Fault Seal Analysis: Integration of Empirical and Deterministic Approaches

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Over the years, a large number of methodologies have been proposed to estimate the sealing capacity of faults. These methodologies can be divided into those that are empirical (evidence-based methods) and those that are deterministic (i.e. forward models). Forward models of fault sealing are based on measurements of fault flow properties (e.g. permeabilities)) and structures (e.g. fault population statistics). Evidence-based approaches are those in which empirical relationships are established between sealing capacity and factors such as fault offset, clay content etc. A problem with the deterministic approach is that fault zones are complex and it is uncertain that we fully understand all of the physical processes that affect flow within and around fault zones. For example, uncertainties exist regarding the lateral continuity of fault rocks, their relative permeability etc. A problem with an evidence-based approach is that interpretation of subsurface data is often non-unique and therefore it is often not possible to determine the sealing capacity of faults based on static and dynamic data. Consequently, empirical databases of fault sealing capacity are often populated with misleading data. The most successful fault seal analyses combine deterministic and empirical approaches. Interpretations of static and dynamic data are often improved by having a constrained fault zone model. On the other hand, forward models of fault-related fluid flow are improved if they are calibrated using static and dynamic data. Examples will be given showing the benefit of integrating empirical and deterministic fault seal methodologies.

Hydrocarbon Column Height Analysis from the Gulf of Mexico Basin: An Integration of Quantitative Seal Analyses and Basin Evolution

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Basins subjected to periods of rapid sedimentation are characterized by a wide range of temperature and pressure histories. Resultant seal rock reflects this range of geo-histories in their compaction state, producing a variety of pore throat radii, which is in turn responsible for the amount of hydrocarbon column height a seal unit may contain. Quantitative analysis of seal rock has been combined with detailed geo-history data to more accurately define these controls on hydrocarbon column height.

The Gulf of Mexico seal project targeted shale samples from regionally extensive maximum flooding surfaces known to trap significant volumes of hydrocarbon. These samples were analyzed using conventional techniques (x-ray diffraction, scanning electron microscopy and capillary pressure analysis) to determine which are representative of seal rock and their physical characteristics. These results were then combined with basin models to provide pressure and temperature histories for the seal rock.

Quantitative shale data and compaction trends were then integrated to define predictive seal capacity trends for the Gulf of Mexico. The trends were calibrated using actual column height data from hydrocarbon accumulations. Without accurate definition and integration of regional pressure-temperature regimes these present day hydrocarbon columns could not be explained. This project culminated in a predictive seal capacity and column height tool, whereby a geo-history, clay content and burial depth was used to define a likely range of hydrocarbon columns for a particular opportunity.

The Role of Hysteretic Two-phase Flow Processes During Capillary Leakage

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Present-day hydrocarbon migration simulators treat capillary leakage as a symmetric process, that is initiation and end of leakage occur at the same hydrocarbon column height and the relationship between column height and leakage rate (or effective permeability to the leaking phase) is the same during drainage and imbibition. In exploration terms, drainage corresponds to both trap fill and establishment of leakage pathways through capillary seals while imbibition corresponds to both trap emptying and successive closure of leakage pathways. However, two-phase and three-phase fluid flow in porous media is hysteretic. Hydrocarbon pressure in a trap has to overcome a critical pressure, the breakthrough pressure P_{br}, to initiate capillary leakage. Experiments in a glass bead trap model show that a different critical pressure, the snap-off pressure P_{sn}, exists at which leakage will stop. Results from the trap model experiment yield values of approximately 0.35 for the ratio P_{sn}/ P_{br}. This indicates that traps which undergo capillary leakage will retain hydrocarbon columns of approximately 35% of the breakthrough column height if the seal remains water-wet during leakage. For identical hydrocarbon column heights, effective permeability to oil or gas (and thus leakage rates) will be higher during imbibition than during drainage. This impacts on the steady-state hydrocarbon column height for a given inflow rate. Application of available capillary pressure data for seal material while neglecting hysteretic processes results in predictions with too high leakage rates and too low estimates of the possible static and dynamic hydrocarbon column height in a trap. This work was carried out at SINTEF Petroleum Research, Trondheim, Norway.

