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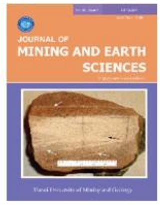

Diagenesis including cataclastic band development in the Permian Penrith Sandstone, Vale of Eden Basin, England

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ABSTRACT

Diagenesis in the Penrith Sandstone is characterized by early hematite and mixed illite/smectite cementation, followed by burial compaction, feldspar and two episodes of quartz cementation. The primary quartz overgrowths are characterized by heterogenous luminescence; however, the secondary quartz overgrowths are characterized by thinner and darker luminescence. Cataclasis post-dates primary quartz cementation, and significantly reduces grain and pore aperture size. The apex of mercury volume for a deformed sample was reduced up to three times in comparison with the undeformed rock. Dissolution occurred during cataclasis as authigenic hematite was removed in deformation zones, improving pore aperture size and consequently enhancing sandstone porosity and permeability. Recent fracturing created fractured-pores and improved porosity and permeability in tight cataclastic samples. Evidence for syn-cataclastic dissolution is observed in the samples studied. This is indicated by the dissolution of authigenic feldspars and the enhancement of poroperm parameters adjacent to cataclastic zones and the absence of hematite cement within them. Based on those the sequence of diagenetic evolution in the Penrith Sandstone can be reconstructed. Host samples were characterized by good to very good poroperm values, varying between 20 and 24% porosity and from 809÷1445 mD permeability. Cataclastic core plugs have 13÷21% porosity and 0.12÷39 mD permeability. The porosity reduction by cataclasis was estimated to be as much as 4.5% on average. Fracturing and dissolution improved poroperm parameters in studied samples. Recently fractured core plugs have about 292 mD permeability on average. Dissolution-cataclastic samples have 32% porosity and 18 mD permeability, whereas dissolution-host samples have 31% porosity and maximum permeability as much as 2469 mD on average. Cataclasis occurred in combination with in situ significant reservoir dissolution and fracturing may improve a sandstone reservoir in excellent quality.

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1. Introduction

Exposure of aeolian Lower Permian Penrith Sandstone Formation provides excellent analogues for investigating the impact of diagenesis and cataclasis on porosity and permeability of subsurface sandstone reservoirs. This is due to its relative simplicity and similarity to reservoir rocks such as the Rotliegendes of the southern North Sea (Lovell et al., 2006). Previous petrographic, petrophysical, and cataclastic characterizations of the high-porosity Penrith Sandstone have been investigated by Waugh (1970 a,b), Knott (1994), Fowles and Burley (1994), Turner et al. (1995), Beach et al. (1997) and Lovell et al. (2006). Fowles and Burley (1994) suggested that the porosity of the Penrith Sandstone was significantly reduced by in situ cataclasis. However, enhancements of porosity and permeability often occur adjacent to and on both sides of a cataclastic zone. To date, the question of whether diagenesis or cataclasis is the main factor influencing sandstone porosity and permeability in the Penrith Sandstone has not been answered. If there is a process, how can we quantify the impact, and specifically how much does it impact sandstone porosity and permeability.

This paper quantitatively evaluates diagenetic and cataclastic effects on potential reservoir quality and shows assessing the relative importance of diagenesis, cataclasis, dissolution and possible fracturing process in the Penrith sandstone.

2. Geological setting

2.1. History of basin

The Penrith Sandstone Formation is located in the Vale of Eden Basin. This basin is one of several NW-SE trending Permo-Triassic basins that formed at the end of Variscan compressional and strike-slip tectonism. The formation of these basins may relate to east-west extensional displacements associated with the opening of the North Atlantic (Fowles and Burley, 1994). The basin is an asymmetrical syncline, bounded on its eastern margin by the Pennine and Dent faults and on the western margin by the deformed Lower Palaeozoic strata of the Lake District block (Figure 1). Westward-dipping, NW - SE trending extensional faults occur within the basin, probably reflecting east-west extension both during and after sedimentation. Smaller NE-SW oriented faults also exist, with lesser displacements than the NW-SE trending faults (Fowles and Burley, 1994).

The burial history of the Penrith Sandstone is highly speculative due to the lack of post-Triassic sediments in the study area (Fowles and Burley, 1994) and is therefore constrained by several uncertainties. A burial history has been inferred from the work of Turner et al. (1995), suggesting that the Penrith Sandstone experienced a maximum burial depth of 3.5 km (Figure 2).

2.2. Sedimentology

The Penrith Sandstone Formation is up to approximately 460 m thick and consists of aeolian dune-bedded, fine- to coarse-grained, well-sorted sandstones (Fowles and Burley, 1994). These sandstones unconformably overlie Carboniferous rocks on the western margin and are overlain on the east by the Upper Permian Eden Shales which lie beneath the St Bees Sandstone (Figure 1).

2.3. Diagenesis

The Penrith sandstone consists of quartz arenites and sublitharenites with minor amounts of K-feldspar (Waugh, 1970 a, b). Authigenic contents are dominated by iron oxide and quartz overgrowths. Sparse feldspar detrital grains have poorly developed overgrowths, but most show signs of post-overgrowth dissolution (Fowles and Burley, 1994). Quartz cementation in the Penrith Sandstone was episodic and occurred in two distinct phases (Turner et al., 1995).

2.4. Cataclastic bands and implication for reservoir porosity and permeability

Cataclastic bands are typically anastomosing, occurring as thin, elongate, and upstanding ribs in the Penrith Sandstone. Their lengths may be estimated at several tens to hundreds of metres. Single cataclastic bands are thin (< 1 mm wide, Figure 3) seams of cataclasis, with shear displacements of a few millimeters or less.

