EA Porosity Determination from Mechanical Measurements in Carbonates Affected by Severe Drilling Fluid Invasion*

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Abstract

A large proportion of Papua New Guinea's hydrocarbon endowment is found in porous and permeable carbonate reefs. Whilst these are prolific reservoirs, they present significant challenges during drilling that arise from the high loss of fluids that are frequently encountered. The resultant severe formation damage adversely affects analysis of electrical logs such that interpretation of porosity and water saturation are compromised by a large degree of uncertainty. This article introduces an alternative method for measuring porosity based on drilling measurements that is unaffected by fluid losses and thus provides a solution for effective reservoir characterisation of these field developments.

The advent of pressurised mud cap drilling (PMCD), where an underbalanced mud (light annular mud, "LAM") is continually pumped down the annulus into a reservoir whilst drilling, allows for safe drilling of highly porous and permeable formations such as carbonate reefs. It has been applied successfully to wells drilled onshore and offshore in Papua New Guinea. The downside of the PMCD technique is high losses of seawater, drilling mud/fluid and cuttings into the formation leading to both porosity occlusion and an altered borehole environment inconsistent with assumptions used in classical log analysis. This makes evaluation of wireline and even logging while drilling (LWD) logs problematic, with difficult determination of porosity and water saturation (Kyi, Han, Lee, Roberts, and Maeso, 2015). Since the initial point at which the bit penetrates the rock is when the rock has had least exposure of time to any invasion, the problems faced by conventional interpretation of electrical logs can be resolved through application of a method that measures mechanical rock properties at the bit as the rock is drilled.

This insight is not new. The term "drilling porosity" refers to techniques by which porosity of a formation could be determined solely from mechanical drilling measurements such as rate of penetration, weight on bit, mud weight and rotational speed without the need for any separate electrical logging tool. It is no coincidence that the introduction of drilling porosity methods coincided with the advent of computerised mud logging units in the late 1970s which facilitated digital recording of surface drilling parameters; accurate monitoring and collection of surface drilling data was necessary for the development of drilling porosity logs. Mud logging companies promoted the use of drilling porosity as a

real-time indication of reservoir quality and pore pressure during drilling (Zoeller, 1972). However, details behind the methods used were not published, presumably to preserve competitive advantage. As LWD tools gained in popularity the technique has fallen into disuse, and drilling porosity is seldom used by industry today.

Well Case Studies

Twinza resurrected the drilling porosity approach to evaluate the reservoir quality encountered by the Pasca A-3 well drilled on the Pasca A carbonate reef in 1983. This well encountered massive lost circulation during drilling with over 22,000 bbl of mud lost to the reservoir, bit drops were encountered, and all five cores cut had poor recoveries. These observations are consistent with a reservoir formation that has high porosity and extreme permeability associated with extensive secondary porosity development including large connected vugs. Yet core plug analysis on Pasca A-3 revealed porosity of only between 2.5 and 8.8 percent. Visual observations reported that larger pores were filled with drilling mud which would have contaminated measurements and the true porosity appeared to be much higher (Figure 1).

To resolve the Pasca A-3 porosity inconsistency, Twinza looked closely at the data recorded during drilling. Fundamentally, rock strength and its drillability are determined by three principle factors: (1) lithology, (2) porosity, and (3) differential pressure. Bingham proposed a general rate of penetration formula that included a bit weight exponent, or “d-exponent”, to normalise the rate of penetration to take account of variable drilling conditions (Bingham, 1964). The d-exponent can be interpreted as a measure of formation drillability. It is a parameter easily calculated from surface measurements of rate of penetration, rotational speed, weight on bit and bit diameter. In practice, a corrected d-exponent (DXC) is often calculated to account for difference between equivalent circulating density and pore pressure. The DXC parameter is affected by both formation porosity and differential pressure, a trait which led to its use as a tool to detect overpressure in shales (Rehm and McClendon, 1971). Alternatively, if formation pressure is known, it should also be possible to infer porosity from DXC. Whilst drilling a porous reservoir with known lithology and mud weight, we expect consistent pore pressures to be encountered since the formation will be in total pressure communication. Variation in pressure is governed by the pressure gradient resulting from the fluid density. Therefore, a change to DXC only results from changes to the formation porosity. This insight is the basis for an empirical approach to drilling porosity measurement. Where both reliable electric logs and drilling parameters are available DXC can be correlated against classical log-based porosity to develop a predictive equation for porosity.

