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Controls of normal diagenesis on poroperm parameters in red beds: examples in Miocene Muddy Creek Formation, Mesquite basin, USA and upper Devonian Old Red Sandstone, Orcadian basin, Scotland

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ABSTRACT

General diagenetic patterns in Miocene Muddy Creek Formation and upper Devonian Old Red Sandstone (ORS) can be characterized as follows: i) early diagenesis characterized by the formation of early hematite, carbonate, and clay cement; ii) burial diagenesis followed by the formation of quartz and feldspar overgrowths, poikilotopic calcite and pore-filling clays; iii) late diagenesis characterized by the formation of late hematite replacing previous poikilotopic carbonate cement. Normal diagenesis has a significant impact on poroperm-parameters as indicated by the destruction of pore spaces from cementation and intergranular pressure solution. Early cementation in unburied sandstones of the Muddy Creek Formation reduces sample porosities to 2÷20% of the total rock volume. Cementation destroyed the original porosity of studied sandstones through pore occlusion due to the formation of equant and meniscus calcite cement. Point-count data indicate that the intergranular cement of studied samples ranges between 22 and 44%; in contrast, the intergranular porosities range from 2÷20% of the total rock volume. These consequently indicate that the intergranular volumes that are considered to represent the original porosities of studied samples, ranged from 35÷50% of the total rock volume. Completely pore-occluding poikilotopic calcite cement in the upper Old Red Sandstone reduces poroperm values to as low as 5% porosity and 0.003 mD permeability. Late reddening is caused by replacive hematite cement in the calcite. In addition, normal diagenesis also has an impact on porosity enhancement due to dissolution in the studied red beds. This improves porosity and permeability by as much as 14% and 254 mD in the upper ORS.

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1. Introduction

This paper presents and discusses a general pattern of diagenetic modifications in selected red beds intending to draw similarities and contrasts between diagenetic and structural deformation studies. The term "normal diagenesis" is taken to mean the diagenesis that occurs to rock during burial (e.g. cementation, dissolution, mechanical compaction, and intergranular pressure solution) but does not include structural deformation (e.g. cataclasis, fracturing). In general, normal diagenesis affects sandstone porosity and permeability in two ways: i) through the destruction of rock porosity and permeability by cementation and compaction (e.g. Wilson and Stanton, 1994); ii) by the enhancement of rock porosity and permeability through the formation of secondary porosity (e.g. Bloch, 1994; Wilson and Stanton, 1994). Practically, cementation occludes pore space, mechanical compaction, and intergranular pressure solution reduce pore volume, and dissolution enlarges the volume of pore space. These effects consequently control reservoir porosity and permeability (Wilson and Pitman, 1987; Bjørlykke et al., 1989; Bloch, 1994; Wilson and Stanton, 1994).

A total of 12 thin sections, several SEM chips, and 6 core plugs were selected for studies of petrography and petrophysical properties in two selected red sandstones: i) the upper Miocene Muddy Creek Formation, Mesquite basin, USA; ii) the upper Devonian ORS, Orcadian basin, UK. The Muddy Creek Formation has been selected for diagenetic study as it presents a red bed succession that has not been buried. In addition, the diagenetic study of the Upper ORS of the Orcadian basin, exposed on the Embo coast, can help to construct an analog for studies of diagenesis in other upper ORS sandstones in the northern North Sea and provides an example of late-stage Cenozoic uplift of a red bed succession.