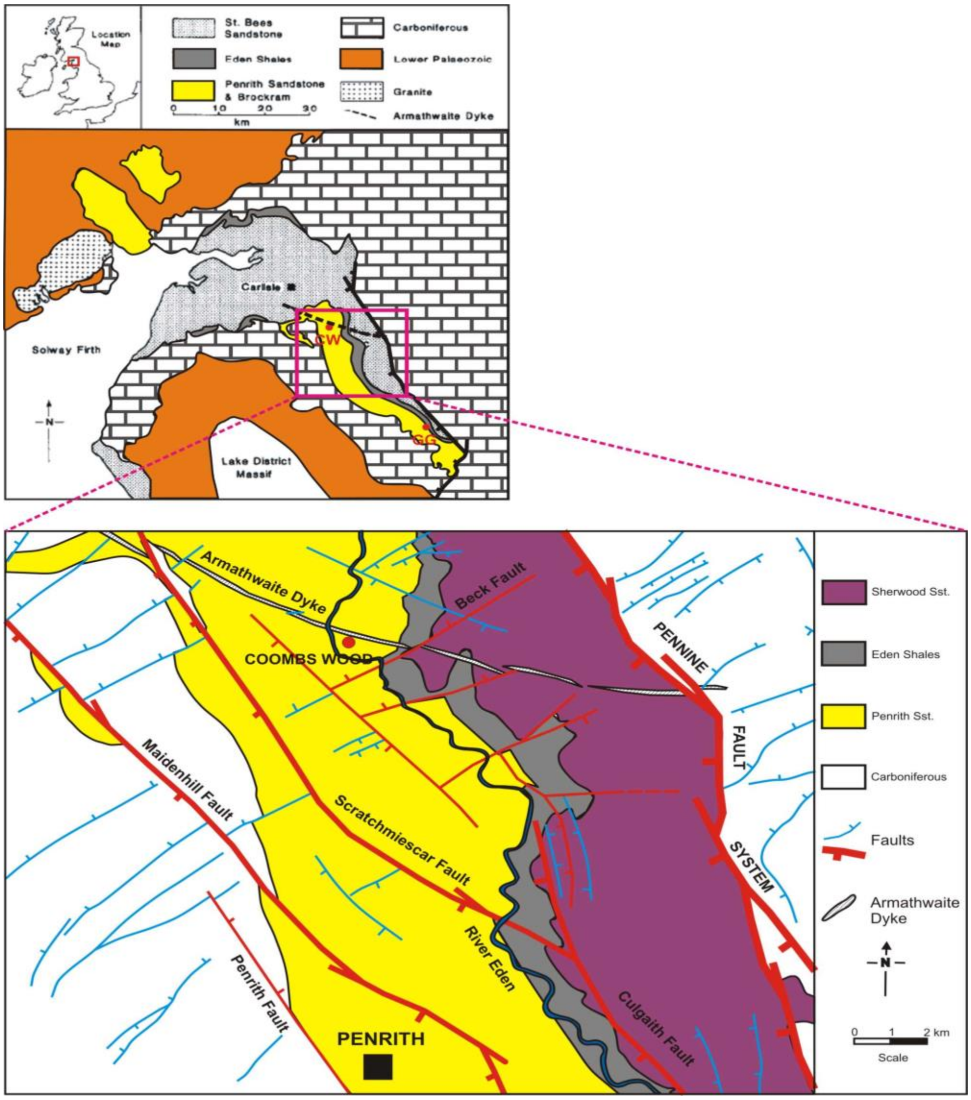

Figure 1. Study area map in the Vale of Eden Basin (modified after Fowles and Burley, 1994; Knott, 1994).

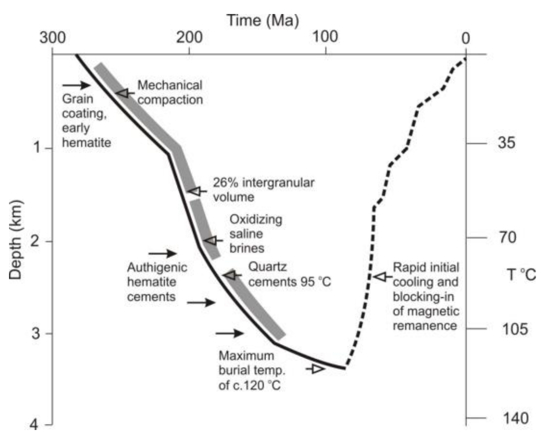

Figure 2. Burial history of the Penrith Sandstone (inferred by Turner et al., 1995).

Figure 3. Photo of a boulder slab of the Penrith cataclastic rock in Coombs Wood, Vale of Eden. Single deformation band (white arrow) is approximate 1 mm width. The black arrow shows an example of small cataclastic zone. 5 cm scale on photo.

The number of cataclastic bands increases towards the largest displacement slip surfaces. No cataclastic bands are developed further than 15÷20 m on either side of the main slip surface. The width of deformed zones where cataclastic bands are developed is approximately 40÷50 m for aggregate shear displacements of less than 10 m (Fowles and Burley, 1994).

Cataclastic bands and zones are associated with subparallel, striated slip surfaces on which there are shear displacements of up to a few meters (Figure 4). Cataclastic bands reduce porosity, relative to the in situ host rock. However, enhanced porosity and permeability existed adjacent and parallel to the cataclastic bands and the zones (Fowles and Burley, 1994).

