Sedimentological control of diagenetic processes of the tidal sandstones of the Upper Cape Hay Formation (Permian, Bonaparte Basin, Australia): Impact on reservoir properties

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Abstract. The deep silicoclastic reservoir (> 3500 m) of the Bonaparte Basin (northern Australia) exhibits wide heterogeneity in porosity (2 to 26%) and permeability (0.001 to 2500 mD). To investigate this variability, 42 samples were taken from five wells drilled through the uppermost Cape hay reservoir. Six facies were identified: (1) mud flat, (2) sand flat, (3) top of tidal bar, (4) mid tidal bar, (5) base of tidal bar, and (6) upper offshore/lower shoreface transition zone facies.

The paragenetic sequence comprises seven diagenetic processes: (1) synsedimentary ferrous chlorite coatings, (2) mechanical compaction, (3) quartz overgrowth, (4) feldspar alteration-dissolution and quartz corrosion, (5) authigenic clays (illite and kaolinite), (6) ferrous calcite cementation, and (7) chemical compaction subsequent to mechanical compaction.

Mid and top of the tidal bars generally exhibiting the best porosity ($\Phi > 15\%$) and permeability values ($k > 10$ mD). Chlorite grain coatings fully covering detrital grains were systematically emplaced in this sand bar facies at the end of the third-order transgressive episode. This clay coating inhibited silicification. This proves to be the key parameter behind good Φ-k qualities.

Keywords: tidal sand bar, grain coatings, petrophysical properties.

1 Introduction

Reservoir quality varies with porosity (Φ) and permeability (k). These parameters depend on initial properties and diagenesis history.

The initial porosity of sand is typically about 40% during deposition; it declines with burial following the general curve of porosity loss with depth (Bahlis & De Ros, 2013). In some instances, abnormal high porosity of deep silicoclastic rocks (> 3500 m) as observed in the North Sea, implies that other parameters should be taken into account (Ehrenberg, 1993). The presence of well-developed clay films or rims around the detrital grains (grain coatings) or the presence of microquartz around quartz grains are factors recognised as inhibiting siliceous cementation and so preserving porosity (Heald & Larese, 1974; Wilson & Pittman, 1977; Ehrenberg, 1993; Ajdukiewicz & Larese, 2012).

The tidal sandstones of the Cape Hay Formation (Permian) in the Bonaparte Basin (Northern Australia) are deeply buried (> 3500 m). This clastic reservoir overcame a high diagenetic overprint, resulting in highly variable reservoir properties, with porosity (Φ) ranging from a few percent up to 25%, and permeability (k) varying from 0.01 mD to several hundred mD. Some of these values are abnormal at these depths. This field is therefore a prime subject to investigate the impact of sedimentology and diagenesis on reservoir properties preservation and to understand how these parameters are correlated.

2 Geological setting

Studied reservoir is located in the Petrel Sub-Basin of the Bonaparte Basin. It is a Paleozoic basin corresponding to an aborted rift that evolved into a passive margin (Gun, 1988).

The basin history is characterized by a rapid subsidence from Carboniferous until Late Permian, followed by a slight regional uplift during Late Trias, then by a gently subsiding phase from Jurassic to present (Kennard, 2002).

Studied reservoir is located in the Cape Hay Formation (Permian). Reservoir R1 corresponds to a second-order transgressive phase, starting by fluvial and estuarine deposits and ending with the deposition of the Pierce carbonates. In accordance with the presence of *Skolithos-Cruziana* ichnofacies it suggests a brakish environment in an estuary setting (Wood & Lemon, 2007).

3 Materials and methods

Porosity and permeability were measured on 418 plug samples from five wells. Out of these samples, 42 were selected, representative of the heterogeneity of facies and petrophysical properties along the five wells.

Depositional facies and diagenetic features were studied using a Leica DM750P optical microscope. These observations were systematically supplemented by cathodoluminescence petrography performed with an OPEA cathodyne, (14–16 kV and 200–250 mA) coupled to a BX41

Olympus microscope and a digital CCD Qimaging QICAM fast 1394 camera in order to refine the different cementation stages. Scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) analyses were carried out on 25 thin sections and 8 fresh broken surfaces with a Philips XL30 SEM. Clay mineral assemblages were identified on 41 samples using a PANalytical X'Pert Pro with a Cu anticathode (Kα1=1.540598, 45 kV; 40 mA) X-ray diffraction (XRD). The proportions of residual primary porosity, secondary porosity (feldspar alteration), detrital quartz, feldspar, lithics, quartz overgrowth, carbonate cement and clays in the 42 thin sections were quantified using a point counting JmicroVision Image analysis system (Roduit, 2007) with a minimum of 300 counts per section by overlaying images obtained with an optical microscope and by cathodoluminescence.

