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Modeling of Shale Smear Parameters, Fault Seal Potential, and Fault Rock Permeability

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Introduction

Since faults commonly occur in sedimentary basins and are associated with many types of structural traps, an assessment of sealing efficiency or flow capability of faults provides critical information for petroleum geologists and reservoir engineers. This problem, which has become a focus of intense research over the past decade (e.g., Knipe, 1992), is on top of the agenda for petroleum geology developments in exploration and production (First Break, 2001). The hydraulic properties of faults have different implications for various elements of petroleum system (from source to trap). On the trap scale and over geological time, the lateral sealing efficiency of faults is of utmost importance; while for reservoir simulation and over production time scale, the permeability of fault rock is most necessary (Figure 1). At JNOC-TRC, we have developed PC-based software (FAULTAP written in C++ language) for fault sealing assessment in a practical way, and based on the current knowledge of fault architecture and faulting processes. This paper describes some the current issues in fault sealing assessment based on our experiences in FAULTAP and our attempts to integrate the shale smear parameters with fault stress analysis and fault rock permeability.

FAULTAP

The input data for FAULTAP include (1) fault traces and seismic horizons from interpreted seismic sections (2D or 3D), which can be imported from Landmark or Charisma in the form of an ASCII file; (2) well data for characterizing the lithology, rock density, porosity, subsurface fluid saturation, and RFT pressure data; and (3) geological data to constrain the stratigraphy and well data. The first function of the software is to reconstruct fault geometry and present the geometric parameters in the form of data-tables and visual profiles. Visualization of model data can be made for 2D fault cross-sections, along strike fault surfaces, and Allan-type juxtaposition diagrams. Currently, the software is applicable to sandstone reservoirs dismembered by normal faults. Tectonic settings of the applications include rift-basin or back-arc basin extensional faults, continental margin growth faults, negative flower structures, and collapsed anticlines.

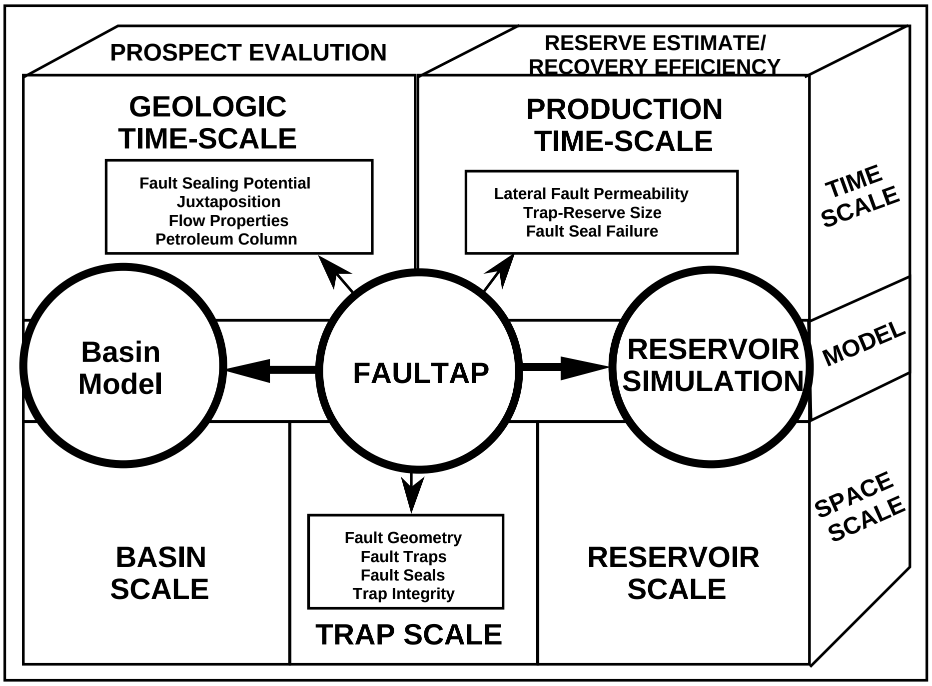

Figure 1. The scope of fault sealing model in the petroleum E&P, and its relation to basin modelling and reservoir simulation.

Shale Smear Parameters

Shale smear along fault planes, although long recognized both in laboratory experiment and filed observations (e.g., Weber et al., 1978), has become a popular tool for fault sealing assessment in recent years (notably in the FAPS software) mainly because it can easily be quantified from seismic and log data. Despite their highly simplified assumptions, the shale smear parameters have been successfully applied to various oil fields. These parameters can be categorized into two groups:

(A) Those accounting for the smearing potential along the whole fault offset: Shale Smear Factor (Lindsay et al., 1993; Gibson, 1994; or Shale Smear Ratio of Younes and Aydin, 1997), and Smear Gouge Ratio (Skerlec, 1999); and

(B) Those accounting for individual points on the fault offset plane: Clay Smear Potential (Bouvier et al., 1989; Fulljames et al., 1996; or Smear Factor of Yielding et al., 1997); Shale Gouge Ratio, and Gouge Ratio (Yielding et al., 1997; Fristad et al., 1997).

