# THE FLUID FLOW PROPERTIES OF FAULTS IN SANDSTONES

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Predicting the fluid flow properties of faults within sandstones is important in fields such as water resource management, mineral exploration, waste disposal as well as petroleum exploration and production. Hydrothermal systems and hydrocarbon seepages provide ample evidence that faults and fractures have the ability to focus fluid flow. Faults can also restrict fluid flow, resulting in the compartmentalisation of petroleum reservoirs. This seemingly paradoxical behaviour continues to attract significant attention. Here we highlight the principal controls on the fluid flow properties of faults in clean sandstones by integrating work on diagenesis and rock/soil mechanics with petrographic observations from faults in petroleum reservoirs. A numerical model for quartz cementation of sandstones is combined with published results from sandstone deformation experiments to develop a simple model for the fluid flow behaviour of faults within sandstones.

## *Natural fault rocks*

Microstructural and petrophysical property analysis has been conducted on >1000 fault rocks from >80 petroleum fields and provides excellent data to compare with published results from deformation experiments. Data are presented from three areas with contrasting geohistories.

### *Faults in clean Brent sandstones of the North Sea*

The Brent reservoirs experienced a major period of extensional faulting during Middle Oxfordian to Early Kimmeridian times. Seismic evidence suggests that Brent sequences did not experience significant fault development or reactivation during deeper burial. Most faults examined (> 90%) within clean sandstones classify as disaggregation zones with microstructures that are usually indistinguishable from their hosts because deformation occurred, under low effective stress conditions, without grain-fracturing.

### *Cataclastic faults in the Rotliegendes of the Southern North Sea UK*

The Rotliegendes experienced extensive rifting during the Jurassic, resulting in the development of extensional faults. The area has since experienced episodic uplift and subsidence. Areas such as the Sole Pit Basin, experienced more than of 2 km uplift.

Cataclastic faults within Rotliegendes reservoirs occur as isolated features or in dense clusters. The isolated features tend to have a broad grain-size distribution due to the presence of large, mostly unfractured, grains as well as small fragments produced by cataclasis. The clustered faults often contain discrete slip surfaces that have experienced extensive grain-size reductions. The cataclastic faults often experience enhanced quartz cementation – especially those that have been buried deeply (i.e. >4 km). Most cataclastic faults within the Rotliegendes reservoirs formed before extensive mesodiagenetic alteration such as quartz and illite cementation. The cataclasites have permeabilities from 0.2 to 0.0001 mD, which are inversely related to their maximum burial depth because those formed at deeper depths experienced larger grain-size reductions and more extensive quartz cementation.

*Dilational faults in quartz cemented clean sandstone*

A reservoir was also examined containing sandstone with a porosity of up to 16% that had experienced extensive quartz overgrowth development (>15% authigenic quartz). Faults in the sandstone formed after the precipitation of significant quantities of authigenic quartz. The resulting fault rocks experienced significant dilation and permeability increase.

## Sandstone deformation experiments

Experiments show that two end-member modes of deformation may be identified based on the post-yield macroscopic structure of sandstones (e.g. Jamison & Stearns, 1982). The first, localised or brittle deformation, results in the formation of discrete slip planes, which accommodate most of the strain. The second, distributed or ductile deformation, does not result in the formation of discrete slip surfaces, instead strain is accommodated throughout the sample. Localised deformation can lead to a permeability increase or decrease depending upon the rock porosity. Wong et al., (1997) showed that faults formed in sandstones with >15% porosity tend to compact, whereas those with <15% tend to experience a permeability increase. Porosity collapse/distributed grain fracturing leads to compaction and decreased permeability.

In log-log space, an inverse linear correlation exists between the product of grain-radius and porosity and yield strength, p*, under hydrostatic conditions (Wong et al., 1997). Their data lie on a curve given by:

$$log(p^*) = 0.5 - log(øR)$$

where ø is the porosity and R is the grain radius (μm). This relationship offers a useful way to estimate sandstone strength. In particular, Wong et al. (1997) give a yield/failure criterion for sandstones, which expresses the failure criterion in a plot of differential stress against effective mean stress, p, each one normalised by division by p*. Dilatant brittle failure occurs when the ratio of p/p* is < 0.25 and compactive grain crushing when the ratio is > 0.4.

