IMPACT OF DEFORMATION BANDS ON FLUID FLOW AND OIL RECOVERY

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ABSTRACT
The effect of deformation bands on localized fluid flow was studied experimentally in two different scales. Saturation Imaging has been used to visualize fluid flow during waterfloods in a sandstone core plug (Magnetic Resonance Imaging) and in a larger block of sandstone (Nuclear Tracer Imaging). Conventional permeability and porosity tests and MRI characterization were performed on deformation bands and the surrounding host rock in order to define basic properties of the samples. Deformation bands have considerable lower permeability compared to its host rock, and may also serve as a capillary barrier for oil flow, if the relative permeability to oil is severely reduced. The results presented here show that the deformation band had minor effect on the ultimate oil recovery, but a significant effect on the local saturation development.

INTRODUCTION
Faults commonly act as barriers or conduits for fluid flow in the brittle crust (e.g. McCaig 1988; Sibson 1992) and may cause major difficulties in the production of hydrocarbons in faulted reservoirs. *Deformation bands* are small faults (sub seismic) with displacements of mm to a few cm that appear in porous sandstone (Aydin 1978; Aydin & Johnson 1978). Depending on their degree of grain rearrangement, pressure solution, granulation, cementation, and clay content (Knipe et al. 1997), deformation bands have considerably lower permeability compared to their host rock (2-4 orders of magnitude) (Antonellini & Aydin 1994; Fowles & Burley 1994; Gibson 1998; Sigda et al. 1999; Ogilvie & Glover 2001; Lothe et al. 2002). Thus, the deformation bands may have a significant effect on hydrocarbon production. They appear as isolated structures, in zones, or in association with faults, where they commonly form dense networks within the damage zones or within the elongate bodies of host rock in the fault core (horses) (Aydin & Johnson 1978; Hippler 1993; Gabrielsen et al. 1998; Beach et al. 1999; Hesthammer et al. 2000; Berg & Skar, 2005). Although there are several analyses on deformation band permeability and porosity, and a few that extend the observations to petrophysical properties as capillary pressure, irreducible water saturations (Ogilvie & Glover 2001), relative permeability, and moisture content (Sigda & Wilson, 2003), there are few attempts to map multiphase flow through deformation bands. Flow mapping is in

particular valuable to determine whether or not the decreased porosity, permeability and pore sizes are capable of trapping oil in the upstream host rock due to severe loss of relative permeability to oil in the deformation band. To address this, scaled-up laboratory waterflood imaging experiments was performed. To investigate the simultaneous interaction between capillary forces, viscous forces and gravity, and to reduce the impact of capillary end effects, a larger block of outcrop rock has been used in addition to several standard core plugs.

GEOLOGICAL SETTING

The rock material analyzed derives from the Moab fault, Utah, USA. The Moab fault is a salt related normal fault located in the northeastern part of the Paradox Basin, SE of Utah. It intersects a c. 5000 meter thick sedimentary sequence of Pennsylvanian to Cretaceous age. Its' total length is 45 km, and estimated displacement at the surface is up to 950 meters. The fault has been active during at least two episodes; from the Triassic to upper-Jurassic and from mid-Cretaceous until early Tertiary (Doelling, H. H, 1988). Younger ages are also proposed (late Tertiary) (Olig, S. S, 1996). The NW-SE striking Moab fault is associated with and strikes parallel with the Moab and Courthouse anticlines. In the NW, segments splay off the main trace towards the West, and curve gradually and become parallel to the main trace some km west of the branching point. The sample derives from a locality along one of these segments (Hidden Canyon) (Figure 1) where the displacement is close to 200 meters. The samples are taken from the Slick Rock Member, in the footwall damage zone ca. 10 meter from the fault core in a cataclastic deformation band zone. The Slick Rock Member is a Jurassic eolian sandstone that is a gray and reddish, fine- to medium grained, cross bedded to well indurated sandstone. The deformation band zone dips 43° towards the NE., i.e. it is sub-parallel with the master fault zone.