Dynamic Analysis of Imperfect Seals

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Many of the techniques commonly used to evaluate both fault and top seal capacity are static in nature, based primarily on the definition of threshold capillary entry pressure. Measured capillary pressure data suggest that extremely large column heights are theoretically possible behind fine-grained mudstones and shale smears, leading to the idea of the “perfect seal”. However, the huge volumes of petroleum which have migrated across thick mudstones in many petroleum

systems testify to the ability of mudstones to leak petroleum on relatively short geological timescales. Furthermore, diverse evidence suggests that at least when petroleum leaks into seals, the wetting state of the pore system changes from water-wet to oil-wet. In this case, there is no capillary entry pressure for the petroleum to overcome; seals are now imperfect and charge rate, seal thickness, relative permeability and fluid viscosity are controlling factors on accumulation and leakage. Simple charge – leakage models show that substantial petroleum columns are still possible in many (but by no means all) cases, as long as petroleum continues to be supplied from an active source. The models also show (a) how gas and oil can be effectively segregated by migration through low permeability units and (b) that if charge ceases, columns will be lost on short geological timescales unless they are held behind thick seals with very low permeabilities. Our models and data show that a full seal analysis should include dynamic seal properties as well as the commonly applied static properties.

Impact of Realistic Shale Properties on Exploration-Scale Vertical Migration Modeling

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Basin models incorporate information from other disciplines: structural and seismic interpretation for geometry, log analysis for lithologies, sequence stratigraphy for depositional framework, biostratigraphy for ages, and geochemistry for source rock properties, thermal calibration, and migration indicators.

Seal behavior has historically been treated differently: instead of using measured values as model inputs, results are often compared after the fact to observed seal properties. Default shales were designed to be excellent top seals and to hold large hydrocarbon columns. Early models for deep-water prospects in West Africa used shales mixed with silts in a high-resolution stratigraphic framework to predict hydrocarbon distribution. This empirical method was not satisfactory, because upward migration was not as great as observed in on-structure wells. Variability of results occurred due to differing modeler skills regarding parameter changes.

The lack of fit required Chevron to develop a methodology that incorporates measured shale/seal properties. Analyses of marine shales reveal six distinct seal lithologies, based on fabric and textural variations. Each type has a different compaction rate, described by porosity-depth and porosity-effective stress relationships, porosity versus permeability, and capillary entry pressure distributions. A regional database relates mudstone properties to stratigraphic position and depositional setting. Data relating interfacial tension to composition, temperature and pressure are also captured.

Subsequent simulations fit observation better and indicate that shale properties play an important role in controlling the distribution of hydrocarbons and composition. The use of basin-specific lithologic parameters, upscaled for stratigraphic variation, improves the assessment of migration, column heights, volumes, and pressure.

Predicting Fault and Top Seal Behaviour: Examples of Static and Dynamic Sealing From The Exploration to The Production Phase

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Different techniques are required to predict fault and top seal behaviour during the hydrocarbon exploration and the production phase. We show examples from different geological settings on how to predict seal behaviour during the different phases of the HC life cycle.

In the deep waters offshore NW Borneo, compressional deformation has resulted in a fold and thrust belt stretching more than 800 km along the southern margin of the NW Borneo Basin. Recent drilling results prove the presence of considerable HC amounts in the basin. Typical trapping geometries occur in elongated faulted hanging wall anticlines of buried folds and ridges. Experience has shown that hydrocarbon columns may be partially lost as a result of hydraulic leakage of the top seal caused by a combination of overpressure and recent uplift. A significant up-side potential of this trap style relies on the seal capacity of the fold propagaton faults between hanging wall and footwall. It appears that fault seal concepts derived from extensional basins also apply to compressional style fold and thrust belts.

Compartmentalisation of a field by faults in different blocks can seriously hamper the field's production performance. A well drilled into a compartmentalised field can only drain part of the field's hydrocarbons in an effective way on the production time scale. Faults can act as baffles or barriers to flow and necessitate drilling more wells to develop the field. On of the challenges in field development is how to realistically translate geological data from thin sections, core plugs, outcrops and seismic into parameter ranges that reservoir engineers can apply as fault seal multipliers in dynamic modelling. Several joined industry and academic efforts have been made to better constrain the geological fault parameters and we demonstrate how these have enabled us to better predict HC flow behaviour during production.

A Comparison between Shale Gouge Ratio (SGR) and Stochastic-JuxtapositionTechniques for Fault Seal

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Traditionally the analysis of fault seal has been purely deterministic or a combination of deterministic and stochastic methods.

In a deterministic model, prediction of the locations of reservoir overlaps is made from the static model of the reservoir horizon and fault geometry. The principal aim is to map faulted reservoir overlaps and determine their sealing character. This is usually performed using a predictive algorithm such as the shale gouge ratio (SGR) that predicts the sealing capacity of the fault rock from the shale content of the formations that have moved past that point on the fault.

