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INFLUENCE OF CEMENTED SUB-SEISMIC FAULTS ON POROSITY AND PERMEABILITY IN POROUS SANDSTONE RESERVOIRS

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Abstract

Sub-seismic scale faults and fractures have considerable negative impact on production from hydrocarbon reservoirs. These structures may have only a few centimeters offset and width, but have considerable lateral continuity and the potential to significantly compartmentalise a reservoir. Porosity and permeability have been mapped across examples of small faults in highly porous reservoir sandstones, showing significant decreases in porosity related to both cementation and grain comminution. In uncemented fractures, the gouge material was found to have a modal grain size approximately half of that for the host rock. This represents the degree of comminution required before the fragmented grains increase the internal friction of the fault sufficiently to lock it up. A stochastic fragmentation model is presented which generates gouge particle size distributions from the particle size distribution of the parent material. Initial results from this modelling show that the particle size distribution of the gouge can be accurately predicted. Permeability plots generated using unsteady state profile permeametry show fine permeability structure within the fault zones that is related to grain cataclasis and cementation, with permeability reduced by up to three orders of magnitude. Clearly, fractures with such low permeabilties have the potential for significantly affecting fluid flow, and contribute to degrading the quality of the reservoir. Complexities such as permeability differences across sub-seismic faults are often overlooked when applying reservoir simulation techniques.

Introduction

It is becoming increasingly apparent that sub-seismic scale faults and fractures have both positive[1,2] and negative[3,4] impact on production from hydrocarbon reservoirs**.**

In the North Sea, for example, such structures commonly developed in chalk have a positive contribution to reservoir permeability and provide conduits for hydrocarbon flow.[5] Many fractures do however have a negative effect upon permeability in reservoirs

Scaling relationships[6,7,8] between shear displacement and fault length for sandstones indicate that faults (0.1-4.0 mm wide) with only a few centimetres offset can be several hundreds of meters in length. These extensional, braided microfault systems are often found as primary structures that precede the formation of larger, seismic faults. They often dissect and compartmentalise highly porous parent sandstones having an important impact upon fluid flow and are commonly referred to as “deformation bands”[8,9,10]

Localised strain hardening[10] is generally accepted as the deformation band mechanism involving a locking of grain contacts as the pore space collapses and grains are crushed. Zones of deformation bands and slip surfaces accommodating subsequent strain hierarchically develop from the initial band.

The aim of this study is to investigate these features at a microstructural level using a variety of petrophysical techniques, and comment upon their significance. Deformation bands in the Permian Hopeman Sandstone (Inner Moray Firth Basin, Scotland) are compared with similar structures in aeolian sandstones cored from the U.K. sector of the Southern North Sea. Porosity has been mapped across cemented and uncemented gouge zones using helium, mercury and image analysis porosimetry. In uncemented fractures, the gouge material was found to have a modal grain size approximately half of that for the host rock. The results of a fragmentation model are presented which show that particle size distribution of the gouge can be routinely predicted. Permeability has also been mapped across slabbed core and outcrop sandstones, showing that small-scale deformation bands have a very large impact on fluid flow.

Porosity mapping

Three-dimensional porosity across gouge zones has been measured using helium and mercury porosimetry. Particle size distributions from host sandstones into gouge zones have been calculated using mercury porosimetry and checked by thin section point counting.

Within the bands the pore network is preferentially developed in a direction parallel to the fault. In most cases this appears to be due to oblate grains aligning with their long axes parallel to the fault direction.

Blue dye has been impregnated into thin sections to highlight the pore spaces in the sandstone. A reduction in the percentage of blue dye in thin section documents up to a 50% porosity decrease across deformation bands. Image analysis, helium and mercury porosimetry all give consistent porosity reductions from host-rock into deformation bands. **Fig. 1** shows the ratios of gouge to host rock porosities for outcrop and subsurface samples. The outcrop values are closer to 0.5 as cementation by fluorite and barite is more prevalent. The cements have mainly been introduced into the host sandstone through reactivated cataclastic deformation bands. However, some have been introduced through purely dilatant bands. Calcite has been introduced through reactivated subsurface bands but is absent in the outcrop sandstones. Some non-cataclastic bands show compaction (negative dilatancy) resulting in a porosity decrease with respect to host rock.