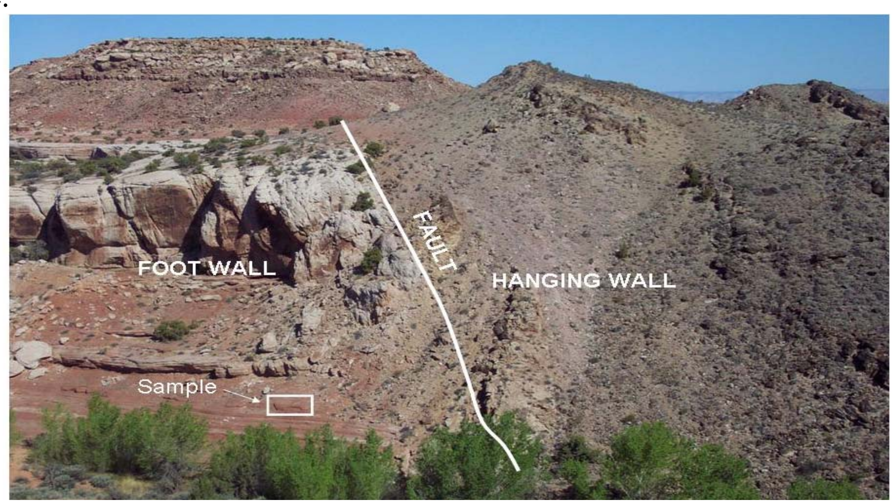

Figure 1. The Moab fault

In addition to six core plugs, a block, approximately 20 cm × 10 cm × 5 cm thick, was cut from one of the samples. Both cores and block were saturated with brine containing 3.8 wt% NaCl under vacuum. Decane was used as the oil phase when draining.

RESULTS AND DISCUSSION

Initial water saturation, S_{wi}, of 23% was established by oil flooding the block sample (Figure 2) with a maximum differential pressure of 125 kPa/cm. Oil was injected both directions and a fairly homogeneous initial saturation was obtained. The block was epoxy coated and mounted in a pressure chamber holding 4 bars during drainage. A Nuclear-tracer imaging technique (Graue, 1993) was used to monitor the saturation development by measuring gamma ray emission from ^{22}Na dissolved in the brine. The block was mounted in a vertical position while flooded and *in situ* fluid distribution was acquired sequentially as function of time.

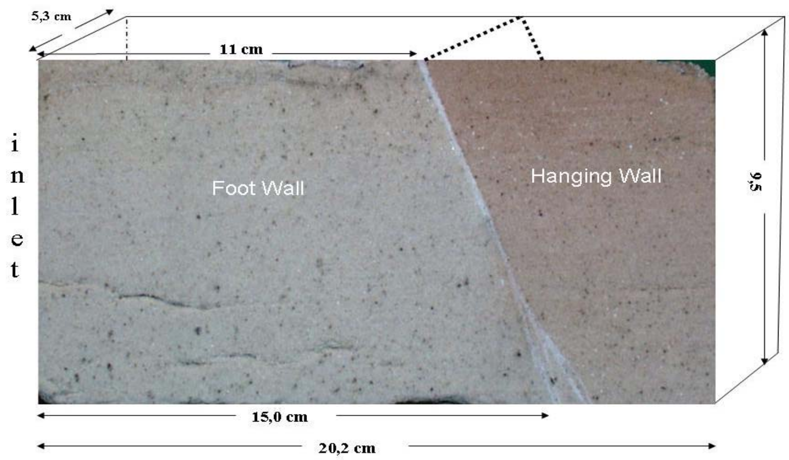

Figure 2. The block sample with dimensions

The waterflood was performed at low flow rate (0.5 cc/h); the average front velocity was 2.5 cm/day. Recovery efficiency was 0.55 fractions of OOIP with a clean cut breakthrough after injecting 0.43 PV of water. The water saturation development is shown in Figure 3. The water advancement seemed to be dominated of capillary forces; no distinct waterfront and no gravity segregation of water were observed. A significant congestion of water occurs upstream before crossing the deformation band. In capillary controlled displacement the imbibition of water is controlled by capillary forces striving to attain equilibrium capillary pressure across the interface separating the layers. Due to inadequate resolution, monitoring the saturation within the 2-4 mm wide deformation band failed. Reduced pore sizes imply a stronger water preference in the deformation band compared to its host rock. The rate of imbibition is controlled by multiple factors; the low permeability in the deformation band would oppose the high capillary pressure and slow down the imbibition rate. It is however not obvious that reduced permeability cause water to retard before crossing. The time extent of the experiment (11 days) and the thickness of the deformation band (2-4 mm) make it less likely. Higher capillarity and high water saturation in the deformation band due to reduced pore sizes will slow down or permanently trap oil in the injection end due to loss of relative permeability to oil in the deformed zone. Thus, deformation bands could potentially act as barrier for up stream oil flow, as observed in layered system [Børresen, 1996]. No such trapping was observed.

