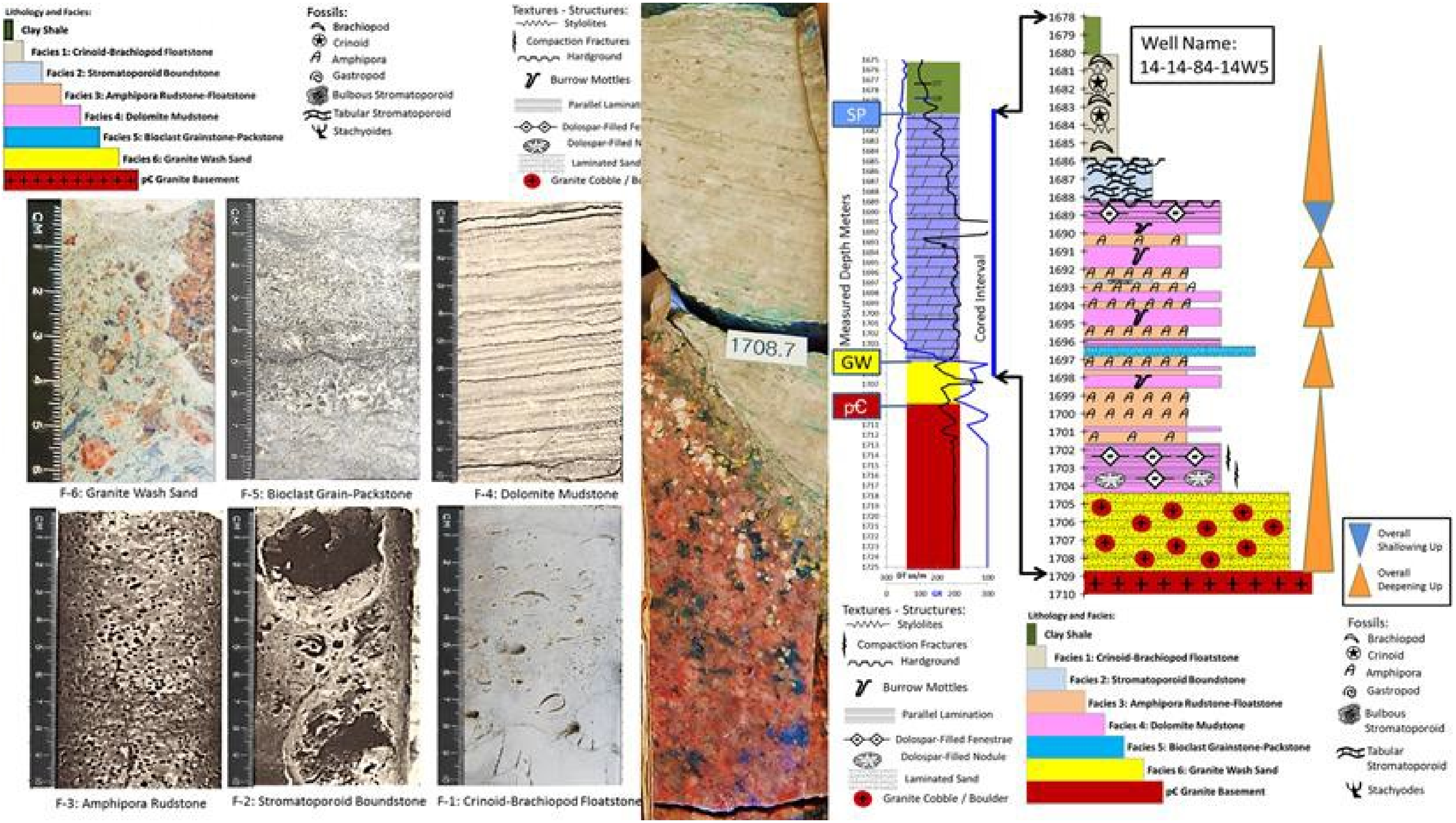

Figure 3. Six different facies types are present in the Slave Point Formation that were deposited during different phases of marine onlap against the flanks of Granite Basement highs. The core photo shows the spheroidal-weathered surface on top of granite. Core descriptions from the 14-14 well show the succession of facies that developed because of progressive marine onlap of basement highs.

