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Comparative pore surface area in primary and secondary porosity in sandstones

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ABSTRACT

Primary and secondary porosity in sandstones possess different pore geometry characteristics, but these are not well quantified. The pore surface area in 2 suites of sandstones exhibiting only primary porosity (Permo-Triassic, Northern Ireland) and only secondary porosity (Cambrian, England) were measured using JMicrovision software. The data show pore surface areas per unit pore volume ~2.5 times as great in the secondary porosity compared to the primary porosity. This difference is great enough to have a significant impact on properties dependent on pore surface area, including oil production and capacity for microbial colonization in the deep biosphere.

1. Introduction

Pore geometry is a subject for study for petroleum geologists and engineers who are concerned with the potential of subsurface rocks to function as hydrocarbon reservoirs. Quantitative data is required at a range of scales from whole sand bodies to micro-pores, to predict their capacity and deliverability. One of the most fundamental approaches to documenting pore geometry is image analysis (e.g. Anguy et al., 1999; Fens, 2000; Cerepi et al., 2002; Yang et al., 2013). This study utilizes a simple image analysis procedure to assess the difference between two fundamental pore types, primary and secondary porosity in sandstones.

Secondary porosity is of fundamental importance to the prospectivity of siliciclastic reservoirs. The development of secondary porosity, i.e. porosity generated during mineral dissolution during burial, is ubiquitous in sandstones that contain feldspars, as the feldspars are readily dissolved by acidic pore fluids (Schmidt and McDonald, 1979). Numerous studies (e.g. Giles and de Boer, 1990; Taylor et al., 2010) conclude that secondary porosity is the norm for sandstone successions, and in some cases it represents the majority of the porosity.

The recognition of secondary porosity is important to reservoir exploitation, as primary and secondary porosity differ in associated permeability, heterogeneity of porosity, and pore surface area. However there is surprisingly little data in the public domain to demonstrate these purported differences. In this study, we present data based on image analysis of two sets of sandstones, one containing just primary pores and the other containing abundant secondary pores due to partial dissolution of feldspar grains, and compare their pore surface areas.

2. Methods

Two sets of sandstones were chosen that are comparable in grain size, sorting (fine-to medium-grained, well sorted) and degree of compaction (predominantly grain point contacts before grain dissolution). Primary porosity was imaged in fluviatile sandstones of the New Red Sandstone (Permo-Triassic) of Northern Ireland, in which pore outlines are well defined by iron oxide grain coatings (Fig. 1A and B). The sandstones were sampled from the Kingsmill borehole (depth 343.8 m), the Larne 1 borehole (1103.4 m), the Blacks Factory, Newtonards, borehole (depth 47.2 m) and surface exposures at Lissan Estate and Bonds Mill Bridge (localities in Parnell, 1992). These sandstones were sampled as part of a hydrocarbon exploration programme (Parnell, 1992; Fitzsimons and Parnell, 1995). Secondary porosity was imaged in shallow marine sandstones of the Cambrian Comley Sandstone, Shropshire, England (Fig. 1C and D), in which a solid oil residue helps to preserve and define intricate pore shape in partially dissolved feldspars (Parnell, 1987; Parnell et al., 2017). This allows us to measure only secondary porosity, not primary porosity that has been subsequently modified. The Comley Sandstone was sampled at Robin's Tump, Shropshire. Both sandstones have well-documented diagenetic histories (Parnell, 1987, 1992). The mean grain sizes recorded from the Permian of the Kingsmill Borehole and from the Cambrian Comley Sandstone are 1.3 ± 0.5 mm and 1.1 ± 0.5 mm respectively, indicating that they are of comparable nature.