An evaluation of the Pandora carbonate reef in the Gulf of Papua was conducted in 1990 by International Petroleum Limited (IPL) (International Petroleum, 1990). No open-hole logs in the 8½" reservoir section were obtained in Pandora-1X, and only cased-hole logs were available. To improve confidence in the cased-hole log interpretation, IPL correlated DXC against the conventional log-interpreted porosity from open-hole wireline logs in the lower 5⅞" hole section, also drilled through the carbonate reef. This relationship between DXC and porosity, which was found to have a high correlation factor, was used to determine porosity in the shallower 8½" hole section from drilling data. It was found that there was a close match between the average porosity measured using cased hole logs in the 8½" gas leg section and the predicted porosity based on the drilling exponent.

Although the results obtained by IPL were based on a single well, published literature indicates that a drilling porosity relationship could be applied to other carbonate formations with success. To test this hypothesis Twinza used the same Pandora-1X data to independently derive a relationship between DXC and porosity. The relationship was tested against data from an analogue Miocene carbonate reef located elsewhere in southeast Asia. The well has a complete mud log containing drilling data and wireline log suite available which allows the drilling porosity relationship to be applied to the drilling parameters and blind tested against the wireline interpreted porosity from the same well.

There is a strong correlation between the drilling porosity log and the electric log-derived porosity log (Figure 2). This validates the approach of using drilling data to determine porosity in a carbonate field. Using a relationship determined empirically from Papua New Guinea carbonate field data it was possible to match wireline porosity for a carbonate field in a different region with only drilling data. The result suggests that the relationship is not field-specific and can be applied to other carbonate fields.

Using Downhole Drilling Dynamics Tools

Modern downhole drilling dynamics tools allow for accurate acquisition of drilling parameters, close to the bit during drilling; these parameters provide more reliable measurement in comparison to surface measurements even with deviated hole trajectories. The tool also allows measurement of torque which is not directly incorporated into the DXC-based approach to porosity estimation. Availability of higher accuracy measurements supports development of an underlying generalised drilling porosity methodology that could be applied to other lithologies.

An improvement to earlier DXC-based empirical drilling porosity methods is proposed through reconciliation of all mechanical input forces with rock strength. The method derives from a first principles approach that honours conservation of energy. The specific energy applied to the drill bit is considered, being the energy necessary to drill a unit volume of formation. Since the volume of rock removed during drilling is related to the rate of penetration, we can define mechanical specific energy (MSE) as the input energy divided by the rate of penetration.

This conservation of energy principle is consistent with actual drilling observations reported in the literature. Teale noted from drilling data that the minimum value of specific energy appeared to be roughly correlated with the crushing strength of the rock drilled using roller-cone bits (Teale, 1965).

MSE can be broken down into components of axial, rotational and hydraulic forces. It is assumed that whilst some of the input energy is lost as heat (a function of mud is to cool the drill bit) most energy is converted to work in breaking apart the formation. Therefore, MSE is equivalent to the confined compressive rock strength being drilled (Figure 3). Input measurements for MSE are best obtained through use of an LWD downhole drilling dynamics tool. Since the tool also measures downhole pressure it can be used to infer the unconfined compressive strength (UCS) of the drilled formation prior to any significant invasion.

Factors that have been shown to influence the UCS of rock include stiffness, porosity, rock mineralogy and pore fluid content. Stiffness is a structural property that is related to the Young’s modulus which is an intrinsic material property. A stiffer material will deform less under a fixed stress. There is a broad relationship between Young’s modulus (E) and UCS whereby an increase in E is associated with an increase in UCS.

