The influence of reverse-reactivated normal faults on porosity and permeability in sandstones: a case study at Castle Cove, Otway Basin

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SUMMARY

An understanding of fault zone structure and transmissibility can have significant implications for reservoir appraisal and development within petroleum systems. Studies tend to focus on low porosity host rocks that have experienced simple tectonic histories while the influence of complex fault systems (that have undergone multiple phases of deformation) on porous rocks within fault damage zones have not been investigated. We present results from a detailed mineralogical and geomechanical investigation of the Castle Cove Fault within the Otway Basin at Castle Cove, southeast Australia. Castle Cove provides excellent exposures of the Lower Cretaceous Eumeralla Formation, which is a fine-grained volcanogenic sandstone with moderate to high porosity (up to 27%) and low permeability (mostly <1 mD). The Castle Cove Fault originated as a normal fault during the late Cretaceous and was reverse-reactivated during Miocene–Pliocene compression. Core plugs were sampled at distances between 0.5 to 225 m from the fault and were orientated with respect to the fault plane. We show that closer to the fault (within 75 m), porosity increases by nearly 10% (from approximately 17% to 24%) and permeability increases by two orders of magnitude (from 0.04 mD to 2.92 mD). Microstructural investigations from thin sections show an increase in microfracture intensities closer to the fault. Also observed is a change in the morphology of pore-lining chlorite, from well-structured away from the fault to broken up and disaggregated adjacent to the fault. This study highlights the importance of detailed mineralogical and petrophysical analyses when attempting to understand the reservoir properties of high porosity and low permeability sandstones.

Key words: porosity, permeability, reverse-reactivated normal fault, Castle Cove, Otway Basin

INTRODUCTION

Brittle fault zones and associated permeability structures form primary controls on fluid flow at a range of scales. An understanding of fault zone structure and transmissibility can have significant implications for reservoir appraisal and development within petroleum systems. Previous studies have demonstrated that micron-scale porosity and permeability are significantly reduced within fault zones due to pore collapse, grain crushing, and cement precipitation during deformation (Caine *et al.*, 1996). Adjacent to brittle faults, a peripheral zone of fracturing and faulting (i.e. the fault damage zone) leads to an increase in structural permeability (Faulkner *et al.*, 2010). Studies tend to focus on low porosity host rocks that have experienced simple tectonic histories while investigations on porous fault-bearing rocks that have undergone multiple phases of deformation have not been attempted. This study investigates the influence of the reverse-reactivated Castle Cove Fault on the porosity and permeability of the Eumeralla Formation, which is a fine-grained and porous volcanogenic sandstone. We present mineralogical and petrophysical analyses conducted on orientated samples collected within the Castle Cove Fault damage zone within the Otway Basin, southeast Australia.

GEOLOGICAL BACKGROUND

The Otway Basin is one of several basins that developed during late Jurassic to early Cretaceous rifting, synchronous with continental separation of Australia and Antarctica (Willcox and Stagg, 1990, Krassay *et al.*, 2004). The basin has since experienced multiple phases of rift-sag and inversion (Krassay *et al.*, 2004), with deformation largely accommodated by the formation and reactivation of large-scale faults and anticlinal structures (Perincek and Cockshell, 1995, Holford *et al.*, 2014). At Castle Cove in the eastern Otway Basin, the Castle Cove Fault initiated as a normal fault during Late Cretaceous extension and was subsequently reverse-reactivated during NW–SE Miocene–Pliocene compression. The fault strikes NE–SW with a strike length of approximately 30 km. Structural mapping within the hanging wall fault damage zone has revealed a complex tectonic history, with up to five fracture sets geometrically related to the Castle Cove Fault (Debenham *et al.*, in preparation).

METHODS

At Castle Cove, 10 orientated sample blocks were collected within the hanging wall at distances between 0.5 to 225 m from the Castle Cove Fault. Fractures and sedimentary structures were avoided when sampling. From the sample blocks, a total of 78 core plugs were drilled in three orientations with respect to the fault plane, i.e. normal to the fault plane (x), along fault strike (y), and parallel to fault dip (z). Thin sections were also prepared in the xz plane (i.e. normal to along fault strike) for mineralogical and textural analysis on a Scanning Electron Microscope with mineral liberation analysis capabilities. Core plug porosity was measured using a helium injection porosimeter and steady state permeability was measured using a nitrogen permeameter at ambient pressures (Klinkenberg corrected), following methods discussed in Farrell *et al.* (2014). For all 10 samples, grain size measurements were undertaken on a LS13320 Laser Diffraction Particle Size Analyser following the methods of Blott *et al.* (2004). Pore throat size distributions and pore connectivity were determined using mercury-intrusion porosimetry following the methods of Tueckmantel *et al.* (2012).

