Grain and pore micro-texture in sandstone sill and depositional sandstone reservoirs: preliminary insights

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Abstract: Petrographic micro-textural analysis and conventional core-plug analysis of samples from a depositional sandstone and a sandstone sill are used to compare with similar data derived from micro-CT (MCT) analysis of the same samples. A remarkable richness of information derived from the MCT data identifies isotropic granular and pore fabrics at micrometre-scale in the sandstone sill that contrast markedly with the laminated fabric in the depositional sandstone. In the sandstone sill, porosity and permeability are more homogenous than in the depositional sandstone, in which lamination creates approaching two-orders of magnitude difference in permeability and enhances horizontal permeability relative to vertical permeability. In the sill lower pore-throat shape factors and larger pore coordinate numbers are present than in the depositional sandstone. Preservation of the isotropic pore and grain structure in the sandstone sill is indicative of significant fluidised flow normal to the fracture margin during emplacement.

Sandstone intrusions, the main reservoir components of sand injection complexes, are identified increasingly as significant reservoir volumes in many deep-water clastic reservoirs (Hurst *et al.* 2005). Characteristics such as discordance with bedding (Huuse *et al.* 2007) give them distinctive oilfield-scale geometry and the highly-connected networks of sandstone facilitate excellent hydraulic continuity (Briedis *et al.* 2007).

Here we examine micro-scale characteristics of a sandstone sill and compare these with depositional sandstone using data from petrographic and electron microscopic analysis and, micro-CT analysis (MCT). Assimilation of data from these different scales of resolution is used to make preliminary investigation of the relationships between geological characteristics, the processes by which they formed and their significance to the reservoir characterisation of sandstone intrusions.

Characterisation of sedimentary rocks using micro-CT (MCT) scanning gives geologists the opportunity to make quantitative, non-destructive measurements of static and dynamic physical parameters. Some of the measurements are complementary to conventional laboratory measurements that estimate porosity and pore-size distribution (Vergés *et al.* 2011) and facilitate modelling of a wide range of fluid-flow experiments that are challenging and time-consuming using traditional laboratory methods (Zhang *et al.* 2014; Berg & Held 2016; Yang *et al.* 2016). From a laboratory geophysics perspective, MCT scanning is a hugely flexible method for conducting series of numerical experiments on the same sample.

This study examines sandstone samples taken from the Panoche Giant Injection Complex (Vigortio *et al.* 2008) specifically to examine granular and pore-structural characteristics of a sandstone sill and to compare them with similar characteristics in depositional sandstone. Because sandstone intrusions form during natural hydraulic fracturing of low permeability, fine-grained strata and concomitant, upward sand fluidisation, MCT data may provide insight into the preservation of evidence of vertical fluidised, granular transport. The depositional sandstone is examined as reference material in which sedimentary lamination occurs that is unrelated to sand fluidisation. Typically the granular structure of sandstone is examined in 2D petrographic (thin) sections, augmented by electron microscopy. Although 3D reconstructions of granular structure are possible by combining the images of multiple thin sections (Bodla *et al.* 2014), MCT imaging gives the opportunity to examine granular and pore structure directly in 3D. To the best of our knowledge, MCT data from sandstone intrusions is not previously investigated.

Geological setting

Sandstone samples were taken from the Panoche Giant Injection Complex (PGIC) that intrudes into deep-water mudstone-dominated strata of the Moreno Formation of Upper Cretaceous and Lower Palaeocene (Danian) age (Vigorito *et al.* 2008). The locations sampled are a depositional, turbiditic sandstone that is unaffected by sand fluidisation and, a sandstone sill that is part of a >1.5 km diameter saucer-shaped sandstone intrusion in Right Angle Canyon (Fig. 1). PGIC outcrop covers an area of ~350 km^2

and is believed to be the largest known outcrop of a giant sand injection complex (Vigorito & Hurst 2010). Exceptional exposure allows the spatial relationships between sandstone intrusions, parent depositional units and sand extrusions onto a palaeo-seafloor to be examined in detail.