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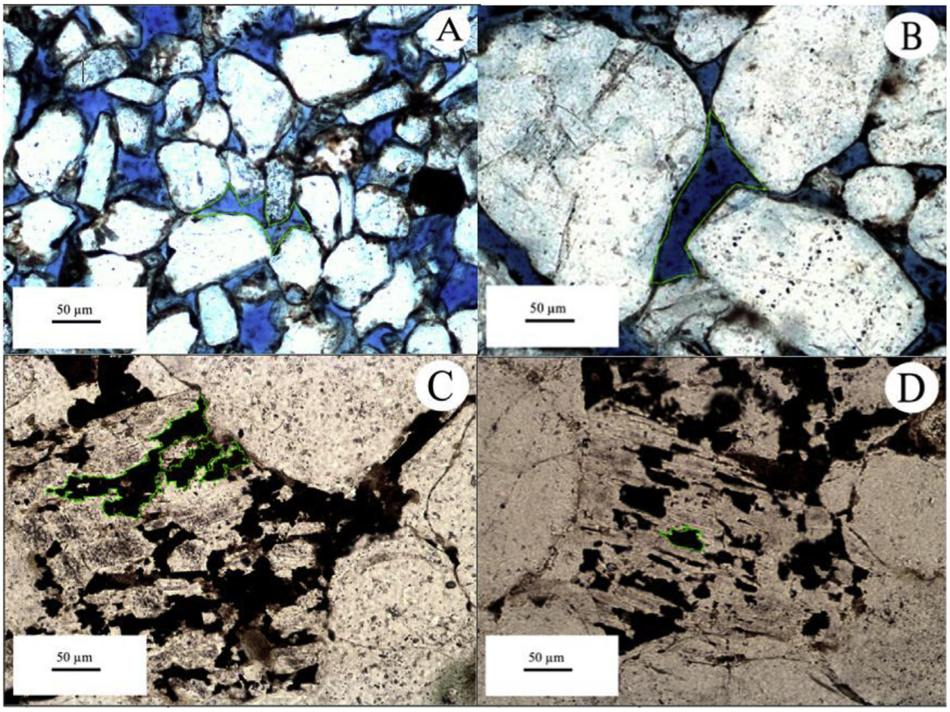

Fig. 1. Thin section micrographs of case study sandstones. A,B, Triassic sandstones exhibiting unaltered sand grain boundaries outlined by iron oxides, and homogenous primary porosity. C,D, Cambrian sandstone in which feldspar grains are partially dissolved to form irregular secondary porosity with high surface area. Porosity is oil-filled (black).

The study uses one example each of primary and secondary porosity, but we believe that they are representative. Both examples are based on 5 to 10 thin sections, so represent an average of many rock samples. They are also characteristic of their type: the Permo-Triassic samples are typical of mineralogically mature (quartz-rich) sandstones with high primary porosity, and the Cambrian samples are typical of feldspar-bearing sandstones in showing partial dissolution of the feldspars (e.g. Haszeldine et al., 1999; Taylor et al., 2010). A large global database of sandstone compositions shows a mean feldspar content of about 20% (Taylor et al., 2010).

The thin sections were first examined with a Meisi Techno microscope. Once a pore space was selected, an Infinity 1 camera with Infinity Analyze software was used to capture an image of the pore, at ×20 magnification. The clearest forty images were chosen for each pore type. Analysis of the eighty images was undertaken using JMicrovision 1.2.7. The colour spectrum for each image was adjusted to maximise the contrast between the pore and the surrounding mineral. Porosity was measured by a background extraction, which allows the user to manipulate the red, green, and blue spectra within the image to highlight a single feature. With the help of a histogram, specific points within the spectrum can be chosen for display in the image. This real time method allows manipulation of the level of colour to one that best displays porosity. Then the area and perimeter of each pore was measured, using the JMicrovision 2D measurement tool. A proxy for pore surface area is given by the ratio pore of perimeter and pore area, the 'pore surface area ratio' (Ehrlich et al., 1984). An autotrack option was used to create a custom polygon to outline each measured pore space. A number of the measured secondary pores contained grain material within the pore space, which would be connected to the pore margin in 3-D. In these cases, additional measurements were made of the enclosed grain material, and appropriate adjustments made to the pore are and perimeter values. To test whether measurements made at a greater resolution would give a different result, a secondary pore was measured at progressively higher magnification up to 10 x the standard resolution.

3. Results

The mean porosities for the New Red Sandstone (primary porosity) and Comley Sandstone (secondary porosity) are 19.6% and 9.0% respectively. The mean surface area ratios are 0.17 and 0.31 respectively. Thus, the mean surface area ratio for secondary porosity is 1.8 times that for primary porosity, i.e. there is 1.8 times as much surface area per unit volume. The mean ratio of 1.8 belies a variation in ratios dependent on the total area measured. In the largest pores, of about 10,000 square microns, the ratio is as high as 2.3, reflecting a greater level of detail that can be measured in the perimeter of the secondary pores. The measurements at up to 10 x higher resolution also show that the greater detail evident in the secondary pore perimeter raises the mean ratio by about 40%, i.e. to about 2.5, but had reached a constant ratio at this level.

The average ratio for primary pores at ×1 is 0.035 and for secondary pores at ×1 is 0.072 (Table 1). The average ratio for primary pores at ×10 is 0.014 and for secondary pores at ×10 is 0.033. The mean primary surface area ratio decreased by 61% and the mean secondary pore surface area ratio decreased by 55%. While the ratio will decrease as magnification increases, secondary porosity surface area is still greater.

Table 1
Perimeter/area (p/a) ratios for primary and secondary pores measured at ×1 and x10.