2. Muddy Creek Formation

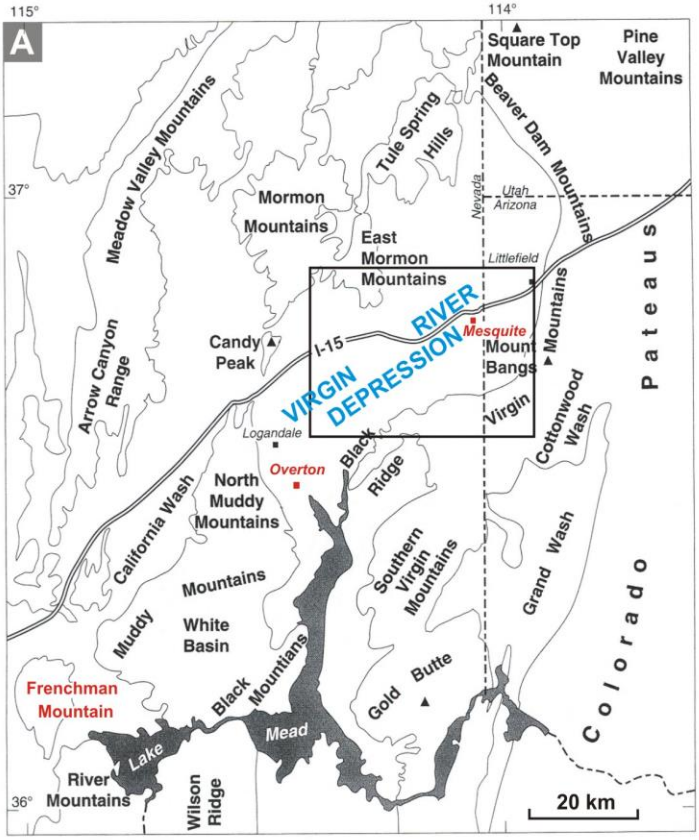
2.1. Local geology

The Muddy Creek Formation (MCF) comprises late Miocene continental sediments within the Mesquite basin and adjacent areas (Bohannon et al., 1993; Pederson, 2001). The Mesquite basin is a rift basin, located in southeastern Nevada/northwestern Arizona, USA (Figures 1A & B). This basin is a part of the Virgin River depression surrounded by the north Muddy Mountains, the Virgin Mountains, the Beaver Dam Mountains, the Tule Spring Hills, and the Mormon Mountains. The basin developed in the late Oligocene/early Miocene with extension and subsidence taking place in three stages (Bohannon et al., 1993) which correspond to the accumulations of the Horse Spring Formation (24÷13 Ma stage), the Lowell Wash Member and the Red Sandstone Unit (13÷10 Ma stage), and the Muddy Creek Formation (post-10 Ma stage). The MCF was deposited under a semi-arid climate and consists of two sedimentary units distinguished by seismic and lithological facies. The lower gypsiferous unit consists of abundant gypsum beds interbedded with pink siltstones, and the upper Muddy Creek unit consists of monotonous pink siltstones. The depocentre of the Mesquite basin was probably near the Piedmont fault (Bohannon et al., 1993). The formation shows a relatively uniform thickness over much of the Virgin River depression (Figure 1B).

2.2. Diagenetic modifications

Five samples of the MCF were collected from surface exposures (Figure 1C). Five standard thin sections were prepared together with several SEM rock chips. The reason for studying the MCF is that it has undergone limited to no burial (Fordham, 2006) and therefore provides an important analog for studying the early stage of red bed diagenesis.

Observations indicate that unstable detrital grains such as mica, volcanic rock fragments, etc., were subject to alteration. This is indicated by the replacement of some detrital grains by hematite and illite, typically on average $< 1.5\%$ of total rock volume in selected samples. Grain coating authigenic hematite (Figure 2A) accounts for $<$ 3% volume (Table 1). Calcite cement occurred following hematite formation and occluded a significant volume of pore spaces (Figure 2A - F), ranging from 17÷37% of the whole rock volume. Calcite cements typically have equant or meniscus



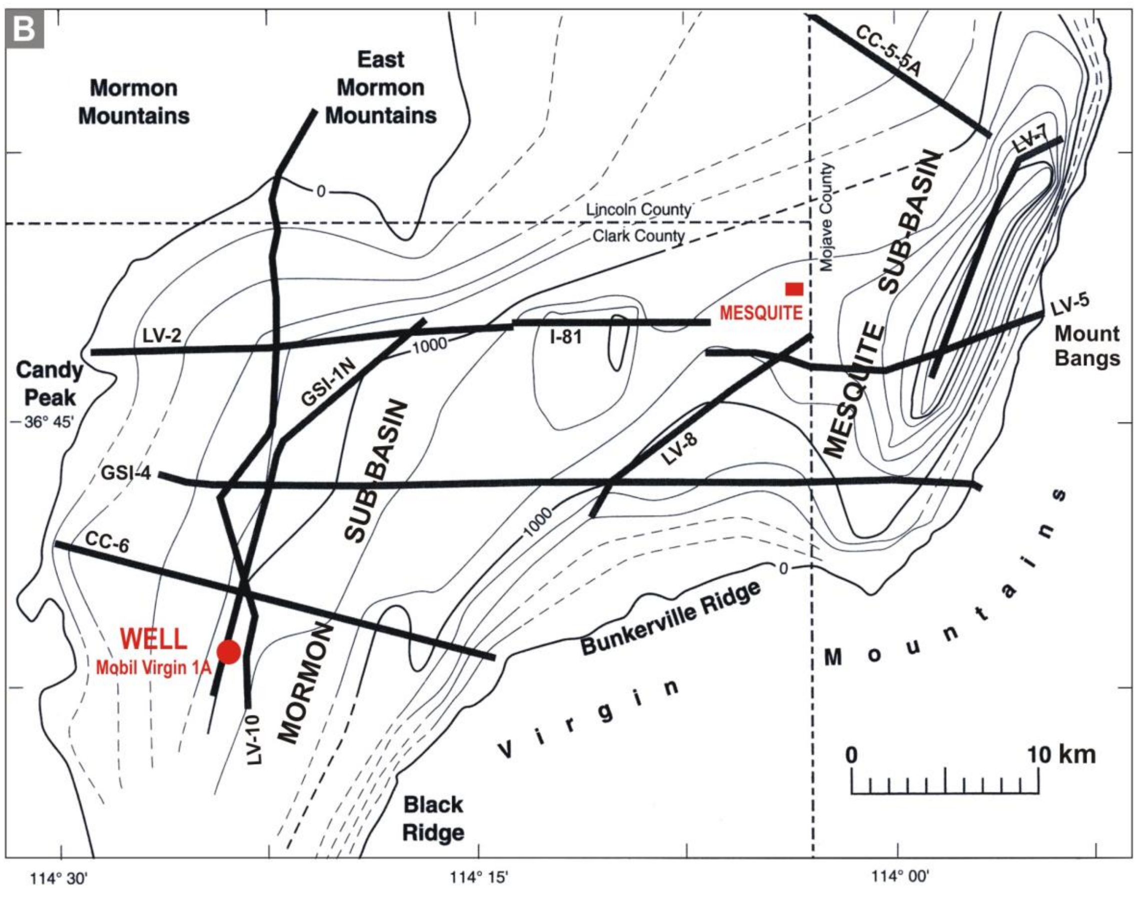


Figure 1. The location of Virgin River depression and Isopach map of the Muddy Creek Formation: A) Index map of Virgin River depression (after Bohannon et al., 1993). Frame is the area of figure B. B) Isopach map of the Muddy Creek Formation (after Bohannon et al., 1993). Contour interval is 200 m. Bold-black lines depict seismic reflection lines.

