Journal of Mining and Earth Sciences
Website: http://jmes.humg.edu.vn

# Diagenesis and the effects of cataclastic deformation on the Permo-Triassic New Red Sandstone, Isle of Arran, Scotland

Tuan Van Pham [1,*], John Parnell [2]

*[1] Hanoi University of Mining and Geology, Hanoi, Vietnam*
*[2] University of Aberdeen, Aberdeen AB24 3UE, UK*

ARTICLE INFO

*Article history:*
Received 5th Aug. 2022
Revised 6th Nov. 2022
Accepted 09th Dec. 2022

*Keywords:*
Cataclasis,
Defoformation,
Diagenesis,
New Red Sandstone.

ABSTRACT

*Diagenesis in the Permo-Triassic New Red Sandstone, Isle of Arran is characterized by early cementation of hematite, clay, and calcite minerals, followed by burial compaction, quartz, feldspar, and pyrite cementation. Cataclasis post-dated the quartz and feldspar cementation and reduced the grain and pore aperture size in deformed samples. Samples with cataclastic bands typically have 18% porosity and 8.81 mD permeability on average. Whereas, undeformed samples have an average porosity of 22% and an average permeability of 381 mD. Cataclasis was not as important as diagenesis in controlling sandstone porosity and permeability. However, cataclasis resulted in lower porosity and very poor to medium permeability in deformed samples. Cataclastic bands compartmentalize reservoir sands and cause a high heterogeneity in undeformed porous sandstones. Poikilotopic and blocky calcite cement postdates early clay and hematite cement. In addition, burial quartz and feldspar overgrowths also postdate the early clay and hematite. However, the poikilotopic calcite fills in framework grains that have larger void volumes than the grain/grain contacts where quartz overgrowths are present. Cataclasis resulted in fracturing of quartz and feldspar overgrowths. Therefore, the cataclasis occurred after the development of quartz and feldspar cementation. Dissolution postdated the formation of authigenic feldspar and pyrite formation resulted from hematite reduction. The distributions of grain and pore sizes against cumulative mercury volumes in studied samples shows a high level of reduction of grain and pore aperture sizes for deformed samples from single-cataclastic and multi-cataclastic bands. The distribution of apex volumes illustrates that the effective mercury porosity of the multi-cataclastic band sample may be reduced up to > 2 times in comparison to undeformed samples. However, the sample of a thin single cataclastic band has only a slightly lower apex volume in comparison to the host sample.*

---

[*] *Corresponding author*
*E - mail:* phamvantuan@humg.edu.vn
DOI: 10.46326/JMES.2023.64(1).09

## 1. Introduction

Faults in the Permo-Triassic aeolian New Red Sandstones of the Isle of Arran have been investigated by Astin and MacDonald (1983), Underhill and Woodcock (1987), and Woodcock and Underhill (1987). The latter showed that they are related to the Tertiary igneous intrusions of the Northern Granite, the Central, and Tighvein Complexes (Figure 1). The faults, zones of faults, or cataclastic deformation bands (the latter appear as conspicuous upstanding ribs in multiple sets) compartmentalized the porous Permo-Triassic sandstones. Most grains are fractured; grains and cement are spalled, resulting in a finer grained matrix, which leads to very poor sorting and low porosity in the central portion of the cataclastic bands. The cataclastic bands, therefore, are believed to act as barriers to fluid migration within the porous sandstones, which represent good analogues for petroleum reservoirs (Underhill and Woodcock, 1987).

In this paper, diagenetic and petrophysical studies have been undertaken on selected samples of deformed and undeformed New Red Sandstone at the coastal areas of Pirate Cove and Brodick Castle (Figure 1). The aim is to investigate the diagenetic and cataclastic impacts on poroperm parameters and construct an analogue for studies of controls of diagenesis and structural deformation on reservoir quality for sub-surface sandstones.

## 2. Geological setting

### 2.1. Basin history

The Isle of Arran is located on the northern side of the Arran basin (Figure 1(b) in McKeever, 1992), situated between southwest Scotland and northwest England. The geology of Arran is controlled mainly by regional NW – SE and NE – SW striking faults (McLean, 1978; McLean and Deegan, 1978) such as the Highland Boundary Fault and the Plateau Fault (Figure 1), which were probably active during Mesozoic times (McLean, 1978). The Isle of Arran hosts the Northern Granite, the Central Complex, and Tighvein Complex of the British Tertiary igneous province that are thought to have been intruded within a few million years of each other. The Northern Granite was dated at approximately 60 Ma (Evans et al., 1973; Dickin et al., 1981).

McKeever (1992) constructed burial history curves for Permo-Triassic sediments in the Sea of the Hebrides Basin (adjacent to the Isle of Arran) and stated that the curves are representative of the buried histories of western UK basins. The maximum burial depth may reach up to 3.25 km for the Permo-Triassic sediments prior to regional Tertiary uplift. However, Shelton (1996) demonstrated that the Permo-Triassic sediments of the Southwest Arran Trough experienced a maximum burial depth of 1.75 km in the period prior to the Tertiary uplift (Figure 2). In this study, it is assumed that Permo-Triassic sandstones in the Isle of Arran have undergone a similar burial history to that of the Southwest Arran Trough; i.e. they reached a maximum burial depth of 1.75 km.

### 2.2. Sedimentology

The New Red Sandstone is well exposed in the coastal regions flanking the Central and Tighvein Complex of the Isle of Arran (Figure 1). It unconformably overlies Carboniferous rocks and has a maximum thickness of 538 m (Clemmensen and Abrahamsen, 1983). The Permian sequence (Brodick, Corrie and Machrie Formations) comprises aeolian sandstones that are interbedded with fluvial breccias whose clasts were derived from pre-Permian rocks. Triassic sediments comprise the Lamlash Sandstone, and silty shales such as the Lag a'Bheith, Auchenhew, and Derenenach Mudstone Formations that are equivalent in age to the regional Triassic Mercia Mudstone Group (Glennie, 2002).

The sedimentology of the Permian sediments on Arran has been described in detail by Clemmensen and Abrahamsen (1983). This study is restricted to the cataclastic bands and deformed well-sorted aeolian sandstones located at the coastal areas of Pirate Cove and Brodick Castle.