At low porosity the strength of rock is determined principally by the mineral composition of the rock matrix and its mechanical properties. As porosity increases, rock strength decreases as load bearing capacity increasingly becomes a function of the rock matrix skeleton. Above a certain critical porosity, the rock skeleton no longer has any significant load bearing capacity, and the pore fluid becomes the primary contributor to strength (Nur, Mavko, Dvorkin, and Galmudi, 1998). Data show that there is an inverse relationship between porosity and UCS; an increase in porosity leads to a decrease in UCS up until the critical porosity.

Adaptation of existing rock physics models can be used to predict rock strength from Young's Modulus as a function of mineralogy, fluid content and porosity. The modelled relationship is a heuristic model designed to honour published data and relationships. For a known formation mineralogy (use of litho-density tool and/or acquisition of side wall cores is crucial to confirm mineralogy) and assumed hydrocarbon content (as confirmed by drill stem tests) there is only one unknown: porosity. Therefore, UCS measured by a downhole drilling dynamics tool can be used to infer porosity.

The MSE-based porosity method has been applied to the Pasca A4(AD-1) well which was drilled into a carbonate reef in the Gulf of Papua, offshore Papua New Guinea, and which acquired a full suite of logging while drilling and wireline logs. Interpretation of the electrical logs has proved problematic because of the high losses of drilling fluids into the formation whilst drilling in PMCD mode. The well utilised a downhole drilling dynamics tool to measure drilling parameters at the bit and the rotational, axial and hydraulic specific energies are calculated (Figure 3). The porosity log derived using this data is compared to the DXC approach and conventional wireline log interpretation (Figure 4).

Results show that the new MSE porosity method is accurate and matches conventional wireline log interpretation where invasion can be shown to be minimal and there is a higher degree of confidence in the electrical measurements. This situation is encountered whilst drilling ahead with no losses and returns to surface during constant bottom hole pressure mode.

Validation of the drilling porosity method can be obtained through comparison against actual measured rock properties. The Pasca A4 (AD-1) well obtained several side wall core samples, of which one had no visible solids invasion and was suitable for laboratory measurement of porosity. This sample has a measured porosity of 37 percent. A comparison between the measured porosity and predicted porosity at the same depth from various methods is shown in Table 1.

The actual measured porosity using rotary sidewall core is higher than the log analysis porosity obtained from both LWD and wireline density and neutron logs. The LWD logs indicate a lower porosity of 28.9 percent and underestimate the true porosity by 23 percent. This shows that the LWD log measurements are not capturing the true porosity reliably for this formation. The wireline porosity is further compromised by the effects of borehole invasion between the time of drilling and the time of logging with an underestimate of porosity that is nearly 40 percent lower.

In contrast the sonic porosity as determined using the Raymer-Hunt method shows a porosity of 39.8 percent and the MSE porosity is 38.1 percent at this depth. These are much closer to the actual laboratory measured value. Given allowance for measurement errors it is reasonable to conclude that the sonic and MSE porosity interpretations agree with the actual porosity whereas the neutron and density logs misrepresent the true porosity as they are not corrected for solids invasion and porosity occlusion.

Conclusions

There is not necessarily a single “correct” porosity method to use. When properly functional and calibrated the electrical logging tools faithfully record data that captures precisely what the tool was designed to measure. For example, the density tool is recording the near wellbore density, including the effects of the formation porosity, reservoir fluid content and near wellbore invasion. Standard interpretation workflows by necessity make assumptions concerning the near wellbore environment; any use of invalid assumptions leads to erroneous determination of porosity. Conversely calculation of drilling porosity is independent of any near wellbore environment assumption and can be used as a reliable indicator of the true formation porosity in formations subject to large and uncertain fluid losses.