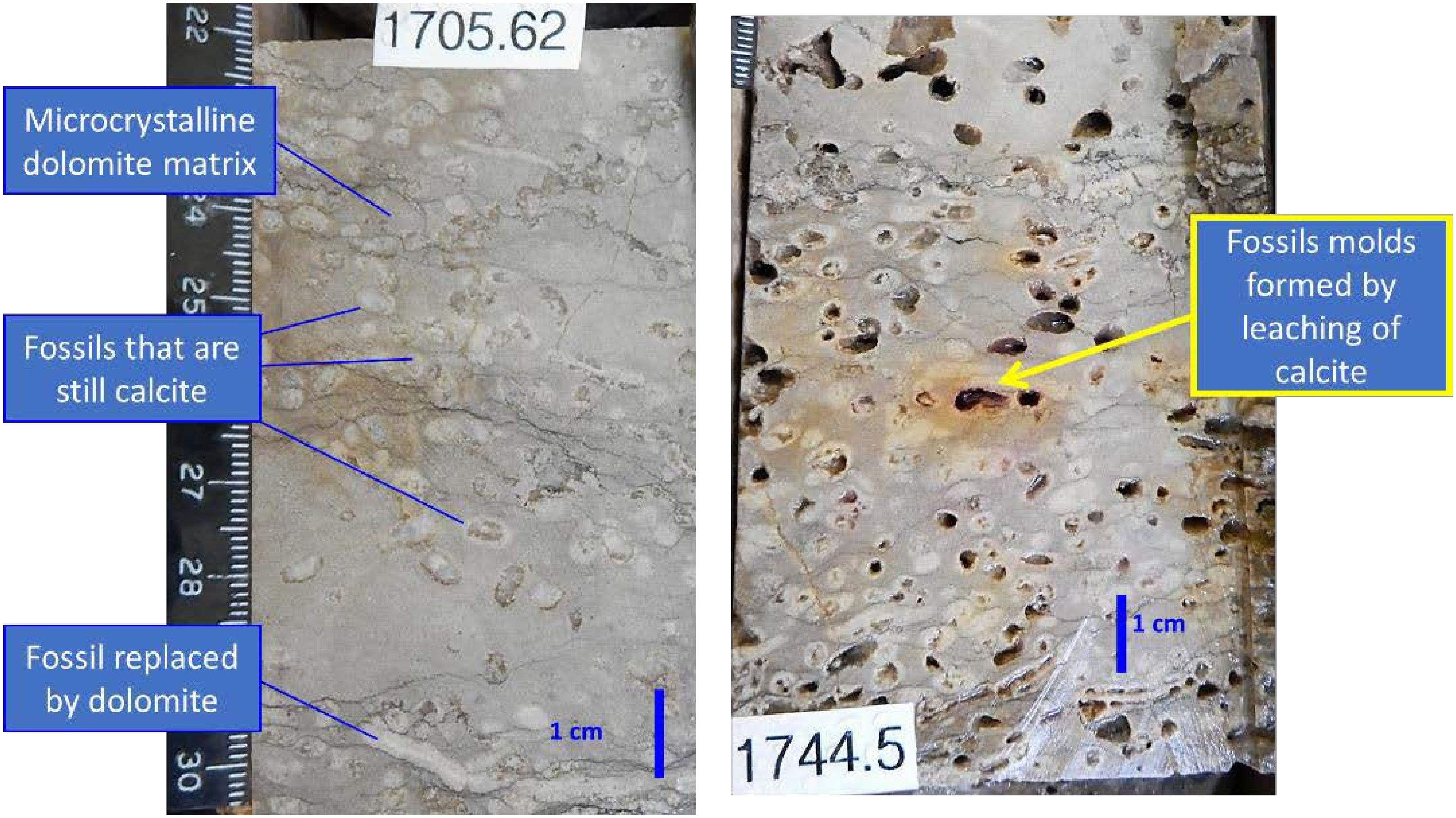

Figure 4. Development of moldic porosity through leaching of calcite fossils encased in dolostone matrix.

Porosity Measurements from 451 Full-Diameter (8.8 cm) Core Samples from 14 Different Wells in Slave Field Devonian Dolostone Reservoir. Porosity Summary Statistics: Mean 5.6%, Standard Deviation 3.9%, Median 4.7%, First Quartile 2.8%, Third Quartile 7.6%.

