PETROPHYSICAL SAMPLING STRATEGY FOR A MODEL-DOMINATED USER GROUP USING AN EXPERIMENTAL DESIGN CHECKLIST APPROACH

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ABSTRACT

Numerical modelling has become standard industry-practice across the upstream disciplines, in the areas of reservoir geology, geophysical interpretation and reservoir simulation. Consequently, the reservoir modeller has become the prime customer for petrophysical properties. This has not happened overnight but rather the modelling software and hardware have evolved to the point where the multi-cellular models are becoming the basis of reservoir management decisions. This provides an opportunity for a re-evaluation of current petrophysical sampling strategies, which are still largely based on traditional techniques.

These traditional techniques rely on samples of a limited volume range (core plugs and, occasionally, whole core studies) at regular (1ft or 30cm) sample spacings. Special core analysis samples tend to be selected on the basis of sample availability, sample preservation, sample homogeneity and other considerations. The model-dominated environment in which we now work requires measurements to be scaled to the block dimensions in the simulation models. In addition, petrophysical data is required for all the rock types, lithofacies, or genetic units present in the field model, along with a consideration of the statistical support and stationarity issues. In particular, a complete suite of petrophysical properties for reservoir simulation (porosity, permeability, permeability anisotropy, relative permeability, capillary pressure), and for time lapse seismic modelling (compressional and shear velocities, attenuation, density, stress sensitivity, saturation dependency and fluid properties) are also often required. These requirements are quite different to those when the key role of core data was to validate (ground-truth) log responses and their interpretation.

In this paper, we review the range of measured parameters, the statistical issues, the needs of the end-user, and detailed screening of selected intervals (Genetic Petrophysics) in the context of a published experimental design framework. We analyse the approach by illustrating its application in a North Sea reservoir unit. The paper introduces a systematic approach to sampling reservoir rocks for reservoir modelling.

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INTRODUCTION

Petrophysical sampling of a reservoir is a complex experiment. Practical strategies for experimenting exist in the engineering literature (the text book of Robinson, 2000 for instance). In this paper, we reconsider experimental design for core analysis in the light of the ultimate use of those data in simulation following a broad checklist (Fig. 1) proposed by Robinson (2000) and adapted to a core analysis programme underway for a North Sea reservoir. This check-list has been applied retroactively (with the additional benefit of hindsight) and highlights the benefits for adopting a more systematic approach in the future. The API Recommended Practices for Core Analysis (API, 1998) and recent textbooks on Petrophysics (Tiab and Donaldson, 1996) give many details of measurement procedures but little or no guidance on sampling strategies.

