CORE ANALYSIS TO CALIBRATE GEOLOGICAL INTERPRETATION

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Abstract: This keynote paper constitutes a personal view of the role and place of core data in geological interpretations for reservoir description in appraisal projects. No apologies are made for placing the geologist in an engineering setting for this purpose and this approach is strongly argued. Core is of pivotal importance in achieving the integrated interpretations which are required for the consideration of development options. This paper reviews many of the applications of new and older technologies in reservoir description for appraisal projects, with the emphasis on maximising their impact by data integration.

INTRODUCTION

Before it is possible to review this subject we must be clear what the objectives of reservoir appraisal are and what motivations exist for establishing a geological model in this early phase of field maturity.

What is the role of geology in reservoir appraisal?

Clearly, when the objectives of the explorationist have been successfully accomplished a Discovery exists and is in need of appraisal. Many of the tools of exploration begin then to fall into disuse, other than for feeding back in-field experience to improve regional geological models; others take on new roles. During appraisal we address the questions, not of whether hydrocarbon-saturated reservoir rocks are present, but of how much recoverable hydrocarbon is present, in what spatial distributions and whether, and by what means, that recovery can be economically achieved. It is not simply a process of "booking" more hydrocarbons-in-place, at increasing levels of confidence, although that is part of the process too. More importantly it is a period that should be dedicated to investigating in three dimensions the continuity (or lack of it!) of porosity and permeability within reservoirs at all scales, and to obtaining a clear view of how this continuity will influence both static and dynamic fluid distributions.

Given these new problems to be addressed, it is hardly surprising that we make different demands of our geologists and of their models at this crucial stage in the evolution of a field. As a consequence, core analysis requirements and core usage becomes more specific to the new tasks, of what has come to be called "Production Geology". My own views on this subject have been formulated over many years of oil company and consultancy involvements, but I grew up in this industry in Shell, where many of the concepts and tenets of modern Production Geology were first formalised. As a result I believe very strongly that Production Geology is, and should be, a separate discipline within petroleum engineering, calling upon geological specialists but being uniquely qualified and placed to communicate effectively the impact of reservoir heterogeneities on reservoir behaviour to both engineers and management.

The commercial reality of our industry dictates that we take decisions of huge commercial consequence on the basis of grossly inadequate data sets. The recognition and minimisation of technical risk in a timely and cost effective fashion is a large part of what appraisal is all about, avoiding loss-making expenditure and accelerating profitable investment. As fewer large and obviously viable discoveries are made within a mature area such as the North Sea, the balance of risks is increasingly a fine one, demanding greater certainty in one's predictions for the development outcome. Indeed, as growth in discovered reserves becomes harder to achieve, another commercially compelling appraisal motivation arises, that of appreciating equity distributions and of maximising your share.

In each and every setting the geological model or interpretation is not an end in itself; it is only one part of the process of ensuring that correct and timely management, investment and design decisions are taken in order to maximise an oil company's profitability. A geological interpretation must, therefore, be "fit for the purpose" and must describe those things of which engineers, managers and commercial planners need to be aware, in a manner which is comprehensible to them. The interpretation is of little value unless its usefulness, applications, consequences and uncertainties can be effectively communicated to such non-geological personnel.

So, what should be the objectives of the Production Geologist during appraisal?

In my view the geological objectives of any appraisal exercise are:

i) to define the size, shape and primary compartmentation of a hydrocarbon-bearing geological structure, usually by a process of calibrating seismic interpretations with correlative geological well data, mostly in the form of logs and cores;

ii) to define the spatial distribution of the accumulated fluids and of the rock types and characteristics that control both static and dynamic hydrocarbon and water distributions (at a scale below that of primary reservoir compartmentation), usually by a process of interpreting log and core characteristics within a geological model that is based upon the recognition of the gross depositional environment and of the facies present.

Meeting these objectives should ensure that estimates of Hydrocarbons Initially In Place and of Ultimate Recovery (for any likely combination of field, reservoir or well performances) can be made, together with a realistic assessment of the levels and sources of uncertainties in those estimates (Risk Assessment).