3. Results

Several rock slabs were collected from quarry sites at the Coombs Wood and George Gill locations (Figure 1) to prepare a total of nice polished thin sections (seven from Coombs Wood and two from George Gill) for petrographic studies, 26 core plugs for porosity and permeability measurement, five plug ends for mercury injection analysis and a number of rock chips for secondary Scanning Electron Microscopy (SEM) analysis. Representatively collected samples include and exclude cataclastic bands, and include dissolution patterns and recent fractures. The results of the studies on petrography, petrophysic, and the relative importance of deformation and diagenesis are presented as follows.

3.1. Petrographic and diagenetic study

Petrographic and diagenetic studies in this research supplement the petrographic characterization of the Penrith Sandstone. Detailed petrographic investigations have been undertaken by Waugh (1970 a,b), and later supplemented by Fowles and Burley (1994), and Turner et al. (1995). The results presented here specifically evaluate the effects of diagenesis and cataclasis on reservoir porosity and permeability, as well as assessing the relative importance of diagenesis, cataclasis, dissolution, and possible fracturing in the studied sandstone.

3.1.1. Detrital and authigenic components

a) Detrital components

Detrital quartz is the dominant component varying from 48÷68%. Of this, polycrystalline quartz is the main type, ranging from 41÷55% of the total rock volume (Table 1). Feldspars comprise approximately 0.5÷6% of the bulk rock volume, consisting of mainly microcline, orthoclase, and very rare plagioclase. Rock fragments typically make up 3÷7% of the total rock volume. Sparse mica is present as trace amounts (< 0.2%) of the rock volume, most of which was not counted. Other unclassified detrital components comprise around 0.2÷3% of the whole rock volume. Selected Penrith sandstone samples are classified in Figure 5.

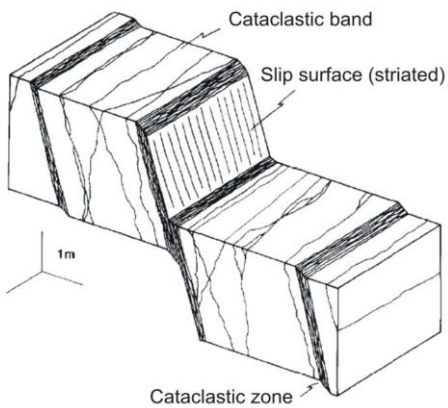

Figure 4. Schematic diagram describing the relationships between cataclastic bands, cataclastic zones and slip surfaces (modified after Fowles and Burley, 1994).

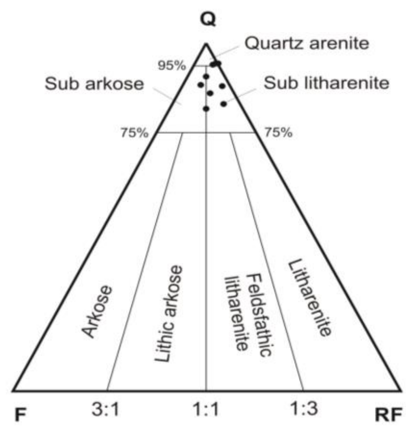

Figure 5. Classification of selected Penrith sandstone samples in this study (Folk's classification, 1974). Data of plots extracted from Table 4.1, were represented on triangular diagram by Graham and Midgley (2000).

b) Authigenic components

Quartz overgrowths are the main authigenic components, typically ranging from 3÷16%. Of this, primary quartz accounts for approximately 3 to 14%, with secondary quartz making up around 0.3÷4% of the total rock volume (Table 1). Syntaxial quartz overgrowths are well developed on detrital quartz grains, reducing intergranular pore volume (Figure 6A, C & F; Figure 7A, B & C). Some shallow burial quartz cements developed coevally with authigenic hematite (Figure 2). Cathodoluminescence (CL) images show that the secondary quartz is thinner and exhibits darker luminescence compared to the primary quartz (Figure 7B).

Burial quartz cementation developed in two distinct episodes. They can be distinguished by particular luminescence characteristics. In this work, CL-SEM investigation performed with an Oxford Instruments Limited CL detector on a Link analytical AN10155S electron dispersive system (University of Aberdeen) shows that quartz cementation in 2 distinct episodes. The primary quartz overgrowths are characterized by a heterogeneous luminescence whereas the second quartz overgrowths are thinner and have a darker luminescence. Turner et al. (1995) also used a cathodoluminescence detector, attached to a JEOL 6400 scanning electron microscope, to investigate CL-SEM images and demonstrated that the boundary between the two episodes of quartz overgrowth is sharp and marked by a discontinuity. The primary quartz overgrowth (inner zone) has a twin fabric on the rhombohedral faces and concentric growth zoning on the prism faces (see Figure 3c, p.48 in Turner et al., 1995). The secondary quartz overgrowth (outer zone) is characterized by an irregular fabric and only a thin concentric growth zone.

Feldspar overgrowths comprise 0.2÷3% of the total rock volume, and are well developed on detrital feldspar grains. The overgrowths show preferential development on single crystals (Figure 6B), merge and overlap (Figure 6C & E) or merge and stack (Figure 6D) of rhombs to produce a larger area of authigenic feldspar. Some authigenic overgrowths exhibit dissolution features (Figures 6F & 7A).

Table 1. Thin section point-counting data used in petrographic study and partially used in the back-stripping model to quantify the relative importance of diagenesis and cataclastic deformation in the Penrith sandstones.

