THE CORE ANALYSIS ELEPHANT IN THE PETROPHYSICS ROOM

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ABSTRACT

Core analysis provides the only direct and quantitative measurement of reservoir petrophysical properties and should provide the ground truth for integrated formation evaluation. However variable data quality, the sensitivity of results to different test methods, poor reporting standards, and the reluctance of some vendors to share experience and expertise have all contributed to basic mistakes and poor data quality. It is easy to blame the vendors, but in too many cases, an inconsistent or inappropriate approach to the design, management and interpretation of the core analysis programme has been adopted and exacerbated by the conflicting requests of the end users. In combination, this has led to a situation where around 70% of legacy SCAL data are not fit for purpose.

We present a core analysis management road map which is designed to increase the value from core analysis investments by enabling a more pro-active, more coherent and more consistent approach to programme design and data acquisition. Firstly, this involves reviewing legacy data and understanding the impact of rarely-reported experimental artefacts on fundamental rock property measurements. Can data be corrected or re-interpreted or are new tests required? Secondly, a multi-disciplinary core analysis management strategy is described. This is designed to encourage more effective engagement between stakeholders and the data acquisition laboratory through improved test and reporting specifications, pro-active test programme management, and real time quality control.

Commercial core analysis has uncertainties which are recognisable and manageable. This paper demonstrates how a pro-active and integrated core analysis management strategy can eliminate data redundancy and reduce uncertainty in reservoir models.

INTRODUCTION

Hydrocarbons in Place and Core Analysis

The volume of stock tank oil initially in place (STOIIP) in a reservoir, can be determined from:

$$STOIIP = GRV\left[\frac{N}{G}\right]\phi(1 - Sw)\frac{1}{B_o} \quad (1)$$

The gross rock volume (GRV) and gross factor (G) in the net/gross ratio (N/G) are the primary responsibilities of geophysicists and geologists. The reservoir engineer is responsible for oil formation volume factor (Bo) from PVT experiments. The petrophysicist is responsible for net (N), porosity (ϕ) and water saturation (Sw). Data input relies principally on logs, but log interpretation must be calibrated or verified by measurements on core. For example, net reservoir is normally defined by a permeability cut off and high resolution permeability data are only possible from core. Porosity interpretation (e.g. from density logs) should be verified by, or calibrated to, stressed core porosities. Resistivity logs require Archie's 'm' and 'n' exponents to quantitatively determine water saturation in clean formations. These are measured on core. Water saturation can be determined directly by extracting water from core using Dean Stark methods or indirectly, from core-derived capillary pressure measurements.

The Importance of Core Data and Data Concerns

Harrison [1] reinforces support for core measurements as "core:

- confirms lithology and mineralogy;
- calibrates estimates of fundamental rock properties;
- shows how fluids occupy and flow in pore space;
- supplies mechanical properties for faster and safer drilling and better completions".

Core analysis is the only direct and quantitative measurement of the "intact" reservoir properties, and should provide the foundation upon which formation evaluation rests. In our experience however an unfortunate negativity over the value of core data has arisen principally due to:

1. Poor inter-laboratory data comparability due to the lack of standardisation and the sensitivity of core data to different test methods. For example, API RP 40 [2] cites three principal methods used to determine porosity in routine core analysis yet these can give completely different results depending on the core plug shape.
2. The lack of thought given to the programme test design by the commissioning end users including: appropriateness of specified core tests; the reliability of the data and their applicability; the lack of understanding of the practical difficulties faced by core analysis laboratories; and the constraints they must work under.
3. Historically inadequate reporting standards which give little real information on the provenance of test data and their interpretation.
4. Strong market competition which has required the core analysis vendors to produce data more reliably, for less money, and with faster turnaround times. Competitive pressure has also limited investment in equipment and R&D, caused high staff turnaround, and constrained management succession planning in some commercial laboratories.

Some core service contractors can produce poor quality data [3], but it is the end user (the client!) who is more culpable. Too often core analysis programmes are ill-considered, badly designed, poorly supervised, and only crudely integrated with other well and reservoir data. The results, in terms of data acquired are often unrepresentative or contradictory. Our conservative estimate, from review and audit of over 30,000 SCAL measurements of different vintages, indicates that approximately 70% are unfit for purpose due to their unreliability, inapplicability or inappropriateness. It may be no surprise therefore that it remains an uphill struggle to convince management in some companies that the project benefits from the knowledge gained from core analysis. Yet, with proper planning and management of the coring and analysis processes, core data should be and can be the "ground truth".