Sand injection and fluidisation occurred during shallow burial (maximum ~1.5 km burial) when mudstone and sandstone were poorly consolidated. Pore-fluid pressure (P_f) exceeded both the fracture gradient and the hydrostatic gradient thereby creating a system of natural hydraulic-fractures into which fluidised sand was injected (Vigorito & Hurst 2010). Turbulent flow prevailed and locally eroded fracture geometry (Hurst *et al.* 2011). Sandstone intrusions formed a pervasive architecture of hydraulic fractures with the pore-fluid pressure (P_f) within them forming a lower dyke zone in which $P_f > \sigma_h + T_h$, a sill zone in which $P_f > \sigma_v + T_v$ and, an upper dyke zone in which $P_f > \sigma_h + T_h$ where, σ_h is the horizontal stress, σ_v is the vertical stress (lithostatic overburden), T_v and T_h are the vertical and horizontal tensile strength of the host strata.

Methods

Experiments

Three core plugs (Φ 25 mm × 50 mm) were drilled, one vertical and one horizontal plug from the depositional sandstone and a vertical plug from the sill. The core plugs were analysed using a ZEISS VersaXRM-410 micro-CT instrument for which the minimum spatial resolution was 0.9µm and the minimum voxel size was 0.1 µm. The scanning voltage and power were set to 140KV and 9.9W, respectively. Scans with resolution of ~23.7µm/pixel (low resolution CT) and ~1.48µm/pixel (high resolution CT) were acquired. Because the sandstone samples are poorly consolidated, inevitable damage to the edges of the core plugs occurred during handling. To compensate for the possible damage, the outer edges of images were removed from the low resolution CT images to ensure that the images represent their undamaged state and to preclude analysis of possible artefacts caused by sample damage. Following the low resolution CT scan, the diameter of which is approximately 21.75 mm, a smaller cylindrical area (~ Φ 1.45 mm × 1.45 mm) was selected in the middle of each core plug for the high resolution CT scan.

Porosity (Ø) and permeability (K) are measured using nitrogen porosimetry and a helium permeameter, respectively. In the vertical plug from the depositional sandstone Ø = 30.7%, K_v = 98.4 mD, in the horizontal plug from the depositional sandstone Ø = 30.5%, K_h = 204.6 mD and, in the vertical plug from the sill Ø = 27.0%, K_v = 136.2 mD. Petrographic sections from both plugs were examined using an IS-ABT-55 scanning electron microscope in back-scattered electron mode; images were acquired to enable comparison with MCT data. Chemical compositions of areas of interest were obtained using a Link Analytical AN10/55S ED X-ray analyser.

Image processing and simulation

To obtain porosity estimates MCT images were segmented using *ImageJ* and *Avizo 9.0* software. The volume fraction (porosity) of the MCT images is obtained directly using *Avizo*. Porosity measurements from nitrogen porosimetry were used to guide and validate the determination of the intensity threshold between pores and minerals during image segmentation.

Because the length-scale of fluid flow is very small in porous media, flow has a very low Reynolds number ($Re \ll 1$) and the convective acceleration terms in the Navier-Stokes equations are negligible. Fluid flow is considered as Stokes flow, also termed creeping flow (Schieber & Córdoba, 2013), and the incompressible Stokes equation as defined by Sciffer (1998) is:

$$\begin{cases} \mu\nabla^2\boldsymbol{u} - \nabla\boldsymbol{p} = 0 \\ \nabla.\boldsymbol{u} = 0 \end{cases} \quad (1)$$

where ∇ is the gradient operator, $\nabla.$ is the divergence operator, ∇^2 is the Laplacian operator, $\boldsymbol{u}$ is the velocity of fluid, m·s^{-1}, μ is the dynamic viscosity of fluid, Pa·s, and $\boldsymbol{p}$ is the pressure of fluid, Pa.