Contents (%) / TS. ID		CW1	CW2	VE2	VE7	VE9	VOE1	VOE3	GG6	GG7
DETRITUS	Quartz	49.70	59.90	48.70	60.20	50.00	48.70	47.90	68.20	60.20
	Mono-crystaline	9.00	4.70	5.20	10.00	4.00	6.70	3.70	13.20	5.20
	Poly-crystaline	40.70	55.20	43.50	50.20	46.00	42.00	44.20	55.00	55.00
	Feldspar	2.70	0.00	5.70	0.50	3.70	4.20	2.50	1.00	1.50
	Microcline	1.70	0	1.20	0.25	1.00	1.20	1.25	0.50	0.50
	Orthoclase	1.00	0	4.50	0.25	2.70	3.00	1.25	0.25	1.00
	Plagioclase	0	0	0	0	0	0	0	0.25	0
	Rock fragments	2.50	3.70	5.70	3.20	4.70	2.50	7.70	3.50	7.00
	Igneous/Volcanic	0	0.20	0.50	0	0.50	0.25	0.50	0.50	0.50
	Metamorphic	2.50	3.50	5.20	3.20	4.20	2.25	7.20	3.00	6.50
	Mica	0.20	0	0	0	0	0.20	0	0	0
	Others	1.20	3.20	0.70	0.20	0.20	0.50	0.50	0	0.20
CEMENTS	Quartz overgrowth	16.20	5.20	8.50	6.50	12.20	14.00	12.00	3.50	3.20
	1st quartz overgrowth	13.70	5.20	8.25	6.25	8.95	10.50	8.80	3.50	3.20
	2nd quartz overgrowth	2.50	0	0.25	0.25	3.25	3.50	3.20	0	0
	K-feldspar overgrowth	0.70	0	1.50	0.20	0.70	3.00	0.50	0.20	0
	Authigenic Clays	7.00	10.00	11.50	7.50	6.70	4.20	3.50	7.70	7.50
	Pore-filling/Grain-coating	7.00	9.80	10.25	7.25	5.00	3.70	3.30	7.50	7.25
	Grain-replacement		0.20	1.25	0.25	1.70	0.50	0.20	0.20	0.25
	Hematite	7.50	4.50	3.00	5.00	9.50	8.70	10.00	7.50	8.70
	Pore-filling/Grain-coating	6.80	4.50	2.75	4.75	7.50	6.50	9.50	7.00	8.45
	Grain-replacement	0.70		0.25	0.25	2.00	2.20	0.50	0.50	0.25

	Others	4.20	1.50	0	0	1.00	0.20	0.20	2.00	0.20
	Total intergranular cement	34.90	21.00	23.00	18.70	26.40	27.40	25.50	20.20	19.10
POROSITY	Intergranular	7.70	11.50	14.50	16.00	10.00	12.80	13.30	5.70	11.00
	Dissolution	0	0.20	0	0.50	1.00	0.70	1.70	0.50	0.20
	Fractured	0	0	0	0	0	0	0	0	0
TOTAL	Detritus	56.30	66.80	60.80	64.10	58.60	56.10	58.60	72.70	68.90
	Cements	35.60	21.20	24.50	19.20	30.10	30.10	26.20	20.90	19.60
	Porosity	7.70	11.70	14.50	16.50	11.00	13.50	15.00	6.20	11.20
Present, but might not be encountered when counting		Mica, 2nd K-feldspar overgrowths								