The Elephant in the Room

Idiomatically, the core analysis elephant in the petrophysics room is an expression that applies to a problem or uncertainty that few want to discuss. The following examples illustrate where small and generally unreported laboratory artefacts and measurement uncertainties have a significant impact on two key petrophysical data inputs: the Archie water saturation equation and capillary pressure measurements. The succeeding section describes a road map to maximize the value from core analysis and reduce or eliminate data redundancy through integrated project planning and real time core analysis management.

CORE DATA INPUT UNCERTAINTIES AND IMPACT

Archie Water Saturation

Archie [4] defined a fundamental set of equations which establishes the quantitative relationships between porosity (ϕ), formation (Rt) and formation water resistivity (Rw), and water saturation (Sw) of reservoir rocks.

$$F = \frac{Ro}{Rw} = \frac{1}{\phi^m} \tag{2}$$

$$I = \frac{Rt}{Ro} = \frac{1}{Sw^n} \tag{3}$$

which, in combination, leads to:

$$Sw = \left[\frac{1}{\phi^m} \frac{Rw}{Rt} \right]^{\frac{1}{n}} \tag{4}$$

Both Rt and porosity are obtained from logs, but porosity logs should be verified from core measurements made at representative stress. The porosity exponent, 'm', and saturation exponent, 'n', are obtained from formation factor (F) and resistivity index (I) tests on core. Many petrophysicists often have to rely on legacy SCAL data of varying vintage, frequently measured at ambient conditions.

Porosity

In the formation factor test, porosity is often measured at stress, in conjunction with core resistivity, Ro, and is used to estimate porosity compaction factors for log calibration. In one of the common test protocols, the sample is saturated in brine under unconfined conditions and, after resistivity stabilisation, is loaded into the test coreholder. As air is resistive and compressible it must be removed from the annulus between the plug and the sleeve, the end stems, and measurement system so the system is filled with brine prior to loading. The sleeve conformance pressure (SCP) and volume (SCV) of brine in the plug/sleeve annulus should be satisfactorily established for *each* test plug so that appropriate corrections can be made to determine the correct pore volume reduction at stress. The confining pressure is increased in small increments and pore volume expulsion and Ro recorded. The SCP (and SCV) are normally pinpointed by an inflexion in the slopes of resistance and/or expelled volume versus confining pressure curves (Figure 1).

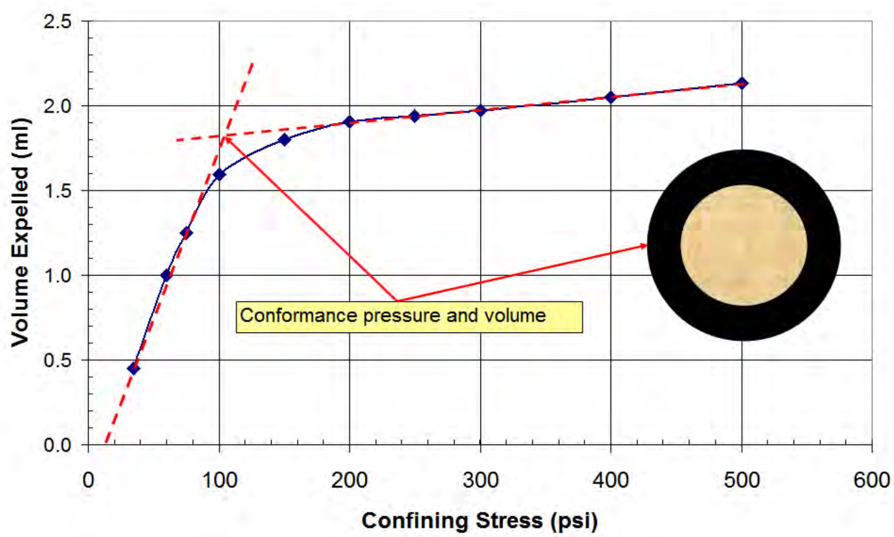

Figure 1: Sleeve conformance pressure and volume from expelled volume-stress curve.