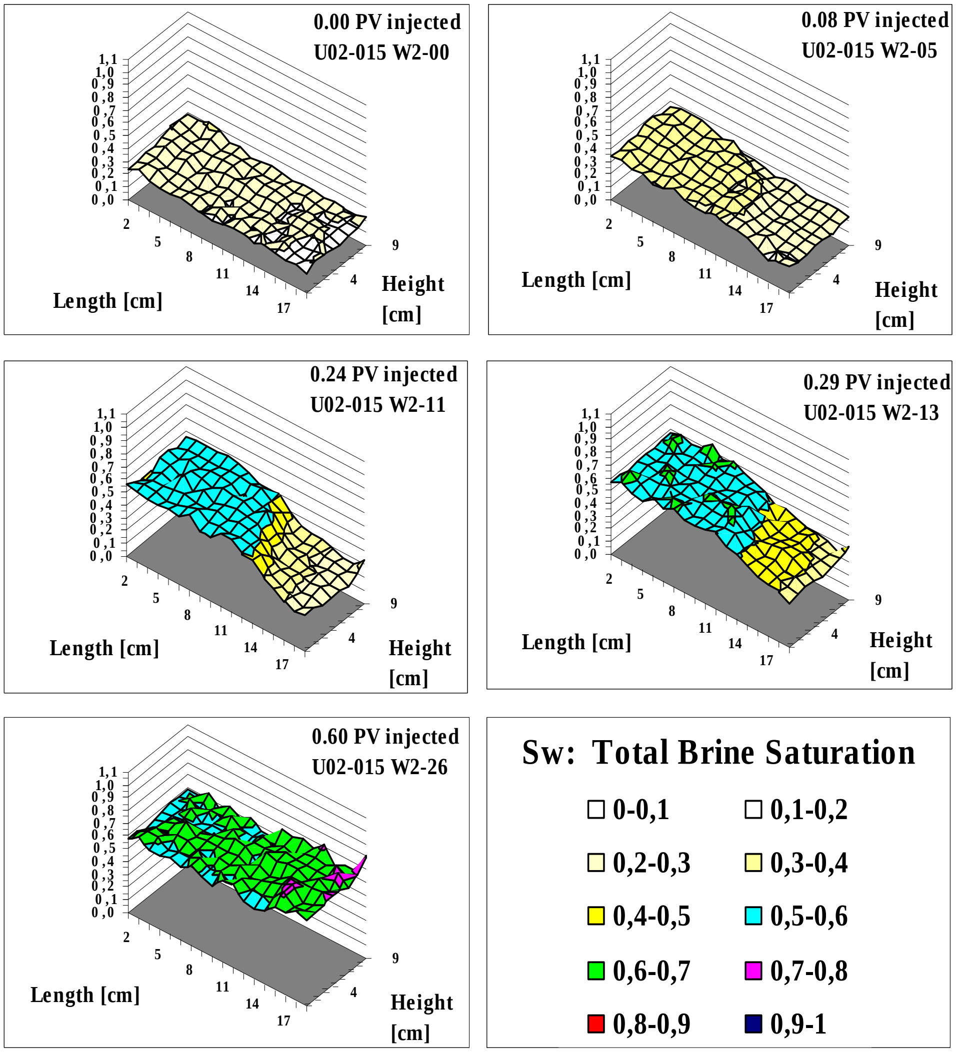

Figure 2. Saturation development when waterflooding the sandstone block. The water halts and forms a front before crossing the deformation band (middle left image).