When solving equation (1) in pore cubes derived from micro-CT, the pressure difference between entrance and exit (ΔP) is assigned, the velocity of fluid ($\boldsymbol{u}$) is obtained from the solution, and flow rate of fluid (Q) can be derived from velocity of fluid ($\boldsymbol{u}$). Then Darcy's law can be applied to estimate the absolute permeability:

$$k = \mu\frac{Q}{S}\frac{L}{\Delta P} \quad (2)$$

where K is the absolute permeability, m^2, Q is the flow rate, m$^3 \cdot$s^{-1}, S is the cross section of the pore cubic, m^2, L is the length of the pore cubic (m), ΔP is the pressure difference between entrance and exit of the pore cubic (Pa).

Equations (1) and (2) are solved using the *Absolute Permeability Experiment Simulation* Module in the *Avizo 9.0* software.

Pore network

Quantitative evaluation of the pore structure and pore network is done by extracting of MCT data using the maximal ball (MB) method (Dong 2007). For a pore or throat, shape factor G is defined by its cross-section area A and its perimeter P (Mason & Morrow 1991):

$$G = \frac{A}{P^2} \tag{3}$$

Coordination number Z, also termed the connection number, is the number of independent throats linked to a single pore (Arns *et al.* 2004; Dong 2007).

Results

Porosity and pore structure

Petrographic sections of the samples show lamination present in the depositional sandstone (Fig. 2a) and no obvious lamination in the sill (Fig. 2b). To elucidate and quantify the difference between the depositional and intrusive sandstone, the low resolution MCT data were processed using the *Avizo analysis tool* to estimate the pore volume fraction. The depositional sandstone is strongly heterogeneous with $Ø_{total}$ = 28.7% but with Ø in different laminae of 37.9% and 19.2% (Fig. 3c). In the sill $Ø_{total}$ = 24.5% that when compared with Ø from three randomly-selected areas of 24.5%, 26.6% and 25.5% reveals that is approximately homogenous (Fig. 3d). In order to demonstrate the spatial porosity difference between depositional sandstone and the sill, 80 small sub-volumes were extracted from both pore volumes of depositional sandstone and the sill (Fig. 3). The sill has a more homogenous porosity distribution than the depositional sandstone (Fig. 4).

Pore networks and pore structure parameters are calculated from the high resolution MCT data: pore radius, pore-throat radius, pore shape factor and co-ordinate number. For all parameters the sill has higher values than the depositional sandstone (Fig. 5) although, $Ø_{total}$ is lower for the depositional sandstone. This may be because the pore radii and throat data are correspondingly lower (Figs. 5c, d). However, this is not the case as pore shape and coordinate number are independent of $Ø_{total}$ (Figs. 5e, f). Visual inspection of the data shows that large pores (red spheres) in pore networks are more homogenously distributed in the sill (Fig. 5b) than in the depositional sandstone (Fig. 5a). In the sill the throat shape factor is higher than in the depositional sandstone (Fig. 5e), which implies that the pore throats in the sill are less narrow and the pores are better connected. Larger pore coordination values in the sill are indicative of greater numbers of connected pore throats than in the depositional sandstone.

Permeability (K) anisotropy

Depositional sandstone gas permeability values record significant anisotropy (K_v = 98.4 mD and K_h = 204.6 mD) that usually are attributed to the presence of sedimentary laminae (Fig. 2a). Smaller-scale heterogeneity in both samples is investigated by evaluating six arbitrary sub-volumes of data that were extracted from the high resolution MCT data (Fig. 6a, b) and used to simulate $K_{absolute}$ by solving equations (1) and (2). Results of the simulation show that in the depositional sandstone the vertical permeability (Z direction, logarithmic mean value is 105.7 mD) is significantly lower than horizontal permeability (X and Y directions, logarithmic mean values are 158.2 mD and 145.7 mD) (Fig. 6c). By contrast in the sill, the permeability values have no specific relationship to orientation and the mean permeability in the Z direction (logarithmic mean value is 204.7 mD) is similar to the mean permeability in X and Y directions (logarithmic mean values are 193.6 mD and 219.4 mD) (Fig. 6d). In the depositional sandstone the relationship between porosity and permeability, which is typically used to predict permeability in the absence of direct measurement of permeability, reveals a permeability range spread over almost two orders of magnitude (Fig. 6e) whereas in the sill the range is less than one order of magnitude (Fig. 6f). Clear linear trends between porosity and permeability in X, Y and Z orientation are not apparent in either sample. At a granular (sub-mm) scale it is grain orientation that determines permeability anisotropy and not the presence or absence of lamination. Visual inspection of the depositional sandstone reveals that pores are better connected in X and Y directions than in the Z direction (Fig. 6a). Fig.7 compares the length scales of the methods used to characterise porous media in this study and the characteristics that dominate the derived characteristics.