Appraisal is a cyclical exercise of data acquisition, data and risk assessment, and data acquisition for risk reduction. Appraisal evolves in a field-specific fashion and no two appraisal programmes involve the same uncertainties and problems, or require the same data sets to resolve. In every case, however, the value of data is maximised by its early acquisition and by its integration with other data items. We must never lose sight of this need to integrate interpretations with non-geological data; I shall, therefore, refer to a range of not-so-geological aspects. Core is the point of contact of geological and non-geological data and is, therefore, the essential vehicle for true technical integration. In this short talk I shall touch on some of the commonest concerns in production geological interpretation and discuss some of the core-based tools available for their resolution.

ATTRIBUTES OF CORE AND CORE ANALYSIS DATA

So what are the characteristics of core data?

Core samples represent a very small volume of a succession of rocks rendering any data-set extracted from the core effectively uni-dimensional. Only rarely is it complete across the interval of interest, but in most cases it can be related in detail to the succession from which it was sampled. Missing section can arise for a number of reasons, from partial coring to a variety of loss of core recovery problems. However, core is unique in that it provides for investigation of phenomena well beyond the resolution and technology of modern log data and for the correlation of such phenomena to log data. The data that core can provide do, of course, include such classical geological information as: biostratigraphic data, structural, diagenetic and sedimentological features, and lithofacies, all of which may influence reservoir correlation. In addition, porosity and permeability and a wide variety of physical properties for petrophysical and reservoir engineering purposes are usually available. With such information porosity and permeability distributions and both potential permeability barriers and conduits can be defined and physically characterised, although only dynamic data can prove the lateral extent and correlative significance of these. Many differing kinds and scales of inhomogeneity can be described within the limitations of the areal significance of such data and numerous physical and chemical tests can be carried out on the same material. All of these data can then be related to the only source of continuous vertical well data we have, that of wireline logs.

It is one of the fundamental truths of nature (Murphy's Law) that the information we need most is that which we don't possess, and, as mentioned, core data inevitably suffers from this problem. Examples are the ultra-high permeability, uncemented sand streaks not recovered or that are unpluggable, the rubble that is the only indication of an intensely fractured or brecciated zone, and azimuthally-selective horizontal plugging where apparent dips are high and horizontal permeability is anisotropic, etc.. All these factors contribute to biasing and reducing the completeness and representativeness of our data set. It is, therefore, essential that we integrate core data with both logs and test data in order to appreciate just what we might have missed.

GEOLOGICAL CORE ANALYSIS IN APPRAISAL PROJECTS

So just what can core analysis achieve to assist in the calibration of the geological aspects of an interpretation during the appraisal process?

The phenomena that control static and dynamic fluid distributions in the sub-surface are all associated with pores, their size, connectivity and continuity, and their surface characteristics. Geological models must permit the prediction of the spatial distribution of such characteristics (porofacies) by recognising those that, within the context of the field and its potential recovery scheme, define significantly different rock/fluid interactions. Correlating these porofacies to rock types, the distributions of which can be predicted based upon geological principles, is one of the most significant contribution core data can make to the reservoir description process.

Structural definition and sedimentological insights obtained from FMS and dipmeter data must always be calibrated by core data, in order for any interpretations of these logs beyond core coverage in any well to be defensible. The automation of goniometric measurements has advanced significantly in recent years and the application of palaeomagnetic orientation techniques has led to improved confidence in core orientation measurements. Better understanding of facies and fractures, and their geometries, allows us to make better judgements about permeability averaging and better estimations of Kx, Ky and Kz anisotropy. However, our use of these data and our appreciation of the limitations and bias of our observations has not always advanced with the technology and I offer a word of caution in this regard to the many who are using these data today. For example, it is only too common for a modern fracture log of a core to identify, describe in great detail and measure the orientation of those fractures that only influence apparent matrix characteristics, the logger having missed (for a variety of very good reasons) the fractures controlling flow and effective matrix block size and geometry all together. These characteristics of a fractured reservoir are vital for development planning and recovery calculations but are rarely available from core alone; fortunately, later production logging will sometimes indicate their presence and spatial distributions may then be interpreted by reference to core data.

