Fluid Flow in Brittle and Ductile Seals: Geomechanical Aspects of Dilatant Fracturing and Fracture Resealing in Top Seals and Low Permeability Reservoirs, with Examples from the Middle East

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Abstract

If the effective stress in a seal satisfies the condition Pf = σ3 + T, extension fractures will form and allow fluids to escape. In this equation, Pf is the fluid pressure, σ3 the minimum principle (total) stress and T the tensile strength of the seal. This is common in highly overpressured systems, where interaction of the in situ stress field and local variations in fluid pressure determine retention. The key parameter to consider here is the retain capacity, the difference between pore pressure and minimum total stress). Prospects with a low retain capacity have a high chance of seal failure. Conditions for the transition from extension or shear fractures can be approximated using a modified Mohr-Coulomb failure criterion, expressed as a function of overpressure ratio λ vs. depth.

In normally pressured systems, permeable shear fractures may still form, and remain open. This is where the rock's ductility, as measured by volume changes during deformation, is the key parameter. A ductile shale is able to undergo plastic deformation without increasing its permeability, whereas a brittle one will increase its permeability when deformed. The main controls on dilatancy during shear failure is a function of (i) mechanical properties of the rock (ii) effective stress tensor and (iii) geometry of the shear zone. At a given effective pressure a stronger (overconsolidated or cemented) rock is more likely to dilate than a weaker one.

With increasing strain, deformation is concentrated in a progressively widening zone, in which the early rock fabric is strongly reworked and transformed into a fault gouge. Under these conditions, the gouge is in critical state, where further deformation can be accommodated without a change in porosity or shear stress and the leaky seal will be resealed by deformation. Another resealing mechanism is precipitation of veins from hydrothermal fluids which are common in shales.

Evaluation strategies to predicting embrittlement of shale topseals can be based on (i) overconsolidation ratio; (ii) degree of cementation, as expressed in the rock's unconfined compressive strength which can be estimated using correlations with acoustic velocities and mineralogy; and (iii) strain history. Criteria for embrittlement in shales are conservative, i.e. a seal classified as brittle may still act as a good seal, because strain may not be high enough to cause dilatancy, dilatant fractures may not transect the whole seal, and initially dilatant fractures may be reworked into a sealing fault gouge.

I illustrate these principles with examples from the Middle East.

In the past decade, the development of unconventional reservoirs and the assurance of subsurface integrity have provided a wealth of new data and insights in seal embrittlement, and lead to improvements in our ability to evaluate seals in undrilled prospects. Improved geomechanical models and multivariate correlations to predict rock properties are combined with microstructural studies using ion beam polishing and electron microscopy (BIB-SEM) to much improve our understanding in this field. I review these new developments and technologies and discuss opportunities for further development.