Porosity														
0.3%	5.0%	4.4%	8.3%	15.6%	3.1%	5.9%	0.5%	1.7%	3.4%	7.5%	4.1%	6.9%	10.2%	5.6%
0.5%	5.4%	4.4%	8.3%	15.9%	3.2%	6.0%	0.5%	1.8%	3.5%	7.5%	4.2%	7.0%	10.4%	5.8%
0.5%	5.6%	4.7%	8.4%	16.0%	3.2%	6.3%	0.5%	1.9%	3.7%	7.6%	4.3%	7.1%	10.4%	5.8%
0.6%	5.7%	4.7%	8.6%	16.5%	3.2%	6.7%	0.5%	1.9%	3.7%	0.5%	4.3%	7.1%	10.5%	5.8%
0.6%	5.7%	4.8%	8.9%	16.7%	3.3%	6.7%	0.5%	2.0%	3.8%	0.7%	4.3%	7.1%	10.8%	5.8%
0.8%	5.8%	4.9%	9.0%	17.2%	3.5%	6.7%	0.5%	2.1%	3.9%	0.7%	4.4%	7.5%	10.9%	6.1%
1.9%	5.8%	5.0%	9.1%	17.4%	3.6%	6.8%	0.6%	2.1%	3.9%	0.8%	4.5%	7.5%	10.9%	7.8%
2.1%	6.0%	5.0%	9.1%	18.8%	3.6%	6.8%	0.6%	2.1%	3.9%	1.4%	4.5%	7.5%	11.4%	8.1%
2.3%	6.1%	5.2%	9.2%	20.1%	3.6%	6.9%	0.7%	2.1%	4.0%	1.5%	4.5%	7.6%	11.5%	8.1%
2.4%	7.3%	5.3%	9.4%	20.8%	3.6%	7.0%	0.7%	2.2%	4.0%	1.8%	4.6%	7.7%	11.8%	9.1%
2.7%	7.5%	5.3%	9.4%	0.1%	3.7%	7.2%	0.7%	2.2%	4.0%	1.9%	4.7%	7.8%	12.1%	9.1%
3.1%	7.9%	5.6%	9.7%	0.5%	3.8%	7.3%	0.7%	2.2%	4.1%	2.0%	4.7%	8.0%	12.1%	9.2%
3.1%	8.4%	5.6%	9.7%	0.5%	4.1%	7.4%	0.8%	2.2%	4.1%	2.2%	4.8%	8.1%	12.2%	9.9%
3.1%	10.0%	5.7%	10.0%	0.5%	4.1%	7.5%	0.8%	2.2%	4.1%	2.4%	5.0%	8.3%	12.3%	10.8%
3.2%	10.3%	5.7%	10.9%	0.5%	4.1%	7.7%	0.8%	2.3%	4.2%	2.4%	5.1%	8.5%	12.4%	11.8%
3.3%	1.6%	5.7%	10.9%	1.0%	4.2%	8.5%	0.9%	2.3%	4.3%	2.5%	5.4%	8.7%	13.4%	14.5%
3.4%	1.8%	5.8%	11.5%	1.1%	4.3%	8.7%	1.0%	2.5%	4.4%	2.6%	5.5%	8.8%	13.7%	18.7%
3.6%	2.3%	5.8%	11.5%	1.2%	4.4%	8.7%	1.0%	2.6%	4.4%	2.7%	5.6%	8.9%	14.3%	
3.8%	2.5%	6.0%	11.7%	1.3%	4.4%	8.8%	1.1%	2.9%	4.5%	2.8%	5.6%	9.0%	15.6%	
3.9%	2.6%	6.1%	12.0%	1.4%	4.4%	9.0%	1.1%	2.9%	4.7%	3.3%	5.6%	9.0%	16.3%	
4.0%	2.7%	6.1%	12.1%	1.5%	4.6%	9.1%	1.3%	2.9%	4.7%	3.3%	5.7%	9.0%	0.5%	
4.0%	2.8%	6.3%	12.8%	1.5%	4.8%	9.9%	1.3%	2.9%	5.0%	3.4%	5.8%	9.2%	0.5%	
4.1%	2.8%	6.4%	12.8%	1.7%	4.9%	11.0%	1.4%	3.0%	5.0%	3.4%	5.8%	9.3%	0.5%	
4.3%	2.8%	6.5%	13.0%	2.0%	4.9%	11.6%	1.4%	3.1%	5.1%	3.4%	5.8%	9.4%	1.8%	
4.3%	3.0%	6.7%	13.4%	2.1%	5.1%	12.2%	1.4%	3.3%	5.2%	3.4%	5.8%	9.6%	1.8%	
4.4%	3.7%	7.1%	13.7%	2.2%	5.5%	0.1%	1.5%	3.3%	5.3%	3.7%	5.9%	9.7%	2.0%	
4.4%	3.7%	7.2%	13.8%	2.3%	5.6%	0.2%	1.5%	3.3%	5.5%	3.8%	5.9%	9.8%	3.3%	
4.6%	3.9%	7.4%	14.2%	2.5%	5.6%	0.3%	1.5%	3.4%	5.5%	3.8%	5.9%	9.8%	3.4%	
4.6%	4.0%	7.7%	14.5%	3.0%	5.8%	0.3%	1.6%	3.4%	6.0%	3.8%	6.5%	10.1%	3.4%	
5.0%	4.3%	7.7%	15.4%	3.0%	5.8%	0.5%	1.6%	3.4%	6.1%	4.0%	6.6%	10.1%	4.7%	
5.0%	4.4%	7.8%	15.6%	3.1%	5.9%	0.5%	1.7%	3.4%	6.7%	4.1%	6.7%	10.2%	5.1%	