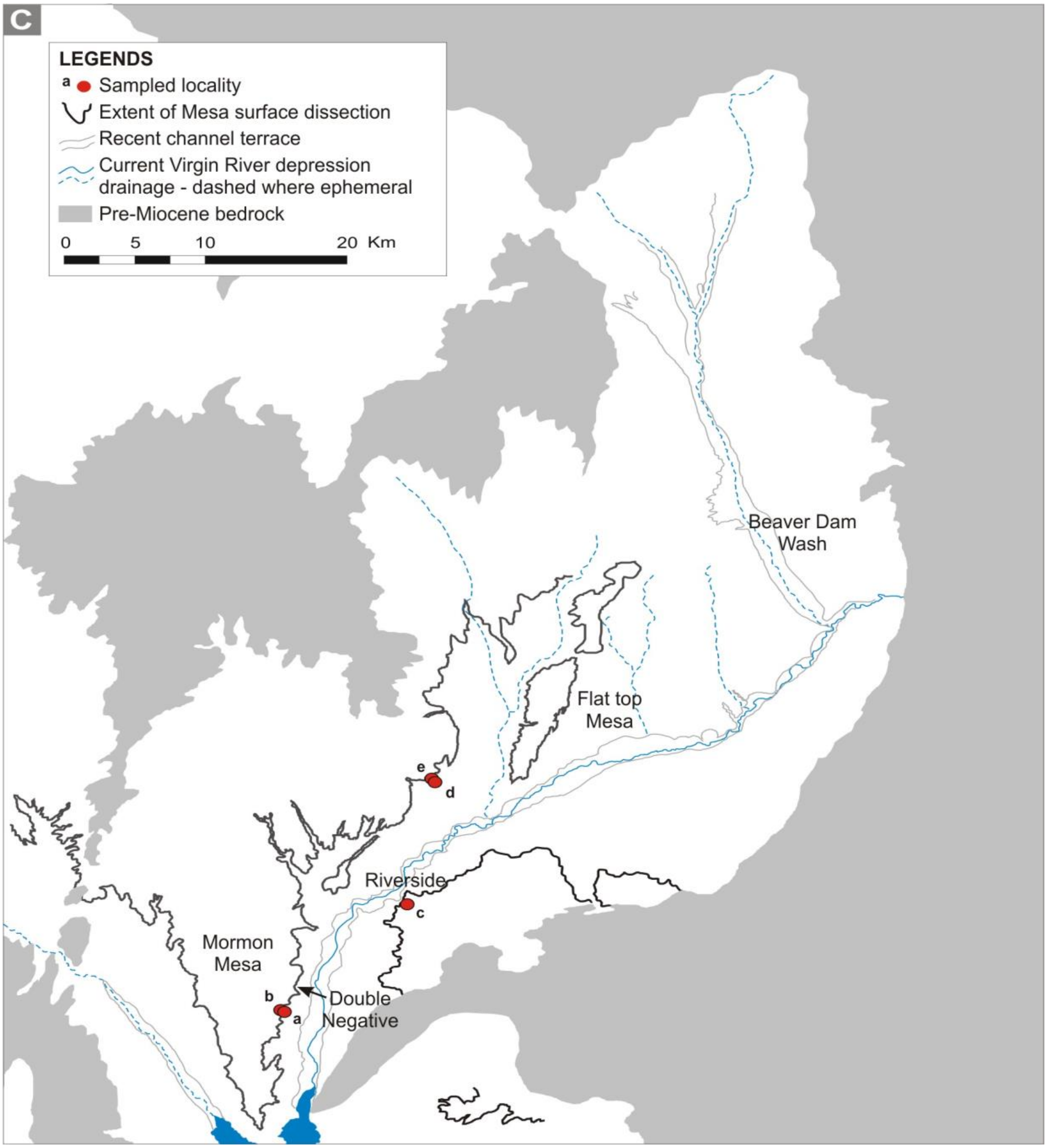


Figure 1C. Map of sampled localities in the Virgin River depression (after Fordham, 2006) having followed details.