Stochastic models offer the possibility to test multiple realisations of the juxtapositions at the fault. Stochastic models capture the uncertainty in the position of the reservoir at the fault by allowing multiple realisations of stacking geometries, where the principal assumption is that these stacked reservoir zones are laterally continuous covering the entire likely fill

area. It is further assumed that all sand-sand connections are likely to be leaky, i.e. that fault-rock does not contribute to fault seal.
Do these conceptually different approaches lead to different predictions of trap fill? Comparison of the predictions between the two methods shows a surprising degree of conformity. The sand-shale proportions in the stochastic model mimic the role of Vshale input in the deterministic SGR method. This presentation covers published case studies, and examines benefits and pitfalls of both methods.

Conceptual Constraints on Fault Seal Potential of Contractional Faults

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Most of the published work to date on the role of faults as seals/baffles for hydrocarbon trapping/production has considered extensional faults. There are reasons to believe that fault seal process may be different in reverse and thrust faults. In this paper we will consider the theoretical differences between normal and reverse faults, and how these differences may impact on the sealing or non-sealing nature of reverse faults in clastic sediments.
Normal faults are usually formed when the maximum principal stress is orthogonal to bedding, with seismic-scale fault zones often exhibiting widths in the 10's of metres and fault spacing over 100's of metres. In many cases normal faults are integral in the trapping of the hydrocarbons forming the “4th side” of 3 way dip closures.
Contractional faults on the other hand are formed in tectonic regimes where the maximum and intermediate principal stresses are frequently horizontal and sub-parallel to bedding. It is very common for displacement to be accommodated by bedding-parallel shear, with large faults kilometres apart forming four-way closures. Reverse and thrust faults often have very narrow fault zones despite the large displacements.
In this paper we contrast and compare the role of faulting styles on fault seal potential. To study the potential difference forward kinematic models of inter-bedded clastic sediments will be compared with outcrop analogues to help compare the evolution of fault rocks through displacement in both styles of faulting.

Assessment of Prospect Compartmentalization and its Impact Upon Valuing Exploration Opportunities

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Fault seal analysis as applied to exploration has traditionally been viewed as a tool to quantify the trap risk of fault bounded structures. Any complexity due to intra-reservoir faulting is often dealt with post discovery or even post appraisal after surprises during early production. This talk will illustrate a workflow for the assessment of intra-reservoir seal risk remote from well control and will discuss the impacts on value. With modern 3D seismic data a significant proportion of the intra-prospect faults can be interpreted producing a fault framework of the main target. The fault properties applied to the framework will be dependant upon the stratigraphic variation, geohistory and the rheology of the lithologies at the time of faulting. Fault zone clay contents obtained from a range of prospect specific depositional models integrated with the fault framework and a fault zone clay percentage estimation technique. The workflow provides a range of sub-surface models that can be developed into initial fluid flow models to test the impact of production. In complexly faulted traps it maybe necessary to discuss sensitivities in sub-areas and scale the effects to the prospect as a whole. The model can be used to assess production rates and ultimate recovery with a given well drilling program. Hypothetical well placements, numbers of production wells and aquifer assumptions can be varied to optimize the model. This workflow allows rapid assessment of the value of exploration prospects with a high probability of compartmentalization and informed decisions to be taken at an early stage.

Detecting and Evaluating Hydrodynamic Sealing by Faults

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Hydrodynamic sealing may cause petroleum-water contact (PWC) variations across minor faults that do not significantly compartmentalize reservoir production. Fault hydrodynamic sealing is analyzed as an extension of classical hydrodynamic sealing theory. Hydrodynamically-sealed faults show two identifying characteristics: (1) water pressure difference across the fault (after correction for the weight of the water), and (2) tilted petroleum-water contacts. Maximum height of pure hydrodynamically sealed petroleum columns can be predicted from the cross-fault pressure difference. If the petroleum accumulation extends across the barrier, the pressures form a single pressure-depth trend, but the PWC will have different elevations. If petroleum pressures on different sides of the barrier fall on different trends, then another mechanism must be active in addition to hydrodynamic sealing, such as membrane sealing or hydraulic-resistance sealing. The relative contribution of hydrodynamic sealing can be interpreted from pressure differences, PWC differences, and filling history. These data also help distinguish membrane sealing from hydraulic-resistance sealing.
The potentiometric gradient in hydrodynamically trapped accumulations is calculated from the PWC dip and fluid densities. Hydrologically averaged permeability is interpreted from the cross-fault pressure change, reservoir potentiometric gradient, and assumed fault width. The membrane sealing capacity of the fault is estimated from average permeability using empirical trends.
In four field examples, the theoretical relations successfully predicted properties of the accumulation or the barrier. In some cases, hydrodynamic theory guided recognition of tilted fluid contacts that were previously unrecognized. These case studies substantiate the importance of hydrodynamic sealing by faults in hydrodynamic regimes.