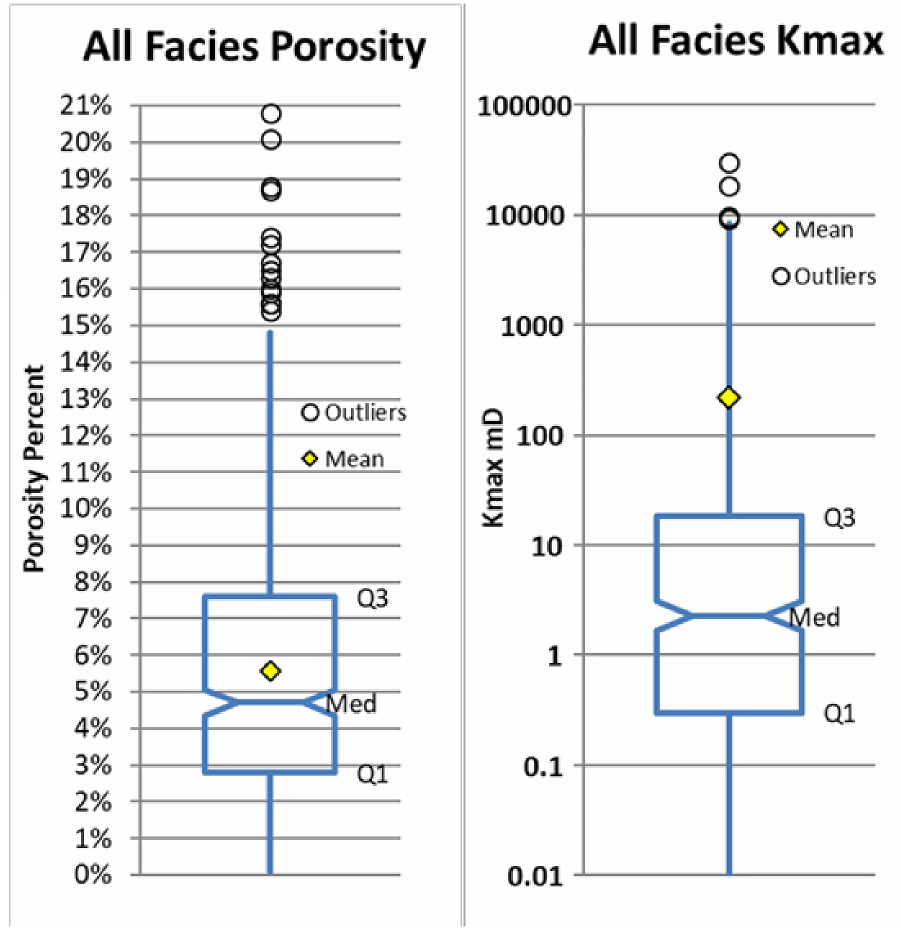

Figure 5. Table of 451 porosity measurements from full diameter cores. Data table itself has little meaning; descriptive statistics communicate more information. Best display is the notched box plot which presents all the descriptive statistics at a glance and illustrates the shape of the distribution. Permeability data are summarized with a notched box plot, with a log scale used to show the shape of the permeability distribution.

