FLUID FLOW BEHAVIOUR OF FAULTS: CRITICAL VARIABLES, UNCERTAINTY LIMITS AND PREDICTION

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Introduction

The primary factors that influence fluid flow behaviour of faults in hydrocarbon reservoirs have been identified by integration of seismic, well tests and well logs, as well as core data during recent years. However, prediction is still limited by uncertainties associated with these key variables. This paper reviews the current understanding of the primary factors controlling fault behaviour and quantifies the impact of related uncertainties. The use of databases and 'advisor systems' to assess the current limits to prediction and examples to illustrate the importance of integrated uncertainty analysis are presented.

Key Variables and Uncertainties

There are four aspects of fault behaviour and flow where analyses of the uncertainties are critical to either the evaluation and risking of fault sealing of hydrocarbons during exploration, and modelling fluid flow for field development and production planning.

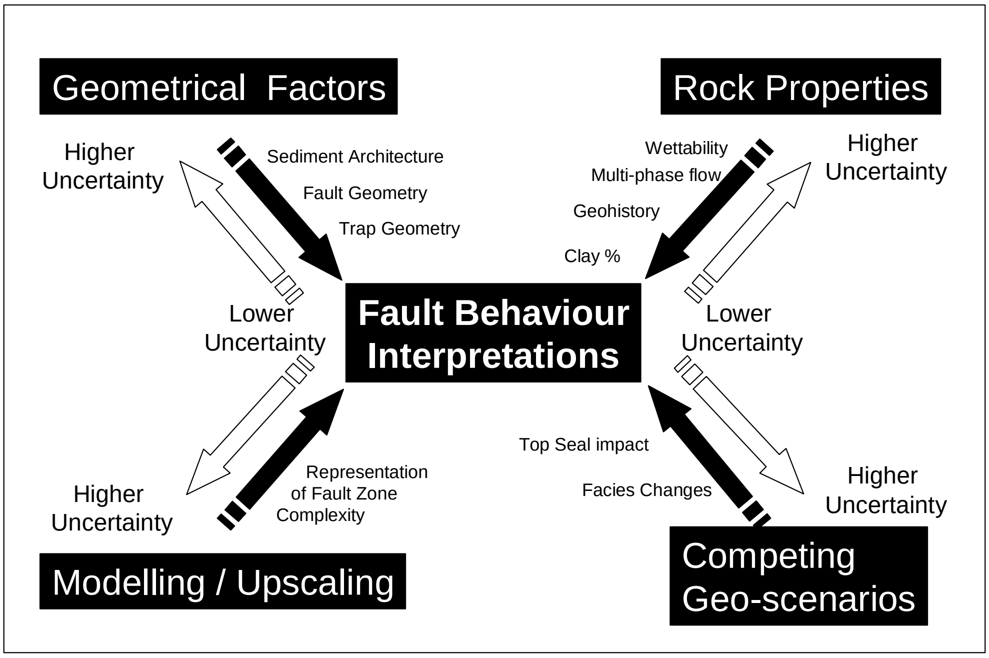
These are reviewed separately before the integrated impact of these uncertainties is discussed.

1 Geometric Uncertainties

<u>a) Sedimentary Architectures.</u> Variation in the thickness, lithology, stacking sequences and 3D geometry of sedimentary units involved in faulting exert a fundamental control on fault flow behaviour (these determine the juxtaposition of low permeability units with reservoir units as well as the fault rock distribution and the redistribution patterns of clays). Well data provides geostatistical data on stacking sequences and their variability, which can be used to construct pseudo-stratigraphic columns that capture the possible variations and uncertainties. This allows the impact of probability-based multi-realisations of different stacking on faulting to be assessed. Examples of the value of this approach for assessing the integrity of fault bound traps will be presented.

<u>b) Fault Zone Geometries</u>. Fault zone architectures determine the distribution of 3D juxtaposition patterns, whilst the operating deformation processes within the fault zone control the type and continuity of fault rocks faults present. Two fault zone geometrical uncertainties can contribute errors to fault analysis; i) the ability of seismic data to accurately define fault throw and, ii) the possible 3D variation in sub-seismic fault architecture. We have used structural logging of cores and outcrop analysis to evaluate fault continuity and population characteristics to build 3D models of complex fault zones for assessing fault flow behaviour.

<u>c) Trap Geometries</u> The uncertainty associated with trap definition and geometry (crestal locations, spill point depths and locations) are critical to assessing fault behaviour. Exclusion of these uncertainties can lead to unrealistic interpretations.