In reservoir description for petrophysical and reservoir engineering applications, it may not be sufficient to plot the logarithm of permeability against porosity, in order to derive transforms for individual litho-facies, as if these were petrophysically significant groupings. The basis of Leverett J-function normalisation of capillary pressure data, for example, draws our attention to the fact that other grouping criteria, not aimed at the prediction of the geometric average of permeability from log-derived porosity data, may be required to group petrophysically related rock types. Almost inevitably, given the intimate pore-scale relationships between capillary phenomena, electrical resistivity and permeation characteristics, such criteria will avoid groupings that cross a wide range of permeabilities. To be most usable such groupings should be independently correlated with log response characteristics. However, if they are not, their recognition in core will at least permit a better appreciation of the imprecision and range of uncertainty attaching to the log analysis and to the reservoir description that seeks to place such groupings together.

An appreciation of reservoir heterogeneity at all scales is required to put into context our geological and physical observations and test results. Indeed, artifact heterogeneity must also be identified to allow its presence to be compensated for or to influence the sample selection. The advent of minipermeametry and X-ray CT scanning has helped address these problems and their use has raised many new questions concerning the relevance of the scale of phenomena we observe in some petrophysical and reservoir engineering tests. Understanding the relationships of the various scales of heterogeneity present in core, within the depths of investigations of logging devices and within the reservoir at the scale of simulation grid blocks, is a major part of the Production Geologist's responsibility in any interpretative setting. Hopefully the development of cheaper and quicker scanning technologies, such as those based on electrical methods (reported in this forum last year), will widen the general access to such techniques.

NMR, NMR spectroscopy and NMR tomography techniques allow quick and accurate assessments of connected porosity, pore-size distributions, permeability and fluid distributions and can be used in many petrophysical and engineering tests to relate these and other rock/fluid data to the performance of the sample under test. Unfortunately, as with all scanning technologies, the results as yet do not provide the pore scale resolution we often would wish to gather.

The conventional tools of the sedimentologist can, however, provide an additional opportunity not only to investigate the mineralogies present in samples, but also their histories and influence on pores and pore characteristics. The value to petrophysicists and reservoir engineers of being made aware of the implications of such data is incalculable.

XRF/XRD and thermogravimetry techniques can identify and quantify the clays present in rocks, well beyond the limitations of optical techniques. Thin-section examination, SEM/EDX (Energy Dispersive X-ray) technologies and transmission electron microscopy (TEM) can then be used to obtain a spatial appreciation of their distribution. The recognition of both clay types and distributions are vital in understanding excess electrical conductivities in some rock types and in selecting suitable shaly sand models and parameters for log analysis in these. It also helps explain capillary pressure and relative permeability phenomena. Equally important is the recognition of what coring, plugging and cleaning methods may do to disrupt the clays found, in order that inappropriate techniques are not allowed to reduce the usefulness of the data obtained in the petrophysical core testing laboratory.

Such techniques, together with SEM cathodoluminescence, fluid inclusion analysis and isotopic analysis, can also assist in interpreting the physical environment and the timing and evolution of diagenetic events, which can and do influence the pore space, its connectivity and surface characteristics. Sampling techniques such as the laser micro-probe now permit individual cementation episodes to be carefully investigated. The relationships of cementation events and of heavy mineral etching and corrosion to the process of accumulating hydrocarbons may assist in understanding the fill history of the trap as well as those rock characteristics that control the accumulation process and which in turn may also influence the recovery process. This approach is particularly helpful where recent influences have obscured other lines of evidence and may allow the identification of cases where imbibition conditions have already become established in a field. These types of data are crucially important in that they may allow the prediction of lateral barriers and of laterally extensive vertical permeability barriers, even before dynamic data are available.

Petrography has much to offer the petrophysicist. In predicting excess electrical conductivity conditions, however, the insights of the petrographer as a means of identifying rock fabrics that may have naturally high brine saturated resistivities have been almost universally ignored for years. Tortuosity, vuggy porosity and low porosity co-ordination numbers are frequently to blame, but these may be subject to artifact improvements in connectivity as a result of the stress and temperature changes that occur during coring, core recovery and sample preparation. Petrographic methods, whilst they may not be able to identify artifacts, can at least alert the log and core analyst to such potential problems and indicate the possible pitfalls of conventional log and core analysis in rock types with such problematic fabrics.

