SEALS – IT'S ALL GEOMECHANICS!

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Summary: The creation and operation of seals represent fundamental issues in basin evolution and in the production of petroleum reservoirs. The thesis of this paper is that understanding the creation, and then predicting the performance, of seals is dependent on adopting a geomechanical context. In particular, the poro-visco-plastic (PVP) material description serves to explain the creation of seals as a normal, "expected" consequence of the compaction of heterogeneous successions of sediments. PVP also explains the ways that seals can fail, allowing a prediction of the hydrocarbon-retention capacity of the sealing lithology. These predictions occur within a single geomechanical paradigm, and one that can account for diagenetic and other alterations.

The PVP Model: The PVP material description is built on the back of abundant previous work. Much of that work consists of laboratory investigations of rock mechanics behaviours, and the syntheses of deformational responses that are derived from those test programmes. Of course, there is an ancestry of theoretical mechanics, and a fair dose of soil mechanics also enters the picture. Observations of natural deformations have helped to shape the way that PVP can be used to interpret and predict geomechanical processes.

So what is PVP? It is a conceptual description of the way that porous rock materials deform. Simply put, it describes the "conditions" (in porosity-stress space) at which permanent deformation (yielding) occurs, AND the details of that deformation (e.g. volumetric strain, strain components), including whether there is work-hardening or work-softening. PVP is applicable to situations such as top-seal and fault-seal analysis. In PVP, porosity (or its cousin, the void ratio) is considered to be a state variable – which means that the current value of the porosity determines what happens next. The "visco" term means that there is a rate dependence to the response (apologies to Newton for generalising "his" term). And both of these aspects are used to enhance long-standing ideas about permanent (inelastic) rock deformation derived from plasticity theory. In reality, PVP is defined in a high-dimension space, but that does not lend itself to visualisation. To simplify the presentation of the concept, PVP is typically shown as a yield surface (identifying conditions of yielding) in a three-parameter space, with one axis being the mean effective stress, another being a "differential stress" (e.g. square root of J_2), and the last being porosity. The state of a material is defined as a single point in this space. Other spaces can represent the state of strain or other mechanical characteristics.

What Is A Seal?: This is a very awkward question to answer with universal clarity. However, it is necessary to adopt a description of "seals" that is based on (petro)physical properties, to allow us to develop an explanation of the creation and operation of seals as a function of the physical processes that occur in basins and reservoirs. In this context, a seal can be defined as a layer/unit of rock that is capable of inhibiting the movement of a fluid phase (note that a seal can exist, but not be apparent, if there is no gradient in potential energy of the fluid). In a single-phase case (which might be of interest for the retention of overpressure), it is only the intrinsic permeability that matters (obviously, the value must be very low, or certainly low enough that the dissipation of energy is slower than the rate-of-supply of energy). In a two- (or three-) phase system, relative permeability, entry- (displacement-) pressure, and wettability can all be important. For all of these properties, the underlying controlling factors are related to the characteristics of the pore network. These same, fundamental characteristics both control the geomechanical properties of the rocks, and are altered as deformation occurs. Thus, there is an intimate, causal link between the evolution of geomechanical state and the operation of seals. Diagenesis, too, impacts the petrophysical characteristics of rocks, but the changes associated with diagenesis equally impact the mechanical behaviour, and can be included within a geomechanical approach.