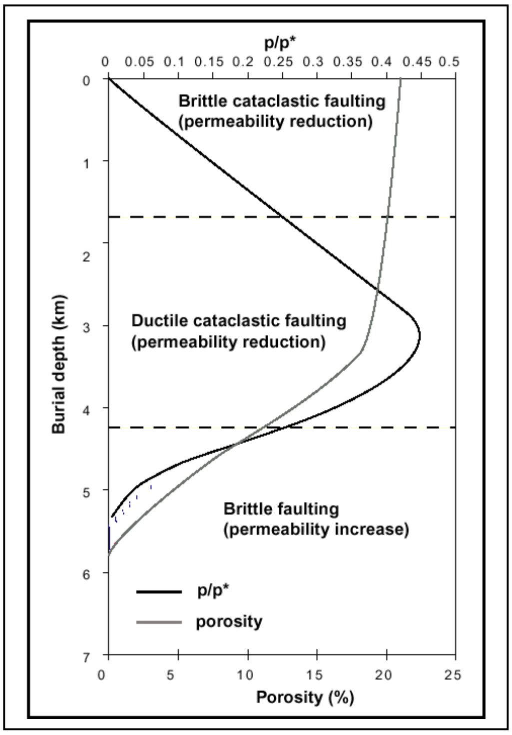
## Changes in strength and deformational behaviour during burial

Burial of siliciclastic sediments leads to lithification by both mechanical and chemical processes. Below ~90$^o$C, mechanical compaction is the main process to affect siliciclastic sediments. On the whole, this reduces the porosity of sediment but does not dramatically increase its strength. Above ~90$^o$C, kinetically controlled, chemical reactions such as quartz cementation and grain-contact quartz dissolution occur at appreciable rates. These reactions tend to decrease the porosity and increase the strength of siliciclastic sediments.

To gain an understanding of the mechanical strength evolution of sandstones during burial, we have adapted the quartz cementation model of Walderhaug (1996) to calculate how the product of grain-size and porosity varies with temperature history. The variation of porosity with time can be obtained for various heating rates. The heating rate is a function of temperature gradient and burial rate, so if burial rates are assumed it is possible to calculate the depth histories of the sample. From the depth, the effective vertical stress was determined from the density of the overburden assuming hydrostatic pore pressure.

In the first simulations, we investigated how p/p* and porosity varied during burial. We simulated the burial of sandstone at a rate of 17.5 Ma/km under a geothermal gradient of 35$^o$C/km. The equation for p*, was adjusted to give lower values by replacing the first term on the right hand side with -0.5. This adjustment enabled us to reproduce the failure modes observed in nature for various depths. The results (Fig. 1) show that deformation-induced permeability changes can be subdivided into three depth-related domains. A) Shallow Failure Domain at burial depths below ~1.8 km, p/p* is <0.25 suggesting that deformation occurs by brittle faulting, which at low effective stress could result in the formation of disaggregation zones but at higher mean effective stresses will produce cataclasites. As the sandstone has a porosity of >15% it is likely that cataclasites will experience a permeability reduction. B) Intermediate Depth Failure Domain, during deeper burial the failure mode becomes more ductile and will result in the formation of compactional cataclasites, with reduced permeability. C) Deep Failure Domain, at depths of >4.2 km the ratio of p/p* falls below 0.25 suggesting that the failure mode returns to brittle faulting. As the porosity of the sandstone is <15% faulting will probably increase permeability. This change from ductile to brittle faulting (hereafter referred to as the ductile-brittle transition –DBT) is important as it marks a change from where faults will tend to be barriers to fluid flow to where they are likely to act as conduits during faulting.