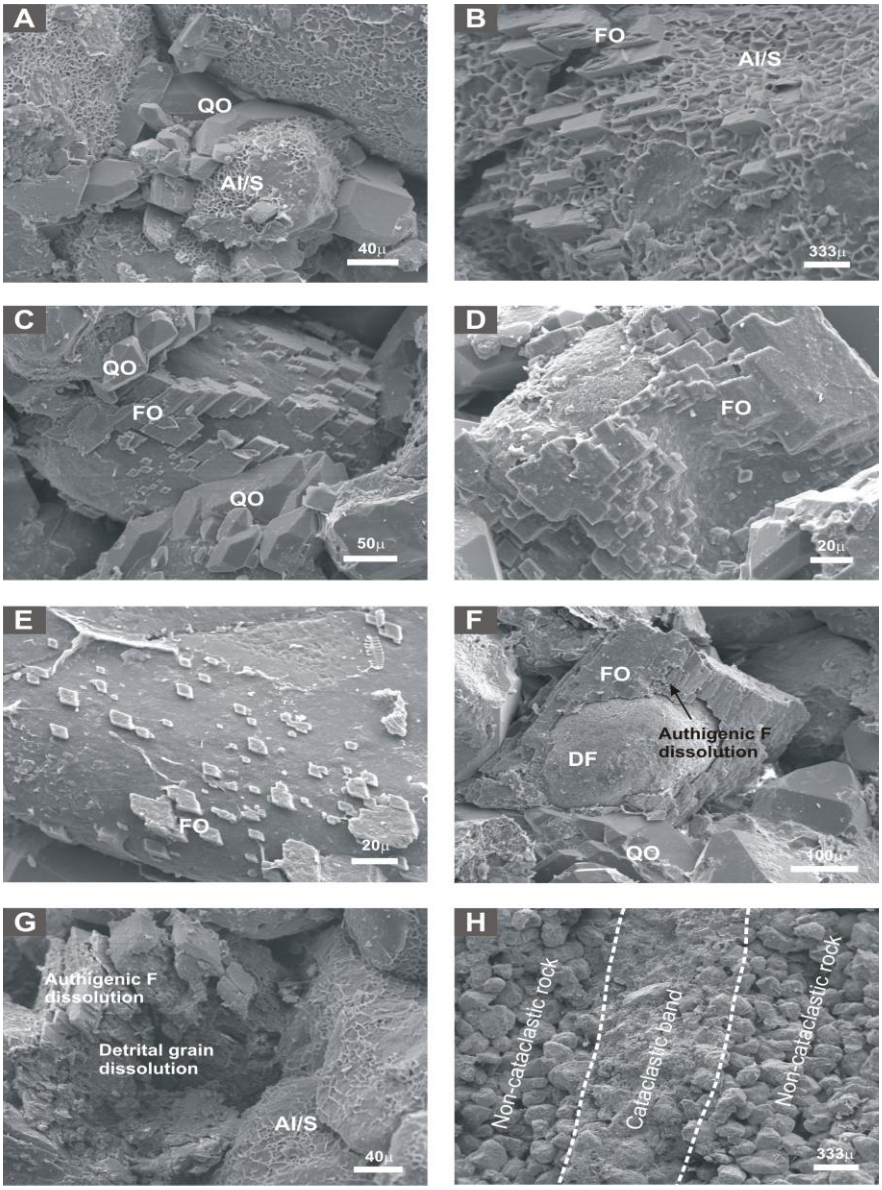

Figure 6. Secondary SEM photomicrographs showing textures of authigenic illite/smectite, quartz and feldspar overgrowths (A, B, C, D, E, F, see text for more detail). Dissolution occurred in feldspar overgrowth (F) and in possible detrital feldspar (G). Single cataclastic band (H) characterized very high reduction of grain and size, probably destroyed pore network (as seen in non-cataclastic rock). QO = quartz overgrowth; FO = feldspar overgrowth; AI/S = authigenic mixed illite/smectite; DF = detrital feldspar.

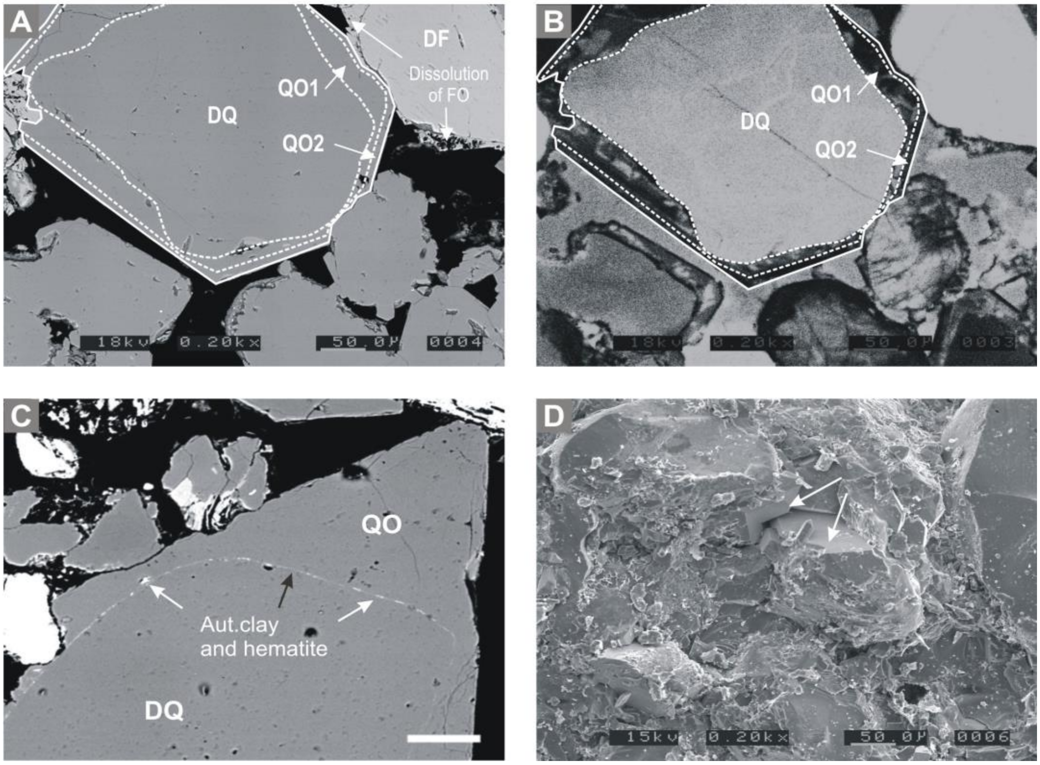

Figure 7. Quartz overgrowths developed in two periods in a B-SEM (A) and CL-SEM (B) photomicrograph. The secondary quartz has thinner, darker luminescence than the primary quartz (B). Noted dissolution of feldspar overgrowth (white arrows in the top-right of image A). Authigenic hematite appears as white dots (white arrows) and authigenic clay appears as blur curve (black arrow) coated on detrital grain boundary in a B-SEM microphotograph (C). White arrows show probable secondary quartz overgrowths postdate cataclasis in a cataclastic band (D). Scale bar is 50 µm. QO = quartz overgrowth; QO1 = primary quartz overgrowth; QO2 = secondary quartz overgrowth; DQ = detrital quartz; FO = feldspar overgrowth; DF = detrital feldspar.

Early authigenic clays are characterized by pore-filling, grain-coating and grain-replacement of mixed illite/smectite. Pore-filling and grain-coating illite/smectite contents are approximately 3÷10%, but replacement illite/smectite makes up about 0.3÷2% of the bulk rock volume. Well-developed, highly crenulated early mixed illite/smectite grain-coatings predate the quartz and feldspar overgrowths (Figure 6A, B & G).