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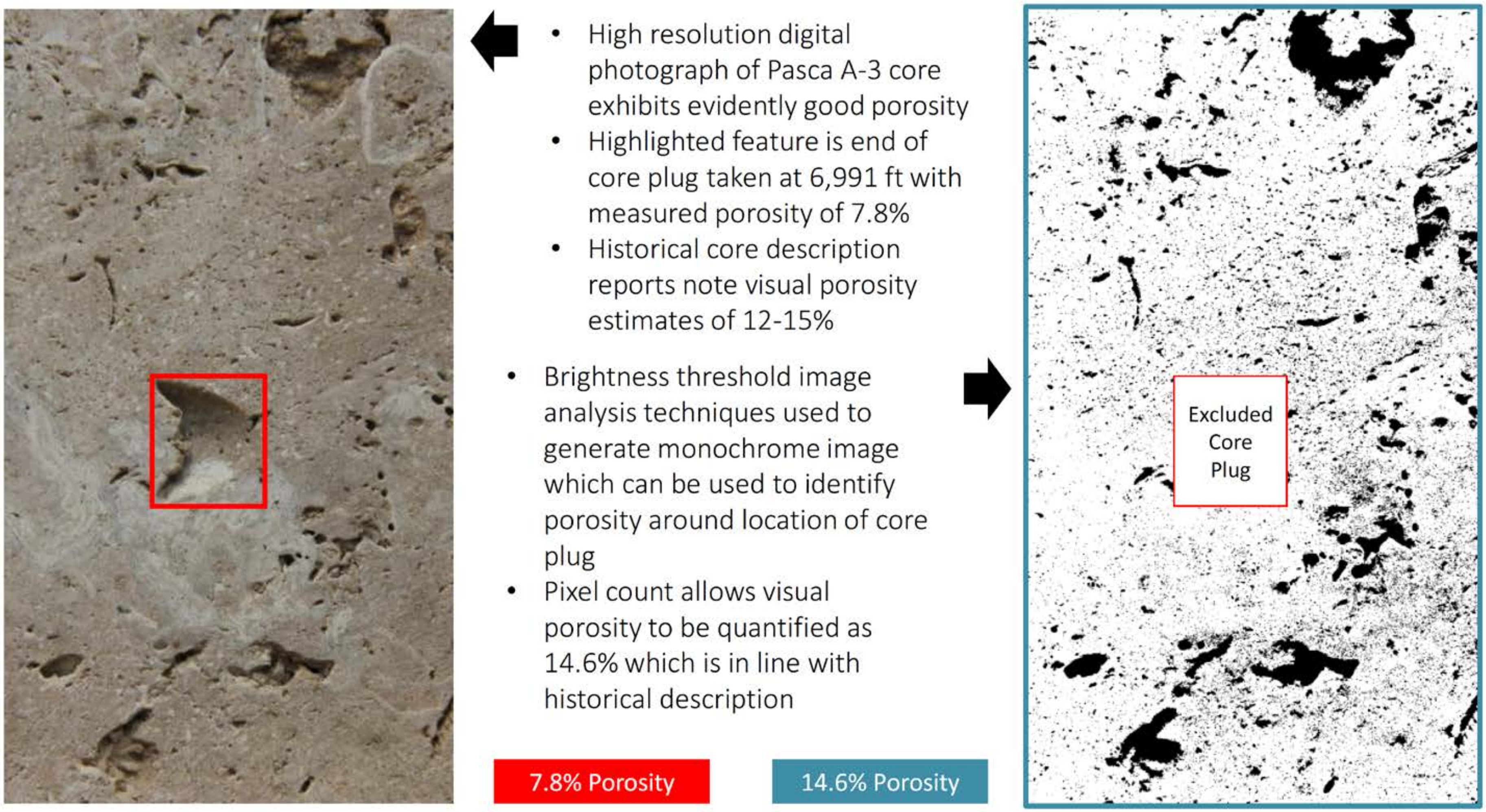

Figure 1. Visual identification of porosity in Pasca A-3 core reveals higher porosity than core plug measurements.

