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Petrology, Diagenesis and Reservoir Quality in the Hawkesbury Sandstone, Southern Sydney Basin, Australia

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Abstract

Petrography of the Hawkesbury Sandstone was described by thin section, scanning electron microscope and X-ray diffraction techniques. Quartz is dominant in the Hawkesbury Sandstone which contains very minor feldspar, lithic grains, mica and heavy minerals. The Hawkesbury Sandstone is quartzarenite to sublitharenite. Quartz includes monocrystalline and polycrystalline grains while the feldspar includes both K-feldspar and plagioclase. Volcanic, sedimentary and chert rock fragments are present. Thin section porosity occurs in the Hawkesbury Sandstone, particularly the coarse-grained deposits. Primary porosity is more common than secondary porosity in the Hawkesbury Sandstone.

Thin sections and scanning electron microscopy were used to describe diagenetic alterations and their influence on porosity in Hawkesbury Sandstone. These diagenetic alterations include compaction, quartz overgrowths, authigenicclay minerals and carbonate cement. Compaction occurred in the Hawkesbury Sandstoneduring throughout diagenesis. The influence of chemical compaction on thin section porosity was greater in the Hawkesbury Sandstone. Quartz overgrowths are common in the Hawkesbury Sandstone where they have a strong influence on porosity. Authigenic clay minerals are the widespread in the Hawkesbury Sandstone filling pores and occurring as grain-coatings on detrital and authigenic grains. Where they coat quartz grains they preserve porosity by preventing growth of quartz overgrowths. Pore-filling carbonate cement reduced porosity whereas dissolution of carbonate resulted in secondary porosity. Dissolution of unstable feldspar and lithic grains is absent in the Hawkesbury Sandstone. The Hawkesbury Sandstone is characterized by primary and secondary porosity, thus it has good groundwater storage and flow potential. Medium- and coarse-grained sandstone beds are common in the Hawkesbury Sandstone but it shows vertical variations in porosity. A few impermeable shale and siltstone units occur in the Hawkesbury Sandstone forming local confining layers.

Keywords Petrography; Diagenesis; Porosity; Primary porosity; Secondary porosity; Quartz overgrowth; Authigenic clay minerals

Introduction

This study includes the Permian-Triassic Hawkesbury Sandstone which forms part of the southern Sydney Basin, New South Wales. It addresses influence of diagenetic alterations on porosity in the Hawkesbury Sandstone, Southern Sydney Basin, Australia. The study area consists of part of the southern Sydney Basin in the Illawarra district of New South Wales, Australia (Figure 1).

The Middle Triassic Hawkesbury Sandstone is exposed widely in the Sydney Basin, lying above the Narrabeen Group and beneath the Wianamatta Group. In the Garie-Bundeena area, the thickness of the Hawkesbury Sandstone is 230 m where the floodplain facies of the Mittagong Formation conformably overlies the Hawkesbury Sandstone and is overlain by the argillaceous Wianamatta Group [1,2].

Previous research has documented the petrology of the Hawkesbury Sandstone, such as Standard [3,4] and Griffith [5]. Standard concluded that the composition of the Hawkesbury Sandstone consisted of detrital grains, heavy minerals and clay minerals [4]. Furthermore, he described the grain size, sorting and roundness of the sandstone. He noted that most grains are medium to coarse in the sandstone, and are moderately to poorly sorted. Also, they occur as sub-angular to sub-rounded grains [4]. Standard and Griffith introduced a study of diagenesis in the Hawkesbury Sandstone [5,6]. Porosity and permeability in the Hawkesbury Sandstone have been analysed by Griffith, Liu et al., Lee, Franklin and Freed [5,7-10].

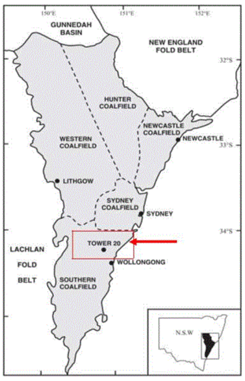

Figure 1: Location of the Sydney Basin and the Coalfields within it, from Grevenitz et al. [67].