FAULTAP utilizes all these parameters as it is important to cross-check the consistency of model data obtained from independent approaches and calibrations. For example, Shale Smear Factor (SSF) calibrated from oil fields has also been empirically derived in the field (Lindsay et al., 1993, and our observations). Furthermore, experiments by Takahashi (unpublished data) show an increase in the fault permeability with increased SSF values. Gouge Ratio, a different shale smear parameter, is actually a theoretical “Clay Content Ratio” that offers a proxy and relative measure of fault rock.

Given that shale smearing is dependent upon ductility of shale rock (for which there are little quantitative data), the shale smear parameters are applicable only to sandstone-shale sequence deformed by syndepositional faults, for which the available calibrated data are applicable.

The shale smear parameters depend upon the thickness of source shale layers, the clay fraction of slipped layers, distance from the source shale layers, and the amount of fault throw. In addition to these, we consider the difference between the timing of shale smearing on target fault smears and their present-day depth levels, and thus integrate the shale smear parameters with their depth profile and contemporary fault stress. In this way, the fault smear targets at deeper levels (greater overburden) or greater normal stress acting upon them will have relatively better sealing potential (lower permeability); therefore:

Shale Gouge Ratio times Depth and normalized to the scale of 0-1.

And:

Normal Stress times (100/Vshale of footwall ^ a) times (100/Vshale of hangingwall ^ a), where a is a coefficient.

Fault Seal Potential

Lateral sealing efficiency of faults expressed in terms of capillary pressure is a critical parameter in fault sealing assessment. Ideally, fault rock samples can be measured by the mercury injection method to obtain displacement (capillary) pressure data. In the absence of such data, the empirical relationship between clay content in the fault gouge and capillary pressure (Gibson, 1998) offers a promising tool.

Geologic and seismic evidence suggest that fault zones are associated with significant channeling of subsurface fluids. Faults in their active stages seem to be conductive of subsurface fluids irrespective of any fault-sealing factor that may operate. This implies that any fault-sealing factor needs to be integrated with the likelihood of fault reactivation (seal breaching). Contemporary stress data of various parts of a given fault may be plotted on Griffith-Mohr diagram, and relative failure probability of points on the fault surface can then obtained. Next, a fault seal probability is derived from an integration of fault failure (hence seal failure) and fault sealing factor; e.g., Shale Gouge Ratio x (1 – Failure Probability) on the scale of 0-1.

Fault Rock Permeability

Quantitative knowledge of fault-rock permeability comes from rock mechanical experiments and field sample measurements. Both the experimental and empirical approaches have their own merits and limitations; they are thus complementary at least in so far as they yield consistent results in qualitative terms.
There are several methods to quantify fault rock permeability, such as (1) the experimentally-derived relationships between permeability changes associated with strain (e.g., Wong and Zhu, 1999); (2) empirical relationship between the Shale Gouge Ratio of fault rock and its permeability (Manzocchi et al., 1999);and (3) empirical relationship between host rock and fault rock permeability (e.g., Fisher and Knipe, 1998).
We constructed a database for sandstones comparing the permeability of host (reservoir) rock and fault rock, both measured perpendicular to fault plane. The database includes mechanical cataclasite, cemented cataclasite, impure sandstone, and deformation band zone categories. In all these, the fault rock permeability generally shows 2 to 3 orders lower permeability in comparison with the host rock. Moreover, the permeability decrease ratio is proportionally related to the host rock permeability: Sandstones with higher permeability values also show higher permeability decrease ratios for their fault rocks.
In contrast to sandstones, our data indicate that fault breccia rocks in carbonates do not show reduced permeability.

Concluding Remarks

Factors involved in the petrophysical properties and flow directions include basin tectonics, fault geometry, fault mode (its timing and activity), fault juxtaposition of sedimentary layers, fault stress field, cataclasis (both grain size reduction and porosity loss due to tectonic compaction), shale smear in sandstone-shale sequences, fault diagenesis (precipitation seal), and fault damage zone (open-mode fractures versus mineral-filled or mechanically-healed fractures bordering the fault). Understanding each of these processes and factors needs to be followed up by quantifying the relations among them. In spite of strides taken in fault sealing assessment over the past decade, the inherent complexity of faults poses major challenges to experimentalists, geologists, and modellers for years to come. For practical purposes in petroleum exploration and production, fault geometric reconstruction, juxtaposition, shale smearing parameters, fault rock characterization, and fault stress regime currently provide some important tools for fault sealing assessment.

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