Sample Number at x1	p/a Ratio	Sample Number at x10	p/a Ratio
secondary 34	0.044	Secondary 34	0.02
Secondary 5	0.049	Secondary 5	0.023
secondary 20	0.062	secondary 20	0.028
secondary 12	0.083	Secondary 12	0.041
secondary 26	0.123	secondary 26	0.051
primary 2	0.017	primary 2	0.007
primary 10	0.013	primary 10	0.005
primary 26	0.034	primary 26	0.013
primary 32	0.044	primary 32	0.016
primary 21	0.067	primary 21	0.028
Primary ×1 mean	0.035	Primary ×10 mean	0.014
Secondary ×1 mean	0.072	Secondary ×10 mean	0.033

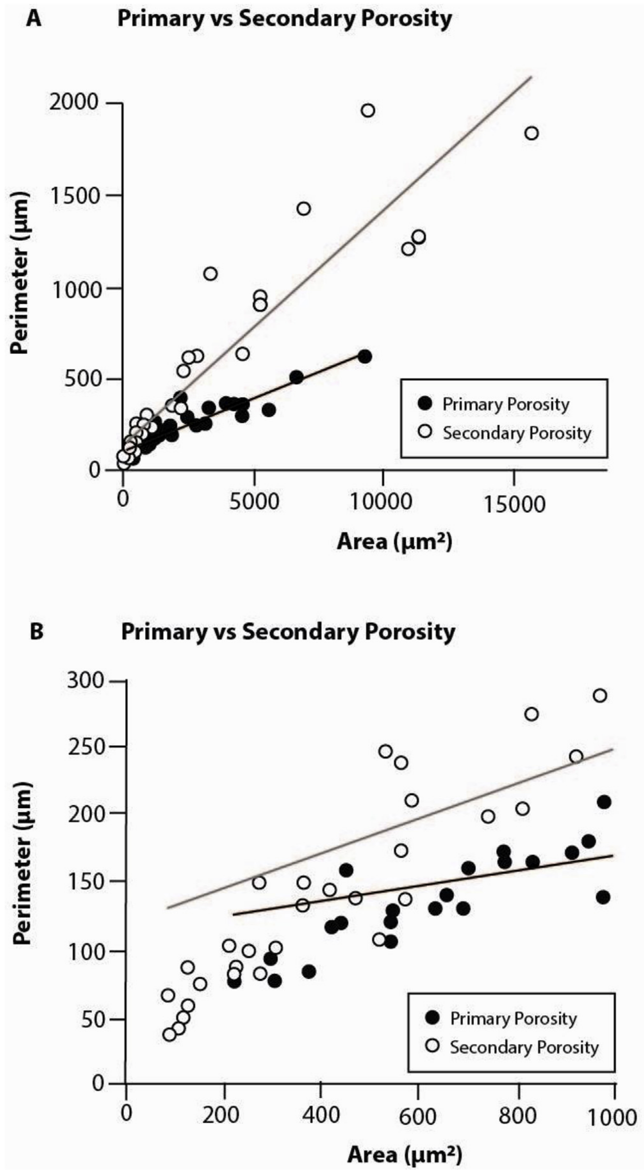

Fig. 2. Cross-plot of pore area and pore perimeter data for case studies of primary and secondary porosity. A, full data: B, close-up of data near origin in A.

The combined plot of area vs. perimeter data (Fig. 2) confirms that, for the same pore area, secondary porosity consistently exhibits a higher perimeter, and hence higher surface area ratio.

Morgan and Gordon (1970) state that larger pores have a smaller surface area while smaller pores have a greater one. Primary and secondary surface area ratios were plotted against pore area to determine how much off an affect the pore area would have on the results (Fig. 3). Fig. 3 shows that surface area for both primary and secondary pores increases as the pore area decreases. The figure also highlights that the secondary pore surface area is higher than that of primary pores with the same area, indicating that pore area has no direct effect when comparing the two.

4. Discussion

Pore surface area is important for several reasons:

(i) Where oil adheres to the grain surfaces, increased pore surface area means a greater proportion of the oil is adhering to the rock.
(ii) Increased surface area influences other important production parameters, including permeability and irreducible water content (Morgan and Gordon, 1970; Baker et al., 2015).
(iii) Greater surface area means a larger template for the growth of authigenic minerals, especially clay minerals, and for further dissolution (Hodson, 1999; Gautier et al., 2001).
(iv) Microbes are ubiquitous in sandstone aquifers to at least 2 km depth (McMahon and Parnell, 2014; Probandt et al., 2018), and the overwhelming majority are resident on grain surfaces, rather than suspended in the pore fluid (Alfreider et al., 1997; Griebler et al., 2002). Therefore, greater surface area means capacity for a greater microbial cell density in the deep biosphere.
(v) In addition to the capacity for microbial loading, the surface area affects the mobility of bacteria, and hence offers a means of their control (Asadishad et al., 2011; Bai et al., 2016).