Member	Formation	Subgroup	Group	Age		
	Ashfield Shale	Liverpool Subgroup	Wianamatta Group		Early and Middle	Triassic
	Mittagong Formation					
	Hawkesbury Sandstone					
	Newport Formation	Gosford Subgroup	Narrabeen Group			
	Garie Formation					
	Bald Hill Claystone	Clifton Subgroup				
	Bulgo Sandstone					
	Stanwell Park Claystone					
	Scarborough Sandstone					
Otford Sandstone Member	WombarraClaystone					
	Coal Cliff Sandstone					
	Bulli Coal	Sydney Subgroup	Illawarra Coal Measures	Tatarian	Late	Permian
	Loddon Sandstone					
Balgownie Coal Member	Eckersley Formation					
Lawrence Sandstone Member						
Burragorang Claystone						
Cape Horn Coal Member						
Hargrave Coal Member						
Woronora Coal Member						
Novice Sandstone Member						
	Wongawilli Coal					
	Kembla Sandstone					
American Creek Coal Member	Allans Creek Formation					
	Darkes Forest Sandstone					
Austinmer Sandstone Member	BargoClaystone					
	Tongarra Coal					
Woonona Coal Member	Wilton Formation					
Kulnura Marine Tongue	Erins Vale Formation	Cumberland Subgroup				
Figtree Coal Member	Pheasant Nest Formation					
Unanderra Coal Member						
Tappitallee Mountain Tuff Member						
Berkeley Latite Member						
MinnamurraLatite Member						

Table 1: Stratigraphy of Southern Coalfield (Modified) [62-65].

The purpose of this study is to investigate the diagenetic history of the reservoir sandstones and the relationship between the preservation of primary porosity and the generation of secondary porosity in the Hawkesbury Sandstone of Southern Sydney Basin, Australia.

Geological Setting

The Hawkesbury Sandstone overlies the Narrabeen Group and underlies the Wianamatta Group (Table 1). In the western area of outcrop, the Hawkesbury Sandstone is between 30-60 m in thick, whereas in the central area of outcrop, it ranges from 210 to 290 m in thick [11-13]. The Hawkesbury Sandstone covers about 20,000 km² of the Sydney Basin and has its maximum thickness of 290 m at the Hawkesbury River [14]. Branagan reduced the unit cover area to about 12,500 km² and the thickness to vary between 30 and 240 m [15]. Lee [8] noted that the thickness of Hawkesbury Sandstone varies from about 160 m in the Mittagong region, to 250 m in the Sydney district.

Methods

The petrography of the Hawkesbury Sandstone was based on thirty six samples. These samples were selected from outcrop and from two wells are EAW 18a and EDEN 115. They comprised twenty nine samples of sandstone, four samples of siltstone and three samples of shale. Thirty two samples were examined under a polarizing microscope. Twenty two of the samples, consist of fine-grained sandstone, siltstone and shale were analysed by X-ray diffraction (XRD). Eight samples were studied by scanning electron microscope (SEM). X-ray diffraction analysis was used to study twenty two samples of fine to medium-grained sandstone, siltstone and shale. These samples were prepared for XRD analysis using a Philips (PW3710) diffractometer (Cu Kα radiation, 35 kV, 28.5 mA) to determine the percentage of each mineral in fine-grained samples, and clay minerals in the sandstone samples (oriented samples of <2 µm clay fractions). A JEOL JSM-T330 scanning electron microscope (SEM) was used to examine about 28 samples to determine morphology, textural relationships, mineral composition, porosity and diagenetic aspects of the sandstone samples. The description of porosity by (SEM) depended on the study of pore types.

Results

Petrography

Petrographic data indicated that the sandstones are quartzarenite to sublitharenite containing abundant quartz, low feldspar and rock fragments, $Q_{90.1}$%, $F_{0.3}$%, $R_{9.7}$% (Figure 2a). The QmFLt diagram from Dickinson indicates that the Hawkesbury Sandstone falls into the craton interior to quartzose recycled provenance classes, $Qm_{89.7}$ %, $F_{0.3}$ %, Lt10 % (Figure 2b) [16].