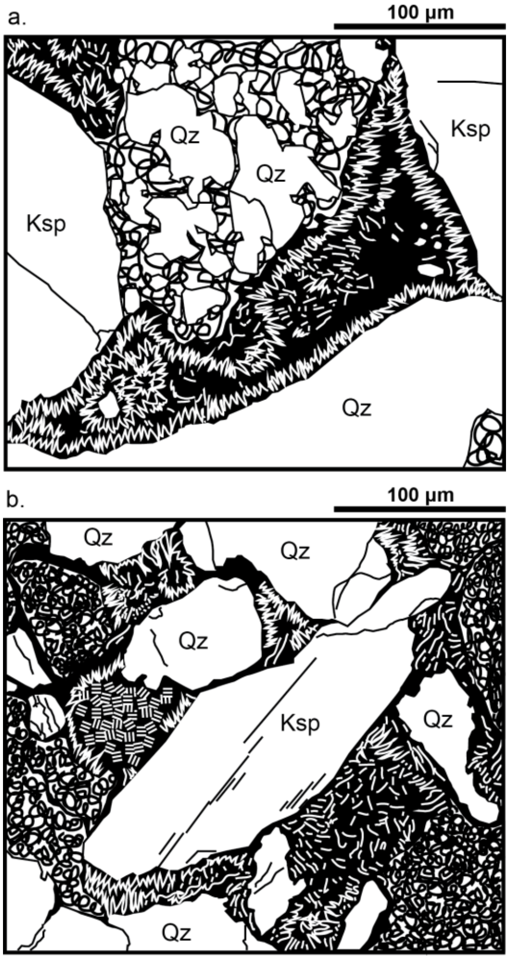

Figure 2: Schematic diagrams of typical mineralogical and textural features in the Eumeralla Formation; (a) 161 m from the Castle Cove Fault showing well preserved intergranular porosity and filamentous pore-lining chlorite, and (b) 37 m from the fault showing a change in chlorite morphology (broken up and filling intergranular porosity) and increased microfractures.

CORE PLUG POROSITY AND PERMEABILITY

Porosities from orientated core plugs are plotted relative to distance from the Castle Cove Fault (Figure 1a). Porosity increases by nearly 10% (i.e. from approximately 17% to 24%) as the fault plane is approached. Within 0.5 m of the fault, high porosities up to 27% are recorded. Steady state permeabilities from orientated core plugs are plotted relative to distance from the Castle Cove Fault (Figure 1a). As the fault plane is approached, permeability increases by two orders of magnitude (from 0.04 mD to 2.92 mD).

PORE THROAT SIZES AND CONNECTIVITY

Pore throat size distributions show a bimodal pattern; one peak between 0.01 to 0.3 μm and a second peak between 0.3 to 0.7 μm (Figure 1b). There is a shift to greater volumes of larger pore throat sizes closer to the fault, whereas away from the fault there are greater volumes of smaller pore throat sizes. Less pressure was required to form a connected pathway between pores and to saturate the samples closest to the fault. Therefore, connectivity is better closer to the Castle Cove Fault.

GRAIN SIZE

Grain size distributions were determined using a Laser Diffraction Particle Size Analyser. There is an increase in volumes of clay, silt, and very fine sand grains (<125 μm) as the Castle Cove Fault is approached, and there is an increase in volumes of fine to coarse sand grains (>125 μm) away from the fault (Figure 1c). These data indicates progressive grain size reduction closer to the Castle Cove Fault.

THIN SECTION ANALYSIS

The Eumeralla Formation at Castle Cove is a fine to medium grained volcanogenic sandstone that is compositionally immature. The mineralogy is dominated by plagioclase feldspar (up to 48 wt%) and quartz (up to 27 wt%), and also contains authigenic pore-lining chlorite (approximately 16 wt%). Other minerals include potassium feldspar, muscovite, kaolinite, biotite, accessory minerals (such as apatite and rutile), and coal fragments. Away from the fault, intergranular porosity is strongly preserved by pore lining chlorite (Figure 2a), however closer to the fault the chlorite is broken up and intergranular porosity is filled with fragments of chlorite (Figure 2b). Microstructural analyses from orientated thin sections show an increase in microfracture intensities closer to the fault. Closer to the Castle Cove, quartz and feldspar grains are deformed and fractured (Figure 2b). Most microfractures observed using a Scanning Electron Microscope are intragranular or occur along grain boundaries.

DISCUSSION AND CONCLUSIONS

An increase in porosity, permeability, and pore throat size and connectivity is recorded closer to the Castle Cove Fault. However, grain size decreases closer to the Castle Cove Fault. Thin section analyses of samples located adjacent to the fault reveal increased deformation from faulting and subsequent microfracturing of grains and reduced intergranular porosity. Thin section analyses also suggest that the larger pore throat sizes (>0.3 μm) measured in mercury-intrusion porosimetry represent microfractures and intergranular porosity preserved by pore-lining chlorite. Smaller pore throat sizes (<0.3 μm) represent microporosity between clays. This suggests that the increase in porosity and pore throat size adjacent to the fault may be attributed to the increase in microfractures. A change in the morphology of pore-lining chlorite, from well-structured away from the fault to broken up and disaggregated adjacent to the fault, may also contribute to changes in pore throat size and permeability.

