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Fault seal prediction of seismic-scale normal faults in porous sandstone: A case study from the eastern Gulf of Suez rift, Egypt

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A B S T R A C T

A study of normal faults in the Nubian Sandstone Sequence, from the eastern Gulf of Suez rift, has been conducted to investigate the relationship between the microstructure and petrophysical properties of cataclasites developed along seismic-scale faults (slip-surface cataclasites) and smaller displacement faults (deformation bands) found in their damage zones. The results help to quantify the uncertainty associated with predicting the fluid flow behaviour of seismic-scale faults by analysing small faults recovered from core, a common procedure in the petroleum industry. The microstructure of the cataclasites was analysed as well as their single-phase permeability and threshold pressure. Faulting occurred at a maximum burial depth of ~1.2 km. The permeability of deformation band and slip-surface cataclasites varies over ~1.5 orders of magnitude for a given fault. Our results suggest that the lowest measured deformation band permeabilities provide a good estimate for the arithmetic-mean permeability of the major slip-surface cataclasites. This is because the cataclastic permeability reduction is mostly established early in the deformation history. Stress at the time of faulting rather than final strain appears to be the critical factor determining fault rock permeability. For viable predictions it is important that the slip-surface cataclasites and deformation bands originate from the same host. On the other hand, a higher uncertainty is associated with threshold pressure predictions, as the arithmetic-mean slip-surface cataclasite threshold pressure exceeds the highest measured deformation band threshold pressure by at least a factor of 4.

1. Introduction

Knowledge of the petrophysical properties of fault rocks appears to improve flow predictions within structurally complex petroleum reservoirs (e.g. Jolley et al., 2007; Zijlstra et al., 2007). A fault can restrict fluid movement by juxtaposition of reservoir against non-reservoir units or by forming fault rocks that have low permeability/high capillary entry pressures (Watts, 1987). Oil companies tend to avoid drilling through and coring seismic-scale faults. Therefore many recent studies of fluid flow in structurally complex reservoirs have estimated the permeability of fault rocks along seismic-scale faults based on the analysis of small-displacement faults collected from cores drilled well away from any seismic-scale faults (e.g. Knai and Knipe, 1998; Ottesen Ellevset et al., 1998; Jolley et al., 2007; Zijlstra et al., 2007). A problem with this approach is that uncertainty exists as to whether properties of smaller-offset features are representative of those of seismic-scale faults. As well as having accommodated more strain, seismic-scale faults often show prolonged activity, which means that they may have deformed under different stress conditions than small-displacement faults. According to Fisher and Knipe (2001) this may result in different fluid flow properties of fault rocks originating from small-displacement faults relative to those developed along seismic-scale faults. However, grain-size and permeability reductions in a small number of seismic-scale faults in the field and in rare core samples analysed by Fisher & Knipe (unpublished results) were found to be similar to their respective smaller-offset features in the surrounding damage zone. Fisher and Knipe (2001) identify two reasons why the microstructure of seismic-scale faults is often similar to that of small-displacement faults in their damage zone. First, the effective stress at the time of faulting may be a more important factor affecting grain-size distribution than the total

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strain. Second, each movement of a seismic-scale fault may be reflected in the deformation of its damage zone, which may then be sampled by core.

To reduce uncertainty in fault seal analysis far more studies are needed that compare the petrophysical properties of seismic-scale faults with smaller-offset features found elsewhere in the reservoir. To this end, we report on a combined field and laboratory study of faults with a range of throws found within porous sandstones in the central eastern margin of the Gulf of Suez rift. In particular, we assess the viability of predicting permeability and threshold pressure of shallow level seismic-scale normal faults (throws >40 m) by analysing cataclastic damage-zone deformation bands (throws <5 cm). In the following section we give a short review of work characterising fluid flow properties of typical fault zone elements in porous sandstone (slip surfaces, zones of deformation bands, single deformation bands, Fig. 1). Then we present the approach of our study and outline the structure of this paper.

Most of the displacement along seismic-scale normal faults in porous sandstone is typically accommodated by one or more slip surfaces that represent displacement discontinuities (Aydin and Johnson, 1978). Cohesion is lost along the slip surface during faulting as two rock masses move past each other. After the cessation of faulting the slip surfaces separating the two rock masses may either remain cohesionless or they may regain cohesion by strengthening processes influenced by the prevailing confining pressure, pressure solution or cementation (resulting in one rock mass with an internal slip surface). Slip surfaces are often delineated by zones of cataclasites on one or both sides that are up to a few centimetres wide without interspersed host sandstone (Antonellini and Aydin, 1994; Shipton et al., 2005). In this paper we will use the term slip-surface cataclasites for this type of fault rock. To our knowledge Antonellini and Aydin (1994) report the only permeability data for slip-surface cataclasites in the literature and we will summarise their findings here. Antonellini and Aydin (1994) refer to slip-surface cataclasites as “wall rock of slip planes” and report that their thickness varies between ∼0.5 and 6 cm for faults in the Navajo and Entrada Sandstone at Arches National Park, Utah. They measured permeabilities of slip-surface cataclasites and deformation bands with a minipermeameter and determined porosity using image analysis. Antonellini and Aydin (1994) report that the porosity of slip-surface cataclasites is below the resolution of their measurement method ($<1\%$) due to “extreme grain crushing and recrystallization”. Permeability of slip-surface cataclasites was reported for three rock units. In the Slickrock member of the Entrada Sandstone (clay content 4–15%) permeability of slip-surface cataclasites is two to three orders of magnitude below its host sandstone, similar to deformation bands in this unit. Slip-surface cataclasites of the clay-free Navajo Sandstone and the Moab member of the Entrada Sandstone have permeabilities lower than their respective deformation band permeabilities and five to seven orders of magnitude below their host rock. Antonellini and Aydin (1994) show that the low permeability of slip-surface cataclasites has a strong effect on across-fault fluid flow at various scales.