The origin of secondary porosity at depth has been re-evaluated since early studies emphasized its importance (Schmidt and McDonald, 1979). It is now appreciated that new porosity cannot be readily added at depths of > 100 m where fluid flow is limited and slow, and feldspar dissolution is most marked at shallow depths (Taylor et al., 2010; Bjørlykke and Jahren, 2012). However there is some potential for redistribution of porosity to create pores with evolved shapes (Giles and de Boer, 1990). Notwithstanding whether secondary pores are generated at shallow depths or by local redistribution at deeper levels, many sandstones exhibit grain dissolution pores at depths of several kilometres. There is, however, considerable variation in the proportion of total porosity attributed to secondary dissolution. In three studies each based on hundreds of sandstones in thin section, the proportion of secondary porosity is 60–65% (Loucks et al., 1979), 11% (Taylor et al., 2010) and 45% (Wang et al., 2011), i.e. a mean value of about 40%. Using the ratio of 2.5 for pore surface area between secondary and primary porosity measured in this study, these three values equate to pore surface areas represented by secondary porosity 79–82%, 24% and 67% of the total area, respectively. Where the proportion of porosity represented by secondary porosity is 30% or more, the pore surface area is predominantly in the secondary porosity. More simply, the total pore surface area increases due to the contribution of secondary porosity. For secondary porosity proportions of 10%, 40% and 60% of the total porosity, the pore surface area is increased by 15%, 60% and 90% respectively.

Our measurements are for sandstones that have been buried to depths of ~2 km. The calculation of the contribution of secondary porosity is based on mean secondary porosity values from large databases covering depths from surface down to 3 km. The mean values belie variations in secondary porosity with depth, but these variations are specific to individual case studies and not readily predictable. In some cases, secondary porosity created near the surface will collapse and be eliminated as it is buried, while in other cases it may be preserved by stable surrounding grain frameworks (Nagtegaal, 1978). These two possibilities could lead to decreasing and increasing proportions of secondary porosity with progressive depth. In the case of the Comley Sandstone, the secondary pores have not collapsed. By using a mean value for proportion of secondary porosity, we are assessing the global influence on pore area. If most generation of secondary porosity is at shallow depths (Taylor et al., 2010; Bjørlykke and Jahren, 2012), the influence of secondary porosity to surface area is relevant to all depth ranges. In the case of subsurface microbial populations, which are most abundant at shallow depth (McMahon and Parnell, 2014), we infer that secondary porosity helps to enhance microbial abundance by providing additional surface area for colonization at all depths.

5. Conclusions

The sample sets measured in this study have provided quantitative evidence of the different pore surface area exhibited by primary and secondary porosity in sandstones. At the maximum resolution, the

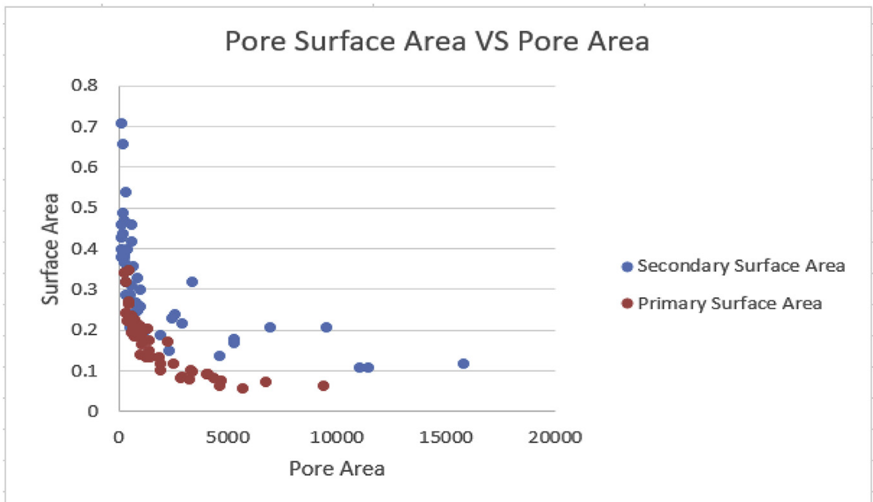

Fig. 3. Cross-plot of surface area and pore area, showing that surface area for both primary and secondary pores increases as the pore area decreases. Secondary pore surface area is higher than that of primary pores with the same area, indicating that pore area has no direct effect when comparing the two.

secondary porosity exhibits about 2.5 x the pore surface area of the primary porosity, for equivalent pore volume. For a sandstone with 40% of the total porosity consisting of secondary pores, the total pore surface area would be increased by 60%.

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