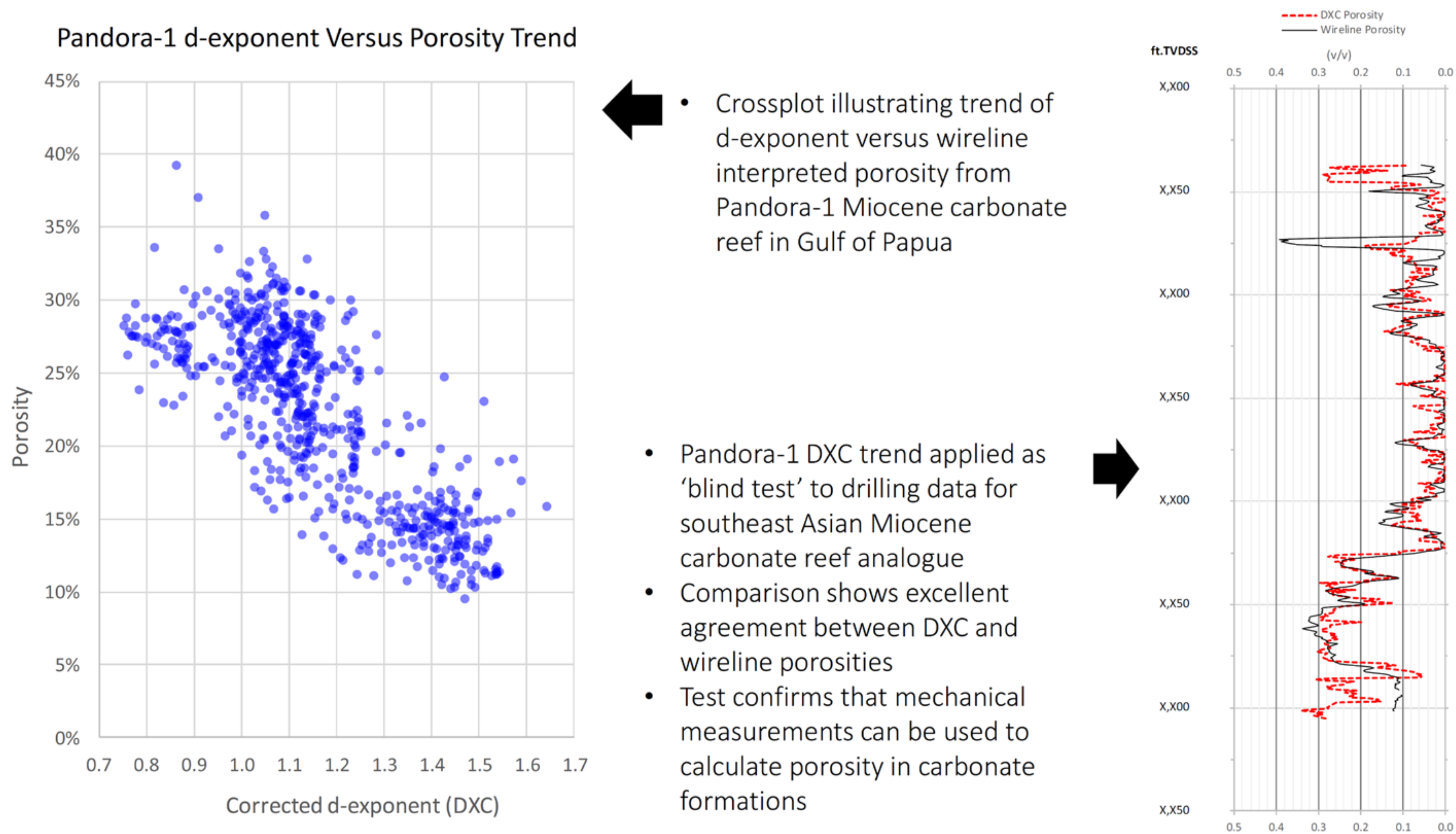

Figure 2. Determination of porosity in Miocene carbonate reef using empirical correlation between DXC and porosity from analogous reservoir formation.