Disscussion

Sandstone intrusion reservoirs

Sandstone intrusions are volumetrically significant reservoirs in the Palaeogene of the North Sea (Hurst *et al.* 2005) and are increasingly identified as significant in a global context (Huuse *et al.* 2010). They are exemplified by high-quality reservoirs, excellent lateral and vertical connectivity and, excellent recovery (Briedis *et al.* 2007; Satur & Hurst 2007; Schwab *et al.* 2015). Borehole-log motifs and sedimentological data often record the presence of homogenous, fine- to medium-grained sandstone (Duranti *et al.* 2002) in which structureless sandstone units are interbedded with sandstone with distinctive internal structures formed during sand fluidisation (Duranti & Hurst 2004; Scott *et al.* 2009). Sandstone intrusions are unusual, primary drilling targets during hydrocarbon exploration hence, they often constitute in-field or near-field targets associated with super-giant fields in mature basins (e.g. Lonergan *et al.* 2007; Pyle *et al.* 2011). In this context, the understanding of micro-scale reservoir characteristics of sandstone intrusions, and its relevance to the optimisation of hydrocarbon recovery are an integral part of prolonging field-life.

Granular texture

MCT data exhibit the presence of laminated internal structure in the depositional sandstone and a structureless character in the sill (Figs. 3a, b) that are similar to respective internal structure seen in the lower resolution petrographic sections (Fig. 2). Distribution of heavy (density >2.9 g.cm^{-3}) minerals is markedly different between the samples with segregation present in the depositional and absent in the sandstone intrusion. With the exception of the largest (>1mm diameter) heavy minerals, we believe that they are primarily detrital grains, which during deposition undergo hydraulic segregation. Large heavy minerals (circled on Figs. 3a, b) are identified using BSEM as diagenetic, pyrite-cemented, detrital-grain aggregates.

Two post-depositional processes are likely to create granular homogeneity in sandstone: i) fluidisation where grains are entrained as part of a fluid flow or, ii) percolation of fluid that re-organises granular structure (typically referred to as liquefaction by geologists). Here, we know that the homogenous granular texture is present in a sandstone sill (Fig. 1c) and that sand fluidisation is implicit (Hurst *et al.*

2011). One can thus with confidence, associate sand fluidisation with the lack of granular organisation that forms sedimentary structures (Fig. 3b) and the homogeneity is caused by a rapid cessation of flow during which deposition had insufficient time to cause hydraulic segregation of grains. Absence of granular segregation is similarly recorded by the uniform porosity distribution in the sill (Fig. 3d). Liquefaction of sand forms elutriation structures such as dish structures, consolidation laminae and associated pillars or pipes (Lowe & LoPiccolo 1974) that are produced by the modification of pre-existing granular heterogeneity and inter-granular re-organisation (Hurst & Cronin 2001). Absence of internal structures and granular homogeneity are not diagnostic of sandstone intrusions (Scott *et al.* 2009; Hurst *et al.* 2011; Ravier *et al.* 2015) however, sand fluidisation and injection frequently create granular homogeneity (Duranti & Hurst 2004).

Sandstone sills form in sub-horizontal fractures that are approximately parallel to bedding but, the isotropic, homogeneous pore fabric records a significant direction of fluidised sand flow that was normal to the fracture-margins. Grains oriented sub-vertically rather than parallel to the lower fracture margin. Thus although sills prop open fractures that formed approximately parallel to bedding, the homogeneity of the granular fabric records a vertical component of fluidised flow. In the absence of diagenetic cementation of the sill, mechanical compaction has preserved the grain and pore isotropy.