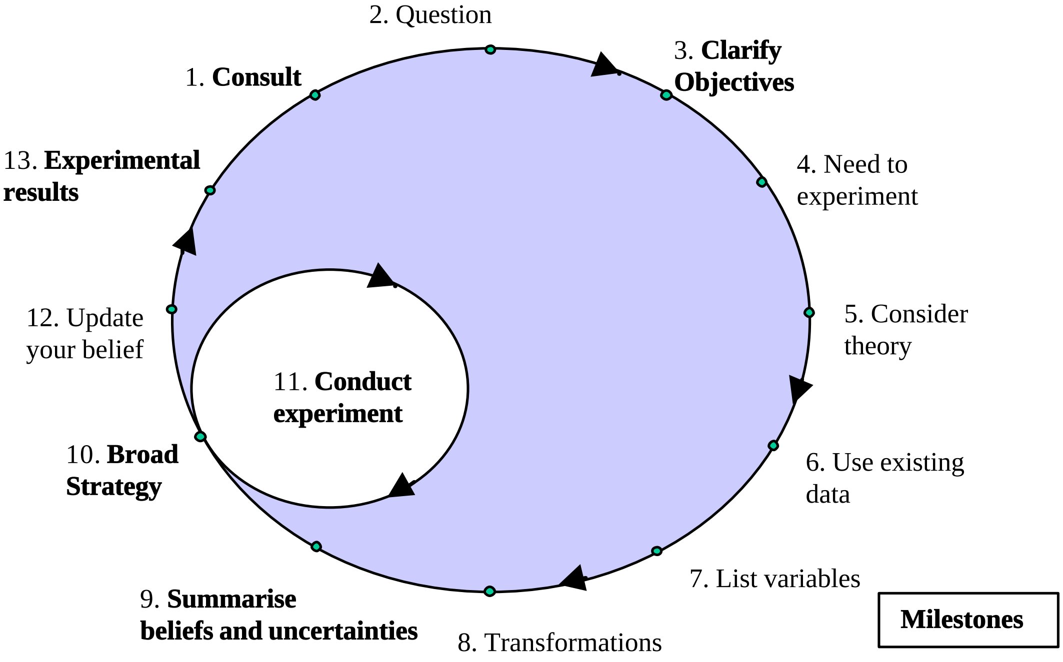

Figure 1: Experimental design checklist for core analysis showing overall experimental programme as an outer circle and a single experiment as an inner circle (adapted from Robinson, 2000)

This is probably because of the complexity of material to be sampled, the conditions under which it might be sampled, the plethora of devices which might be used (for an increasing number of properties) and many local and international practices. This is a challenge which the Industry can address by adapting procedures from other branches of experimental science, tempered by a consideration of the ultimate objectives for measurements on rocks for reservoir modelling usage. This is the *experimental design checklist* approach taken here.

EXPERIMENTAL DESIGN CHECKLIST

1. Consult

Ask the question – why are the data being collected? Whether the data are required to ground-truth a wireline log response or are for reservoir modelling, will affect what ancillary data are needed and what sampling framework is required. Is the experimental design to be determined by the volume and spacing appropriate for the log response function, or determined by the number of rock types and the scales of geological features thought to be present? In this paper, we wish to consider that the data are ultimately required for modelling, so the latter route is taken.

2. Question

At this stage, appropriate questions might be asked to help prepare the experimental programme.

What are the expected rock types (genetic units, lithofacies)?
What are the range of textural properties?
Are the reservoir rocks well cemented?
Is the core material representative?
Are properties dominated by primary texture or secondary diagenetic cements?
What is the production mechanism?
Are seismic methods being used to monitor production?

In our example, the responses gathered at this stage would indicate that the target reservoir is a shallow marine sandstone reservoir. The reservoir material is fine to medium grained sandstone and reasonably well cemented. No loose sand intervals are present. The reservoir properties are dominated by primary texture (this might be checked in the experimental design). The reservoir is being waterflooded. The reservoir pressure is being maintained.

3. Clarify the objectives

Robinson quotes an earlier worker here to indicate that it is better to seek an approximate answer to the right question rather than an exact answer to the wrong question! Here you are receiving supporting information from experts and the client that the objectives are accurate. In our case, we will have upper and lower shoreface units (the former coarser), and interbedded offshore mudstones to characterise. Lagoonal or behind-shoreface facies may also be present in such an environment, but not in this case. A waterflood production mechanism with pressure maintenance should result in fluid-substitution only affects being present. Local pressure depletion effects (and thermal effects) around wells might be present if the rock is very stress-sensitive. A supplementary question at this time might be – what are the characteristics of the faulting in the field and their effect on rock properties?

The complexity and precision required in the model should be defined at this stage as part of the clarification of objectives. In the subject case study, the field is thought to be a simple layered system with contrasting layer properties due to primary textural variations between the upper and lower shoreface with interbedded shales. The faulting is thought to be of secondary importance. Fluid substitution in the main reservoir units is to be investigated. Stress sensitivity is to be evaluated. For reservoir simulation, the capillary pressure, relative permeability and wettability of the main rock types is to be evaluated. Down-dip reduction of reservoir properties is to be investigated under a later set of experiments. The properties of the layers will be estimated to an acceptable tolerance.