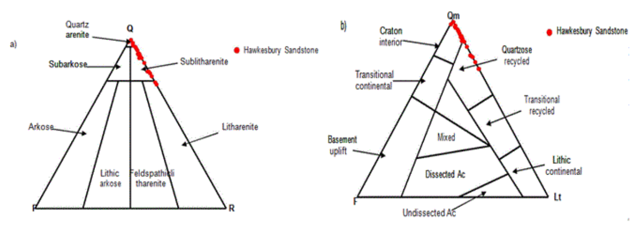

Figure 2: a) Classification of the Hawkesbury Sandstone (after Folk Q=quartz, F=feldspar, R=rock fragments [66]. B) The provenance of the Hawkesbury Sandstone [16]. Qm=monocrystalline quartz, F=feldspar, Lt=rock fragment+chert.

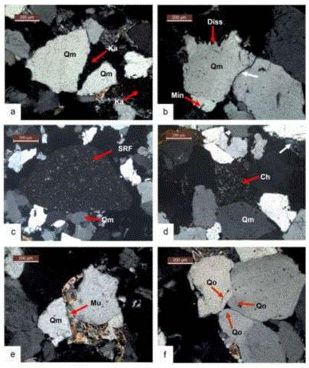

Figure 3: a) Monocrystalline quartz grains (Qm) and kaolinite (Ka) in the Hawkesbury Sandstone. b) Mineral inclusion (Min) and concavo -convex contacts (white arrow). Dissolution (diss) on margins of monocrystalline quartz grain (Qm). c) Sedimentary rock fragment (SRF) and monocrystalline quartz (Qm) grains are associated in the Hawkesbury Sandstone. d) Chert (Ch), monocrystalline quartz (Qm) grains in the Hawkesbury Sandstone. e) Muscovite grain is bent between monocrystalline quartz (Qm) grains. f) Well developed quartz overgrowths (Qo) occur as pore-filling cement along the margins of detrital quartz grain and obliterates chemical compaction in the Hawkesbury Sandstone.

In examined samples, the Hawkesbury Sandstone is quartz-rich sandstone. Quartz grain abundance varies between 24.4% and 83.3% (Figure 3a; Appendix 1). Feldspar grains are mainly rare. Its abundance ranges from 0 to 0.5% (Appendix 1). K-feldspar is slightly more common than plagioclase but most samples do not include feldspars. Rock fragments consist entirely of sedimentary rock fragments with a complete absence of volcanic and metamorphic rock fragments in both the sandstone and siltstone samples (Figure 3c; Appendix 1). Chert is clear and observed in most samples and varies between 0 and 17.3% (Figure 3d). Muscovite exists in the Hawkesbury Sandstone, varying between 0 and 3% (Figure 3e). In this study, the occurrence of heavy minerals was recognized in sandstone and siltstone in minor amounts, varying between 0 and 2.5% (Appendix 1). Matrix is mainly observed in the Hawkesbury Sandstone between 0 and 53.5% (Appendix 1).

Diagenesis and Diagenetic Minerals

The diagenetic alteration in the Hawkesbury Sandstone was described from thin section and SEM data. Authigenic minerals include quartz overgrowths, authigenic clay minerals, carbonate cement, authigenic feldspar and dissolution.

Quartz cementation

Most samples include authigenic quartz which is identified as syntaxial overgrowths on quartz grains and as euhedral crystals (Figure 3f) [4]. It is also present as pore-filling cement and is widespread close to places with long intergranular contacts. Authigenic quartz content varies between 0.5 % and 9.1% (Appendix 1). Quartz overgrowths are usually the first cement in this unit. Sandstone contains more quartz overgrowths than siltstone because of the higher percentage of quartz grains in sandstone.