Porosity, pore networks and pore structure

Large pores (red spheres in Figs. 5a, b) are more homogenously distributed in the sill than in the depositional sandstone. This correlates with the general homogeneity and lack of internal structures visible in the MCT image and the lack of stratification that is depicted by the heavy mineral distribution (Fig. 3b) and, reflects the presence of an isotropic pore structure in which K_v is similar to K_h. As expected, in the depositional sandstone lamination persists during compaction and the pore structure is strongly controlled by the granular fabric formed during deposition (Figs. 3a, c and Fig. 5a), a characteristic that is consistent with high-density probe permeameter data from laminated sandstone (Halvorsen & Hurst 1990; Hurst & Rosvoll 1991). When fluidisation stopped and pore-fluid pressure fell, rapid loss of fluid occurred, which preserved the homogenous granular texture and eventually forming a present-day $Ø_{total}$

= 24.54% (Figs. 3b, d and Fig. 4b). The granular volume of naturally fluidised sand is not constrained however, laboratory experiments using glass spheres suspended in silicon oil showed that during fluidisation no more than 50% granular volume was possible and, a most likely range is ~17% to 50% (Gibilaro *et al.* 2007; Di Felice, 2010).

Although the precise history of porosity reduction is unconstrained it is unlikely that the ~45% loss of pore volume was instantaneous. It seems likely that reduction of porosity to its present-day value while preserving the original pore-structure was enabled by continuous gradual mechanical compaction of grains without observable evidence of intergranular shear. Independent mineralogical data from a nearby locality estimate burial temperatures for these strata as <50°C (Hurst *et al.* 2017), well below the temperature associated with the onset of chemical compaction (Nadeau 2011).

Permeability estimation

In the depositional sandstone, permeability estimates in X and Y orientations (K_h) are generally higher than in the Z orientation (K_v) (Figs. 6a, c) and the permeability of all estimates (40.9 mD to 483.5 mD) has a range greater than one order of magnitude. The sub-horizontal orientation of grains (Fig. 3a) enhances horizontal pore connectivity and K_h and, the heterogeneity caused mineralogical variability in sedimentary laminae (Fig. 2a), causes the >1 order of magnitude permeability range. By contrast, but consistent with the pore structure data, permeability estimates in the sill have similar values independent of orientation. Also the range of permeability present has a range of approximately a half order of magnitude (107.0 mD to 678.2 mD), which reflects the more homogenous grain fabric and pore isotropy present.

It is unusual for sandstone to have $K_h \approx K_v$ because depositional structures tend to be sub-horizontal and when consolidated they create permeability baffles to vertical flow. Thus sedimentary structures have a strong influence on cm-scale (0.01 to 0.1 m) measurement of permeability (Weber 1982; Hurst & Rosvoll 1991). Our higher-resolution data allow the examination of permeability at a finer scale and confirm the importance of pore structure and the orientation of granular fabric on permeability anisotropy. In the sandstone sill permeability is isotropic. It should not be inferred that sandstone intrusions have higher permeability than associated depositional sandstone, in fact all data from Palaeogene, subsurface sandstone-intrusions in the Norwegian and UK continental shelves show that for similar porosity, permeability is consistently lower than in spatially-associated depositional sandstone (Duranti *et al.* 2002; Hurst *et al.* 2011).

Conclusions

MCT images differentiate sedimentary structures and structureless sand in the depositional sandstone and a sandstone sill and provide a quantitative measure of pore and granular structure and anisotropy. Lamination pervades in the depositional sandstone and creates orders of magnitude difference in average porosity and enhances horizontal permeability (K_h) relative to vertical permeability (K_v).