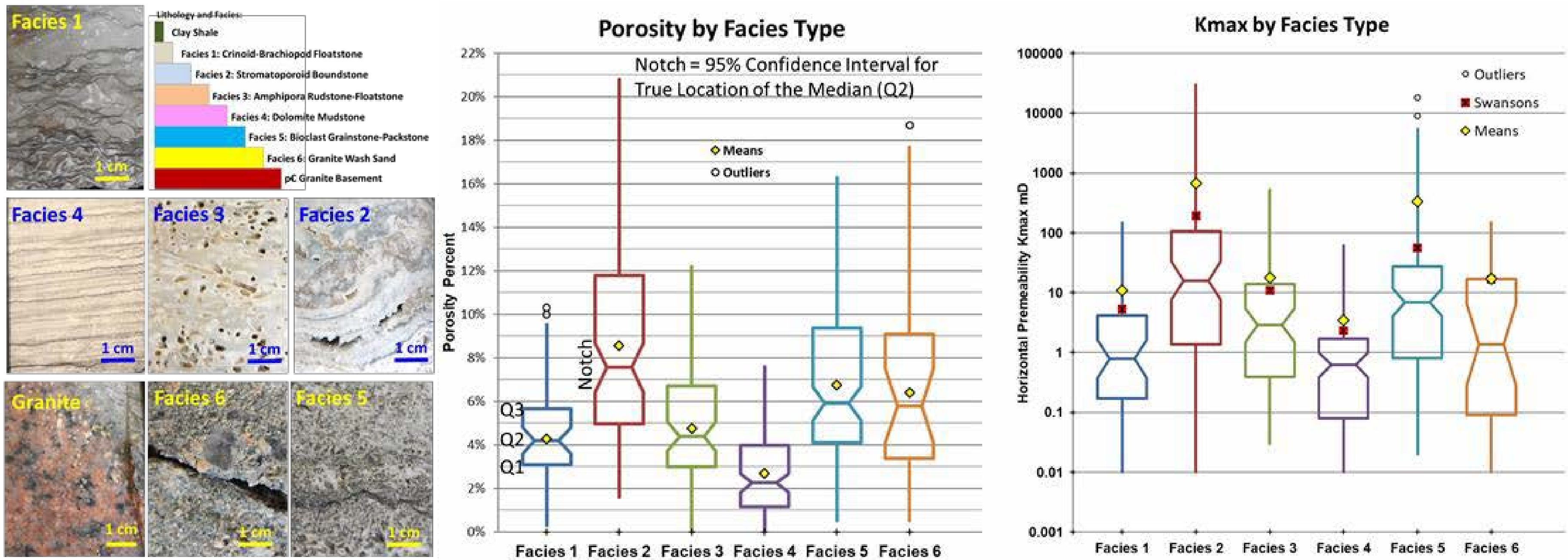

Figure 6. Notched box plots of porosity and permeability distributions for each facies type in Slave Field cores.

Visible Porosity Classification Example:

Facies Type 2: Stromatoporoid Bindstone

Core 16-3-84-14W5
Sample 46: 1770.05 – 1770.35 m
Porosity: 11.5%
Kmax: 0.78 md
K90: 0.22 md
Kv: 0.08 md

Pore Fabric: Fabric Selective leached nodular stromatoporoids.

Visible Porosity Classification Example:

Facies Type 2: Stromatoporoid Bindston

Core 6-23-84-14W5
Sample 4: 1663.6 – 1663.86 m
Porosity: 13.7%
Kmax: 1550 md
K90: 298 md
Kv: 37.8 md

Pore Fabric: Fabric Selective leached tabular stromatoporoids.

Visible Porosity Classification Example:

Facies Type 3: Amphipora Rudstone

Core 16-3-84-14W5
Sample 9: 1761.9 to 1762.15 m
Porosity: 11.6%
Kmax: 52 md
K90: 41 md
Kv: 0.03 md

Pore Fabric: Fabric Selective leached Amphipora.

Visible Porosity Classification Example:

Facies Type 3: Stick Strom Floatstone

Core 14-14-84-14W5
Sample 39: 1690.37 – 1691.5 m
Porosity: 4.4%
Kmax: 0.07 md
K90: 0.05 md
Kv: 0.01 md

Pore Fabric: Fabric Selective leached Amphipora and nodular stroms.

"Permeability depends not on Porosity, but rather on whether the pores are Touching or not."
-Jerry Lucia

Figure 7. Porosity and Permeability variations within the same facies and between different facies. Note that permeability can be very different for samples that have similar porosities.