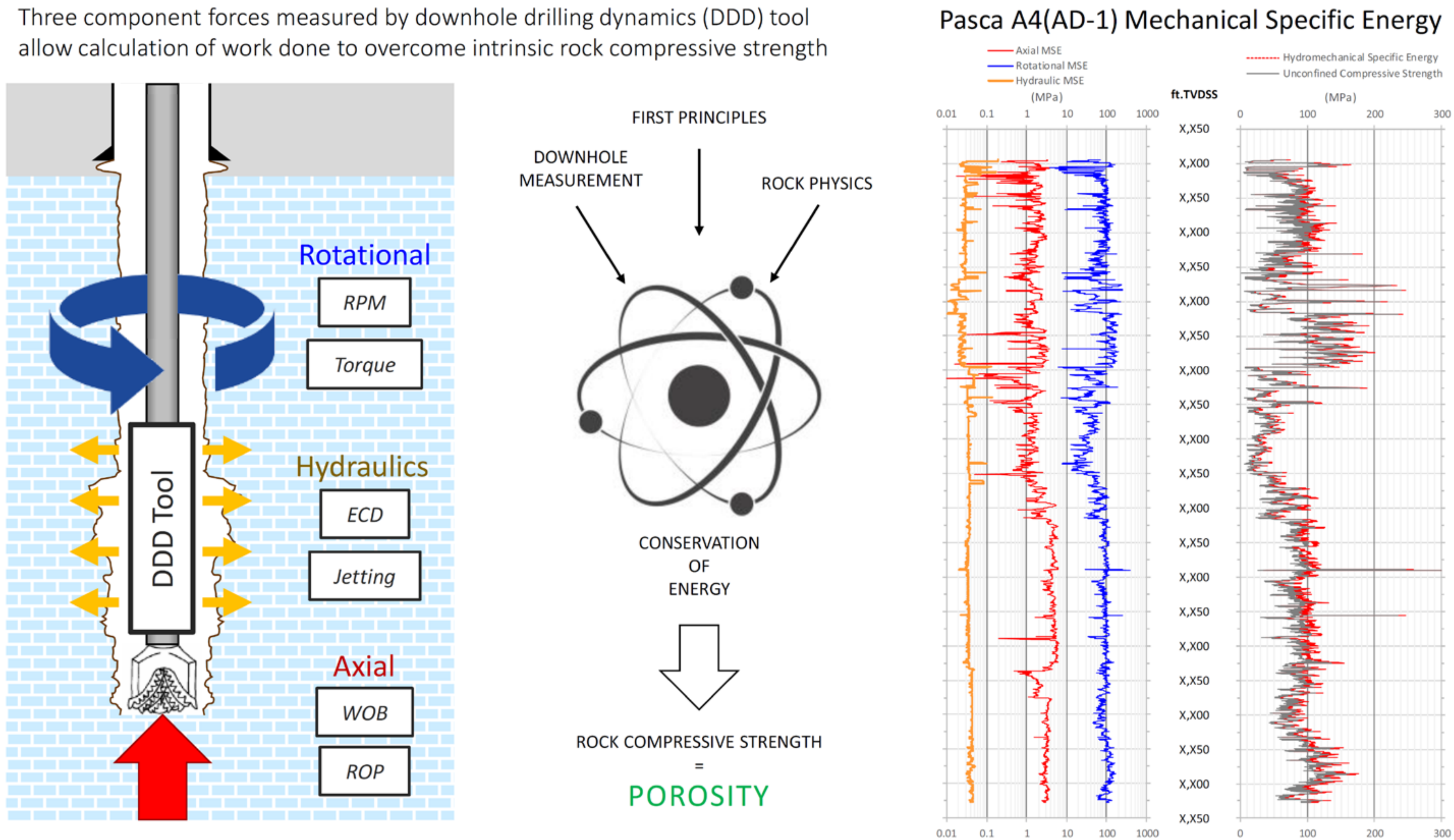

Figure 3. Input forces measured by downhole drilling dynamics tools used to equate mechanical specific energy to unconfined rock strength and porosity.