### 2.3. Diagenesis

Several petrographic investigations have been undertaken on the New Red Sandstone, Isle of Arran. The Corrie sandstone has undergone early diagenesis as quartz grains are coated by an early red iron oxide (Harland and Hacker, 1966).

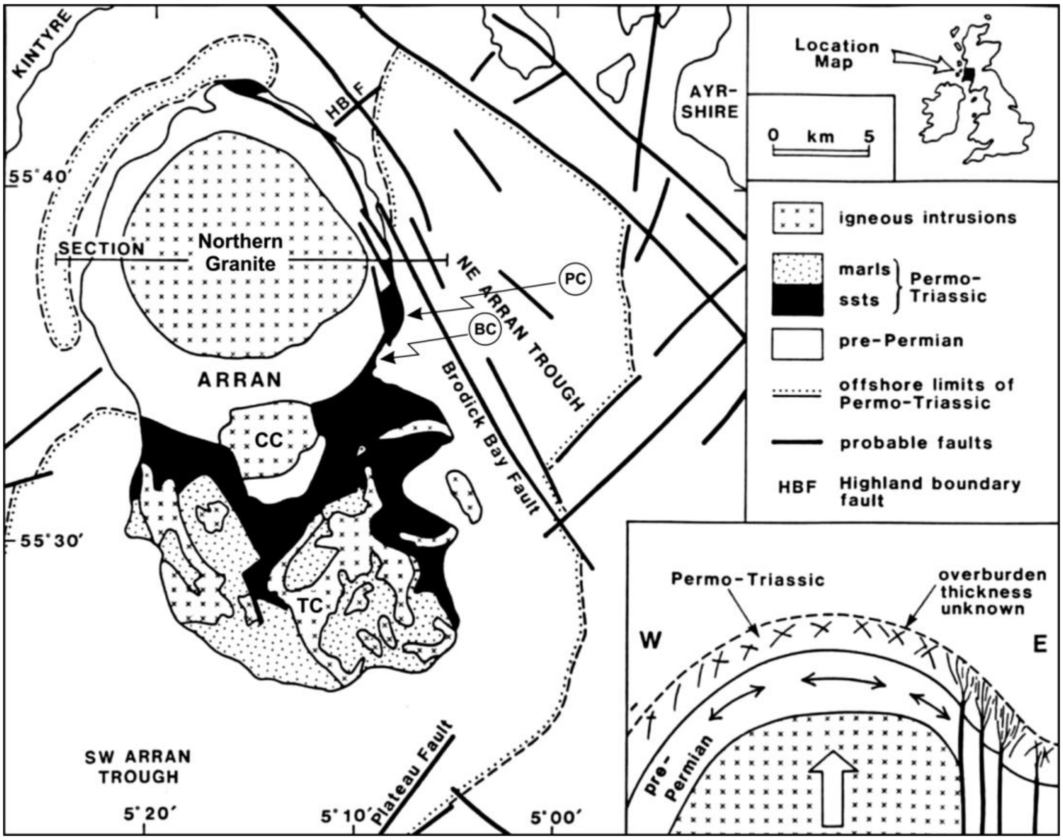


*Figure 1. General geological map of the Isle of Arran and adjacent areas (after McLean and Deegan, 1978). Inset is a cartoon at the same scale during intrusion of the Northern Granite (Underhill and Woodcock, 1987). HBF = Highland Boundary Fault; CC = Central Complex; TC = Tighvein Complex; BC = Brodick Castle Gate (NS018379); PC = Pirate Cove (NS030396).*

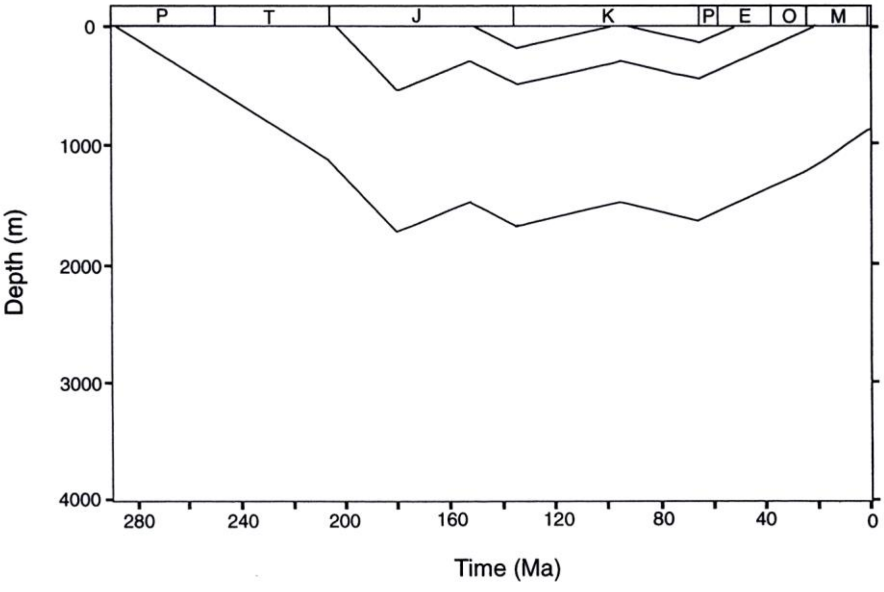


*Figure 2. The burial history of the SW Arran Trough indicates that the Permo-Triassic sediments may reach 1.75 km maximum burial depth and have undergone regional Tertiary uplift (Shelton, 1996). It is assumed that the Permo-Triassic sandstones in the Isle of Arran also have experienced a similar maximum burial depth.*

The Brodick breccias and surrounding sediments underwent early lithification as they are cemented with grain coatings of iron oxide (possibly mixed with clay mineral), and secondary blocky dolomite (Astin and MacDonald, 1983). Underhill and Woodcock (1987) described authigenic components including iron oxide coatings and quartz overgrowths in undeformed sandstones.