The volume-stress data are rarely reported, and many labs assume the same SCP (and hence SCV) for every sample irrespective of the plug shape and surface topology. Even when data are available, the interpretation of SCP and SCV can be subjective. Unfortunately, the impact on the porosity measurements is significant. The example shown in Figure 2 plots stress-normalised porosity (the ratio of porosity at stress to unconfined or ambient condition porosity) as a function of confining stress for the same formation. The only difference is the test laboratory. Lab A determined SCP and SCV for each sample. Lab B assumed an SCP that was too low, which resulted in an apparently lower porosity at stress. When the Lab B results were used to calibrate the density log interpretation in this gas reservoir (prior to the Lab A results), porosity was underestimated by 7% and gas initially in place (GIIP) by 4%.

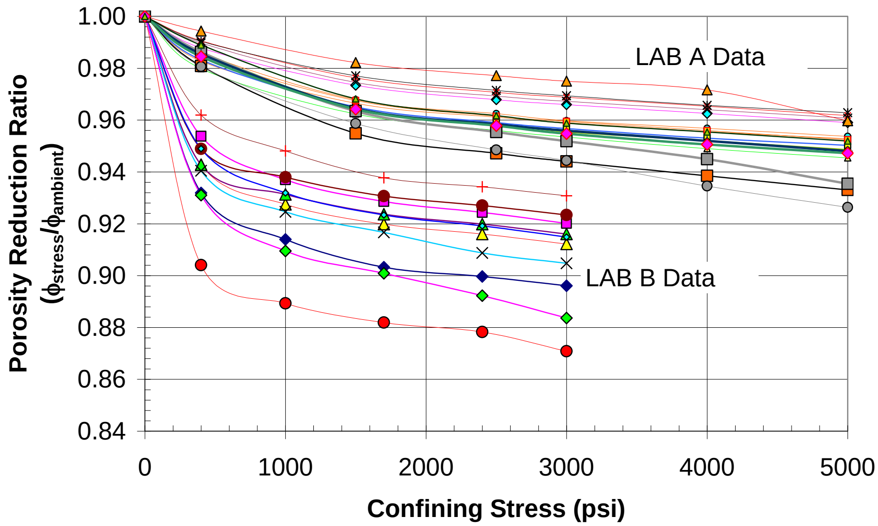

Figure 2: Effects of sleeve conformance volume uncertainty on stressed porosities

<u>Archie m and n</u>

This excess brine can also have a significant effect on Archie's cementation and saturation exponents. Although this is not an issue for tests carried out at stressed conditions (above SCP), in ambient condition F measurements, brine clings to the surface of the plug after saturation. This must be removed otherwise the surface brine will provide a conduit for current flow so that the measured resistivity is too low. A film of surface brine of just 2.5 micron thickness will produce an underestimation of F of nearly 30% in a low porosity sample [5]. If F (and Ro) are too low, then the ambient condition resistivity index (Rt/Ro) and 'n' will be too high. Although these effects disappear if both F and I tests are measured at stress, petrophysicists often do not have the luxury of working with such data.

Excess brine effects are clearly evident in Figure 3 where stress-normalised formation factor is plotted versus stress. F apparently increases abruptly between 0 psi and 200 psi but this is a direct result of ambient Ro being too low due to surface brine on the plug. At 200 psi the surface brine has been expelled by the core sleeve conforming to the plug surface. The dataset can be corrected by determining the "true" Ro from extrapolation of the F-stress trend to 0 psi.

At ambient conditions, surface brine produces an average negative error of -30% in 'm' and a positive error of +15% in 'n' (Figure 4).