Sampled localities	*UTM NAD83*	*Easting*	*Northing*
a	*11S*	*736926*	*4053324*
b	*11S*	*736376*	*4053472*
c	*11S*	*745018*	*4062805*
d	*11S*	*746601*	*4073641*
e	*11S*	*746513*	*4073650*

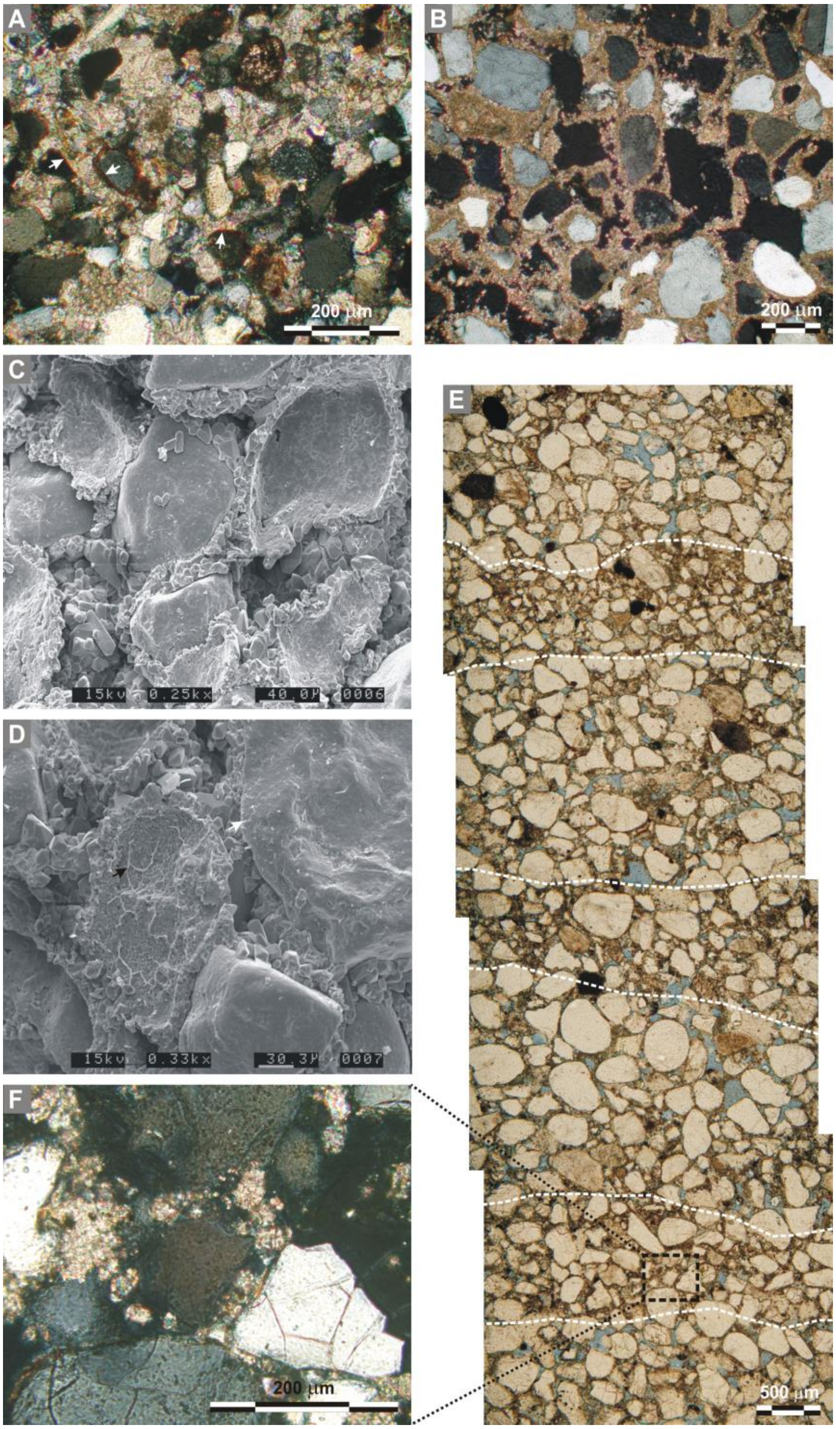


Figure 2. Early cementations in selected samples of the Muddy Creek Formation: A) Cross-polarized TS photomicrograph (location c) shows early hematite cement (arrowed) that coats detrital grains, and predates calcite cementation; B) Cross-polarized TS photomicrograph (location d) showing that cementation has occurred prior to compaction of grains (floating texture) on the equant calcite cement; C) Secondary SEM photomicrograph (location d) shows detrital grains cemented by equant calcite cement; D) Secondary SEM photomicrograph (location d) shows dust (white arrow) and hairy (black arrow) illites that predated the formation of blocky calcite cement; E) Plain-polarized TS photomicrographs (location a) showing more intensive developments of meniscus (possibly less likely-equant) calcite cement within sedimentary laminae; F) Cross-polarized TS photomicrograph enlarged from the frame on figure A, showing pore occlusions by meniscus calcite cement. Terms used for morphologies of calcite cement were proposed by Harwood (1988).

textures, according to the classification of Harwood (1988). Of which, the equant cement shows a higher occlusion of void spaces than the meniscus type (Figures 2B - D), but the meniscus calcite cement shows a more significant destruction of void spaces within sedimentary laminae (Figures 2E & F). Limited dusty and hairy authigenic illite coating on detrital grains is developed between detrital grains and equant calcite cement (Figure 2D).