The decrease in porosity within the band is more accentuated where the porosity in the host-rock is higher. Porosity reduction appears to result from cataclasis. This has varying manifestations from a few patches of crushed grains in aligned pods and pockets to a fully developed cataclastic zone up to 3 mm thick. Most sandstones have well-developed cataclasis as evidenced by a narrow grain size distribution (**Fig. 2**).

Cataclasis has brought about a reduction in modal grain sizes typically from 0.2 mm in the host to 0.1 mm in the gouge. At this point the granulated quartz increases the internal friction of the fault to effectively lock it up. However, in some gouge zones up to 50% of constituents are still made up of host-sized material. The minimum grain size in a band can drop into the clay size range (<0.004 mm) and at these sizes no measurable porosity is present

Fragmentation modelling. **Fig. 2a** shows an example of a particle size distribution calculated by mercury porosimetry for the gouge material present in a deformation band and that of host rock nearby. In this particular example the rock is a typical poorly cemented aeolian reservoir sandstone. **Fig. 2a** also shows the results from a reiterative stochastic fragmentation model developed in this study, that requires the input of the host rock particle size distribution and a fracture probability distribution which is a function of particle size (**Fig. 2b**). It can be seen that the model reproduces the measured gouge particle size distribution remarkably well. The dependancy of fracture probability upon grain size is a direct result of the "theory of nearest neighbour"[11], which states that juxtaposed particles of the same size are more likely to fracture than a particle surrounded by a range of smaller sized particles. This is because similar-sized particles in contact concentrate the load at fewer points of contact, than if a larger particle were surrounded with a population of smaller sized particles. Grains of a larger size surrounded by smaller grains are commonly uncracked. Feldspar, polycrystalline quartz and rock fragments are virtually absent within the gouge due to their susceptibilty to grain fracturing along crystal cleavages and planes of weakness. The fragmentation modelling has shown that the fracture probability commonly increases logarithmically from zero as grain size increases from a threshold value below which fracturing of grains does not occur **(Fig. 2b).**

Permeability mapping

Probe permeametry has been carried out with an unsteady-state pressure decay profile permeameter[12] which is a reliable, rapid, non-destructive method for determining core permeability and heterogeneity. This technique is particularly advantageous as a wide range of permeabilities from 0.001 to 30 000 md can be measured accurately.

Permeability has been quantified both at 10mm and 5mm grid resolution on core and slabbed outcrop sandstone specimens. This enables the identification of thin, highly permeable beds, permeability barriers and diagenetic features. A grid spacing of 5 mm enables a more elaborate portrayal of permeability microstructure in the specimens. Excel™ macros from Corelab generated contour maps from computer stored data.

The lowest permeabilities in the small faults occur where the permeabilities of the host rock are highest. Little contrast is observed between the permeability of deformation bands and already low host rock permeabilities. However, where the original interconnected porosity is high (up to 1000 mD) a decrease of up to three orders of magnitude can occur in individual small faults. Interconnected porosity parallel to the bands appears to be greater than interconnected porosity in a direction perpendicular to the bands.

The permeability profiles on a 5 mm grid across uncemented gouge zones show a fine permeability microstructure (**Fig. 3**). Permeability clearly decreases as the amount of granulated quartz increases. The dark red permeability shades on **Fig. 3a** coincide with the dark strands on the accompanying core image which are the areas of most advanced grain communition. This fine detail does not show up on the centimetre grid plot. The anastomosing strands on **Fig. 3b** clearly border an area of low permeability. The host sandstone pods between the gouge strands have a slightly higher permeability but are isolated.

In some cases permeability decreases are caused by the diagenetic introduction of pore-occluding cements **(Fig. 3c)** and not cataclasis. In the subsurface sandstones calcite appears to have been introduced along reactivated gouge zones. In the majority of outcrop cases the original bands formed by extension have been re-opened and have acted as dispersive conduit systems allowing the passage of brines from which barite ($BaSO^4$) and fluorite (CaF^2) have been precipitated. Authigenic cementation starts at grain contacts[13] where less free energy is required to nucleate the cementing material as the distance between the grain contacts decreases. If this distance is sufficiently small it is possible to precipitate cement from an undersaturated solution. The smallest pores among crushed grains in the gouge provide sites where nucleation of cement can be triggered more readily than in host rock. These reactivated bands have opened on one (semi-dispersive) or both sides allowing the precipitation of fluorite and barite cements which become less pervasive and more poikilotopic distal to the faults. The cements introduced into the host sandstone from reactivated bands reduce the level of preserved permeability, which is highest in a direction parallel to the faults.