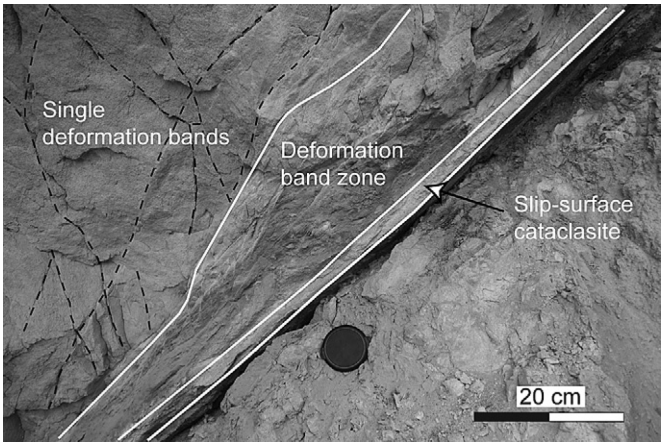

Fig. 1. Seismic-scale normal fault in porous sandstone showing typical fault zone elements in the hanging wall (South Baba fault, eastern Gulf of Suez rift, ∼100 m throw, for location see Fig. 2).

Complex zones of deformation bands with intermittent pods of host or slightly deformed sandstone are another important element of fault zones in porous sandstone. These zones can be observed on their own or associated with large faults and bordered on one or two sides by slip surfaces and their cataclasites (Aydin and Johnson, 1978; Wibberley et al., 2007). Where zones of deformation bands are delineated by major slip surfaces they are sometimes referred to as fault cores (e.g. Shipton et al., 2002). Displacement accommodated by zones of deformation bands depends on the number of individual deformation bands present in the zone and is typically less than 1 m (Aydin and Johnson, 1978). Shipton et al. (2002) report permeability data for one fault core sample of the Big Hole fault, Utah, recovered from ∼60 m depth at a site where displacement is 3–5 m. The host rock is very fine to fine-grained aeolian arenite of the Navajo Sandstone for which a wide range of permeability values (5–3000 mD) were reported by Shipton et al. (2002). The lithostatic load during faulting was estimated to be 40–80 MPa and temperatures to be 45–90 °C. The fault core is bounded by one or more slip surfaces and comprises a dense deformation-band network in relatively undeformed host rock. Permeability perpendicular to the zone of deformation bands was tested at confining pressures ranging from 400 to 4350 psi and is reported to be relatively constant at ∼1 mD. This value is similar to the permeability of a single deformation band from the same fault zone. Fossen and Bale (2007) report permeability reduction of one to five orders of magnitude for clusters and dense clusters of deformation bands, mostly from southern Utah. The densely clustered deformation bands populate the lower permeability range of this data set. Al-Hinai et al. (2008) present an extensive petrophysical data set, including relative permeability and air-water capillary pressure curves, for seven fault core plugs of a dense deformation-band network from the Clashach fault, Scotland. The fault has a minimum displacement of 20 m and its host rock is a medium-grained sandstone. Significant quartz cementation affected both host and fault rock samples. The absolute gas permeability reported by Al-Hinai et al. (2008) for the seven plugs varies between 0.001 and 0.006 mD with the respective host rock permeability ranging from 10 to 700 mD.

Cataclastic deformation bands, first described by Aydin (1978), are a common element of damage zones of larger faults in porous sandstones. They consist of a typically ∼1 mm wide zone of crushed and compacted quartz grains that accommodates displacements of less than 3–4 cm (for a comprehensive review see Fossen et al. (2007)). Deformation band porosity and permeability is reduced and their threshold pressure is increased relative to the host rock. Several authors report deformation band permeability for a wide range of field areas and petroleum reservoirs (Pittman, 1981; Antonellini and Aydin, 1994; Fowles and Burley, 1994; Crawford, 1998; Gibson, 1998; Fisher and Knipe, 1998, 2001; Shipton et al., 2002; Fossen and Bale, 2007). The reported data ranges from zero to six orders of magnitude permeability reduction relative to the host rocks. Antonellini and Aydin 1994 report an average permeability reduction of three orders of magnitude. Crawford (1998) measured permeability for porous sandstone experimentally faulted in shear and reports a one order of magnitude