The results from this study show that the formation of microfractures and change in morphology of chlorite as a result of faulting can improve the porosity and permeability structure of the host rock. This study highlights the importance of detailed mineralogical and petrophysical analyses when attempting to understand the reservoir properties of high porosity and low permeability sandstones.

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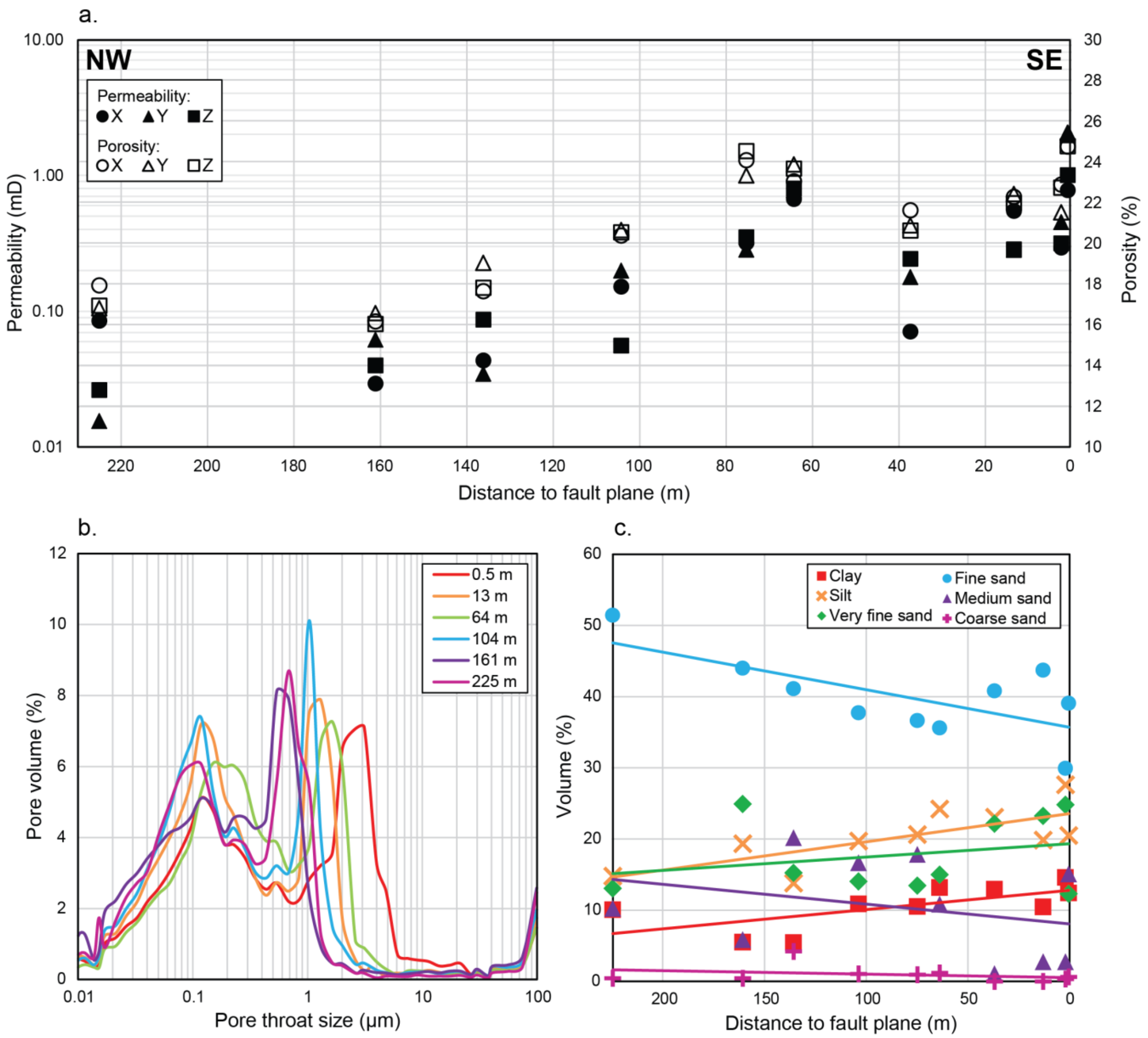

Figure 1: (a) Average permeability (closed symbols) and porosity (open symbols) plotted relative to distance from the Castle Cove Fault. Different shaped symbols indicate different core plug orientations relative to the Castle Cove Fault plane. The x-axis has been reversed to represent the outcrop configuration, i.e. 220 m is northwest and 0 m is southeast. (b) Volume of porosity contributed by pore throat sizes. Pore throat size distributions show a bimodal pattern; one peak <0.3 µm and a second peak >0.3 µm. Different colours represent different distances from the Castle Cove Fault. The graph shows that there are greater volumes of larger pore throat sizes closer to the fault. (c) Particle size distribution at different distances from the Castle Cove Fault. Different colours and symbols represent grain sizes. This graph shows a progressive grain size reduction closer to the fault.