4. Need to experiment

Here there should be sufficient value (information) to be gained from the experiment to proceed. In our case, the experiment was designed to see if a single 7.3m(24foot) section including the two main rock types (a single shoreface parasequence comprising upper and lower shoreface units) could provide the same information as the 122m (400foot) section of core in the well. We were testing that a representative element selected on geological criteria could adequately describe the petrophysical properties of a well (Fig. 2).

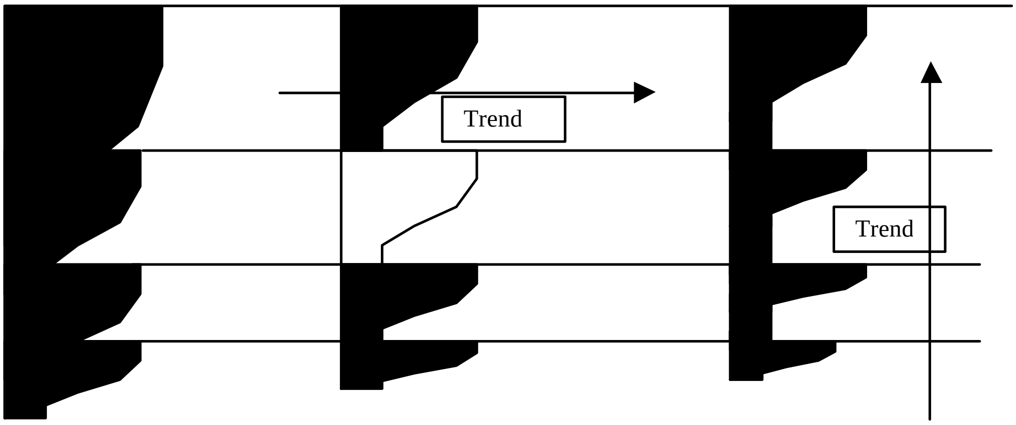

Figure 2: The experimental design incorporated the knowledge of the geology of shallow marine reservoirs to determine the sampling programme. A single representative shoreface parasequence (white) was selected from a model of prograding shoreface units (seaward to the right).

This new information in itself has value, as it provided a more detailed petrophysical description of the key rock types and it could also be exploited in the future experimental design in the field. Review of existing data identified some missing special core analysis data.

5. Consider theory

If a model is available for the measurements, then experiments can be conducted according to the response surface and therefore experiments can be made more efficient. If you know a straight line relationship fits the predictor and response from theory, then only 3 experimental data points might be needed to confirm the physics. An unknown response surface (i.e, with more than predictor variables) might require more. The discrepancy between a model and an observed response can be used, rather than the observed results, to guide interpretation. This aspect wasn't used enough in the design of our initial experiment because the theoretical models weren't identified. However, following the initial screening experiment, models were recognised and these can now be incorporated into subsequent designs. Reference to existing models – for porosity/permeability relationships, for example, - are traditionally not as readily available to the experimentalist as they might be for use in experimental design (in physics for example).

Prior knowledge of distributions of properties – normal, log normal - can also be exploited to design sampling programmes. Knowledge of their variability can be used to design sampling programmes for estimating mean properties (Corbett and Jensen, 1992). Knowledge of spatial distribution can be used to design sampling strategies for variogram analysis.

6. Use existing data

Where existing data for the well are available, these can be used for distribution and variability analysis and used to design sampling programmes. Often the patterns in property variation can be compared with the geological description to see if these are logical – in terms of the theoretical or empirical models available. When using existing data, one has to be cautious about the quality of the data (cleaning conditions, stress conditions, orientation, calibration, raw flow rate versus interpreted permeability data, nature of missing data). Bias in data due to coring issues (competency of beds, thin beds, location of plugs, etc) have to be carefully investigated. In the example we discuss, all the special core analysis (relative permeability) data came from upper shoreface units. None came from the lower shoreface – which made up a significant proportion of the reservoir. This was due to selective sampling of the more homogeneous upper shoreface units, as a result of the experimental procedure for the interpretation of core flood experiments.

