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Predicting Fault Zone Architecture in the Subsurface from Outcrop Analogues and the Expected Impact on Flow

R.K. Davies* (Rock Deformation Research USA Inc.), R.J. Knipe (Rock Deformation Research Ltd), C. Souque (Rock Deformation Research Ltd), M. Welch (Rock Deformation Research Ltd), H. Lickorish (Consultant) & C. Tueckmantel (Rock Deformation Research Ltd)

SUMMARY

The importance of defining the petrophysical properties of fault rocks within fault zones for reservoir flow modeling is well understood. A common observation, however, from well-exposed outcrop examples of faults is a zone of imbricated lenses and splays along the fault, which show a more complex architecture than can be captured with existing models. Modifications of the algorithms and models for the fault zone development are shown based on the outcrop examples that incorporate these fault zone complexities.

The importance of defining the petrophysical properties of fault rocks within fault zones for reservoir flow modeling is well understood (Fisher and Knipe, 1998). Shale gouge ratio and algorithms for shale smear (Yielding et al., 1997) are commonly applied to estimate the distribution of clay content, which is related to the fault rock permeability and capillary threshold pressure distributed along a fault surface. These algorithms, however, do not capture the complex architecture of lenses and interconnecting fault segments inherent to many faults and the impact of these on the flow. A common observation from well-exposed outcrop examples of faults is a zone of imbricated lenses and splays along the fault (Figure 1). These zones shear intact stratigraphy along the fault influencing the flow; the lowest permeability stratigraphy within the lense of sheared rock has the greatest control on reducing cross-fault flow, but high permeability stratigraphy may act as thief zones increasing fluid flow along/across the fault. Modifications of the algorithms and models for the fault zone development are needed to incorporate these fault zone complexities.

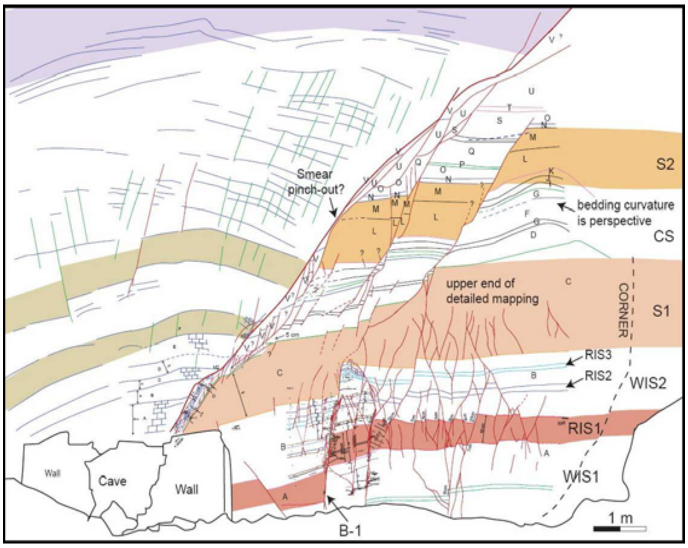

Figure 1 *Detailed outcrop map of a fault in cross-section from the Gulf of Suez. The fault juxtaposes an interlayered sand, silt and shale section in the footwall against a limestone section in the hanging wall. Although most of the slip is along the main fault segment, a zone of imbricate slices is sheared into the fault within the footwall.*

The differences in the style of the deformation along the fault are related to the unique mechanical properties of the stratigraphic intervals, or the mechanical stratigraphy. Lenses of fault bound rocks typically develop early in the deformation by the fracturing of brittle layers. With offset the more ductile layers deform around the faulted brittle layers. The imbricated fault bound slices in the brittle layers shear into the fault zone often attenuating the layers but keeping the stratigraphic stacking intact.

Faults formed at shallow depths in a less cohesive section may smear both sands and shales, but at a deeper level in the crust following compaction, and diagenesis strengthening the sediments, the layer deformation depends on the strength and brittleness of the section. With a significant contrast in mechanical properties between brittle and ductile layers, fault bound lenses will develop. With an increase in the slip the faults tend to break along sharp corners of the lenses forming a longer straighter through-going fault. Most of the subsequent slip is along this straight through-going segment (short-cuts) preserving the lenses locally along the fault length.

The properties that define the mechanical layers are often difficult to determine in the subsurface especially at the time of deformation. This timing, however, may be constrained by restorations and the mechanical boundaries estimated from standard down-hole information constrained to the present day stratigraphy and conditions. Mechanical and kinematical models demonstrate the response of different layers to the imposed deformation. Simple models recently developed including Quadshear (Welch et al, this volume) improve the prediction of the fault styles. The more brittle, weaker layers which fracture first are the more likely to form imbricated lenses. The thicknesses of the surrounding layers also play a role in the subsequent propagation of the faults and fracturing of the underlying and overlying sections. These models improve the ability to predict the likelihood and location of lenses in the section.

The lenses that develop generally deform over a length equivalent to the host stratigraphy thickness. This is equivalent to a shale smear factor (Yielding et al., 1997) of 3. The shale smear, however, accounts only for the properties of a single smeared unit. A more appropriate algorithm is the effective shale gouge ratio (Knipe et al., 2002) which weights the contribution of the clay content of the stratigraphy smeared into the zone. The result is unique hanging wall and footwall properties, which are consistent with the deformation observed in the fault zones. A proper flow model should account for these different footwall and hanging wall properties and for flow along the fault.

Outcrop examples support the general synthesis of fault zone architecture developed here. These examples, however, are still limiting because of the low throws common to well-exposed faulted outcrops. The suggestion, however, is that the lenses and imbricated zones develop early and are preserved in the later deformation. Outcrop exposures of faults with throws at a larger seismic scale show some evidence that the lenses are preserved locally to the host stratigraphy.

The preserved lenses present a wider flow path for cross-fault flow than a single width based on throw, but the bulk permeability across the zone is a function of the separate permeabilities and thicknesses of the individual sheared layers. Simple models for determining the bulk effect of the permeability from a harmonic average across these separate sheared layers shows that the lowest permeability and, in most cases, most clay rich unit controls the flow. A thin but very low permeability shale, for example, along the main fault surface may swamp the impact of the sheared layers in the lens. The lenses may have connected high permeability zones, however, that will impact the along-fault flow. A determination of the impact on the flow in the subsurface is a function of the modeled fault zone architecture, appropriate algorithms for stratigraphic shear and juxtaposition, petrophysical properties of fault rock and sheared host. These results depend on an integrated approach that combines the mechanical and petrophysical properties with the appropriate kinematic and mechanical models. Any analysis of the details of the fault zone, however, needs to be part of a complete assessment of the trap geometry requiring a 3 way dip closure.

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