4 Results

4.1 Sedimentology

Logs and facies association were described by Desaubliaux & Bucherie (2011). Sedimentary facies were refined as followed: Facies F1a (Mud flat) is a poorly sorted heterolithic wavy to lenticular bedded sandstone. Facies F1b (Sand flat) is a fine to medium grained, bi-directional current ripple bedded sandstone. Facies F2a (Top of sand bar) is a clean fine sandstone. Facies F2b (Middle of sand bar) is a fine to medium grained, sigmoidal cross-bedded sandstone. Facies F2c (Bottom of sand bar) is an 50cm-bedded heterolithic sandstone facies with erosinal base and sedimentary structures evolving from current ripple in the lower bed to swaley cross stratification and sigmoidal mega-ripple at the top. Facies F3 is a heterolithic very well sorted, fine grained, wavy cross bedded sandstone.

These facies are associated with a tidally dominated estuarine depositional environment, near outlet (tidal delta and spit).

4.2 Diagenesis

Seven diagenetic events have been identified from the petrographic study of the 42 samples. Each of these events is described and replaced in a paragenetic sequence (Figure 1).

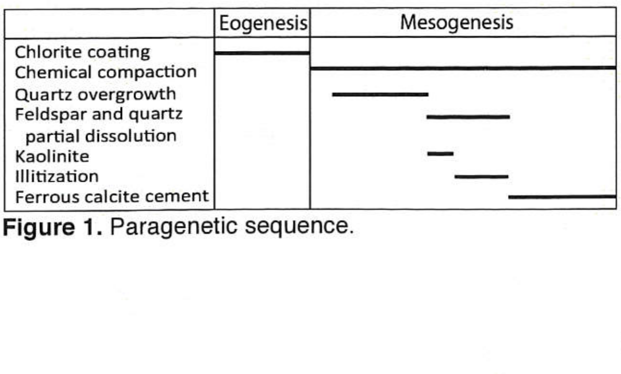

Figure 1. Paragenetic sequence.

Automorphic ferrous chlorite particles, arranged perpendicular to the detrital grain surface, are forming a 2 to 10 μm thick coating (Figure 2). These coatings may be discontinuous and were formed during eodiagenesis. Chlorite may be interstratified as chlorite/kaolinite according to the various specific peaks identified by XRD.

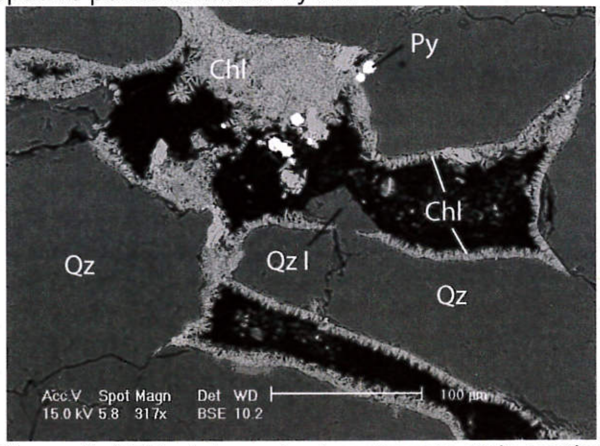

Figure 2. SEM photograph of continuous grain coating and grain filling of chlorite. Qz: quartz, Qz I: quartz overgrowth, Chl: chlorite, Py: pyrite.

The types of contact between quartz detrital grains vary significantly from the simple point contact to grain suture. Compaction began after the grain coatings had formed because the coatings are found at the interfaces between the detrital grains and coatings are generally continous around grains. Authigenic quartz cements developed around detrital quartz grains after grain coatings chlorite. Overgrowths thickness varies from a few micrometres to more than 100 μm, with an average value of about 70 μm. Two major phases of silicification are observed: (1) the first is a brown-orange luminescence and (2) the second stage is black-purple and weakly luminescent. Silicification rate ranges from 2 to 30%. In some samples, quartz overgrowth occludes almost totally porosity. $\delta^{18}O$ isotope measurements were made on the two types of quartz overgrowth. The $\delta^{18}O$ values of the first quartz overgrowth (n=13) range from 11‰ to 20‰ SMOW with a median value of 13.8‰ SMOW. Half of the values are between 12.6‰ and 15.5‰ SMOW. The $\delta^{18}O$ values of the second quartz overgrowth (n=17) oscillate between 13‰ and 24.2‰ SMOW with a median value of 18‰ SMOW. Half of the values are between 15.7‰ and 19.8‰ SMOW.