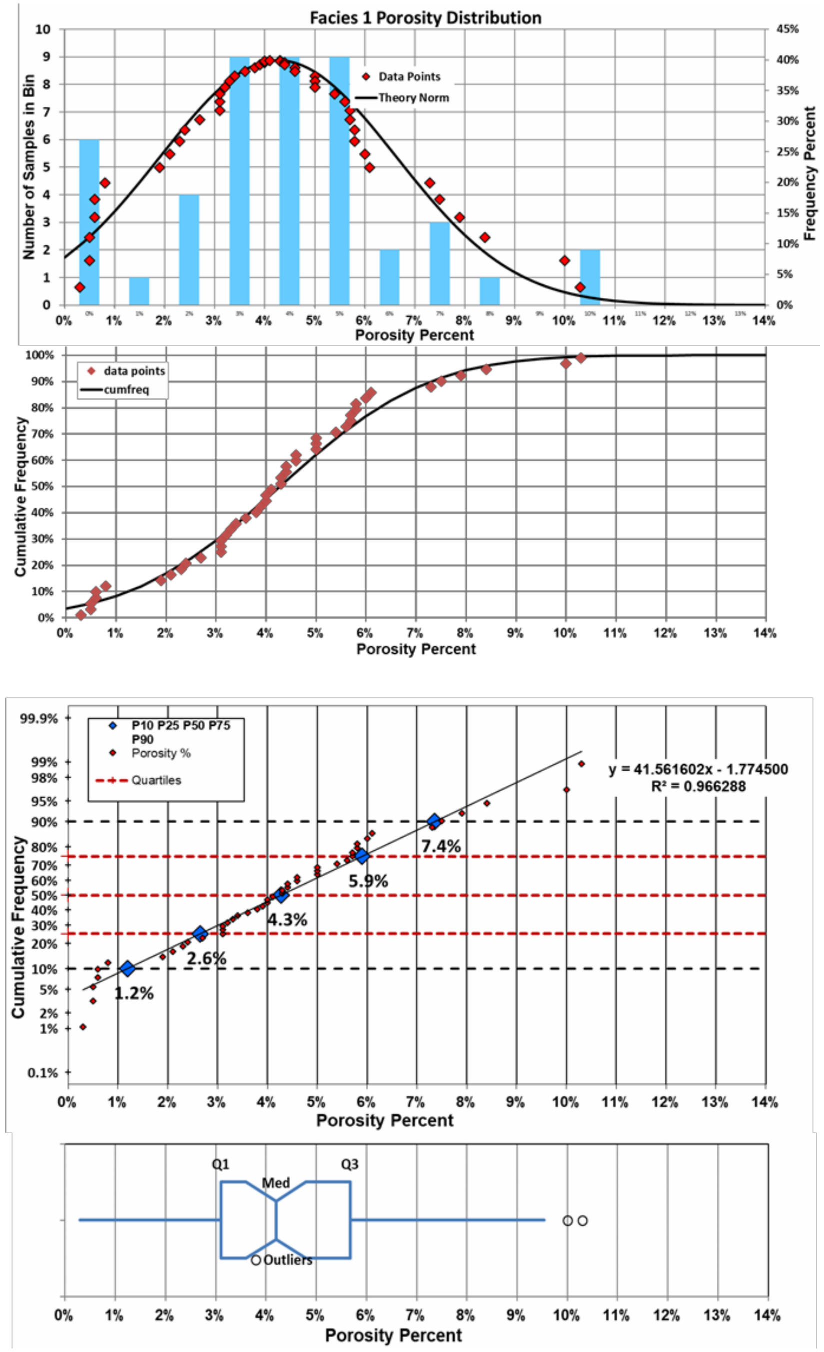

Figure 8. Graphical display of porosity distribution of Facies 1.