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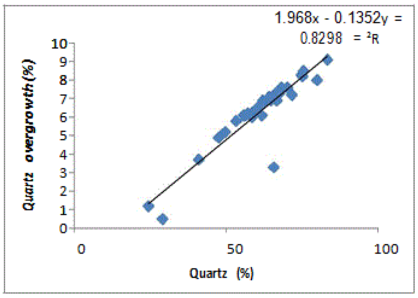

Figure 4: Strong positive correlation between quartz and quartz overgrowths in the Hawkesbury Sandstone.

Thus, the presence of quartz overgrowths is controlled by detrital quartz grains and large pores, as indicated by the high positive correlation between detrital quartz and quartz overgrowth (r^2=0.8; Figure 4). Coarse-grained sandstones contain common quartz overgrowths and have high porosity. Thus, with increasing grain size and porosity, quartz cement increases (Figure 5).

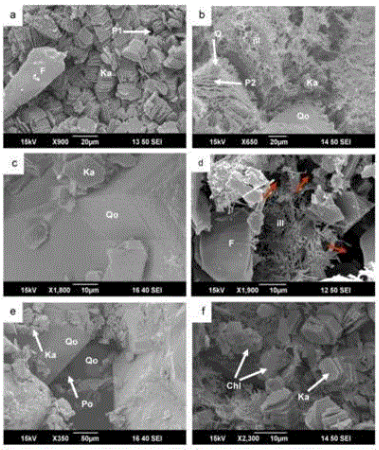

Figure 5: a) Small pore between authigenic kaolinite (Ka), detrital feldspar (F) and primary porosity (P1) in the Hawkesbury Sandstone. b) Fibrousillite (ill) occurs as a grain coating around kaolinite (Ka) and quartz grains (Q). Kaolinite (Ka) fills pore between grains. Minor secondary porosity (P2). Quartz overgrowth (Qo) is enclosed by authigenic kaolinite (Ka) in the Hawkesbury Sandstone. c) Late stage quartz overgrowth (Qo) is coated by later diageneticKaolinite (Ka) in the Hawkesbury Sandstone. d) Fibrous illite (ill) fills pore space and in the Hawkesbury Sandstone. Also, detrital feldspar (F) and primary pores (red arrows) are observed in the Hawkesbury Sandstone. e) Late diagenetickaolinite (Ka) overlies quartz overgrowth (Qo). Porosity (Po) is preserved in the Hawkesbury Sandstone. f) Chlorite (Chl) is associated with kaolinite (Ka) in the Hawkesbury Sandstone.

Quartz overgrowths occur along the detrital quartz grain edge, perpendicular to the quartz grains. Some authigenic quartz contains local anhedral terminations, or is intergrown with a clay phase. The clay coatings and fluid inclusions determine the boundaries between detrital quartz and quartz overgrowths (Figure 6a). The overgrowth features that characterise quartz may be changed by authigenic clay minerals [17]. Fluid inclusions have sizes exceeding 3 μm but are uncommon. Figure 3f shows three stages of quartz overgrowths. Quartz overgrowth of first stage is overlain by quartz overgrowth of a second stage, which is overlain by quartz overgrowth of the third stage. This indicates the presence of reworked quartz from previous sandstone. The first stage occurred by silica released from decomposition of less stable minerals whereas the migration of silica-rich fluids from distant sites contributed to the formation of the second stage. Recrystallization of quartz supported the formation of the third stage of overgrowths.

Authigenic clay minerals

Authigenic clay minerals principally comprise kaolinite, illite, mixed-layer illite/smectite and chlorite.

Kaolinite: It is ubiquitous in the Hawkesbury Sandstone. It is present as booklets and vermicular aggregates and occurs in the mud matrix, pseudomatrix and detrital grains, as pore-filling cement, and as grain coatings (Figure 5a). Primary and secondary pore spaces are often filled by authigenic kaolinite (Figure 5a). Kaolinite is present with illite and quartz overgrowths in most samples (Figures 5b-5c). Quartz overgrowths are enclosed by authigenic kaolinite and this indicates that the latter was precipitated after the quartz overgrowths (Figure 5c). Kaolinite formation depends on the presence of porosity and permeability, which leads to migration of interstitial pore waters. The authigenic kaolinite tends to increase in areas which include poorly developed authigenic feldspar [18]. The SEM images showed that dickite is characterised as thick blocky crystals with smooth surfaces, thus it is different from kaolinite which occurs as booklets and vermicular aggregates with thin and etched surfaces.