7. List variables

List the response variables (e.g., porosity, horizontal and vertical permeability, capillary pressure, relative permeability, wettability, compressional and shear velocities) with indication of typical values, variability, sensitivity and robustness. Consider the precision and cost of these variables and client requirements. Response variables are indicators of the aspects of a process that are important (Robinson, 2000). The process might be defined as the petrophysical variability of rock type and these should matter to your ultimate client (the reservoir modeller in this case). Avoid giving priority to measuring what is easy (e.g, permeability in clean sands) over things that are difficult (permeability in heterolithic intervals). Look at the customer specifications remembering that this is codified – the real requirement being that the experimental output produces no problems when used as input to their reservoir models.

List factors (e.g., sample volume, sample location, cleaning, texture, age, core handling) which might influence the response variables. Brainstorming with a wide range of people is useful at this stage. Indicate the complexity (and cost) associated with investigating these parameters. A factor in some trials can be a response variable in other trials.

8. Transformations

Response variables can be transformed to incorporate background knowledge into experimental design and analysis. The log of permeability for instance is often used to explore trends. Transformations can make the variance constant across the space of measurements. Robinson (2000) suggests adding half the minimum detectable value instead of zero if a log transform is to be used (this would be 0.005mD for all those 'zero' permeabilities where 0.01 is the limit of the plug measurements). More general power transforms (including reciprocal, square root, etc) are also available.

9. Summarize beliefs and uncertainties

At this stage it is important to summarisze beliefs and uncertainties about experimental protocol, likely sampling and testing variability and the effects on the variables of interest. Here the one-foot core plug versus other sampling techniques might be evaluated. One-foot sampling can be biased due to the nature of heterogeneous core intervals. Deciding what is vertical in the context of the material to hand (normal to bedding or parallel to borehole direction) is another consideration. Strongly laminated and friable intervals tend to be avoided. A discussion on support and stationarity issues (Corbett et al., 1999, 2001) with the modellers would be useful at this stage. Subjective opinions and value judgements, carefully used, are important to efficient sampling strategies (Robinson, 2000).

The beliefs and uncertainties are best summarised in the tender document and subsequent contract with the core analysis company, listing:

Sample material source
Sampling methods (volumes, core plugs, etc)
Measurement of response variables (protocols, methods, sample spacing)
How variables (e.g., sample spacing, cleaning) will be kept constant
How factors (e.g., stress, wettability) will be altered
Budget available
Precision expected

10. Broad strategy

Robinson (2000) suggests that experimentation should be thought of as a sequential, staged process consisting of a number of simple experiments. The outer circle and inner circle of Fig. 1 represent two such stages. He suggests spending 10% of the budget on a preliminary trial, 50% on a substantial trial and holding 40% in reserve to be used as indicated by the results of the substantial trial.

In the “Genetic Petrophysics” approach adopted by Potter and Corbett (2000) initial screening by CT, acoustic, probe permeametry, organic geochemistry techniques might represent the preliminary trial phase on a single well. Detailed plug measurements under cleaned and stressed conditions would follow as the substantial trial phase. Infilling missing data or undertaking more detailed analysis (or new rock types, facies) on further wells in the field would use up the reserved budget, as appropriate. This avoids the compartmentalisation of either Routine Core Analysis or Special Core Analysis, as the range of measurements would be programmed in the strategy at the outset. Clearly, strategies for single wells at the appraisal stage (with little existing data) versus multiple well projects (and much existing data) will be different. In both cases, sequential staged processes can be envisioned. In the former case, preliminary screening data are needed. In the latter, more emphasis on preliminary interpretation and processing of existing data is advised.

An important consideration at the initial strategy stage is to consider the ultimate complexity of the model. This is related to how well the mathematical functions can approximate reality over a given range. Sometimes the range investigated will affect the complexity of the model (e.g., in the linear flow regime at moderate flow rates, the Darcy flow model can ignore the effects of slippage and inertia). Models in this context can be either engineering models (equations relating response variables to factors) or the ultimate reservoir model (finite difference simulation model).