The formation of hematite, illite, equant, and meniscus calcite cement occurred during early diagenesis, indicated by the fact that most of the detrital grains have no grain-grain contact, and they float within the equant calcite cement (Figure 2B - D). It is inferred that mechanical compaction has had a relatively insignificant effect. The formation of hematite and illite cement predated calcite cementation. Grain replacement illite formed during early eogenesis as a result of the alteration of detrital feldspar or unstable grains. The formation of replacement illite may occur when the clastic formation is in contact with meteoric water which results in a slightly acidic environment (Burley, 1984). Dissolution or alteration of unstable iron-containing grains has been considered as the most likely source for the formation of early hematite (e.g. Walker, 1967; Walker et al., 1978; Burley, 1984; Burley et al., 1987).

Cementation destroyed the original porosity of studied sandstones through pore occlusion due to the formation of equant and meniscus calcite cement. Point-count data indicate that the intergranular cement of studied samples ranges between 22 and 44%; in contrast, the intergranular porosities range from 2÷20% of the total rock volume (Table 1). These consequently indicate that the intergranular volumes that are considered to represent the original porosities of studied samples, ranged from 35÷50% of the total rock volume.

3. Upper Devonian Old Red Sandstone

3.1. Local geology

Red sandstones of the upper ORS are exposed on the coasts of Embo and Tarbat Ness, in the Moray Firth and formed part of the Orcadian basin (Figures 3; 4A & B; and 5A & B). This is one of several Devonian extensional basins in Northern Scotland, e.g. Midland Valley. The basin experienced rapid subsidence in the Devonian, followed by Carboniferous-Permian compression, and was subsequently uplifted in the Mesozoic and Cenozoic (Coward and Enfield, 1987; Coward et al., 1989; Parnell et al., 1998).

The upper ORS sequence was deposited under semi-arid conditions, by fluvial and locally aeolian processes (Trewin and Thirlwall, 2002) with extensive calcrete development in places. The sequence mostly lies conformably on the Middle ORS in the Orcadian Basin (Trewin and Thirlwall, 2002). The sequence is conformably overlain by Carboniferous strata.

Table 1. Summary of point-counting data from five unburied samples of the Muddy Creek Formation. Total 500 points counted with the noted-point number providing information of the mineral and porosity content. Intergranular volumes, possibly considered as similarity to the original porosity values, are typically between 35 and 50% of the total rock volume.

Contents (%)/Sample/Location/points counted		#10/a/430	#11/d/463	#12/c/484	#13/e/479	#14/b/458
Detritus	Quartz	57.44	42.33	35.12	40.71	38.65
	Feldspar	1.16	2.16	3.10	1.88	1.31
	Rock fragment	2.79	5.40	2.69	6.26	5.24
	Mica	0.23	0.00	0.41	0.84	0.00
	Carbonate nodules	0.70	0.65	5.79	13.15	2.40
	Others	3.02	3.01	1.86	2.09	3.93
Authigenic	Authigenic clay	3.72	0.43	1.24	0.21	0.66
	Authigenic carbonate	16.74	33.26	37.19	29.02	23.36
	Hematite	0.70	0.86	3.10	2.30	2.62
	Others	1.16	0.07	2.69	1.46	1.75
Porosity		12.33	11.83	6.82	2.09	20.09
Total	Detritus	65.35	53.55	48.97	64.93	51.53
	Cement	22.33	34.62	44.21	32.99	28.38
	Porosity	12.33	11.83	6.82	2.09	20.09
	Intergranular volume	34.65	46.45	51.03	35.07	48.47