*Figure 1. Plot showing the change in p/p* for a sandstone that is buried at rate of 17.5 Ma/km under a geothermal gradient of 35$^{o}$C/km. The mode of faulting and its affect on permeability have also been highlighted*.



Further simulations were run using various burial rates and geothermal gradients to investigate their affect on the depth of the DBT. The simulations suggest that the increases in geothermal gradients are associated with significant reductions in the depth of the DBT. For example, the DBT occurs at 18 km under a geothermal gradient of 10$^{o}$C/km, whereas under a geothermal gradient of 80$^{o}$C/km it occurs at ~2 km. There is a general decrease in the depth of the DBT with decreasing burial rate. This effect is very small in comparison to that caused by variations in geothermal gradient. It should be noted that the large depths quoted above (18 km) are normally associated with crystal plastic behaviour, however, in the situation modelled the very low geothermal gradients would suppress this process.

To understand these results we have plotted the porosity and quartz cement content of the sandstones at the DBT (Fig. 2). The DBT in sandstones deposited under high geothermal gradients occurs at shallow depth where porosities are high and quartz contents low. On the other hand, sandstones deposited under low geothermal gradients can continue to behave in a ductile manner during deep burial when quartz cement contents are high and porosities are low. Early cementation by quartz due to the high geothermal gradients allows the rocks to behave in a brittle manner very early. On the other hand, sands deposited under low geothermal gradients become buried under very high confining stresses while they are still weakly cemented - a condition that favours ductile behaviour.

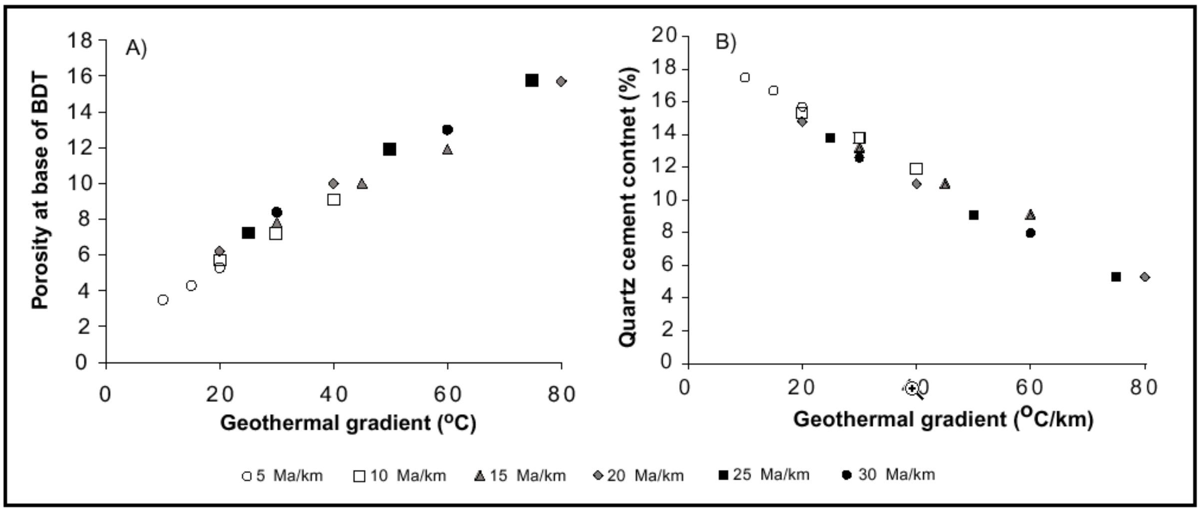


*Figure 2. Plot of the A) porosity, and B) quartz cement content at the DBT against geothermal gradient. The results have been subdivided according to burial rate.*

In summary, faulting of sandstones before significant sediment lithification tends to produce barriers to fluid flow. The extent of permeability reduction tends to increase with increased mean effective stress and temperature. Following extensive quartz cementation, sandstones tend to fault to form conduits for fluid flow. The depth at which this change occurs is controlled by geothermal gradient.

## References

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