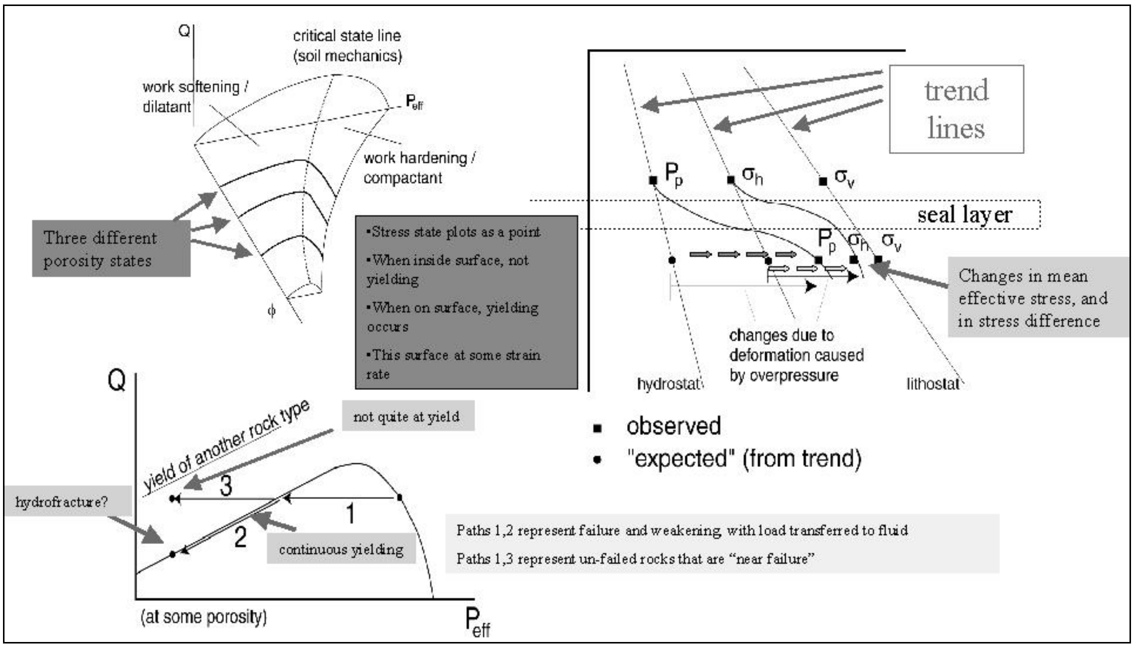

Figure 1. (top, left) Schematic drawing of a poro-visco-plastic yield surface at some strain rate. (bottom, left) Section through PVP yield surface showing state paths during overpressure increase, and consequent stress-state changes. (right) Changes in P_p and stress across a seal layer.

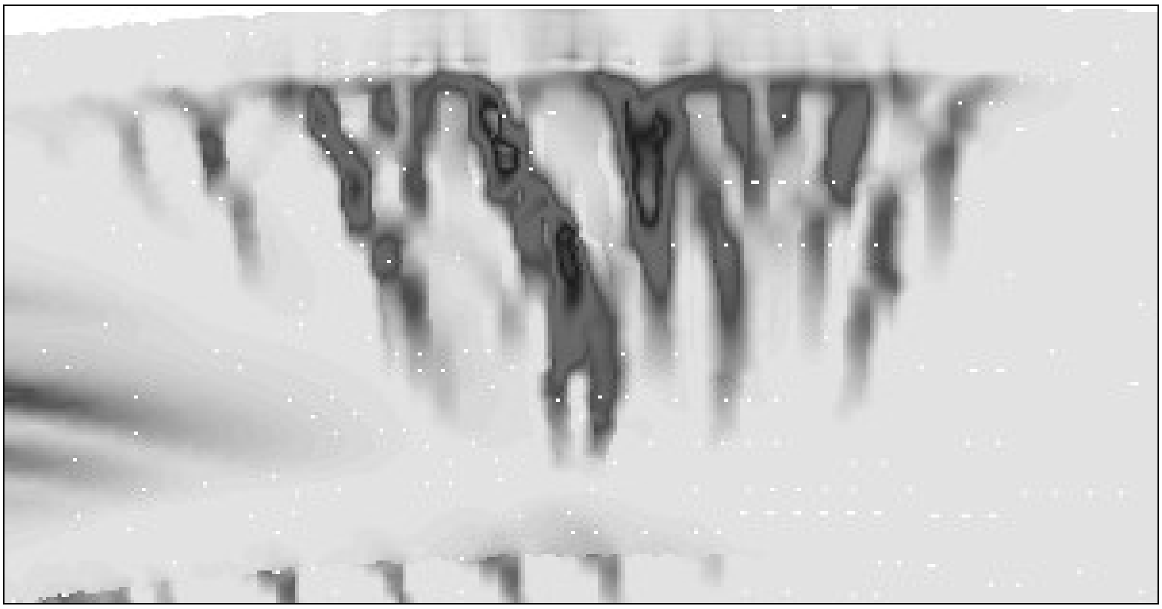

Figure 2. Part of a geomechanical simulation result showing realistic pattern of shear zones ("faults"), represented here by contours of plastic strain. Note how the shear zones react to layer boundaries. [Model created with Nigel Higgs]

<u>A Process-Based Approach</u>: The PVP material model can be used to explain the creation and growth of seal layers (top-seals, or caprocks) within a heterogeneous, muddy rock succession that develops overpressure, as shown in Figure 1. The seal capacity can be predicted using this approach, by relating porosity (framework) changes to the geomechanical state, and associating petrophysical

changes with the porosity evolution. The method also predicts the full state of stress – including the often-observed increases in horizontal stresses. By considering mudrock compaction as a geomechanical process, an integrated and self-consistent model can be developed. Similar reasoning can be applied to the prediction of the sealing characteristics of intra-reservoir shale units.

The prediction of fault-sealing is also improved by considering the deformation processes. Modern simulation methods can achieve remarkable realism when used to study the development of fault arrays. Figure 2 illustrates the distribution of total plastic (permanent) strain in a model representing a “crestal-graben” situation, using a material type that has localisation behaviour. The constitutive relationship used here captures much of the PVP behaviour. The mechanical state calculated by such models (at a series of stages in the development of the structure) can then be used to predict the evolution of petrophysical properties (through empirical relationships, or from first-principles). Flow simulations of various types can then be employed to discover the sealing characteristics of such systems.

By acknowledging the direct link between geomechanics and petrophysics – through the underlying pore- and grain-network – it is possible to understand how seals develop and operate during geological time and due to anthropomorphic events. This understanding, and then the predictions that are possible, represent a robust approach to the study of sealing.

<u>Future Directions</u>: Although it is not the subject of this paper, rock physics (acoustic properties) responses are also related to the same underlying pore- and grain-network referenced above (including fractures, of course), so there is potential to develop approaches that are fully integrated. Demonstrations of these linkages have been performed in time-lapse seismic studies based on fully-reactive (coupled geomechanics and flow) reservoir simulations.