Cataclastic bands and their significance to fluid flow within reservoirs

Faults or cataclastic bands compartmentalizing undeformed sandstones (Figure 3A-E) appear as conspicuous upstanding ribs in multiple sets (Underhill and Woodcock, 1987). A single cataclastic band is typically 1 mm wide and metres to tens of metres long with a low displacement (< 10 mm). However, with higher displacements (>10 mm) subparallel bands conjugate to form a zone of cataclastic bands millimetres to metres wide (Figure 3E). Within some zones that have a displacement > 1 m, a discrete striated slip surface occurs (Woodcock and Underhill, 1987).

In thin section, cataclastic bands are characterized by grain fracture and spalling of iron oxide coatings and quartz overgrowths to form a seam with highly reduced grain size, poorer sorting, higher angularity, and lower porosity than the host rock (Figure 3F). Cataclastic bands and the zones of cataclastic bands compartmentalize areas of undeformed porous sandstone.

## 3. Results

Samples were collected at the coastal areas of Brodick Castle (NS018379) and Pirate Cove (NS030396) (Figure 1) to prepare a total of 6 polished thin sections for petrographic studies, 22 core plugs and 3 plug ends for petrophysical studies, and a number of rock chips for secondary SEM analysis. Results of the studies of petrographic, petrophysical, and the impacts of deformation and diagenesis on the New Red Sandstone, Isle of Arran are summarized as follows.

### *3.1. Petrographic and diagenetic study*

Previous work on the petrography of Permo-Triassic sandstones in the Isle of Arran has been undertaken by Gregory (1915), Barrett (1925), Tyrrell (1928), Friend et al. (1963), Lovell (1971), Astin and MacDonald (1983) and Underhill and Woodcock (1987). The work presented here focused on the early and late authigenic processes, and was used to construct a general paragenesis. In addition, this work quantified the impact of diagenesis on reservoir properties and supplied petrographic data in order to determine the relative importance of cataclasis and diagenesis in affecting the porosity and permeability of the sandstone.

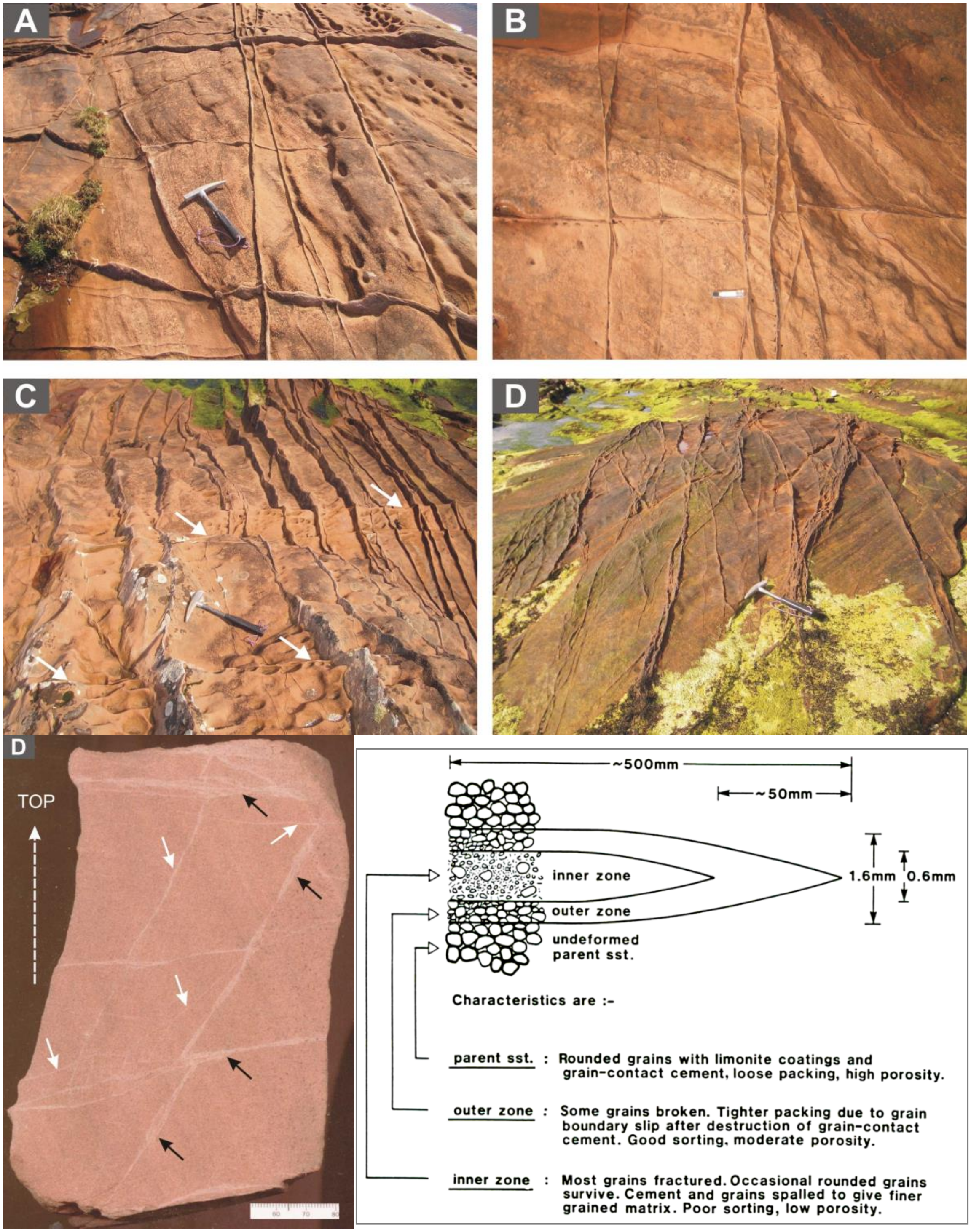
### *3.1.1. Detrital and authigenic components*

*Detrital components*

Detrital quartz is the dominant component of the sandstones, determined using a standard point-counting method (400 points counted). It ranges from 54 to 63% of which the polycrystalline quartz content varies from 13 to 33% and the mono-crystalline quartz content is between 28 and 48% of the total rock volume. The feldspar component forms approximately 3÷4% of the bulk rock volume and comprises mainly microcline and orthoclase with very rare plagioclase. Rock fragments typically approximate 2÷5% of the total rock volume. Mica is present in trace amounts. Other unclassified detrital components account for 0.2÷1% of the whole rock volume. Selected samples for Arran sandstone are classified in Figure 4.