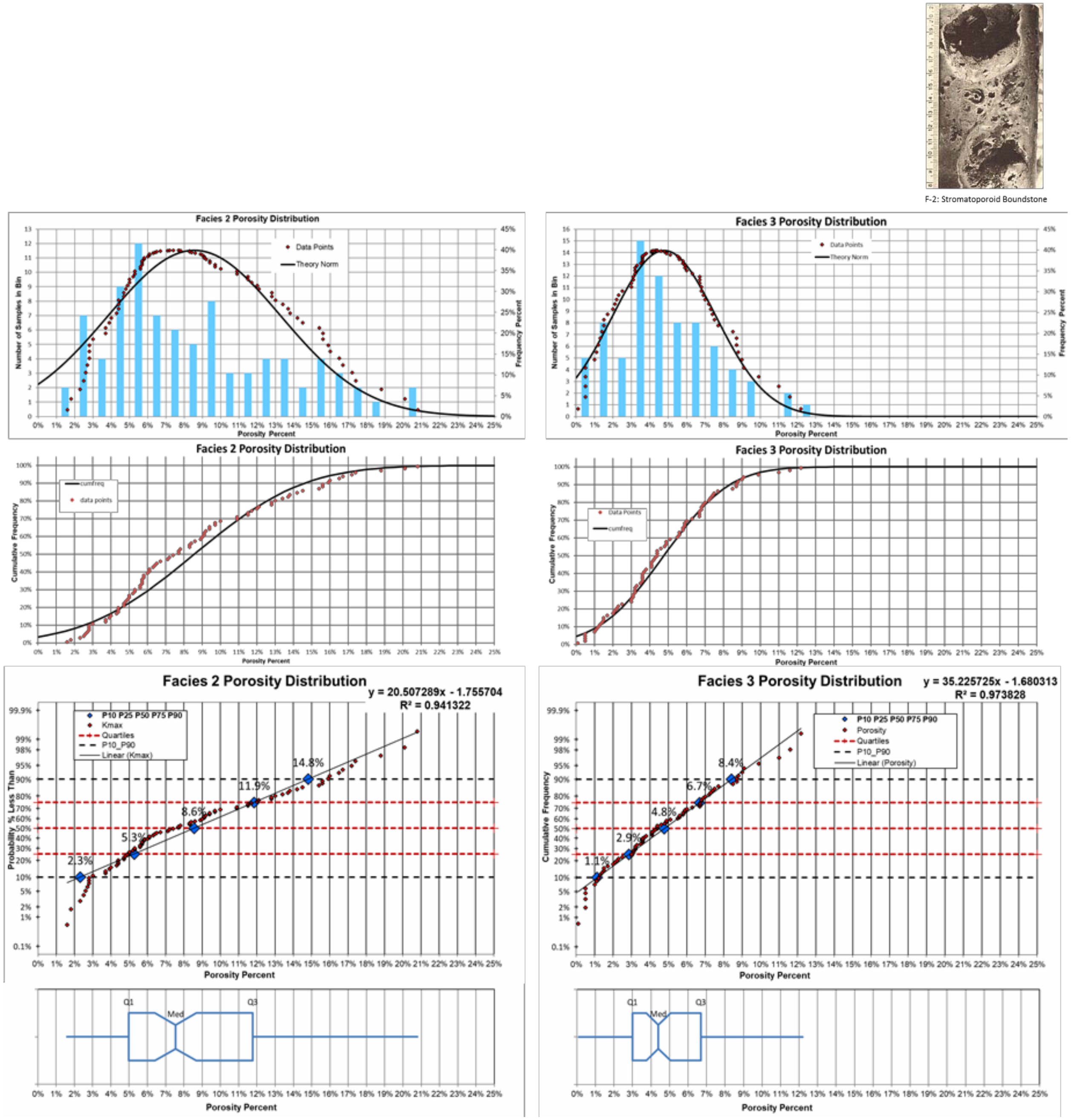

Figure 9. Comparison of porosity distributions between Facies 2 Leached Stromatoporoids vs Facies 3 Leached Amphipora. Facies 3 porosity is a close match to a normal distribution while Facies 2 significantly departs from a normal distribution.

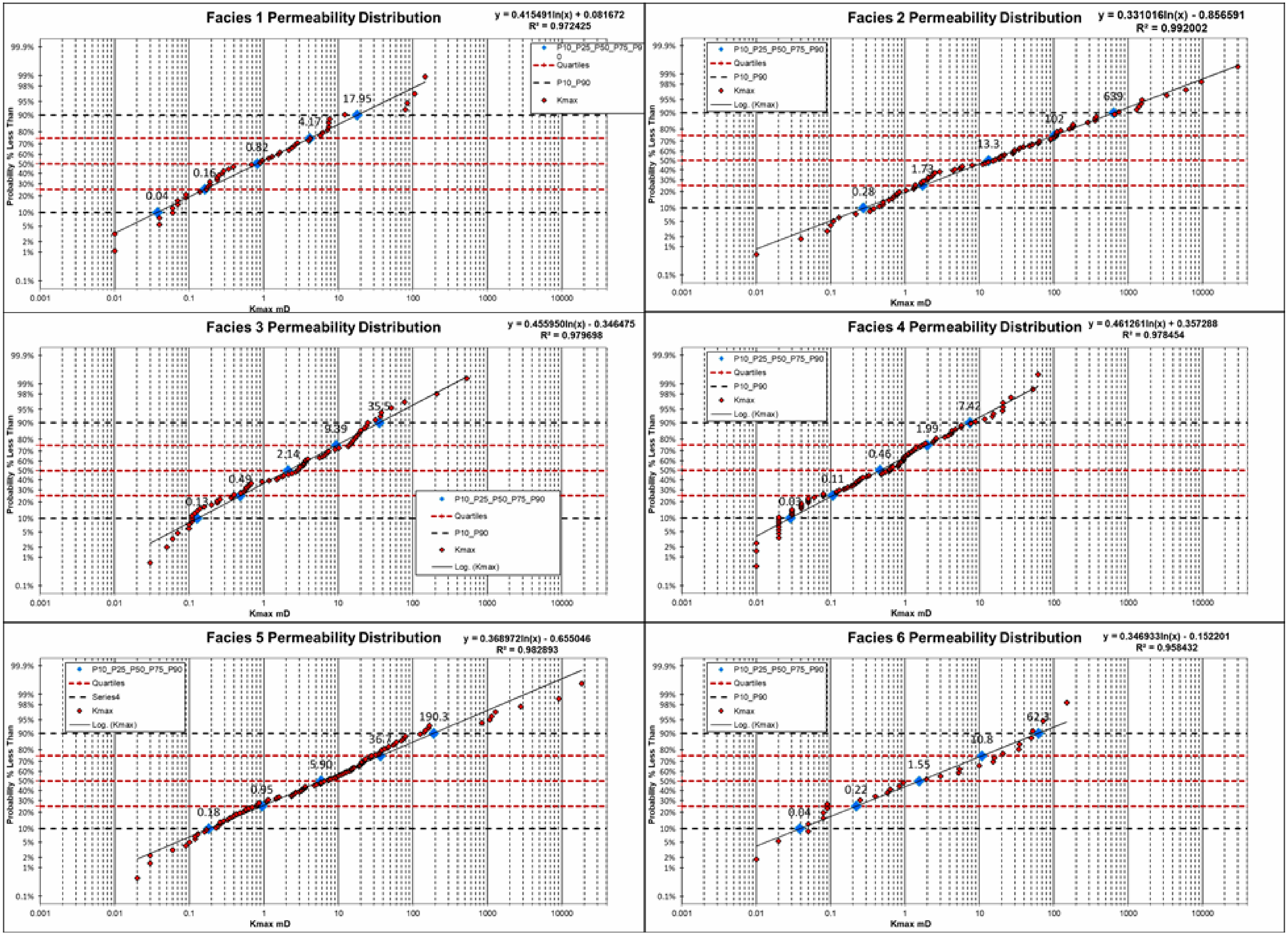

Figure 10. Probability plots of permeability distributions show good fit to a lognormal distribution for all facies types.