The advent of computerised image analysis techniques has allowed us to gather a whole range of pore fabric data such as pore dimensions, pore geometry and surface roughness, from 2D images. It has also permitted some degree of automated mineral recognition, as we shall hear later. In addition, orthogonal image analysis techniques, stereoscopic surface image analysis and limited depth of investigation 3D laser techniques (3 - 5 pore diameters) have all taken the technology further. The current techniques permit prediction of some of the most important petrophysical parameters ($\emptyset$, k, Sw_{ir}, So_r and FRF), albeit at a significant cost and with some significant uncertainty.

In my view the limitations of 2D images and even of restricted 3D images are that they fail to resolve with any certainty the 3D pore connectivity or lack of it, or the influence of artifacts. Since these aspects will crucially impact upon many of the rock characteristics of interest to petrophysicists and reservoir engineers, there is a need to integrate image analysis data with petrophysical data before either set are interpreted. This is all too commonly ignored at present. However, used in conjunction with mercury-vacuum porosimetry, particularly if both directional and continuous injection methods are employed, and with electrical conductivity testing, the usefulness of image analytical techniques is perhaps yet to be realised. The objective should not perhaps be limited to the prediction of permeability etc, but should be the fundamental understanding of resistivity, capillarity, permeability and relative permeability phenomena at the pore scale.

In addition to the physical description of pore surfaces by image analysis, pore surfaces can be further investigated by X-ray photo-electron spectroscopy and by secondary ion mass spectrometry. These techniques allow the quantification of the amounts of carbon and nitrogen at the surface of the inorganic substrate which can be correlated to wettability determinations made by more conventional methods. Thus a qualitative expectation of wettability influenced behaviour can be obtained.

CONCLUSIONS

So what else can we learn from core which may be of use to the geological interpretation during appraisal?

The final lessons that all core has to give us are possibly also those we should remember before starting to use core or core data. These lessons are to do with uncertainty. We must constantly ask ourselves:

a) Is the core all there is to know about this interval?
b) Is it misleading or potentially misleading me?
c) What have I assumed in obtaining and using these data?
d) Were the samples properly selected for the purpose of describing the reservoir and the reservoir process under investigation?
e) Are the uses or applications of these data restricted by considerations of scaling effects?
f) Were the samples affected by outside influences to do with the coring/plugging/cleaning process?
g) What are the objectives of my reservoir description?
h) Am I meeting these (or my own) needs?

Pre-study screening, testing and detailed core X-ray CT scans (and others under development) may help us to avoid many of the problems of inappropriate sampling and sample handling, of hidden artifact effects and of failing to recognise unavoidable sampling bias. The technologies I have described can then be applied in an integrated interpretation in the full understanding of their limitations and applicability to your project. However, only the about, avoiding loss-making expenditure and accelerating profitable investment. As fewer large and obviously viable discoveries are made within a mature area such as the North Sea, the balance of risks is increasingly a fine one, demanding greater certainty in one's predictions for the development outcome. Indeed, as growth in discovered reserves becomes harder to achieve, another commercially compelling appraisal motivation arises, that of appreciating equity distributions and of maximising your share.

In each and every setting the geological model or interpretation is not an end in itself; it is only one part of the process of ensuring that correct and timely management, investment and design decisions are taken in order to maximise an oil company's profitability. Therefore, a geological interpretation must be "fit for the purpose" and must describe those things of which engineers, managers and commercial planners need to be aware, in a manner which is comprehensible to them. The interpretation is of little value unless its usefulness, applications, consequences and uncertainties can be effectively communicated to such non-geological personnel.

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ii) to define the spatial distribution of the accumulated fluids and of the rock types and characteristics that control both static and dynamic hydrocarbon and water distributions (at a scale below that of primary reservoir compartmentation), usually by a process of painstakingly truthful answering of my last two questions, (g) and (h), will ensure that we maximise the use of the core to the benefit of the appraisal project in which we are involved.