*Authigenic components*

Early authigenic clays and hematite typically show pore-filling, grain-coating and grain-replacement textures (Figures 5B & E). The pore-filling and grain-coating mixed-layer illite/smectite contents are approximately 5÷8%, but the replacement illite/smectite contents are about 0.2÷3% of the bulk rock volume. The pore-filling and grain-coating hematites account for between 4 and 10% of the total rock volume; however, the replacement hematite varies from 0.7 to 2% of the whole rock volume. Early calcite cement (Figure 5F) has poikilotopic and blocky textures in some samples collected at the coast near Brodick Castle. The calcite component may account for up to 2% of the total rock volume.



Characteristics are :-

parent sst. : Rounded grains with limonite coatings and grain-contact cement, loose packing, high porosity.

outer zone : Some grains broken. Tighter packing due to grain boundary slip after destruction of grain-contact cement. Good sorting, moderate porosity.

inner zone : Most grains fractured. Occasional rounded grains survive. Cement and grains spalled to give finer grained matrix. Poor sorting, low porosity.

*Figure 3. Cataclastic bands show compartmentalization of sandstones in the Isle of Arran. A) sandstone is compartmentalized by crosscut bands; B) cataclastic bands show visual horizontal displacements ranging from 1 to 4 cm; C) sub-parallel deformation bands appear as upstanding ribs, cross-cut by other bands marked by arrows; D) sandstone is compartmentalized by anastomosing bands. A, B, C are outcrop photos at Pirate Cove, but D at outer Brodick Castle gate. E) single deformation bands (white arrows) on sample slab, are approximately 0.2÷1 mm width; the black arrows show examples of conjugates of cataclastic bands, 3 cm scale. F) a sketch of cataclastic zones proposed by Underhill and Woodcock (1987).*

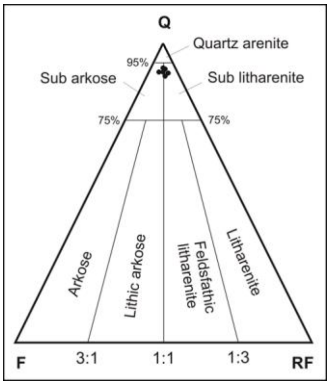


*Figure 4. Classification of selected New Red Sandstone samples in the Isle of Arran (Folk's classification, 1974). Data of plots were represented on triangular diagram by Graham and Midgley (2000).*

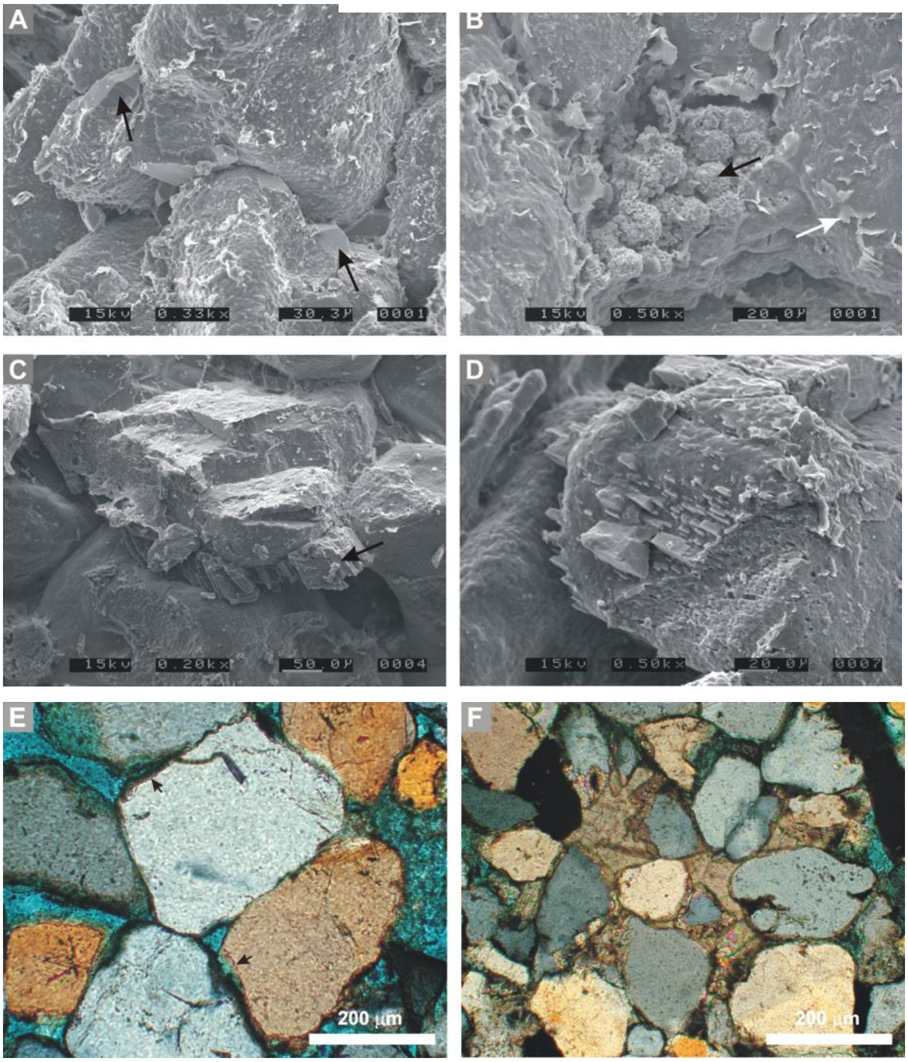


*Figure 5. Secondary SEM photomicrographs showing textures of authigenic clay, quartz and feldspar overgrowths. A) authigenic quartz (black arrows) developed partially on detrital grains; B) grain-coating authigenic mixed illite/smectite (white arrow) and pore-filling pyrite (black arrow); C) feldspar overgrowth has trace of dissolution (arrow); D) preferential development of feldspar overgrowths. E) cross-polarized thin section photomicrograph shows a grain-coating early hematite cement (arrowed); F) an example of early diagenetic poikilotopic calcite in cross-polarized thin section photomicrograph.*

Quartz overgrowths partially developed on detrital quartz grains reduced the intergranular pore volume (Figure 5A). The authigenic quartz represents a burial cement, typically ranging from 2 to 6% of the total rock volume. Feldspar overgrowths are poorly developed on detrital feldspar grains and were not seen during point-count analysis, but under SEM overgrowths are seen to be present and show typically preferential development of single crystals (Figure 5D). Dissolution postdated feldspar cementation and affected some authigenic overgrowths (Figure 5C). Pore-filling authigenic pyrite (Figure 5B) was present in minor amounts and may be derived from the reduction of hematite (Burley, 1984).