Interpretation. From outcrop evidence the deformation bands with offsets of the order of a few millimetres to centimetres have a considerable lateral continuity (often hundreds of metres). A common displacement length scaling relation[6] is given by,

$$D=cL^n$$

The value of n is controversial; On downscaling of seismic faults into the sub-seismic domain a linear relationship is common.[6,7] Deformation bands obey a power law relation with exponent close to 0.5 and are therefore very long with respect to their maximum displacements compared to faults with well developed slip planes.[8] The deformation bands of **Fig. 3b,** which have a displacement of 4 mm would on a slope of 0.5 have a length of 10 m.

The braided systems of small faults studied in both outcrop and subsurface would have a detrimental impact upon flow acting as barriers due to the cataclastic reduction of porosity and permeability in the fault zone. Each band is a barrier to fluid flow in reservoirs during production (**Fig.3a**) with permeability reductions up to 3 orders of magnitude observed. They clearly have lower permeability than sedimentary barriers mapped in this study. Multiple bands are closely spaced and therefore they have a cumulative effect on permeability. Pods of host sandstone surrounded by deformation bands in reservoirs may lack hydrocarbons because of impervious seams[4]. Furthermore, the host rock pods are bounded by impermeable deformation bands and are clearly isolated (**Fig. 3b**).

The deformation bands have played multiple roles in the control of fluid flow. They have restricted flow in the cataclastic stages and later acted as conduits for diagenetic fluids. The introduction of the cements into the porous sandstones from the deformation bands degrades its quality outwards from the fault and reduces pore connectivity which is most strongly developed in a direction parallel to the band (**Fig. 3c**).

The reiterative fragmentation model accurately predicts gouge particle size distributions for mature quartz arenites. It is possible to input host rock particle size data into the model and generate gouge grain size distributions distributions based on the theory of nearest neighbour[11].

Conclusions

Comparison of (extensional) deformation bands in the subsurface to those in analog sandstones together with scaling relationships indicate that faults with a maximum 1cm offset have considerable lateral continuity. In analog and reservoir sandstones these bands commonly dissect and compartmentalize otherwise good quality reservoir sandstones to a high degree. The deformation bands characteristics relevant to reservoir quality are:

1. Porosity reductions of up to 50 % (from host into faulted sandstones) are caused by the deformation bands studied. This is related to a cataclastic halving of modal grain sizes of host sandstone representing the degree of comminution required to produce strain-hardened structures. They have a greater effect upon the permeability and porosity of reservoir sandstones where the permeability and porosity of the host rock is highest.
2. Host rock grain size distribution and fragmentation factors have been put into a fragmentation model which accurately predicts gouge size distributions. This could be of use in predicting the occurrence of deformation bands.
3. Permeability microstructural maps show the potential of small faults as barriers to fluid flow, and highlight the regions of lowest permeability which are the seams. The pods between the seams have a slightly higher permeability but they are isolated. Permeability reductions up to 3 orders of magnitude are observed.
4. The deformation bands have the capacity for reactivation as conduits, along one or both margins. Intense cementation within and around the deformation bands gives tight, impermeable structural/cement flow barriers in the porous sandstone. The cements have a pervasive influence upon porosity in and around the gouge zone and patchily degrade the petrophysical quality of the sandstone distal to the faults.

Nomenclature

D=fracture displacement
L=fracture length
c=scaling relation constant
n=scaling relation exponent

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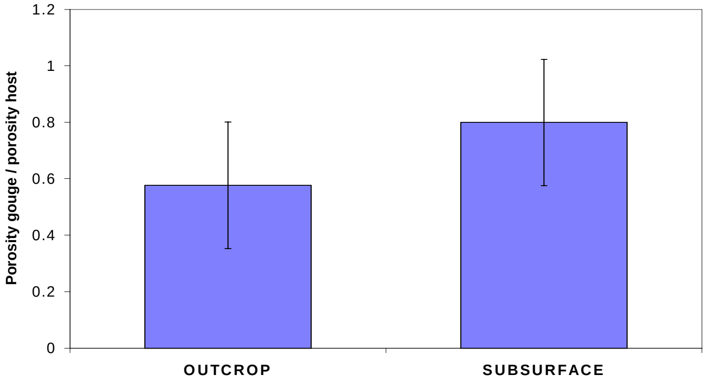