Hematite appears as pore-filling, grain-coating and replacement textures. The pore-filling and grain-coating hematite account for 3÷10% of the total rock volume (Figure 7C).

3.1.2. Relative timing of diagenetic and cataclastic processes

Early reddening and mixed illite/smectite formation predated burial quartz and feldspar overgrowths (Figure 6A, B). However, early hematite also formed coevally with shallow burial authigenic quartz (Figure 2) by oxidizing saline brines (Turner et al., 1995). Cataclasis spalled primary quartz overgrowths and detrital grains in situ (Figure 6H). In contrast, secondary quartz overgrowths are unbroken, forming syntaxial textures within the cataclastic zone. Thus, cataclasis occurred after the development of primary quartz and before the formation of secondary quartz (Figure 7D).

Evidence for syn-cataclastic dissolution is observed in the samples studied. This is indicated by the dissolution of authigenic feldspars (Figures 6F & G; & 7A) and the enhancement of porosity and permeability (poroperm) parameters adjacent to cataclastic zones and the absence of hematite cement within them (Turner et al., 1995). The sequence of diagenetic evolution in the Penrith Sandstone is illustrated in Figure 8.

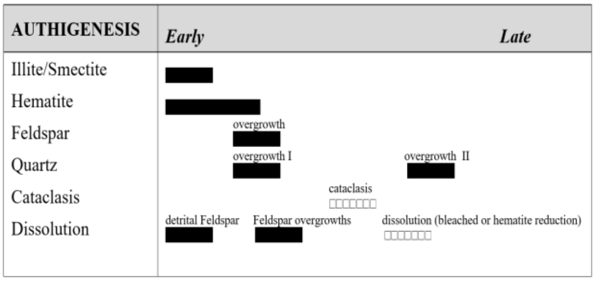

Figure 8. General paragenesis of diagenetic processes and cataclasis in the Penrith Sandstone.

3.2. Petrographic and petrophysic characterization

3.2.1. Petrographic characteristics

Observations from rock slabs (Figure 3) and SEM chips (Figure 6H) suggest that individual deformation bands are highly localized, typically less than 1 mm in width. Deformation in cataclastic bands is characterized by spalling of individual grains and/or their overgrowths into very small angular fragments. Reductions in grain and pore sizes are most pronounced at the centre of cataclastic bands (Figure 6H).

3.2.2. Petrophysical properties

a) Grain and pore size

The particle diameter and pore aperture radius of cataclastic samples are significantly reduced in comparison with host samples (Figure 9A & B). Host and cataclastic samples with dissolution patterns exhibit increased pore volume, as the dissolution samples have larger pore aperture sizes than the cataclastic samples. Cataclastic samples with recent fractures also have larger pore aperture sizes compared to the very tight cataclastic samples (Figure 9B).

b) Apex volume

The apex volumes of cataclastic samples are approximately three times smaller than those of the host samples (Figure 10). Apex volumes, or effective mercury porosities, of cataclastic samples that have undergone dissolution and fracturing processes, are generally higher than those of deformed samples that have not experienced these processes.

c) Poroperm cross-plots

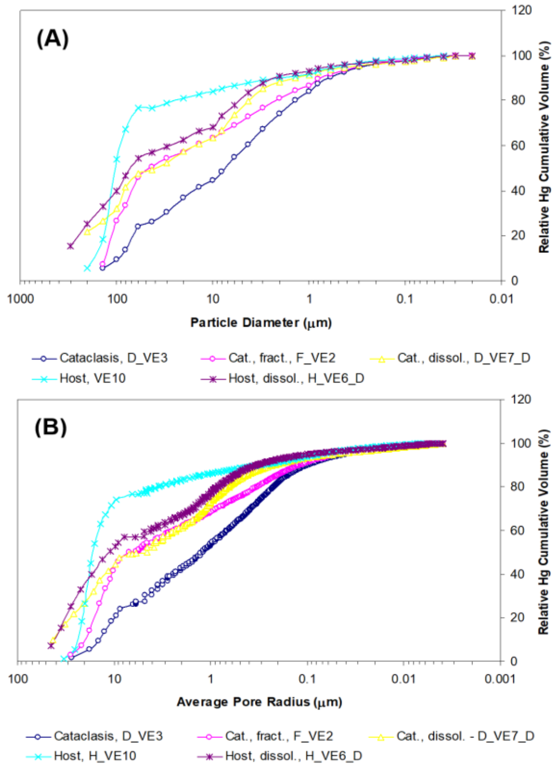

Figure 9. Distribution of grain particle diameter (A) and pore aperture radius (B) for representative samples in the Penrith Sandstone. Particle grain and pore aperture radius sizes of the cataclastic sample (D_VE3) were reduced significantly in comparison with the host rock (H_VE10), whereas dissolution and recent fracturing improved pore aperture radius significantly (D_VE7_D and F_VE2).

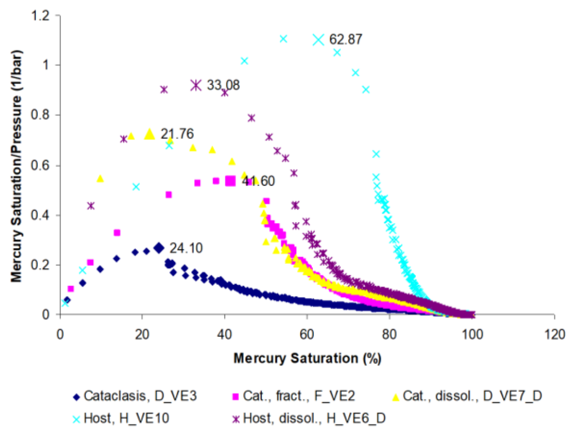

Figure 10. Diagram showing the distribution of apex volumes (larger symbols) for representative samples in the Penrith Sandstone. The apex volume (effective mercury porosity) in a cataclastic sample (24.1%, sample D_VE3) was reduced by approximately 3 times in comparison with the host rock (62.9%, sample H_VE10).