#### *3.1.2. Relative timing of diagenetic and cataclastic processes*

Poikilotopic and blocky calcite cement postdates early clay and hematite cement (Figures 5E & F). In addition, burial quartz and feldspar overgrowths also postdate the early clay and hematite. However, the poikilotopic calcite fills in framework grains that have larger void volumes than the grain/grain contacts where quartz overgrowths are present. Therefore, the calcite cementation can be interpreted as occurring prior to quartz cementation.

Cataclasis resulted in fracturing of quartz and feldspar overgrowths (Figure 3F). Therefore, the cataclasis occurred after the development of quartz and feldspar cementation. As noted, dissolution postdated the formation of authigenic feldspar (Figure 5C) and pyrite formation resulted from hematite reduction (Burley, 1984). The general paragenesis of diagenetic evolution and cataclasis in the New Red Sandstone, Isle of Arran is shown in Figure 6.

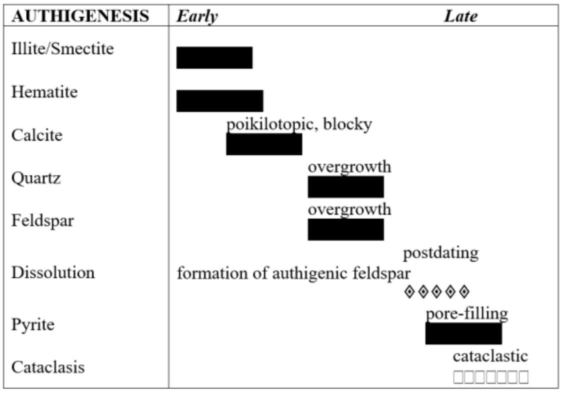


*Figure 6. General paragenesis of diagenetic processes and cataclasis in the New Red Sandstone, Isle of Arran.*

### *3.2. Petrographic and petrophysical characterization of host and cataclastic samples*

#### *3.2.1. Petrographic characteristics*

Outcrop and boulder slab photos (Figures 3A-E) show that individual cataclastic bands are localized, typically less than 1 mm in width. At the inner cataclastic zone individual grains and their overgrowths are broken to generate a finer-grained matrix, which has very low porosity and may act as a barrier to fluid flow (Figure 3F).

#### *3.2.2. Petrophysical properties*

*Grain and pore size characterization*

The distributions of grain and pore sizes against cumulative mercury volumes were derived from mercury injection for representative samples of the New Red Sandstone. The distribution shows a high level of reduction of grain and pore aperture sizes for deformed samples from single-cataclastic and multi-cataclastic bands (Figures 7A & B). The distribution of apex volumes illustrates that the effective mercury porosity of the multi-cataclastic band sample (32%) may be reduced up to > 2 times in comparison to undeformed samples (65%, Figure 8). However, the sample of a thin single cataclastic band has only a slightly lower apex volume (55%) in comparison to the host sample.

*Cross-plots of plug porosity and permeability*

Cross-plots of core plug poroperm data (Figure 9) display the general distribution of porosity and permeability in the Arran Sandstone. Deformed samples have core plug poroperm values ranging from 16 to 21% porosity and 0.07 to 83 mD permeability (18% and 8.81 mD on average). In contrast, host samples have higher plug poroperm values varying from 21 to 22% porosity and 315 to 448 mD permeability (22% and 381 mD on average). The amount of porosity difference between host and cataclastic core plug samples, as estimated by the arithmetic mean method, is approximately 3%.