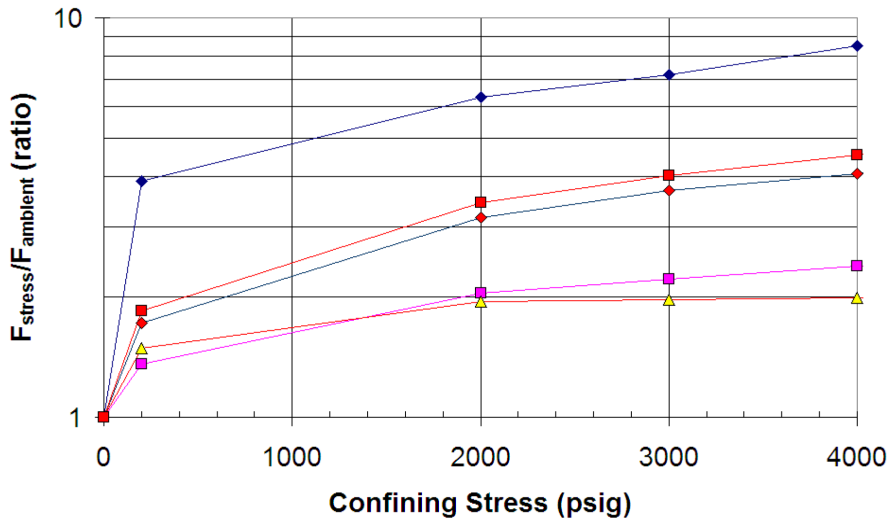

Figure 3. Stress-normalised formation factor versus stress.

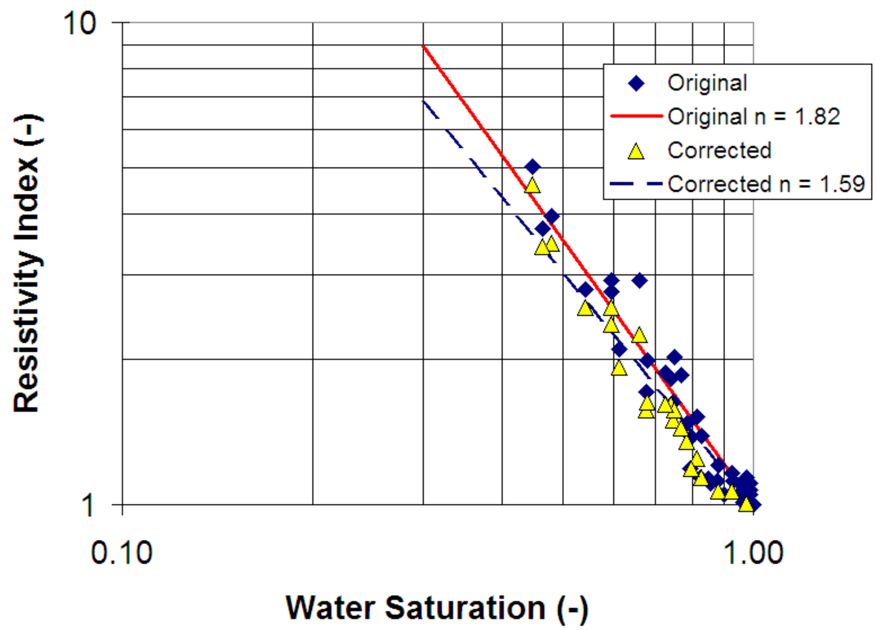

Figure 4. Resistivity index data corrected for excess brine effects.

<u>Water Saturation</u>

Grain loss from plug handling during testing can result in considerable uncertainties in the calculation of saturations from gravimetric measurements. A loss in weight might be interpreted as a loss of water so that the calculated water saturation is much less than the true value. For a 16% porosity, 140 gram plug, a grain loss of only 2% dry weight translates to a 20 saturation unit error in Sw for a gas-water experiment. The error is magnified for an oil-water system as the fluid density difference is smaller. The goal of grain loss correction is to predict the fluid-filled pore volume at each stage of the handling and test procedures, and to validate these estimates, where possible, using measured data. Unfortunately, such corrections can be subjective.

Impact of Uncertainties

The magnitude of these porosity and resistivity errors is put into context by Table 1 for a typical North Sea reservoir with 20% porosity, 20% water saturation and 100 MMstb STOIIP.

Table 1: Impact of errors in core-derived input parameters on STOIIP uncertainty.