Mixed-layer illite/smectite: It is the second most abundant clay mineral in the Hawkesbury Sandstone. Mixed-layer illite/smectite has a honeycomb-like texture. Mixed-layer illite/smectite is observed as pore-lining to pore-filling clay with a ragged-platy morphology. It occurs within quartz overgrowths in some samples. Mixed layer illite/smectite is present as grain coatings on authigenic kaolinite and is associated with illite.

Illite: It is visible as hair like wisps and as fibrous illite within kaolinite, the mud matrix and mud intraclasts (Figures 5b and 5d). It is oriented perpendicular to grain surfaces and has a high birefringence. In most samples, illite is associated with kaolinite (Figure 5b). It fills pores spaces and is observed as grain-coatings (Figures 5b and 5d). Grain-coating illite thickness ranges from thin to thick with ultra-thin layers and thin mat like crystals. The coatings are identified as continuous to discontinuous layers.

Chlorite: It exists in the succession as pore-fill ing cement and as grain-coatings on authigenic minerals (Figure 5f). It occurs as scattered crystals, as rims on quartz overgrowths and is intergrown with authigenic kaolinite (Figure 5f). In some samples, chlorite is also present as grain-coatings on kaolinite.

Carbonate cement: It is the third most abundant cement in the Hawkesbury Sandstone succession, ranging from 0 to 20.1% (Appendix 1). The carbonate cements consist of siderite, ankerite, calcite and dolomite.

Siderite (0-15.7%): It is the dominant carbonate cement in most samples (Appendix 1). Siderite exists as fine and medium-grained rhombs, as microcrystalline siderite (≤ 50 μm) and as coarse crystalline siderite (up to 200 µm; Figure 6b). Siderite is usually stained by iron oxide and contains rare fluid inclusions. Also, thin sections showed that siderite has developed in the pores between quartz grains and also occurs as grain coatings (Figures 6b-6d). Siderite cement is observed with quartz grains in most samples where it fills small pores between tightly packed quartz grains.

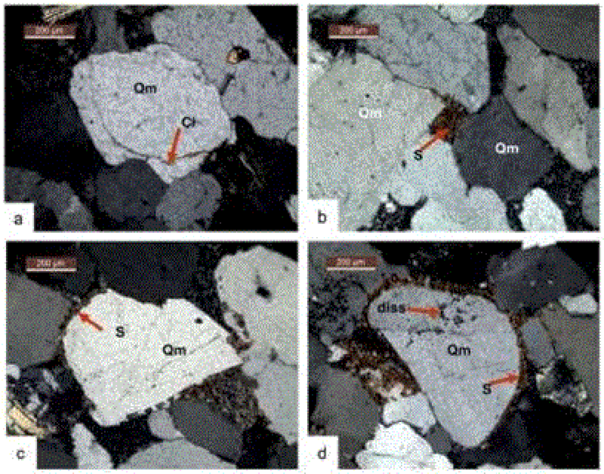

Figure 6: a) Early stage clay (Cl) and late diagenetic quartz overgrowths (Qo) in the Hawkesbury Sandstone. b) Siderite cement fills a small pore in the Hawkesbury Sandstone. c) Margin of monocrystallineguartz (Qm) grain is coated by fine-grained rhombs of siderite (S) cement. d) Siderite (S) cement occurs as fine and medium rhombs coating the margins of monocrystalline quartz (Qm) grains.

Ankerite (0-13.2%): It is missing in most samples. One sample contained 13.2%, while a few samples have trace amounts (Appendix 1). Ankerite cement also fills pore between quartz grains and is present as poikilotopicankerite cement.

Dolomite (0-5.4%): It is also only recorded in a few samples, while trace amounts of calcite are restricted to four samples (Appendix 1). Thus, calcite cement is less prevalent than dolomite cement.