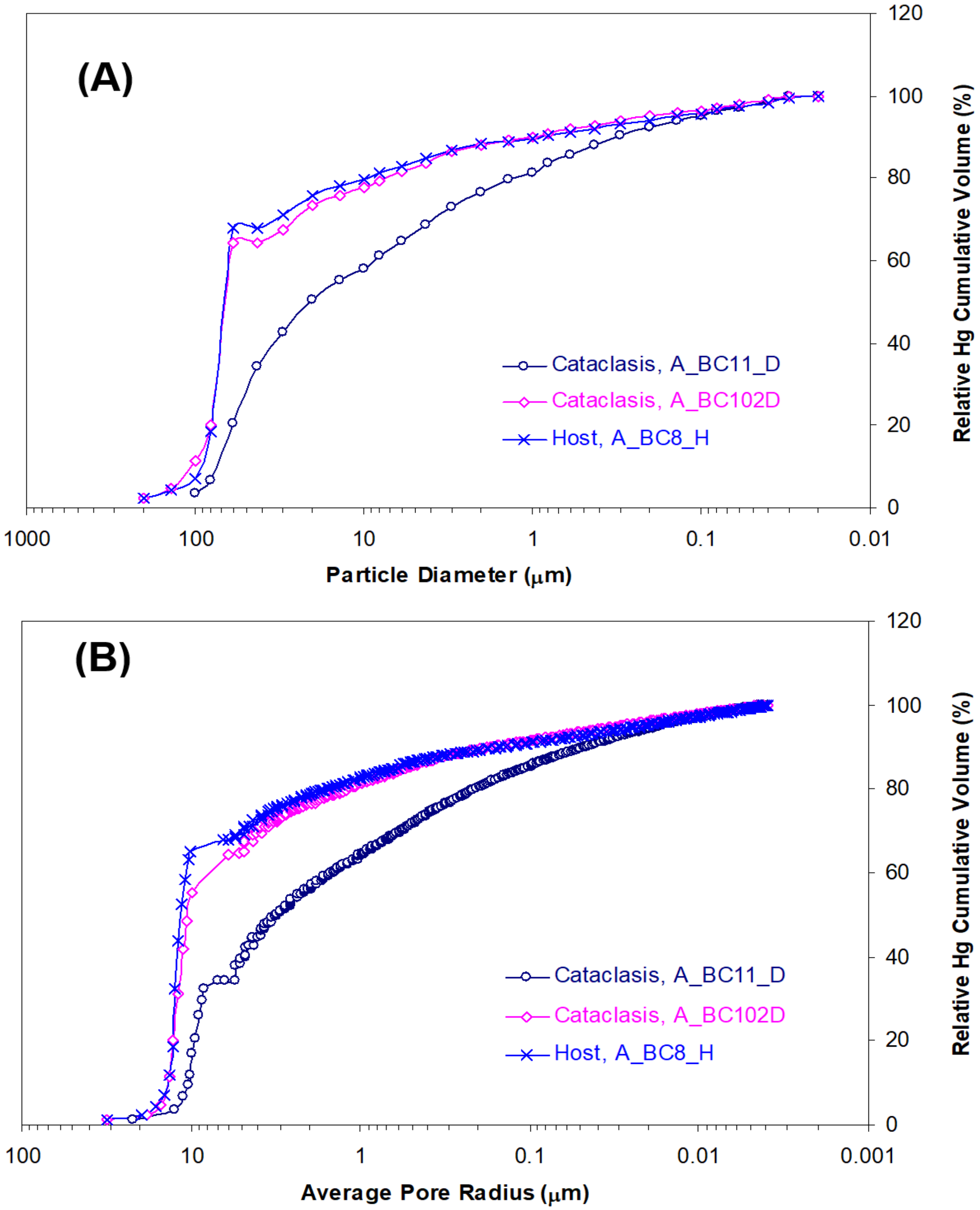


*Figure 7. Distribution of grain particle diameter (A) and pore aperture radius (B) for representative samples from the Isle of Arran. In comparison to the host rock (A_BC8_H), the particle grain and pore aperture radius sizes of the sample of multiple cataclastic bands (A_BC11_D) were reduced significantly, whereas these parameters from the sample of a single cataclastic band (A_BC102D) were only reduced slightly.*

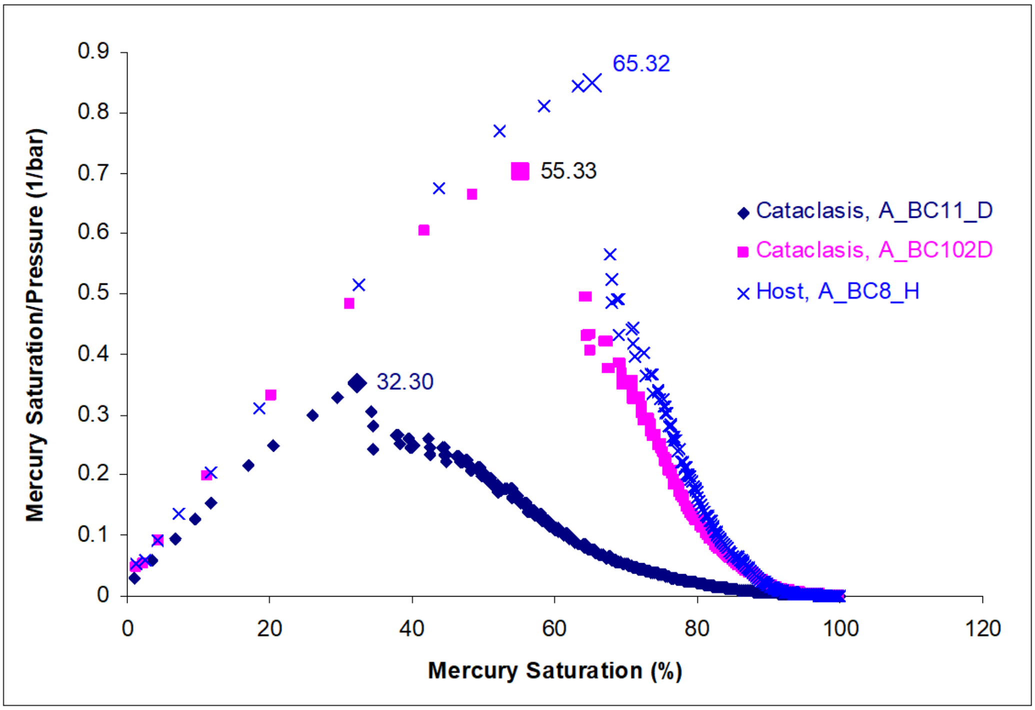


*Figure 8. Distribution of apex volumes (bigger symbols) for representative samples of the NRS, Isle of Arran. The apex volume or effective mercury porosity of the sample with multiple cataclastic bands (32%, sample A_BC11_D) was reduced approximately twice that of the host rock (65%, sample A_BC8_H). The deformed sample that comprises a single cataclastic band has an intermediate apex volume value (55%, sample A_BC102D). The apex volumes are derived using Pittman's method (1992).*