Frequent feldspars, partially or totaly dissolved are observed. Dissolution occured preferentially along the cleavage planes. Point counting of this secondary porosity yields values from 0 to 12%. The silicification phase grows in the intergranular pore space but never in the dissolution pore space. Feldspar alteration occurred after the silicification stages. Quartz overgrowths exhibit corrosion stages as well. These two dissolution/corrosion stages seem to be closely related.

The kaolin group clay minerals are found in 14 samples. These crystals are found in the intergranular pores only and often on the edges of highly corroded quartz grains indicating that they likely formed after silicification and dissolution.
Illite is found in all of the samples, and consist of fibre-like crystals, developping along the cleavage of altered feldspars or in contact with kaolin group clays.
Only two samples display ferrous calcite cement which forms poikilotopic crystals. It represents 15 to 20% of the samples. Calcite and dolomite cements fills intergranular and secondary porosity. The apparence of calcite cements after the quartz overgrowths and illite crystallisation can be clearly observed. Four analyses of stable isotopes performed on calcite cements display $\delta^{13}C$ values from -5.69‰ to -5.26‰ PDB and $\delta^{18}O$ values from -16.94‰ to -16.53‰ PDB. Two analyses of stable isotopes performed on two dolomite cements reveal $\delta^{13}C$ values of -7.14‰ and -7.04‰ PDB and $\delta^{18}O$ values of -11.75‰ and -11.42‰ PDB.

5 Discussion

5.1 Relation between depositional environment and petrophysical properties

Only two facies exhibit good reservoir properties: the top (F2a) and middle (F2b) parts of the estuary sand bars. But these facies do not invariably have good Φ-k properties, implying that this factor alone cannot predict the location of reservoir rocks.
Good reservoir properties are generally associated with poorly sorting and coarse sandstone facies.

5.2 Relation grain coatings, petrophysical properties and sequence stratigraphy

Only ferrous chlorite and chlorite/kaolinite coatings that entirely cover the detrital grains promote high porosity (10 – 25%) and permeabilities (1 – 2500 mD). Such total chlorite coatings are only found in the sandy tidal bar facies (F2a, F2b, F2c) of the top of the reservoir R1. Grain coatings is associated with chlorite filling only in the bottom of sand bar (F2c). The sequence stratigraphy can be used to predict the location of grain coatings in the sandstones and therefore to predict the good-quality reservoirs. Grain coatings develop at the end of the second-order transgressive hemi-cycle during the maximum marine influence. At higher frequence, total grain coatings develop during the 3rd or 4th order transgressive hemi-cycle in the top of sand bars. This high hydrodynamic depositional environment corresponding to the estuary inlet seems to be favorable to formation/deposition of chlorite.

5.3 Relation between burial diagenesis and petrophysical properties

Quartz overgrowth is mainly controlled by grain coating. More continuous coating, less silicification is developed and more porosity is preserved. Silicification can filled up to 30% of initial porosity, resulting in < 15% porosity. The $\delta^{18}O$ values (fluid) for temperatures from 80 to 130 °C vary between -11‰ SMOW and -2‰ SMOW for the first overgrowth (brown-orange), and therefore correspond to meteoric waters. For the second generation (black-purple), the $\delta^{18}O$ range from -8‰ to 2‰ SMOW, also corresponding to meteoric fluids if considered temperature is in the order of 80–90°C or to sea water if temperature is close to 130 °C. Feldspar alteration creates secondary porosity proportionally to the quantity of initial feldspar (3 – 17%). Half of the initial feldspars are dissolved following acidic fluid circulation, creating up to 8% secondary porosity. However, top of reservoir have the lowest initial feldspar contents and yet there is the most porous. This is therefore not the most important factor controlling the location of porous zones. In addition, the release of silica, aluminium and potassium into the solution during feldspar dissolution allows the formation of authigenic minerals including kaolinite and fibrious illite. Feldspar dissolution promotes the precipition of clay and is ultimately the cause of the loss of porosity, which can be reduced to less than 5%. Calcite cementation, which is present only locally, entirely fills the porosity, resulting in porosity of less than 5%. Assuming temperatures ranging from 100°C to 130°C and given the $\delta^{18}O$ PDB values of -16‰ for calcite, it suggests circulation of basinal fluids which lost their ^{16}O, with $\delta^{18}O$ water of -2‰ to 2‰ SMOW. $\delta^{18}O$ PDB values of -11‰ for dolomite and temperatures of between 100 °C and 130 °C also suggest basinal fluids having lost their ^{16}O, with $\delta^{18}O$ water values of between 0‰ and 4‰ SMOW.
To summarize, the presence of total grain coatings largely controls the physico-chemical processes occuring during burial, such as the silicification.