Ferroan calcite (0-0.8%): It is uncommon in the Hawkesbury Sandstone and is associated with detrital carbonate components. Low permeability for the circulation of Mg-rich fluids is a reason to allow ferroan calcite to survive dolomitization.

Authigenic Feldspars: These are rarely present in the Hawkesbury Sandstone as K-feldspar and plagioclase alteration. They are observed as overgrowths on detrital feldspar grains.

Diagenetic Sequence

The diagenetic sequence in the Hawkesbury Sandstone shows the relative timing of diagenetic changes during both early and late stages (Figure 7).

Compaction

Two types of compaction are recognised in the Hawkesbury Sandstone-mechanical and chemical compaction. Mechanical compaction is represented in the Hawkesbury Sandstone by bent flexible grains such as mica (Figure 3e), and pseudoplastic deformation of mud intraclasts forming pseudomatrix. Compaction is recognizably more abundant in sandstone than in siltstone samples. Mechanical compaction post-dates some of the main cementing minerals. If calcite cement is uncommon, compaction is more abundant [17]. Compaction occurred during both early and late stages of diagenesis. Chemical compaction is indicated by pressure dissolution, long and concavo-convex grain contacts and sutured contacts (Figure 3b). The presence of pressure dissolution is identified along intergranular contacts. Widespread pressure dissolution occurs when the quartz grains are covered with thin illite coatings or when mica occurs at the interface along the quartz grain contacts. Some ductile components are mainly compressed. Additionally, chemical dissolution of detrital grains has occurred because of chemical compaction.

Authigenic clay minerals

SEM studies indicated that kaolinite pore-filling and kaolinite grain-coating occurs as an early authigenic mineral. Edges of large pores are coated by booklets and vermicular aggregates of kaolinite indicating that the kaolinite was formed during early diagenesis. The characteristic vermicular texture of kaolinite indicates an origin during early diagenesis [19]. Chlorite grain-coatings are also observed to form during early to mid diagenesis. Kaolinite is coated by chlorite in some samples. This indicates that kaolinite pre-dates chlorite in the Hawkesbury Sandstone. Chlorite and illite formation can be derived from earlier kaolinite [20].

Dissolution of feldspar can control kaolinite precipitation [21]. Ions may become available for kaolinite authigenesis by dissolution and overgrowths of feldspar [22]. Morad et al. and El-Ghali et al. attributed the formation of kaolinite and the associated unstable framework grain dissolution to near surface and meteoric water diagenesis [23,24].

Wolela and Gierlowski-Kordesch indicated that the reactions that occur between the unstable grains, carbonate cements and acidic pore water play a role in increasing kaolinite precipitation as alkalinity increases [22]. Low pH and low ionic strength waters are recorded as supportive factors to the precipitation of kaolinite [25,26]. The conversion of kaolinite into dickite is indicated by the presence of vermicular stacks and booklets with the thick to blocky habits of dickite [19,27]. According to Abouessa and Morad, dissolution and re-precipitation can play an active role in the conversion of kaolinite into dickite which characteristically occurs at a temperature >100°C [19,27].

Illite grain-coatings are also characterised as early to mid authigenic minerals. Illite coats earlier authigenic kaolinite and quartz grain margins (Figure 5b). High activities of K^+ and H_4SiO_4 support the precipitation of grain-coating illite [28]. Identification of the relative timing of authigenicillite is difficult because the textural relationships between illite and other authigenic minerals were not observed [29]. The authigenic mineral assemblage and original sandstone composition indicate the timing of authigenicillite to be during early diagenesis.

Carbonate cement

Carbonate cements, represented by siderite, ankerite, calcite and dolomite, formed during early diagenesis in the succession. The presence of grain-coating and pore-filling siderite supports this interpretation. The margins of some detrital quartz grains are coated by carbonate cement as seen in thin section (Figures 6c-6d). Large

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pore-spaces which are available for the development of euhedral siderite crystals provide enough evidence for the deposition of siderite during early diagenesis [30]. Minor ferric oxide is formed by oxidation of the siderite [4]. Abouessa and Morad showed that siderite precipitated at high temperatures with high Fe and low Ca contents [19]. Also, high Fe/Ca supports the interpretation of the precipitation of siderite cement within the early stage of diagenesis [30].