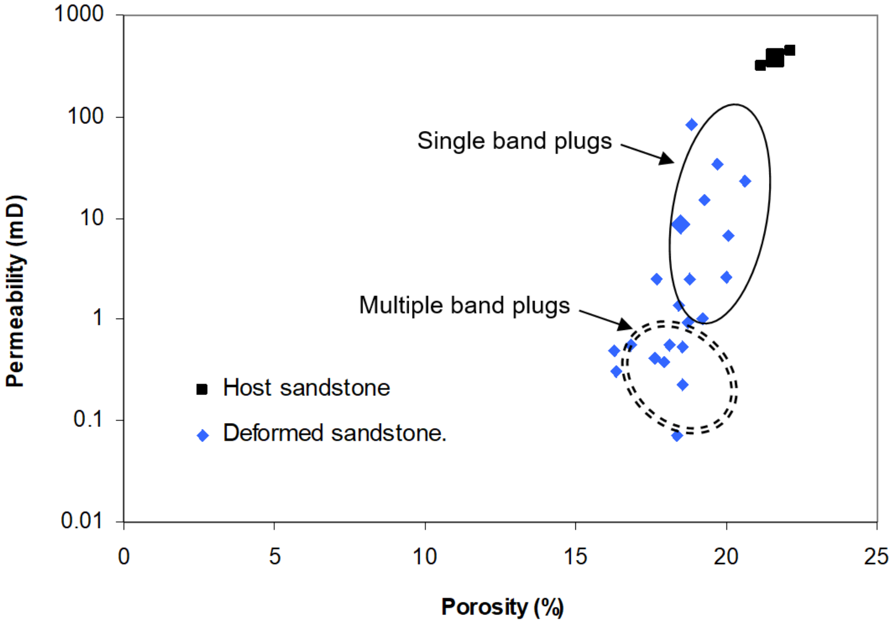


*Figure 9. General distribution of core plug porosity and permeability for the selected sandstones in the Isle of Arran. Samples including multiple cataclastic bands are characterised by the lowest poroperm values. Bigger symbol shows the appropriate average value.*

## 4. Discussion

Early diagenesis in the New Red Sandstone, Isle of Arran resulted in pore occlusion due to the precipitation of authigenic clay, hematite, and calcite cementation. It is characteristic of all general patterns of early diagenesis in red beds (Walker, 1967; Walker et al., 1978; Burley, 1984). The Brodick Breccias and surrounding sediments are also cemented with grain coatings of blocky dolomite cement (Astin and MacDonald, 1983). However, in this work, the calcite cement with poikilotopic and blocky textures was only encountered in the samples collected from the coastal area at Brodick Castle. The pore occlusion by calcite cementation postdated clay and hematite cementation.

Burial diagenesis influences the New Red Sandstone through pore occlusion from the formation of quartz and feldspar overgrowths, and pore-filling pyrite. Authigenic quartz partly developed on detrital grains, and of all the different burial cement types, is the main control of porosity. Authigenic feldspar is very common in the Scottish Permo-Triassic Sandstone (McKeever, 1992); however, feldspar overgrowths were only encountered in the SEM study and are therefore a very minor component. A similar observation was made by McKeever (1992) who studied the Permo-Triassic sandstones in the Inner Hebrides, Colonsay, Loch Indaal, and South Shetland Basins. Development of quartz and feldspar overgrowths is relatively limited and could be inhibited by early authigenic clay and hematite grain-coating cements. Hematite cutans (Figure 5E) can possibly prevent the formation of quartz overgrowths (Mundy and Evoy, 1997). Additionally, grain coatings of authigenic clays (Figure 5B) can also partially prevent the development of quartz and feldspar cements and contribute to the preservation of intergranular porosity (Heald and Larese, 1974; Storvoll et al., 2002; Worden and Morad, 2003). The limited development of quartz and feldspar overgrowths could also be a result of burial cementation at just shallow burial depths (< 1.75 km). This is because the main window of quartz cementation conventionally occurs at 2÷3 km burial depths in sedimentary basins (e.g. Bjørlykke and Egeber, 1993; Worden and Morad, 2000).

Cataclasis affected sandstone porosity and permeability by spalling detrital grains and their overgrowths, resulting in a decrease in pore space and very low porosity and permeability within the inner zone of a single deformation band (Figure 3F). Underhill and Woodcock (1987) documented a drastic increase in percentages of < 0.03 mm grains corresponding to a decrease in percentages of > 0.1 mm grains when moving from the undeformed sandstone towards the inner zone of single cataclastic bands. In addition, a reduction of pore volume between the inner and outer zones of bands is also apparent. This work demonstrates that the significant reductions of grain and pore sizes in deformed samples in relation to undeformed rocks are apparent using mercury injection analysis (Figure 7). The injection analysis shows the apex volume of samples including multiple cataclastic bands is approximately reduced up to > 2 times relative to the host samples (Figure 8). Samples including multiple cataclastic bands are characterized by a higher reduction of grain and pore size (Figure 7A & B) and the lowest plug porosity and permeability (Figure 9). Furthermore, the aggregation of multiple deformation bands results in the formation of thicker impermeable or low permeability zones (Figures 3E & 9). Cataclastic bands compartmentalize the rock and form barriers to fluid flow, and thus represent a heterogeneity that controls fluid flow within the reservoir.

Pham (2007) used a back-stripping model to reconstruct the average values of intergranular porosity both before cataclasis and before quartz cementation. The model indicates that cementation reduced the intergranular porosity more significantly than burial compaction and cataclasis in these stages. It also indicates that early cementation contributed more significantly to porosity loss than compaction in terms of effects on the original porosity.

## 5. Conclusions

Diagenesis in the Permo-Triassic New Red Sandstone, Isle of Arran is characterized by early cementation of hematite, clay, and calcite minerals, followed by burial compaction, quartz, feldspar, and pyrite cementation.

Cataclasis post-dated the quartz and feldspar cementation and reduced the grain and pore aperture size in deformed samples. The reduction of pore volume between undeformed and deformed sandstones is represented by the reduced apex volume of the analyzed samples.

Cementation, including early authigenic minerals and particularly burial quartz cement, was a more important factor than burial compaction and cataclasis in controlling the porosity of the sandstones. In contrast, dissolution postdating the formation of authigenic feldspar improved porosity by 1.3% secondary porosity.

Cataclasis was not as important as diagenesis in controlling sandstone porosity and permeability. However, cataclasis resulted in lower porosity and very poor to medium permeability in deformed samples. Cataclastic bands compartmentalize reservoir sands and cause a high heterogeneity in undeformed porous sandstones.

## Acknowledgments

We would like to thank MOET, Vietnam, and Aberdeen University, the UK for partial funding for this work. We also would like to thank GeoFluids Group members for their valuable discussions every Thursday morning. Many thanks to Collin Taylor for sample preparations and an introduction to Mercury Injection Porosimeter's operation.

## Contribution of authors

Tuan Van Pham - sample collection, analysis and interpretation; draft the paper and revise for submission; John Parnell - recommended the outcrops, academic supervision and made critical comments for paper preparation.