The experimental design strategy might be to do single experiments at a time – e.g., measure porosity and permeability on a core plug – or consider more powerful aspects of experimental design by using multiple factors at a time. Reservoir engineers have used an experimental design approach (Jones et al, 1993; White et al., 2001) to reduce the degree of numerical experimentation required in order to consider the sensitivity to all properties. The approach might be extended to the laboratory when many responses and their interactions are needed.

Strategies for studying sampling and testing errors are required. Within a multi-lab project the cross-validation and calibration of measured properties is an important consideration (Potter and Corbett, 2000).

11. Conduct experiment

Decide whether to measure a single property (response variable) or a group of response variables. In this paper, we will avoid discussion of the details of the experimental procedure (measuring permeability or relative permeability for example) and proceed to the post-experimental analysis phase. The API guidelines (API, 1998) can be followed at this stage for experimental details. Aspects of experimental design can be extended to these procedures.

Replications are useful, but care must be taken to detail all aspects of the 'replicate experimental run' (Robinson, 2000). The process of sample extraction, preparation, set-up of equipment, measurement operation and generation of the number that is the result should be detailed. Replicate samples (often taken as adjacent samples) would not necessarily produce replicate results in different labs unless all the procedures were followed and the target region for the samples was homogeneous. Randomisation of the samples (by depth for instance) will help minimise the effect of any drift in the measurements. Care needs to be taken to avoid bias in sampling and measurement.

12. Update your belief

Following data acquisition, cross-examine the data by plotting histograms and crossplots (Fig. 3) – looking for outliers, checking missing data and other quality control procedures. Checking the new data against the previous models and refining them as appropriate. New trends and data clusters may be identified requiring calibration checks and review of the core material. This may require a further consultation with the client before proceeding into a second stage of the process.

In the example that we have been considering, the upper and lower shoreface were distinctly characterised by unit-specific poroperm relationships. These could be related, with the help of pore scale models and observations, to the contrasts between a quartz-overgrowth dominated, coarse, clean upper shoreface and a fining-up, illite-bearing lower shoreface unit. Outliers were identified as barite-filled fractures.

13: Experimental results

Providing the experimental data to the client with a summary of the procedure used and the uncertainties. Facies-specific poroperm description and genetic basis (Fig. 3) might be provided to the client. This could be extended to stress-acoustic data with a consistent facies coding as a matter of course.