Cross-plotting core plug poroperm data display the general distribution of porosity and permeability in the Penrith Sandstone (Figure 11). Cataclastic core plugs (black rhombuses) have 13÷21% porosity and 0.12÷39 mD permeability (average 19% and 13 mD). In contrast, host samples (black squares) have higher poroperm values varying between 20÷24% porosity and 809÷1445 mD permeability (average 23% and 1023 mD). Therefore, the porosity difference between host and cataclastic samples, as estimated by the arithmetic mean method, is approximately 4.5% on average.

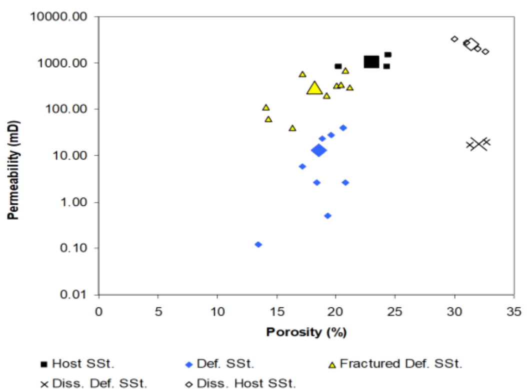

Figure 11. General relationship of core plug porosity and permeability in the Penrith Sandstone. Bigger symbol shows the appropriate average value.

Additionally, dissolution improved porosity and permeability in both cataclastic and host samples (Figure 11). The cataclastic samples that have undergone dissolution (cross marks) have to 32% porosity and 17÷19 mD permeability (32% and 18 mD average). The host samples that have undergone dissolution (empty rhombuses) have the highest poroperm values, ranging from 30÷33% porosity and from 1791÷3295 mD permeability (average 31% and 2469 mD). Recent fractures have not enhanced the porosity of cataclastic samples (triangles). However, they have improved permeability to an average value of 292 mD, compared to 13 mD in the unfractured cataclastic samples.

4. Discussion

Qualitative and quantitative assessment of the impact of individual diagenetic and cataclastic processes on sandstone porosity and permeability in this study supplements previous investigations of diagenesis and deformation in the Penrith Sandstone undertaken by Waugh (1970 a,b), Knott (1994), Fowles and Burley (1994), Turner et al. (1995), Beach et al. (1997) and Lovell et al. (2006). Additionally, the assessment provides essential results and data to better understand the relative importance of cataclastic and diagenetic processes on reservoir quality.

4.1. Impact of cataclasis and diagenesis on the Penrith Sandstone

Diagenesis influenced porosity and permeability by burial compaction and the formation of authigenic minerals. The maximum burial depth of the Penrith Sandstone is inferred to be up to 3.5 km (Turner et al., 1995) and the window of burial for the development of quartz cementation is between 2.5 and 3.5 km (Figure 2). According to the back-stripping model developed by Pham (2007) (Figure 12), porosity loss due to burial compaction during quartz cement formation is estimated to be as much as 6% of the total rock volume. Petrographic analysis in this

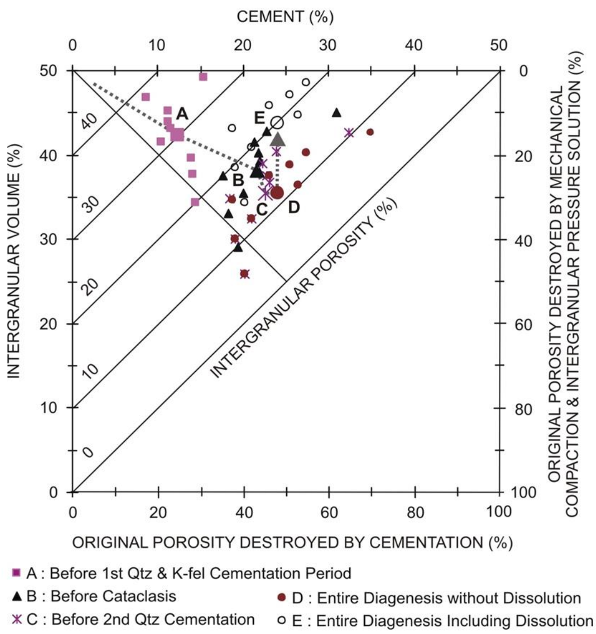

Figure 12. Relative importance of diagenetic processes and cataclasis revealed by back-stripping model and represented on the diagram of Houseknecht (1987). The 0ABCDE trend represents the general paragenetic pathway for the Penrith Sandstone (Pham, 2007).

study shows that burial quartz overgrowths are the dominant authigenic component, averaging 9% of the total rock volume. Burial quartz cementation occured in two separate episodes. The primary quartz overgrowths are characterized by a heterogeneous luminescence, whereas the second quartz overgrowths are thinner and have darker luminescence. These overgrowths significantly occluded intergranular pore volume.

The contribution of authigenic feldspar (0.8% of the total rock volume) to total porosity loss is insignificant compared to the contribution by quartz cementation. Its impact is an order of magnitude less than that of authigenic quartz (9% of the total rock volume). The formation of authigenic clays and hematite during early diagenesis (point A in Figure 12) contributed more significantly to porosity reduction than compaction, as it destroyed 25% of the original porosity, whereas compaction only destroyed 15% (Pham, 2007).