5.4 Rock typing for a possible prediction of petrophysical properties

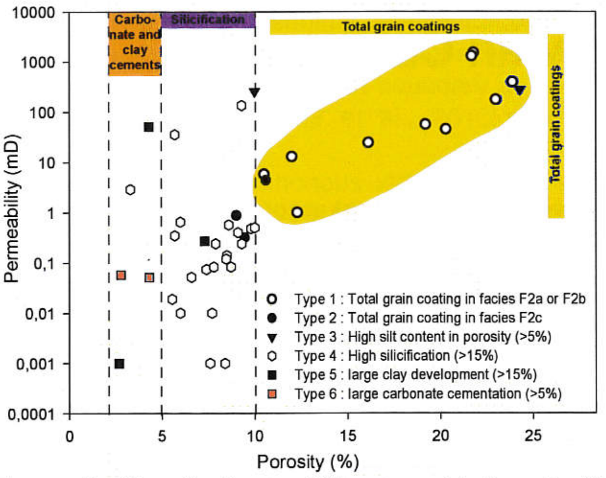

Figure 3. Porosity-Permeability crossplot for all 42 samples showing appurtenance to Rock type.

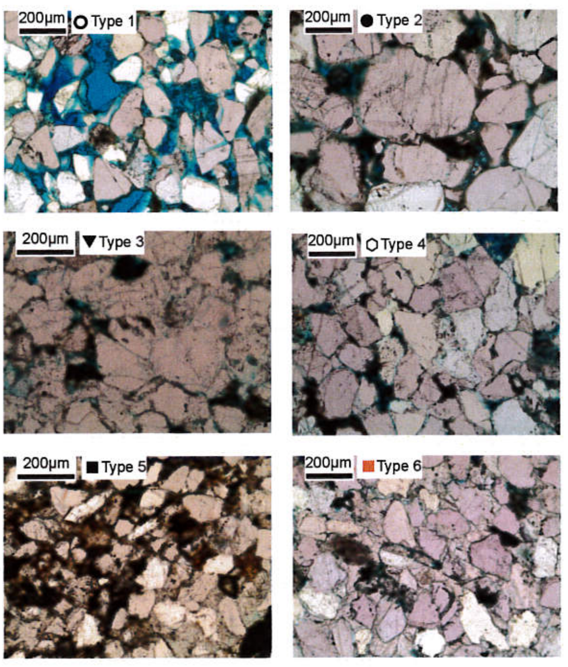

Figure 4. Rock typing of the 42 samples. Blue resin fills porosity.

From the relationship of porosity and permeability with the sedimentological and diagenetic parameters, and principal component analysis (PCA) six rock types of sandstone was created (Figure 3-4).

High Φ-k values (> 10 % and > 1 mD) are explained by the presence of total chlorite or interstratified chlorite-kaolinite coatings associated with top (F2a) and mid (F2b) tidal bar facies (Rock Type I).

The presence of continuous grain coatings and intergranular space filling in the base of tidal bar facies (F2c) (Rock Type II) is associated with moderate Φ-k values (8–12% and 0.1–10 mD).

The presence of silts in porosity is associated with permeabiity values greater than 100 mD (Rock Type III).

Porosity values between 5 and 10% corresond to intense silicification (> 15 %) (Rock Type IV).

The presence of filling by authigenic clays (Rock Type V) or by ferrous calcite cement (Rock Type VI) occludes porosity reducing it to less than 5%.

6 Conclusion

The detailed study of the Cape Hay Formation has permitted to identify five facies corresponding to estuary inlet environment with tidal sand bar deposits.

Seven phases of physico-chemical transformation related to basin history has been characterized. These diagenetic processes have an influence on petrophysical properties. In the case of the studied reservoir, the presence of continuous chlorite or interstratified chlorite-kaolinite coating is a determining factor for the preservation of good quality reservoir. These coating developed preferentially in the upper part of sand bar facies during the end of a second-order transgressive hemi-cycle.

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