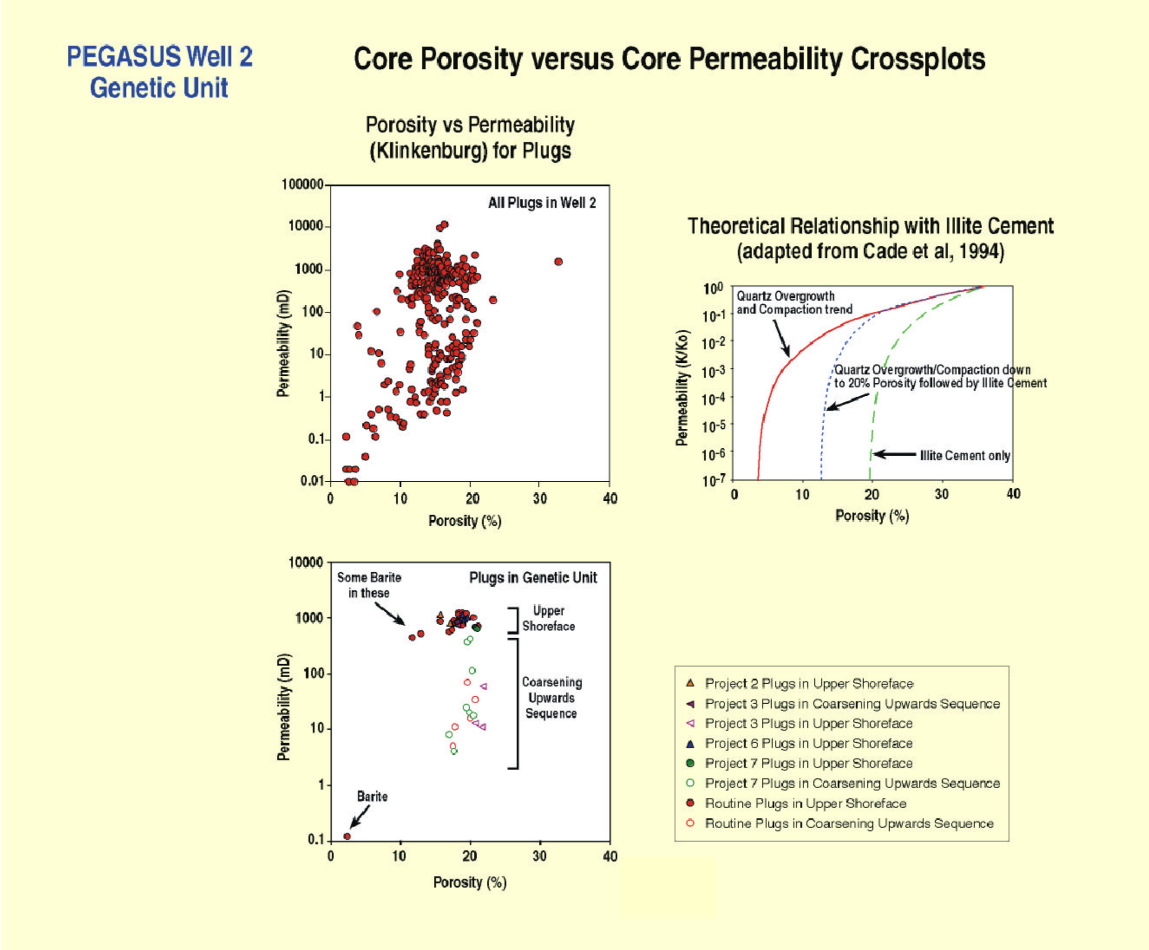

Figure 3: The experimental results showing that our selected interval was representative for the whole well (from Potter and Corbett, 2000). The selection of single parasequence revealed the trends within upper and lower shoreface intervals. The review of published petrophysical models (Cade et al., 1994) suggests that the poroperm properties of the upper shoreface is largely controlled by quartz overgrowths and the lower shoreface by illite. This factor can be built into further experimental design criteria of shoreface units.

A simple log threshold (e.g., gamma ray cut-off in this case) might be used to identify the facies on wireline logs for use in subsurface characterisation. In other circumstances a more complex approach (e.g., neural nets) might be needed to identify rock types.

Understanding how the data is to be used will help develop the experimental procedure for the user. In our study, a second well is undergoing analysis – the specific objective of which is to understand the controls on diagenesis and its impact of reservoir properties. The feedback from seeing the use of the data in the reservoir model will also help validate the models used in the experimental procedure.

MILESTONES

The phases of the experimental design checklist in which the petrophysicist can seek out specific interaction with other asset team colleagues (and if appropriate, management) are:

- Consult
- Clarify objectives
- Summarise beliefs and uncertainties
- Broad strategy
- Conduct experiments
- Experimental results
- Consult

This process is naturally a circular one of developing beliefs, experimenting, moderating beliefs and reporting. With each circuit, the belief should be getting stronger, confidence increasing and uncertainty reducing.

SUMMARY

An experimental design checklist has been evaluated against an in depth petrophysical procedure. The following aspects are emphasised in this evaluation:

- The experimental procedure for core analysis is a staged process
- Experimental design should start with clear definition of objectives from the client, which in the modern industry is often a modeller
- Experimental design encourages the incorporation of theoretical models and previous data in the design of new data acquisition
- A broad strategy can be developed using experimental design to take into account a range of petrophysical, statistical , geological and engineering issues
- The application of experimental design in a wider range of studies can provide a rigorous but flexible sampling strategy for the industry

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