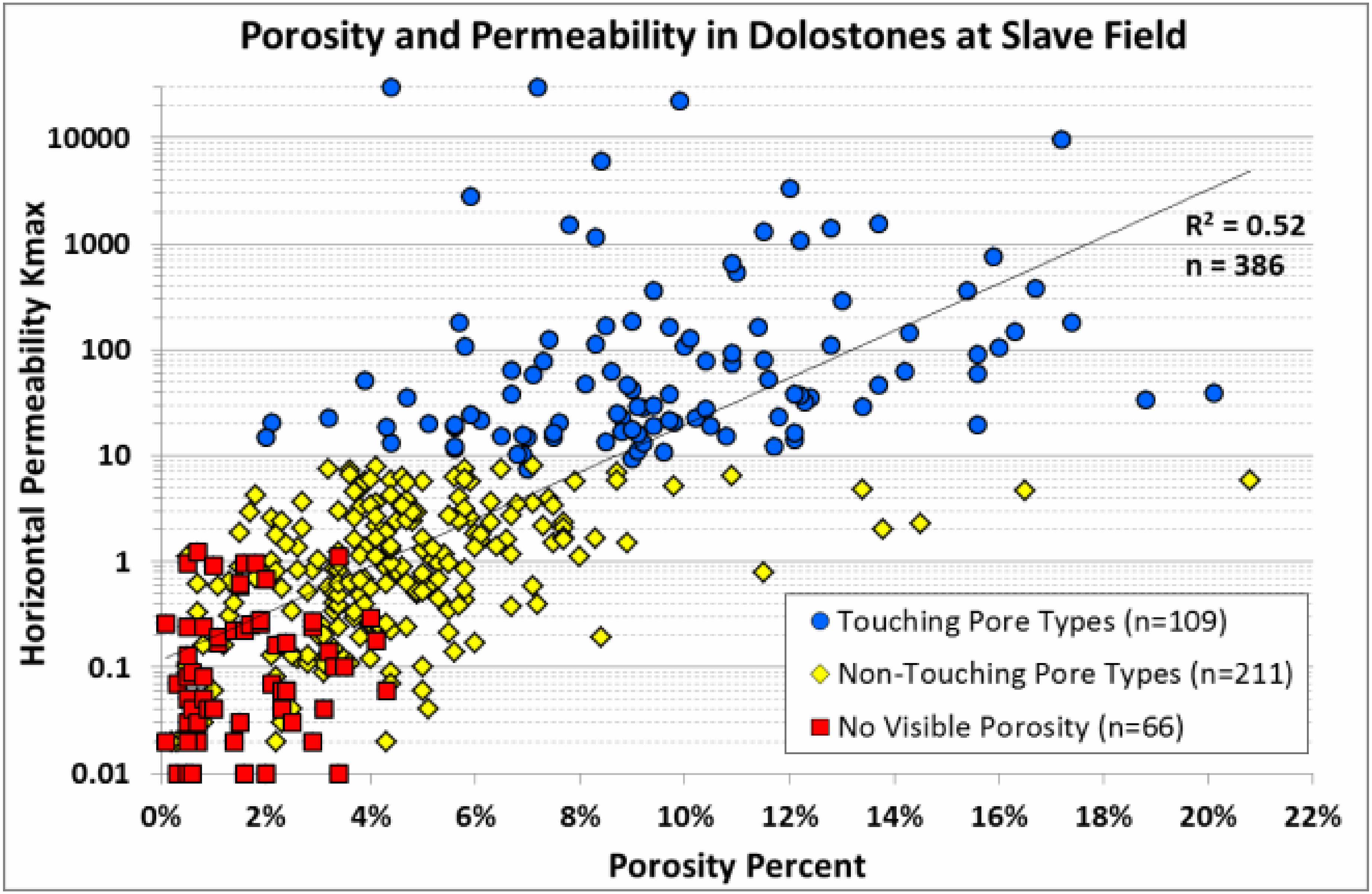

Figure 11. Poor correlation between porosity and permeability; samples are coded by those that show physical touching of vugs, and those that do not.