High Resolution MRI

Prior to the block experiment, 6 cores were drilled out and porosity, absolute permeability, wettability and endpoint water saturation were determined. Two of the cores were drilled across the deformation band and four were sampled from the host rock. The porosity was in the range of 18-22%. Permeability was 600-800 mD for the host rock and 0.5-1 mD for the deformation band. The deformation bands exhibited fairly symmetrical architecture, with a low porosity central zone and a transitional zone of intermediate porosity. Some areas did however show a wider zone of deformation. Bright lenses (higher porosity) appeared parallel to the displacement, suggesting that some areas were left undeformed due to local shear variations. The average porosity in the deformation band was found to range from 8-11 % compared to 23 % for the host rock.

No significant difference in oil recovery was observed between samples. Two waterfloods were carried out in the MRI using deuterium oxide (D_2O) and decane.

The only fluid sensitive for magnetic resonance is decane, appearing bright on the images. Two constant rate experiments were carried out (front velocity of 5 cm/day and 30 cm/day), while sequentially imaging a 4 mm wide sagital slice in the center of the core plug. A similar behavior as seen for the block experiment was observed for both experiments (Figure 4): Water fills the upstream host rock before crossing the deformation band. The relative drop in MRI intensity was less for the deformation band compared to the host rock which suggests a higher initial water saturation and a lower mobile fraction of oil. The fact that the deformation band has a similar effect on the water propagation that would be the case for an open fracture in a strongly water-wet system suggests that cracks with low capillary pressure may be present. This contradicts with earlier characterization of such bands. It is also possible that the host rock on the outlet side was of higher pore sizes, but it is unlikely that the capillary equilibrium between host rock layers is so far apart in saturation that it could explain the observed water congestion.

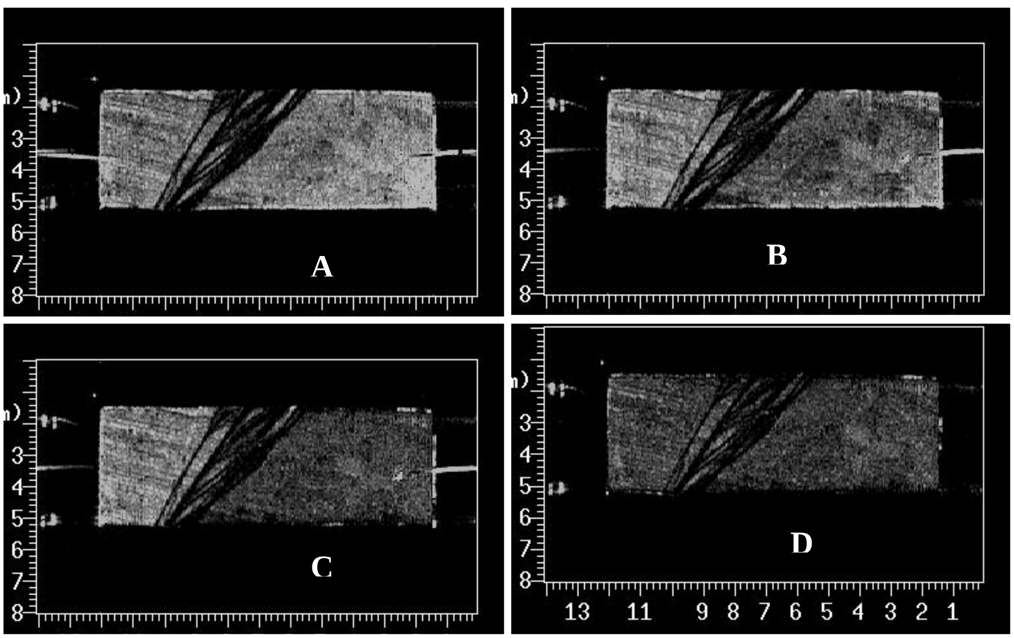

Figure 4: Waterflood in core with deformation band (low rate). Oil (appearing bright) displaced by D_2O from right. A) Sw=29% B) Sw=50%, C) Sw=60%, D) Sw=66%.

CONCLUSIONS

- The deformation band had a significant effect on the local saturation development and induced an accumulation of water before crossing. This may be explained by development of micro fractures inducing capillary barriers.
- The deformation band did not have any significant effect on the ultimate oil recovery.

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