Fig. 1-Histogram of porosity ratios across cemented and uncemented outcrop and subsurface samples

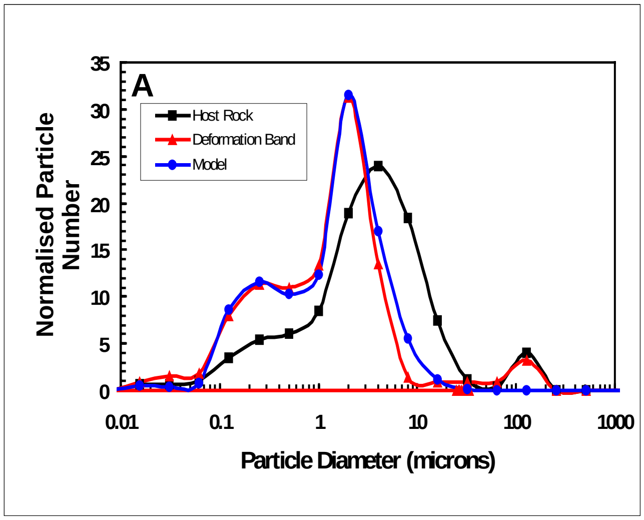

Fig. 2-(a) Typical grain size distribution curves for reservoir and outcrop sandstones. The results of modelling of gouge particle size distribution is shown by the extra line which reproduces the calculated distribution well.

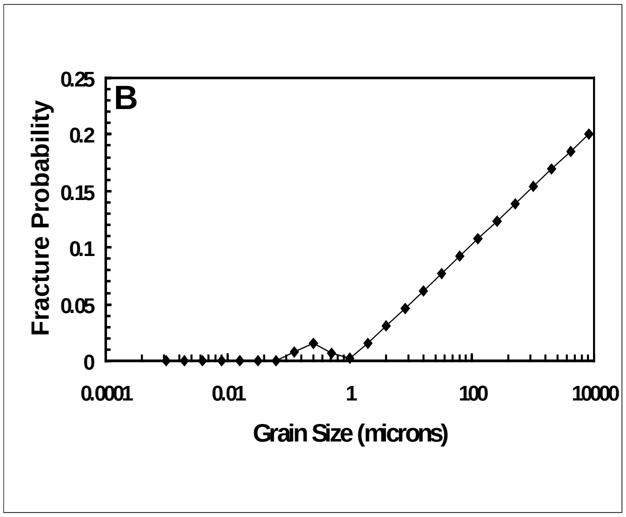

Fig.2-(b)Fracture probability as a function of particle size

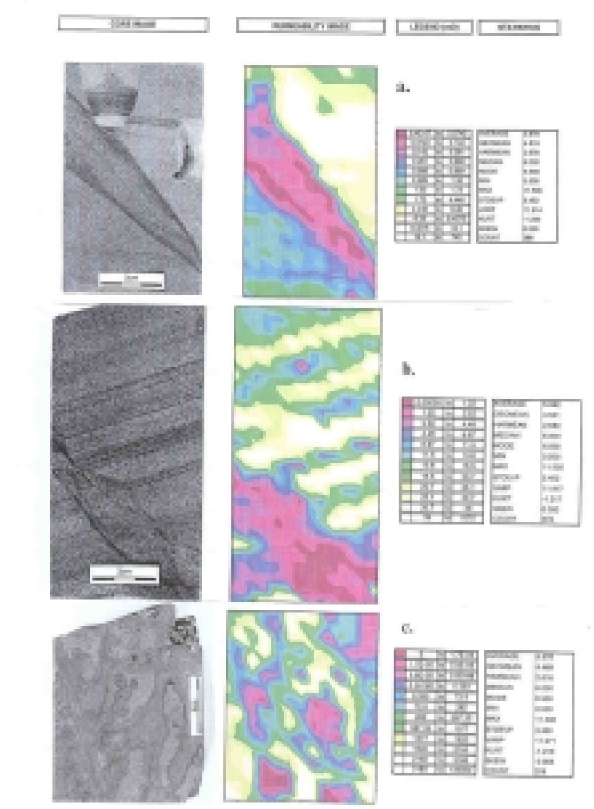

Fig.3-Fine permeability microstructure in and around uncemented (a,b) and cemented (c) deformation bands.