2 Fault Rock Property Uncertainties

Fault rock properties, such as permeability, threshold pressures, and strength are recognised as being fundamental to an understanding of fault flow behaviour. The critical influence of fault rock clay content on permeability has been noted by many workers, but the uncertainties associated with its prediction (e.g. from V-shale, V clay logs) is often not included in seal analysis. We will illustrate the importance of this uncertainty and the value of new quantitative X-Ray diffraction techniques for validating V-clay predictions. In addition, the uncertainties of predicting clay contents in fault rocks, (e.g. from SGR, Shale Gouge Ratio) is illustrated by detailed studies of natural faults where both host and fault rock clay contents can be monitored. This highlights a need to use clay prediction algorithms that allow the impact of the uncertainties in the range of faulting processes, the growth of the fault zone, the influence of local lithologies and along/across fault flow to be included. The use of a new Effective Shale Gouge Ratio (ESGR) algorithm that provides such a base is reviewed.

The importance of the Geohistory (temperature, effective stress history) on the evolution of fault rock properties can override the impact of the clay content and the integration of burial histories with fault activity is an important component of fault property prediction.

Where faults in siliciclastic sediments are buried and/or deformed at temperatures above ~90^{o}C, the rate quartz cementation and dissolution is significantly increased and can create very low permeability fault rocks. Examples from the Rotliegendes of the Southern North Sea and the Brent of the Northern North Sea are used to illustrate the geohistory controls.

Fault rock permeability, combined with an estimate of fault rock thickness, usually provides a transmissibility multiplier for input into reservoir flow simulations. However, the uncertainties associated with determining the hydrocarbon saturation levels, the multi-phase flow behaviour and the wettability of fault rocks can have a large impact on the fault behaviour. These critical parameters are usually excluded from fault analysis but represent a critical area for future work. A striking example of this is the possibility that kaolin, the main clay mineral present in many fault rocks from the Brent Province of the North Sea is often preferentially oil-wet. This implies that such faults should not act as effective seals over geological timescales.

3 Modelling / Upscaling Uncertainties

An important constraint on the prediction of fault behaviour is the ability of modelling packages to capture the complexity of the geological system under investigation. Upscaling into these models needs to be effective and efficient in the level of detail included and excluded. Some of the largest uncertainties in upscaled models involving faults are; the location and size of 'leaky' windows on the fault planes and the probability distributions of representative values for the fault rock properties, such as permeability, capillary entry pressures and strength. We will review a series of new numerical models aimed at assessing the upscaling properties of complex fault zones. These models allow the assessment of flow in zones containing $>10^5$ faults with defined population and clustering characteristics. The contribution of the small faults in the damage zones and the main slip plane to the upscaled bulk permeability of the fault zone for varying throws and different fault to matrix permeability ratios will be reviewed to demonstrate how the uncertainty in the fault zone properties impacts on flow predictions. Of particular importance is the impact of capillary effects where the threshold entry pressure of the fault rocks are not exceeded and faults may have high water saturation levels. This means that fault rocks with the same threshold pressures can act as an effective seal near the hydrocarbon water interface, but allow flow and act as flow retarders at higher structural levels. Reservoir models that are based only on permeability variations and ignore the capillary effects will overestimate the communication.

4 Competing Geo-Scenario Uncertainties

Faults represent only one component of the behaviour of any hydrocarbon flow system under consideration. Assuming an overriding fault control may divert attention from the possibility of top seal or sedimentary facies influences. The probability that other competing flow-controlling scenarios, or combinations of scenarios, operate should be incorporated into the analysis. Examples of these issues and the impact on the calibration of fault behaviour will be presented

Integration.

The prediction of fault behaviour clearly involves the evaluation of a mutli-component system where it is unusual for the variables to be defined in detail. Definition of uncertainty ranges, uncertainty distribution types and correlated versus uncorrelated uncertainties for different geo-settings and geohistories is the key to robust and realistic prediction. Interpretation of fault behaviour requires; a) the construction of databases on the key properties, b) the generation of flexible 'advisor systems' that highlight the primary uncertainties, allow identification of likely outcomes, provide probability estimates and quantify the impact of the uncertainties, and c) the calibration of behaviours from the best constrained examples. We will illustrate the use of such databases and 'advisors' and highlight the current limitations of fault behaviour interpretations with examples of column height prediction in prospects and of production in compartmentalised reservoirs.