Input Parameter	**Error**	**STOIIP Change**
Porosity	+ 7%	- 8 MMstb
Archie ‘m’ (ambient)	- 30 %	+ 12 Mmstb
Archie ‘n’ (ambient)	+ 15%	- 7MMstb

Mercury Injection Capillary Pressure

Before the mid 1990’s, nearly all mercury injection capillary pressure (MICP) tests were made on core plug samples (1” or 1.5” diameter by up to 2” to 3” long) using manual equipment at injection pressures up to 2,000 psi. The non-wetting and wetting phase saturations were determined from the injected mercury volumes and the core plug helium pore volume. Today, virtually all measurements are made with automated high pressure equipment that is capable of injection pressures of up to 55,000 psi. These instruments were specifically designed for pore size distribution tests on papers, catalysts and ceramics, not for core plugs. The sample chambers (penetrometers) are size-limited to ~ 10 ml (Figure 4), but typical core injection samples are around 5 ml bulk volume. For a 20% porosity sample, this means that the injection chip pore volume is less than 1 ml, compared to a pore volume of 14 ml for a 1 ½” by 2 ½” plug. As the impact of volume errors on saturation estimated from immersion bulk volume and helium grain volume on small samples are large, most laboratories inject mercury to define the total mercury-filled pore volume. This requires pressures in excess of around 25000 psi.

In certain formations high pressure mercury injection appears to cause distortion of the capillary pressure vs. water saturation curves. In the example shown on Figure 5, mercury injection tests were run using conventional manual equipment on 1.5” plugs whereas the tests on the “chip” samples were run on 4 ml to 6 ml size specimens. In both cases the test plugs were unconfined (3D injection). The phenomena involved are not as yet clearly understood. They may be related to sample size percolation dependencies [6], but they appear worse on samples containing clay-filled micropores not normally accessed by mercury at 2000 psi where injection appears to progressively and permanently damage the pore system. However they have a significant impact on saturation-height curves derived from MICP tests.

Figure 4: High pressure mercury injection equipment sample penetrometer.

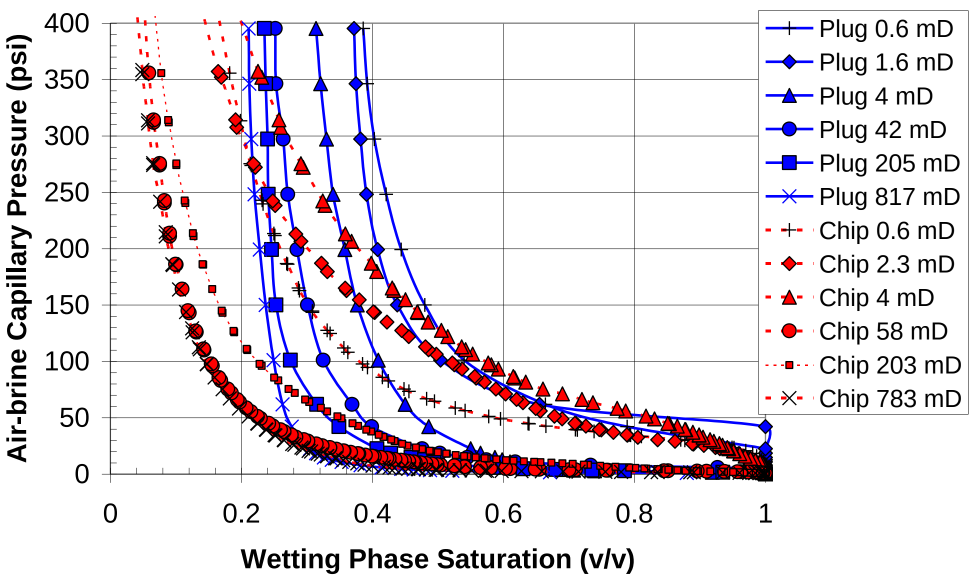

Figure 5: Capillary pressure curve distortion from high pressure mercury injection in small chip samples.

A CORE ANALYSIS MANAGEMENT ROADMAP

Key Questions

The chance to acquire new core data provides an ideal opportunity to minimize the uncertainties in key core-derived model inputs. The key questions that should be asked prior to embarking on this process are:

1. Are there areas of concern or anomalies or suspicious data in the database that need to be resolved? How closely does the core, log and test data agree for the well in question and the reservoir in general?
2. What core analysis tests do we actually need? It is important not to select tests from a "menu", or to "do what we have always done".
3. Is the contractor interpretation correct? In SCAL reports the saturations reported are

often laboratory interpretations of volumetric or gravimetric measurements – they are not measured data. Data interpretation can be subjective and less than rigorous. It is essential that the lab provide "raw" or experimental data so that figures can be checked and interpretations verified.