In the sill (sandstone intrusion) a homogenous granular texture is preserved in which the pore structure is isotropic. Also the sill has lower throat-shape factors and larger pore coordinate numbers than depositional sandstone. Large pores are more homogeneously distributed in the sill; this is consistent with the greater textural homogeneity in the sill.

At millimetre- to micrometre-scale in the depositional sandstone, K_v (Z direction) is consistently lower than K_h (X and Y directions). In the sandstone sill K_v is similar to K_h and at micrometre-scale is isotropic. This is caused by pore structure and grain orientation rather than the sedimentary lamination.

Preservation of an isotropic pore and grain structure in the sandstone sill is indicative of significant fluidised flow normal to the fracture margin during emplacement.

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Figure captions

Fig. 1. (**a**) Location of the Panoche Giant Injection Complex (PGIC). (**b**) The saucer-shaped intrusion in Right Angle Canyon with lithostratgraphic units in the Moreno Formation (Upper Cretaceous-Palaeocene) shown (after Vigorito and Hurst 2010). Units are as follows: red, sandstone intrusions; yellow, depositional sandstone; grey, mudstone and siltstone; orange, sand extrudites. Sample locations X, depositional sandstone (turbiditic channel) and Y sandstone sill.

Fig. 2. Petrographic images in plane-polarised light. (**a**) Vertical section from the depositional sandstone that is from a turbiditic channel-fill (X in Fig. 1) showing depositional lamination. (**b**) Vertical section from the sandstone sill with no lamination nor gradation of grain size (Y in Fig. 1).

Fig. 3. Density variations derived from low resolution MCT images of depositional sandstone and a sandstone sill (note that the sampled volume is < 20 mm high): (**a**) Depositional sandstone in which small variations in density correspond to depositional laminations, heavy (density >2.9 g.cm^{-3}) minerals that form bright areas are highlighted in red; (**b**) Sandstone sill in which no density segregation is observed. Heavy minerals are highlighted in blue, most heavy minerals are detrital but the largest grains (an example is highlighted) are pyrite cement. (**c**) Pore distribution in the depositional sandstone in which porosity between different laminae varies from 19.2 to 37.9%, averaging 28.7%. (**d**) The sill in which porosity is approximately homogeneous, 24.52 to 26.61%, averaging 24.5%. Pores are segmented from the low resolution MCT images in (**a**) and (**b**).

Fig. 4. Porosity ranges in the depositional sandstone and sandstone sill. 80 sub-volumes (each one with the size of 3555μm ×3555μm ×3555μm) were extracted from the total pore volumes in both samples (Fig. 3) and the volume fraction (porosity) of each sub-volume calculated. The depositional sandstone has a wider range of porosity than sandstone sill.

Fig. 5. Pore network and pore structure parameters derived from MCT. Spheres represent the pores, with red spheres representing the largest pores. Pore throats are represented as lines between pores (spheres). (**a**) Pore network in the depositional sandstone. (**b**) Pore network in the sandstone sill. (**c-f**) Frequency distributions from the sample volumes in (a) and (b): (**c**) pore radius, (**d**) pore throat radius, (**e**) pore shape factor and (**f**) pore coordinate number. All parameters are greater in the sandstone sill.

Fig. 6. Permeability anisotropy derived from MCT data. Areas of the six sub-volumes were extracted and used for the simulation of absolute permeability in each sample. (**a**) Schematic of a sub-volume extracted from the segmented pore volume of the depositional sandstone. (**b**) Schematic of sub-volumes extracted from the segmented pore volume of the sandstone sill. (**c**) Comparison of permeability in the depositional sandstone in X, Y (both K_h) and Z (K_v) orientations. In K_h (X and Y orientations) > K_v (Z orientation). (**d**) Comparison of permeability in the sandstone sill in which X, Y and Z orientations have similar K_h and K_v values. (**e**) Cross-plot of porosity and permeability for all sub-volume samples from the depositional sandstone. (**f**) Cross-plot of porosity and permeability for all sub-volume samples from the sandstone sill.

Fig. 7. Comparison of the length scales of the methods used to characterise porous media in this study and the characteristics that dominate the derived characteristics.