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Fault-zone Localisation in High-porosity Sandstone Reservoirs and Impact on Flow Efficiency

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SUMMARY

We present results from a study of the distribution of deformation bands and larger ultracataclastic faults in a high-porosity sandstone reservoir outcrop analogue. We show that tectonic loading path and the nature of the stress changes causing deformation may strongly influence strain distribution. Localisation of deformation onto a smaller number of larger ultracataclastic fault zones is more likely in an extensional context than a compressional one because of the work-hardening nature of deformation band formation: In the extensional context, the differential stress required to continue deforming deformation bands is much less than in the compressional case, and may be achieved by subtle differences in stress variation around faults or small fluid pressure changes.

Using new permeability measurements of host rock and deformation structures, we test models for the impact of these structures on flow rates in a producing field. Calculations of flow efficiency show that a small number of larger ultracataclastic faults may severely impede flow during production. Low-displacement deformation bands, with a much less reduced permeability however, will have a much lower impact on flow rates despite their higher densities. The impact of small deformation bands is likely to be greatest when produced by tectonic shortening.

Objectives

The recognition that fault zones can act as conduits and/or barriers to fluid flow has encouraged research into both the petrophysical properties and the spatial distributions of fault zones in reservoir and topseal contexts to understand how to predict the likely control that faults exert on fluid-flow patterns in a reservoir (e.g. Seeburger et al., 1991; Caine et al., 1996; Gibson, 1998; Knipe et al., 1998). In high-porosity sandstone reservoirs, fault zones are typically clusters of "deformation band" faults of moderate to low porosity and permeability. They are often cut by, or are contemporaneous with, larger cataclastic fault zones and/or discrete slip surfaces of greatly reduced porosity and permeability (e.g. Pittman, 1981; Antonellini & Aydin, 1994; Fowles & Burley, 1994; Fisher & Knipe, 1998; Shipton et al., 2002). Yet both of these types of structures can be significantly present below the resolution of seismic detection. In the absence of large amounts of core, predicting the presence and sealing/compartmentalization effect of such structures is best approached by understanding the mechanics of how they form, coupled with petrophysical measurements of analogue structures. Here, we use an extensive study of faulting in high-porosity sandstone reservoir analogues from the Upper Cretaceous of SE France to place mechanical constraints on the generation of each type of structure, along with laboratory measurements of fault zone permeability. We use these data to illustrate the contexts in which the generation of such structures may, or may not, have a significant effect on flow rates in a producing high-porosity sandstone reservoir.

Field area

The field studies were carried out on high-porosity sand and sandstone outcrops in active and abandoned quarries from the Upper Cretaceous of the Bassin du Sud-Est, Provence, France, which provide excellent 2-D and 3-D exposures of deformation band networks and larger faults. These sands/sandstones are essentially composed of a large range of quartz grain sizes which vary between the study areas. These sands generally have a marine origin from deltaic to beach sands, with some aeolian levels. The sand outcrops show a low to moderate cohesion between the quartz grains due to a lack of cement, but nevertheless can form vertical quarry faces for some months to years before erosion and outcrop collapse sets in. These sand units have recorded a low depth of burial, possibly less than 1000 metres in some cases. Nevertheless, deformation bands and larger faults show extensive microstructural evidence for intragranular fracturing and cataclasis, although they are mostly uncemented. Field evidence for the influence of deformation bands on recent groundwater circulations is frequently observed (Fig. 1).

Figure 1 *Deformation bands array in the Massif d'Urchaux, showing evidence of their impact on recent groundwater circulations.*

Results

At Orange, a 250m-long outcrop recording late Cretaceous shortening has a persistently high density of reverse-sense deformation bands which did not appear to cluster around any mapped faults. Thus despite the extensive distributed deformation accommodated during compression, no localisation into larger faults seems to have occurred.

Two study areas in the Massif d'Urchaux and Bedoin experienced significant Oligocene-Miocene extension, and have moderate, undulating background densities of normal-sense deformation bands. Larger ultracataclastic faults and slip surfaces (e.g. Fig. 2) are found localised within or at the edges of some of these clusters, whilst other clusters are present which showed insufficient development of deformation to large faults.

Permeability measurements up to 100 MPa confining pressure decrease from the host sandstones down by 1 – 1.5 orders of magnitude for the deformation bands and around 4 orders of magnitude for the larger ultracataclastic faults.

Figure 2 *Localised ultracataclastic normal fault zones at Bedoin, cross-cutting an earlier array of low-angle reverse deformation bands.*

Interpretation

Tectonic loading path and the nature of the stress changes causing deformation may strongly influence strain distribution. Localisation of deformation onto a smaller number of larger ultracataclastic fault zones is more likely in an extensional context than a compressional one because of the work-hardening nature of deformation band formation: the increased differential stress required to continue deforming the deformation bands into larger faults is probably unfeasible if it is easier to accommodate further deformation in the undeformed sandstone volume elsewhere. In the extensional context, the differential stress required to continue deforming deformation bands is much less, and may be achieved by subtle differences in stress variation around faults or small fluid pressure changes.

The impact of deformation distribution on flow rates in reservoirs is significant. Calculations of flow efficiency show that a small number of larger ultracataclastic faults may severely impede flow during production. Low-displacement deformation bands, with a much less reduced permeability however, will have a much lower impact on flow rates despite their higher densities. The impact of small deformation bands on flow efficiency is likely to be greatest when produced by tectonic shortening.