Cataclasis significantly affected sandstone porosity and permeability by reducing grain and pore sizes, as well as apex volume (Figures 6H; 9A & B; 10). It also influenced the aggregation of deformation bands that develop parallel or sub-parallel to cataclastic zones (Figure 4). The distribution of cataclastic bands and zones governs fluid flow properties and can create significant heterogeneities within a sandstone reservoir (Fowles and Burley, 1994).

Lovell et al. (2006) investigated the degree of heterogeneity in Sandstone samples from the Stoneraise Quarry in the Penrith Sandstone by integrating petrographic and petrophysical studies. They used conventional optical images (thin section and secondary SEM), along with electrical resistivity, porosity, mini-permeability images, and plug poroperm analyses. Their findings demonstrated that heterogeneity results from fine-grained laminae with more pervasive quartz overgrowths within typical clean, relatively high poroperm sandstone. These laminations are interspersed with areas of more uniform or massive beds. The low permeability zone identified by Lovell et al. (2006) can be characterized by a plug permeability of 1.6 x 10-14 m^2 (16 mD), compared to adjacent areas which have permeabilities up to 800 - 1000 mD. In contrast, plug samples containing cataclastic bands in this study show a low permeability of up to 0.12 mD, compared to host rocks with an average permeability of 1023 mD. It is inferred that cataclasis in this study has resulted in a higher degree of heterogeneity - up to more than 100 times greater - than the sedimentation and diagenesis effects by Lovell et al. (2006) in terms of permeability reduction in the aeolian sandstone reservoir.

Enhanced porosity and permeability are often developed adjacent to and on both sides of cataclastically deformed zones. Enhanced porosity and permeability are often developed adjacent to and on both sides of cataclastically deformed zones. This enhancement results from fluid flow during the cataclastic process, which removes iron oxide grain coatings and leads to the formation of post-fracturing quartz cement (Fowles and Burley, 1994). Petrographic and petrophysical analyses (Figures 6G; 9; 10 & 11) show that dissolution, as a result of the enhanced fluid flow, contributed significantly to sandstone porosity through enlarging pore aperture size, effective mercury porosity and subsequently improving sandstone permeability.

Studies on deformed samples, including recent fractures, can provide an analogue to predict and characterize the impact of fracturing on poroperm parameters. Petrophysical analyses of samples including cataclastic bands and recent fractures (Figures 9 & 10) showed that fracturing substantially increased pore aperture size and apex volume. Fracturing can therefore have a particularly important role in improving poroperm parameters in very tight, cataclastic samples (Figure 11).

4.2. Relative importance of cataclasis and diagenesis

The evolution of intergranular porosity in the Penrith Sandstone is controlled by various cementation and compaction processes integrated with cataclasis, dissolution and possible fracturing. Pores were occluded by the formation of authigenic minerals such as early mixed illite/smectite and hematite, burial quartz and feldspar. The reduction of intergranular volume by mechanical compaction and pressure solution before and during quartz cementation occurred in the interval of 2.5÷3.5 km. The pore volume was reduced significantly by cataclasis. However, pore dilation occurred by dissolution at the site of deformation zones.

Pham (2007) used a back-stripping model (Figure 12) which shows that diagenesis is more important than cataclasis in porosity reduction during the development of reservoir porosity. However, cataclasis is more important than secondary quartz cementation in the reduction of porosity. The decompaction equation used to calculate reservoir porosity through the entire burial compaction according to the inferred maximum burial depth of 3.5 km is not well-matched with the real effects of diagenesis constrained by a back-stripping model for the Penrith Sandstone.

Considering that the host rock has 23% porosity and 1023 mD permeability at present, and had 50% and 30 Darcies of original porosity and permeability at the depositional stage on average, using cross-plots of poroperm-loss ratios which allows us to conclude that cataclasis is less important than diagenesis in the control on sandstone porosity and permeability, and changed the sandstone to one with a very poor to medium permeability.

5. Conclusion

Diagenesis in the Penrith Sandstone is characterized by early hematite and mixed illite/smectite cementation, followed by burial compaction, feldspar and two episodes of quartz cementation. The primary quartz overgrowths are characterized by heterogeneous luminescence; however the secondary quartz overgrowths are characterized by thinner and darker luminescence. Cataclasis post-dates primary quartz cementation, and significantly reduces grain and pore aperture size. Dissolution occurred during cataclasis as authigenic hematite was removed in deformation zones, improving pore aperture size and consequently enhancing sandstone porosity and permeability. Recent fracturing created fractured pores and improved porosity and permeability in tight cataclastic samples.

The porosity reduction by cataclasis was estimated to be as much as 4.5% on average. However, in terms of permeability reduction in the host rock to generate reservoir heterogeneity, cataclasis can result in up to 100+ times reduction in comparison to the impact of sedimentation and diagenetic alteration in the work of Lovell et al. (2006).

Fracturing and dissolution improved poroperm parameters in studied samples. Dissolution-cataclastic samples have 32% porosity and 18 mD permeability, whereas dissolution-host samples have 31% porosity and maximum permeability as much as 2469 mD on average. Cataclasis occurred in combination with in situ significant reservoir dissolution and fracturing may improve a sandstone reservoir in excellent quality.

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Contribution of authors

Tuan Van Pham - sample analysis and interpretation; draft the paper and revise for submission; John Parnell - provided the studied rock boulders, academic supervision and made critical comments for paper preparation.

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