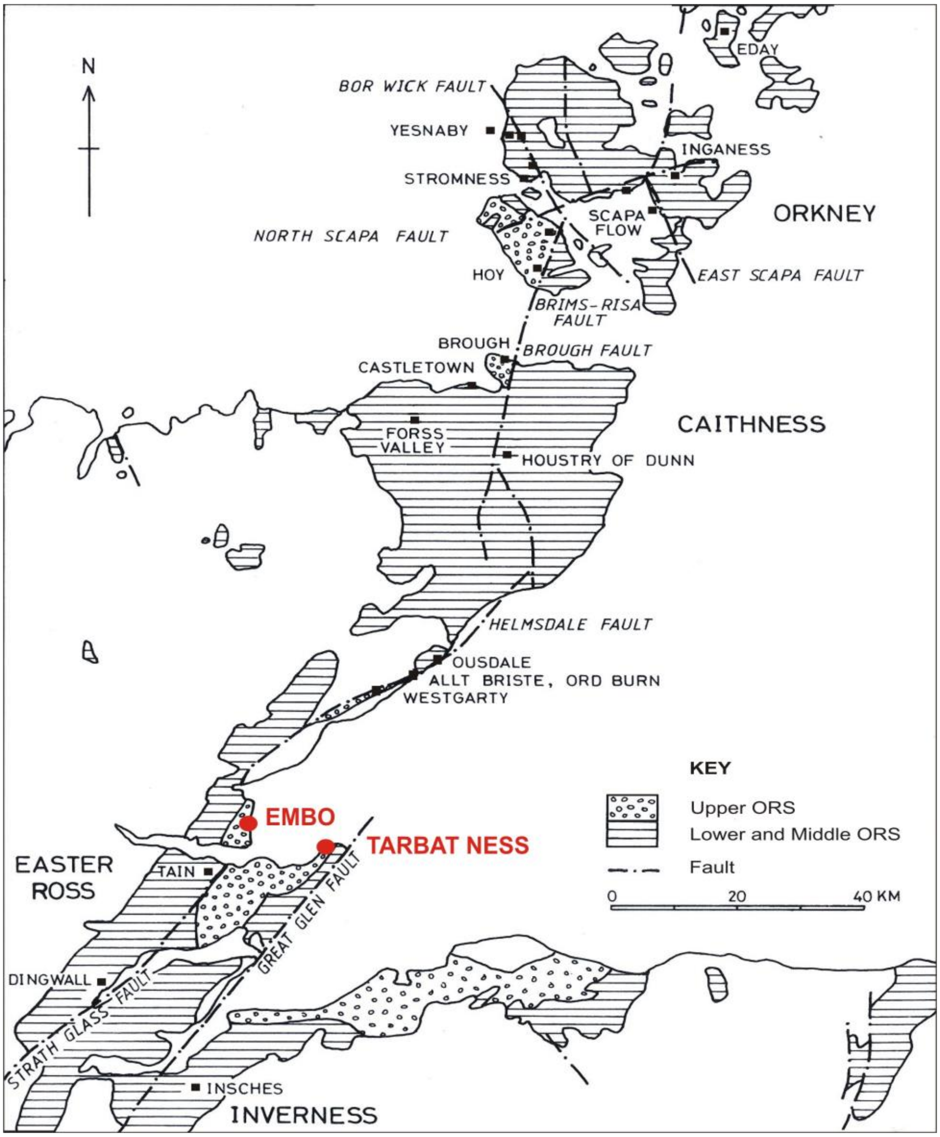


Figure 3. Map of Orcadian Basin, showing the distribution of ORS (modified after Parnell, 1985), and the localities of selected upper ORS samples in the coastal areas of Embo (NH 820922) and Tarbat Ness (NH 945873).

3.2. Diagenetic modifications

Nine polished and standard thin section (TS) (6 polished and 1 standard TS in Tarbat Ness; 2 polished and standard TS in Embo localities), and a number of SEM rock chips and SEM polished hand-specimens were selected for petrographic study (Table 2).

In addition, six core plugs were taken and used to determine the porosity and permeability to illustrate the effects of diagenesis on poroperm parameters for the studied samples. Early diagenesis is characterized by the formation of an early hematite cement coating on detrital grains (Figure 5D). It is followed by the formation of quartz, kaolinite, and poikilotopic calcite cement (Figures 4C - F; and 5C). Late reddening is caused by the formation of late hematite cement as a replacement of poikilotopic calcite (Figures 4F, G & H). Late hematite is believed to form the characteristic red spots or the whole red color of the ORS samples collected at the Embo coast (Figures 4A & B).