## References

Astin, T. R., & MacDonald, D. I. M. (1983). Syn-depositional faulting and valley-fill breccias in the Permo-Triassic of Arran. *Scottish Journal of Geology*, 19, 47-58.

Barrett, B. H. (1925). The Permian breccia of Arran. *Transactions, Geological Society of Glasgow*, 17, 264-270.

Bjørlykke, K., & Egeber, P. K. (1993). Quartz cementation in sedimentary basins. *AAPG Bulletin*, 77, 1538-1548.

Burley, S. D. (1984). Patterns of diagenesis in the Sherwood sandstone group (Triassic), United Kingdom. *Clay Mineral*, 19, 403-440.

Clemmensen, L. B., & Abrahamsen, K. (1983). Aeolian stratification and facies association in desert sediments, Arran basin (Permian), Scotland. *Sedimentology*, 30, 311-399.

Dickin, A. P., Moorbath, S., & Welke, H. J. (1981). Isotope, trace element and major element geochemistry of Tertiary igneous rocks, Isle of Arran, Scotland. *Transactions of the Royal Society of Edinburgh*, 72, 159-170.

Evans, A. L., Fitch, F. J., & Miller, J. A. (1973). Pottasium-agon age determinations on some British Tertiary igneous rocks. *Journal of the Geological Society*, London, 129, 419-443.

Folk, R. L. (1974). *Petrology of sedimentary rocks*. Hemphill, Austin, 182p.

Friend, P. F., Harland, W. B., & Hudson, J. D. (1963). The Old Red Sandstone and the Highland Boundary in Arran, Scotland. *Transactions, Edinburgh Geological Society,* 19, 363-425.

Glennie, K. W. (2002). Permian and Triassic. In: Trewin, N. (eds.). *The geology of Scotland* – 4th edition. Geological Society, London, 301-321.

Graham, D., & Midgley, N. (2000). *Triangular diagram plotting spreadsheet* (TRI-PLOT). http://www.lboro.ac.uk/research/phys-geog/tri-plot/index.html. Department of Geography, Loughborough University.

Gregory, J. W. (1915). The Permian and Triassic rocks of Arran. *Transactions, the Geological Society of Glasgow,* 15, 174-187.

Harland, W. B., & Hacker, I. F. (1966). *Fossil lightning strikes 250 million years old.* Report of the British Association for the Advancement of Science, 22, 663-71.

Heald, M. T., & Larese, R. E. (1974). Influence of coatings on quartz cementation. *Journal of Sedimentary Petrology*, 44, 1269-1274.

Houseknecht, D. (1987). Assessing the relative importance of compaction processes and cementation to reduction of porosity in sandstones. *AAPG Bulletin*, 71, 633-642.

Lovell, J. P. B. (1971). Petrography and correlation of sandstones in the New Red Sandstone (Permo-Triassic) of Arran. *Scottish Journal of Geology*, 7, 162-169.

McKeever, P. J. (1992). Petrography and diagenesis of the Permo-Triassic of Scotland. In: Parnell, J. (eds.). *Basins on the Atlantic Seaboard: Petroleum Geology, Sedimentology and Basin Evolution*. Geological Society, London, Special Publications, 62, 71-96.

McLean, A. C. (1978). Evolution of fault-controlled ensialic basin in northwestern Britain. In: Bowes, D. R. and Leake, B. E. (eds.). *Crustal evolution in northwestern Britain and adjacent regions.* Seel House Press, 325-346.

McLean, A. C., & Deegan, C. E. (1978). *A synthesis of the solid geology of the Clyde region*. Institute of Geological Sciences Report, *78*(9), 93-114.

Mundy, D., & Evoy, R. (1997). *A synopsis of the Old Red Sandstone reservoir in the 21/1A-8 well, Buchan field, U.K.C.S.* Talisman Petroleum Company, UK. Internal Report. Aberdeen, March, 1997.

Pham, T. V. (2007). *Controls of Diagenesis and Structural Deformation on Reservoir Quality in Red Beds*. PhD Thesis in Geology & Petroleum Geology, University of Aberdeen, 260p.

Shelton, R. G. (1996). *Basin evolution in the North Channel Region*. PhD thesis, Queen's University of Belfast, Ireland.

Storvoll, V., Bjørlykke, K., Karlsen, D., & Saigal, G. (2002). Porosity preservation in reservoir sandstones due to grain-coating illite: a study of the Jurassic Garn Formation from the Kristin and Lavrans fields, offshore Mid-Norway. *Marine and Petroleum Geology*, 19, 767-781.

Tyrrell, G. W. (1928). *The geology of Arran*. Mem. Geol. Surv. U.K.

Underhill, J. R., & Woodcock, N. H. (1987). Faulting mechanisms in high-porosity sandstones: New Red Sandstone, Arran, Scotland. In: Jones, M.E. & Preston, R.M.F. (eds.). *Deformation of Sediments and Sedimentary Rocks.* Geological Society, London, Special Publications, 29, 91-105.

Walker, T. R. (1967). Formation of Red Beds in Modern and Ancient Deserts. *Geological Society of America Bulletin*, 78, 353-368.

Walker, T. R., Waugh, B., & Grone, A. J. (1978). Diagenesis in first-cycle desert alluvium of Cenozoic age, southwestern United States and northwestern Mexico. *Geological Society of America Bulletin*, 89, 19-32.

Woodcock, N. H., & Underhill, J. R. (1987). Emplacement-related fault patterns around the Northern Granite, Arran, Scotland. *Bulletin of Geological Society of America*, 98, 515-527.

Worden, R. H., & Morad, S. (2000). Quartz cementation in oil field sandstones: a review of the key controversies. In: Worden, R. H. and Morad, S. (eds.). *Quartz Cementation in Sandstones.* International Association of Sedimentologists, Special Publications, 29, 1-20.

Worden, R. H., & Morad, S. (2003). Clay minerals in sandstones: controls on formation, distribution and evolution. In: Worden, R. H. and Morad, S. (eds.). *Clay Mineral Cements in Sandstones.* International Association of Sedimentologists, Special Publications, 34, 3-41.