4. Can operators improve on the lab interpretation? As Harrison [7] states when discussing log interpretation : "end users must not abdicate their responsibility for the interpretation". It is equally true, if not more so, for core data.

Planning and Programme Design

Coring and core analysis are often poorly planned. Test programme design is too often ill-considered which results in under-utilisation, poor appreciation and poor application of the resultant core data. Proper planning and supervision of a core analysis programme can do much to reduce the data redundancy rate. Petrophysicists, geologists, reservoir engineers, and drilling and completions engineers all have a role to play in the planning team, which must include the laboratory that will carry out the work.

Core Analysis Focal Points

Recurring themes in many core laboratory audits are the need to improve communication between the laboratory and the client, and client education in core analysis acquisition and interpretation. In particular the vendors felt that they are too often faced with conflicting and contradictory instructions from within the operator's different discipline functions, and would prefer to deal with a single, knowledgeable, core analysis focal point who understands the applications and limitations of core analysis tests. This should ensure that the data quality requirements are maintained and, more importantly, that the data are fit for purpose. The client focal point is the liaison between the client's different subsurface disciplines and the lab, and is accountable for laboratory supervision and real time quality control. Amongst the key focal point responsibilities are:

- design and costing of the test programmes, with the assistance of the laboratory;
- preparing justifications to management;
- coordination with drilling and wellsite engineers and lab staff to review core drilling, core recovery and wellsite handling, storage and transportation procedures;
- design and specification of the test and reporting procedures to be adopted in the scope of work, including deliverables, milestones and project reporting;
- reviewing contractor performance against initially set goals, objectives and deliverables;
- analysis and checking of the contractors' data as soon as possible after they are received;

- preparing a final report on the SCAL study, which reconciles core results with other well and reservoir data, and provides appropriately interpreted and reliable core analysis data that can be used for petrophysical and reservoir simulation models.

The laboratory also should have a project manager with the key responsibilities of client expectation management; organising and controlling the work; and documentation of the project requirements, test specifications, lab worksheets and analysed data. Peer review of both intermediate and final data are essential before delivery to the client.

Real Time Quality Control

Regular monitoring of vendors' performance and the provision of, and checking, experimental data can ensure that any problems or unusual, anomalous or inconsistent results can be identified as soon as possible, so that they can be rectified before the test programme is completed. Thereafter, it is too late, and costs are often incurred in re-testing which can lead to largely undeserved but lingering resentment over lab performance. Contractor supervision and quality control will ensure that complete records of the test methods and procedures together with laboratory experimental data are available, so that there is a complete audit trail.

Laboratory SCAL reports must include a detailed description of the work performed, the equipment and procedures used, and details of the methods used by the lab in analysing the data. Understanding the plug history is essential in QC of the SCAL data – particularly in formations sensitive to stress cycling and rock/fluid incompatibilities – but deciphering plug history from standard SCAL reports can be challenging. Figure 6 shows an example of a single page plug history sheet that charts the history of each sample through the plug preparation and testing sequence. More effective knowledge sharing – e.g. highlighting of unusual or anomalous data in the report text, tables and figures – will allow the client to gain and benefit from the lab's undoubted expertise and experience in similar lithologies.

Relevant experimental data, details of appropriate instrument calibration data, and the equations used to generate the analysed data from "raw" measurements should also be provided. Labs often charge for compiling this information and although the data might never be reviewed, they can prove invaluable in audit trailing and unitisation.

Laboratory-Client Relationships

In our experience, labs have enthusiastic, committed and highly experienced management teams, but they tend to be reactive and not pro-active. This is not helped by the traditional master-servant relationship. Engaging the labs through regular meetings and lab visits during ongoing projects means they become more aligned with, and involved in, the client stakeholder objectives, and better understand how important their data really are in field development planning and decisions.