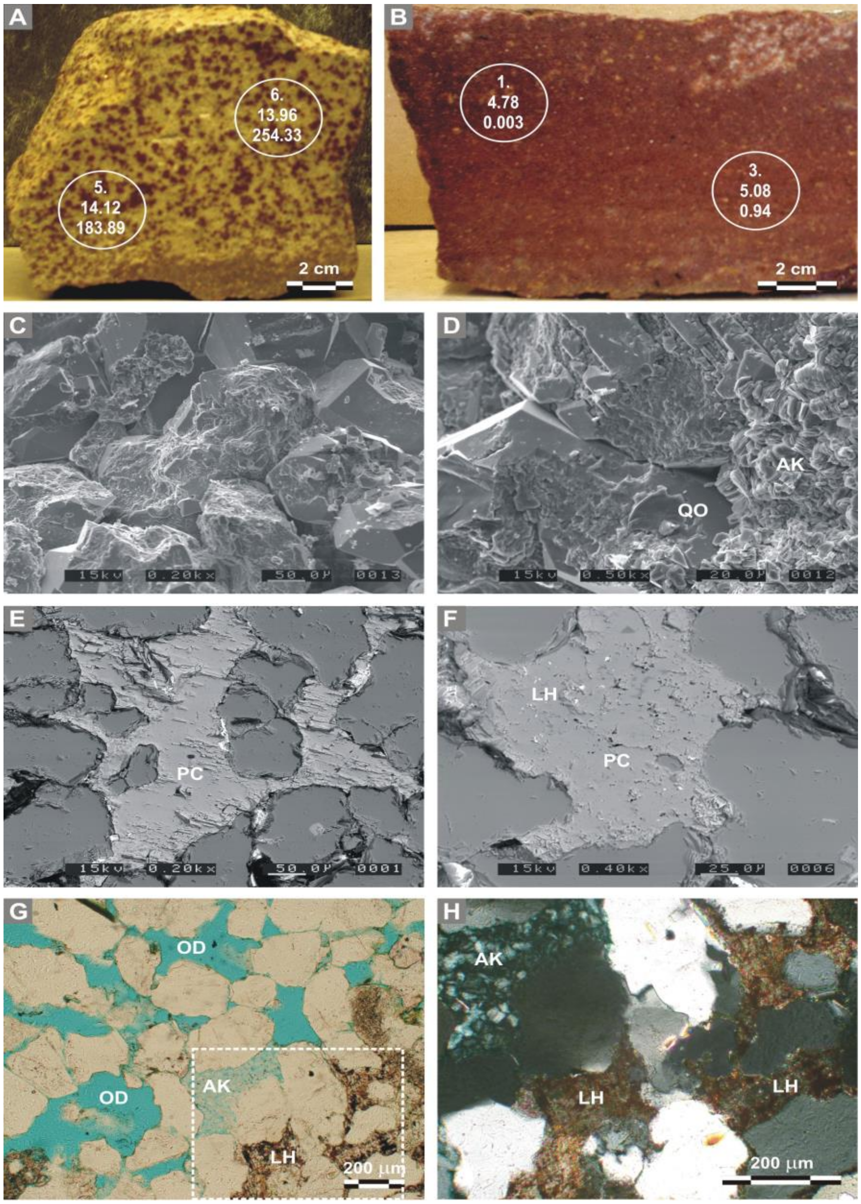


Figure 4. Core photos, SEM and thin section photomicrographs of upper ORS: A) Core slab photo shows selected Upper ORS at the Embo locality, including red spots; B) Core slab photo shows selected Upper ORS as being appeared as whole red color at the Embo coast; C) SEM photomicrograph shows general characteristics of quartz overgrowths; D) SEM photomicrograph shows developments of quartz cement and pore-filling authigenic kaolinite; E) Back-scattered SEM photomicrograph of polished hand-specimen shows poikilotopic calcite cement in un-redden area of sandstone sample; F) Back-scattered SEM photomicrograph of polished hand-specimen shows poikilotopic calcite cement in redden area (red spot) of the analyzed sample. Late replacement hematite cement is thought to cause the red color in the studied sample; G) Plain-polarized TS photomicrograph shows oversized dissolution pores, pore-filling kaolinite cement and the development of late hematite in poikilotopic calcite cement. Dashed box is the area of figure H; H) Cross-polarized TS photomicrograph, showing more details of pore-filling kaolinite cement and replacement of late hematite on pore-occluding poikilotopic calcite cement. Samples collected at the coast of Embo. Circles are core plug positions: plug ID, Φ(%) and K (mD) in upper - lower order. QO = quart overgrowth; AK = authigenic kaolinite; PC = poikilotopic calcite; LH = late hematite; OD = oversized dissolution.