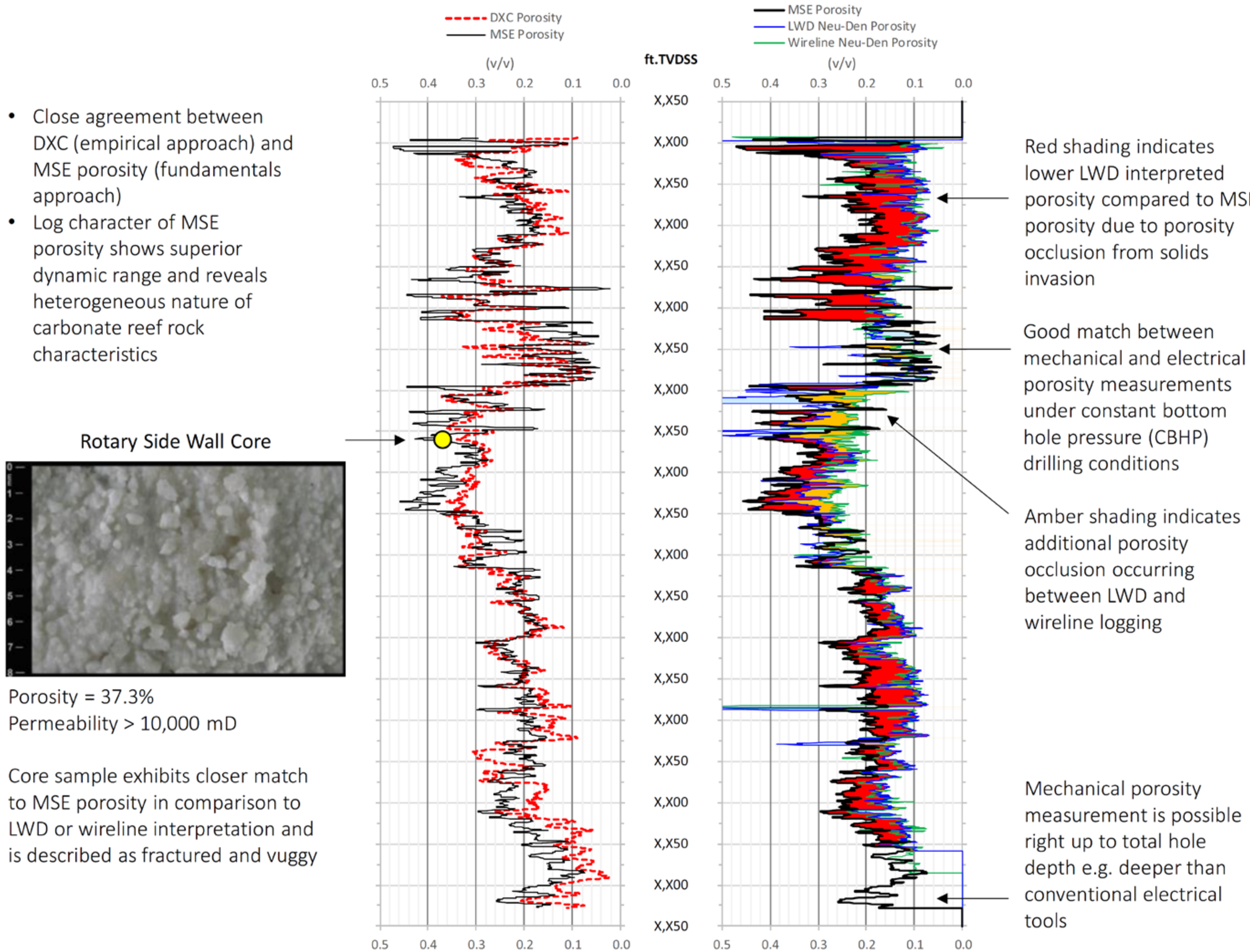

Figure 4. Comparison of Pasca A4 (AD-1) Miocene carbonate reef porosity measurements using mechanical, LWD and wireline techniques.

Method	Measured Porosity	Difference
Side Wall Core (Laboratory Measurement)	37.3%	
LWD Logs (Neutron-Density)	28.9%	−23%
Wireline Logs (Neutron-Density)	22.7%	−39%
Wireline Logs (Sonic)	39.8%	+7%
Drilling Porosity (DXC Method)	31.3%	−16%
Drilling Porosity (MSE Method)	38.1%	+2%

Table 1. Comparison of Pasca A4 (AD-1) porosity measured using side wall core, mechanical and electrical methods.