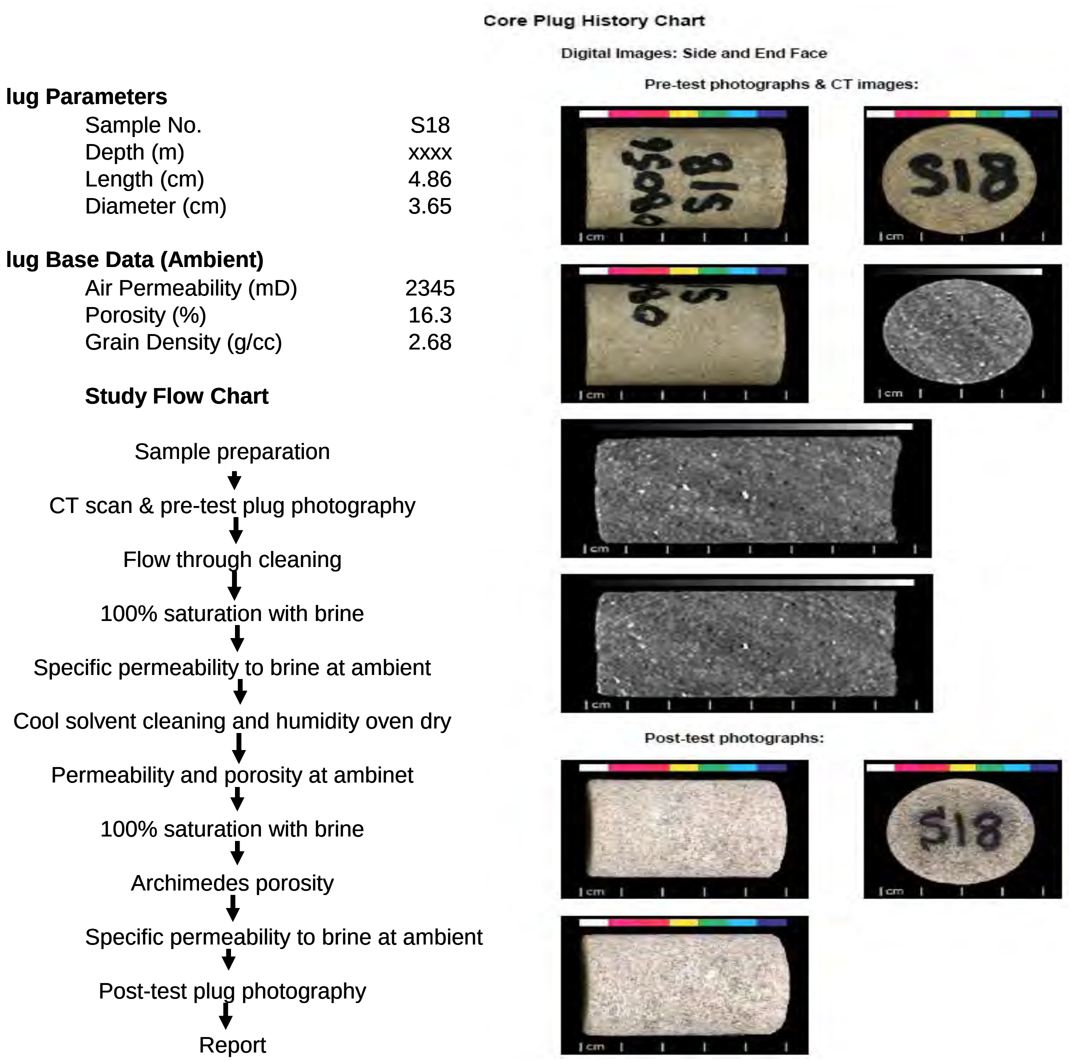

Figure 6. Example plug history sheet (courtesy Woodside Energy)

Benefits

In practice an integrated core analysis management strategy will bring significant benefits to the end users. While problems still occurred in some programmes, real time quality control was able to capture the issues and the test workflow, procedures, and interpretation were modified accordingly. Overall, this has resulted in a marked improvement in data quality and positive technical communication with core analysis vendors. Our estimate is that data redundancy has been reduced from 70% to less than 10%.

CONCLUSIONS

The examples of laboratory artefacts presented here have a significant impact on petrophysical interpretation. Yet, with experience, learnings, and the appropriate diagnostic tools, these uncertainties are recognisable and manageable.

A pro-active and synergistic core analysis management strategy can deliver high quality data through developing a more effective relationship between the end user and the data acquisition laboratory. This enables:

- improved communication and learnings;
- better understanding of core analysis procedures and methods;
- more coherent and consistent approach to data acquisition;
- reduction in uncertainties and data redundancy;
- full data audit trail, which brings better equity and unitisation positions, easier and more efficient presentation of core analysis plans and results to partners, and most significantly;
- added value from core analysis investments.

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