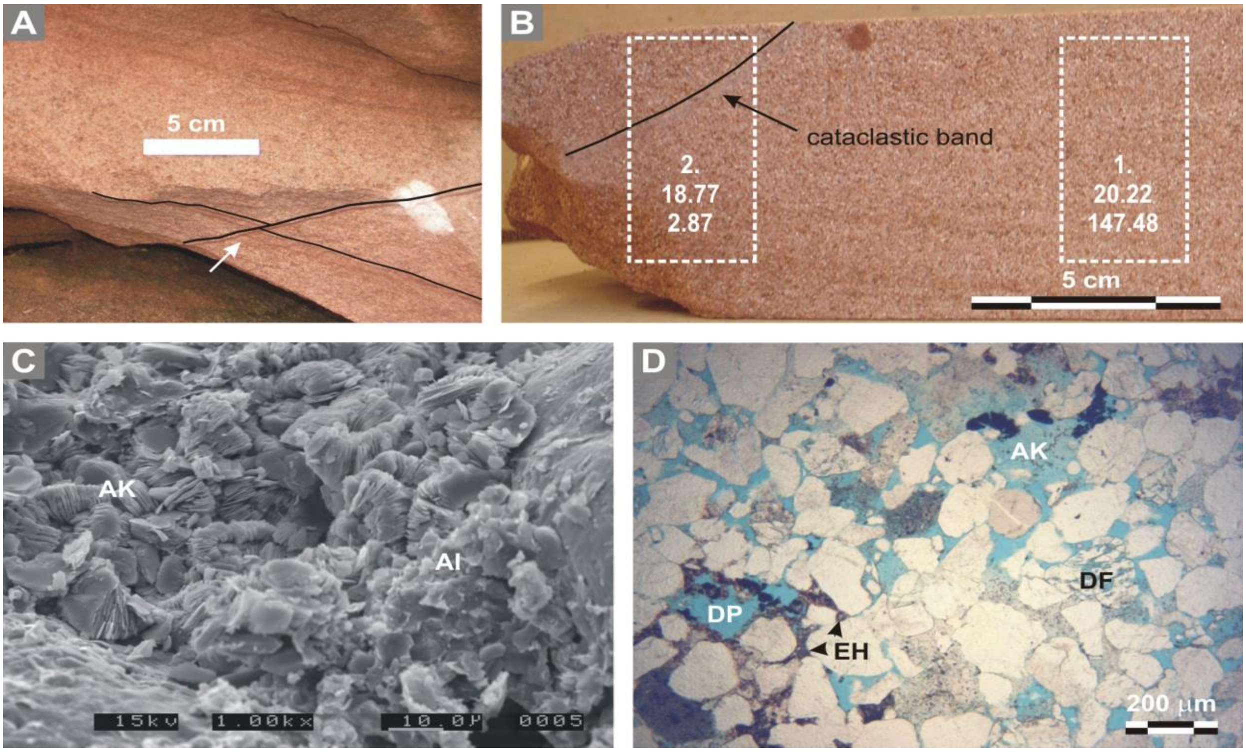


Figure 5. Core photos and thin section photomicrographs of upper ORS: A) Photo of the Upper ORS at the Tarbat Ness locality. Juxtaposition of deformation bands possibly suggesting that the Upper ORS has been experienced some different deformation phases. B) Core slab photo showing example of different porosity and permeability values between deformed and undeformed host rock core plugs. Left plug including a cataclastic band, has lower porosity and permeability. Rectangulars are cylindrical core plug positions: plug ID, Φ(%) and K (mD) in upper - lower order. C) SEM photomicrograph shows pore-filling authigenic kaolinite and illite. D) Plain-polarized TS photomicrograph shows dissolution on detrital feldspar, dissolution pores, authigenic kaolinite and late hematite cement. AK = authigenic kaolinite; AI = authigenic illite; DP = dissolution pore; EH = early hematite; DF = dissolution of feldspar.

Table 2. Summary of petrographic and petrophysical analyses for the samples collected at Embo and Tarbat Ness localities.

Location	Petrophysical analyses				Petrographic notes
	Core plug				
	I.D.	Φ (%)	K (mD)	Description	
Embo	1	4.78	0.003	Completely red	2 polished and standard thin sections; SEM analyses
	3	5.08	0.94	Completely red	
	5	14.12	183.89	Red spots, dissolution	
	6	13.96	254.33	Red spots, dissolution	
Tarbat Ness	1	20.22	147.48	Host rock	6 polished and a standard thin sections; SEM analyses
	2	18.77	2.87	Including a cataclastic band	

The dissolution of detrital feldspar grains (Figure 5D) and the occurrence of oversized dissolution pores (Figures 4G & 5D) indicate that the studied sandstones have been significantly affected by dissolution processes. Abundant pore-filling authigenic kaolinite (Figures 4D, G & H; 5C) contrasts with adjacent oversized dissolution pores (Figure 4G). The origin of the oversized pores is problematic. They may have been generated by feldspar dissolution or possibly by the dissolution of early carbonate cement. Dissolution within the ORS may be related to a phase of uplift, such as that recorded for the Inner Moray Firth during the Cenozoic (McQuillin et al., 1982; Roberts et al., 1990; McKeever, 1992), where the sandstones were possibly in contact with meteoric water (e.g. Permian uplift indicated by Coward and Enfield, 1987; Parnell et al., 1998).

Dissolution improved the rock's poroperm values through the formation of oversized void spaces. Core plug porosity and permeability may reach as much as 14% and 254 mD (Figure 4A; Table 2). However, completely pore-occluded calcite cement shows extreme reductions in poroperm values as small as 5% and 0.003 mD (Figure 4B).

Deformation bands were observed on the Tarbat Ness coast, west of the Great Glen Fault (Figure 3). They are typically < 2 mm thick, dark brown, and have a localized development (Figure 5A). Deformation bands are characterized by spalling of detrital and authigenic grains in situ. A core plug cutting across a deformation band was taken to determine porosity and permeability with the aim to make a comparison with poroperm values of adjacently undeformed host rock core plug (Figure 5B).

A core plug including a cataclastic band (Figure 5B) shows a small reduction of porosity and an extreme reduction of permeability (19%; 2.87 mD) in comparison to the porosity and permeability of an adjacent host rock plug (20%; 147 mD). The cataclastic band acts as a barrier to fluid flow within the deformed rock and therefore causes an extreme reduction of permeability. However, since the plug porosity with a thin deformation band contains a significant volume of undeformed rock, the reduction of porosity is relatively small in comparison to an undeformed host rock core plug.

4. Discussion and conclusion

Normal diagenetic patterns in the two selected red beds can be characterized as follows: i) early diagenesis characterized by the formation of early hematite, carbonate, and clay cement; ii) burial diagenesis followed by the formation of quartz and feldspar overgrowths, poikilotopic calcite and pore-filling clays; iii) late diagenesis characterized by the formation of late hematite replacing previous poikilotopic carbonate cement.

Normal diagenesis has a significant impact on poroperm parameters in the selected sandstone formations as indicated by the destruction of pore spaces from cementation and intergranular pressure solution. Early cementation in unburied sandstones of the Muddy Creek Formation reduces sample porosities to 2÷20% of the total rock volume. Completely pore-occluding poikilotopic calcite cement in the upper ORS reduces poroperm values to as low as 5% porosity and 0.003 mD permeability. Late reddening is caused by replacive hematite cement in the calcite. In addition, normal diagenesis also has an impact on porosity enhancement due to dissolution in the studied red beds. This improves porosity and permeability by as much as 14% and 254 mD in the upper ORS.

The study of unburied sandstones of the Muddy Creek Formation indicates that the sandstones have undergone non-burial early diagenesis, and typically have intergranular volumes ranging between 35 and 50% of the total rock volume. These values are in the range of the original porosities reviewed by Houseknecht (1987) and are useful references for the selection of the original porosity values for the other studied red beds.

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Contribution of authors

Tuan Van Pham - sample analysis and interpretation, draft the paper and revise for submission; John Parnell, Adrian Hartley - recommended the studied locations, made critical comments for paper preparation.

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