Dissolution/alteration of detrital grains

This is recorded in the Hawkesbury Sandstone (Figures 8a-8b). The precipitation of secondary silica was accompanied by, and most probably succeeded, partial or complete dissolution of carbonate cement (Figure 8a). The presence of silica overgrowths maintained the framework, so that the oversized pores left after the dissolution of the carbonate fragments were preserved. In general, secondary porosity was formed by dissolution in the Hawkesbury Sandstone (Figures 8a-8b). Some detrital quartz grains were dissolved in the Hawkesbury Sandstone (Figures 8a-b). Dissolution post-dates compaction but pre-dates quartz cementation. Leaching of the carbonate cement is observed because of fresh water influx. Authigenic feldspar is recorded during mid to late diagenesis in the Hawkesbury Sandstone. Precipitation of feldspar is supported by the activities of K^+, Al_2^+ and Si_4^+ [18]. Feldspar dissolution was also determined in the Hawkesbury Sandstone.

Authigenic quartz

Quartz overgrowths occur as mid to late diagenetic minerals. The SEM studies indicated mid to late stage secondary quartz overgrowths (Figure 5c). The occurrence of quartz cement in the form of overgrowths supports this interpretation. Some authigenic clay grew before the quartz overgrowths and this indicates the late stage of quartz cementation (Figure 6a). Quartz overgrowth deposition continued after the precipitation of clays and this is indicated by the syntaxial growth of quartz cement on grains with thin chlorite coatings. Chlorite-clay formation pre-dates quartz overgrowths in all places, except where chlorite coatings occur on quartz overgrowths [31]. Late diagenetic quartz overgrowth were described by Al-Gailani who showed that quartz overgrowth is attributed to acidic waters percolating into the subsurface and containing dissolved silica and alumina [32]. The mixing of the fresh acidic waters with the more alkaline indigenous waters would decrease the acidity of the percolating waters, leading to a decrease in the solubility of silica and alumina" and hence precipitation of quartz overgrowths.

In some samples, secondary silica is precipitated around detrital quartz grains (Figure 5c). The pore waters required for the precipitation of these overgrowths would have been acidic, in an environment containing sufficient dissolved silica to allow quartz overgrowth formation. Compaction is prevented because of quartz overgrowths, thus some primary intergranular porosity is preserved. The widespread quartz cementation indicates initial clay-poor quartz-rich sediment with a high permeability that allowed silica-rich solution circulation to the necessary sites for the nucleation of quartz overgrowths [18]. Quartz overgrowths are common in coarse-grained clean sandstone because its high permeability allowed easy percolation of water and silica-rich fluids [33].

Al-Harbi and Khan interpreted that dissolution of quartz grains, replacement of feldspar and quartz grains by carbonate, alteration of smectite to illite, pressure dissolution, alteration and dissolution of volcanic rock fragments are the sources of quartz cement [33]. The grain contact types, such as concavo-convex contacts and microstylolites, show that pressure dissolution of quartz grains is a major source of the silica in the Hawkesbury Sandstone [34]. The feature of syntaxial overgrowths of quartz cement and the association of quartz cement with sites of intergranular dissolution indicate a mesogenetic origin [23,24,35]. In the Hawkesbury Sandstone, pressure solution of quartz at grain contacts forming stylolites, solution of fine quartz particles and decomposition of silicate minerals may be the sources of quartz overgrowths [6]. Obsorne suggested that regional cementation by secondary silica in the Hawkesbury Sandstone is because of groundwater action.

Late authigenic kaolinite, illite and chlorite

Authigenic kaolinite occurs as a late stage diagenetic mineral that was precipitated after the quartz overgrowths, as indicated by SEM studies. In most samples, the late phase of kaolinite cement was precipitated on the quartz overgrowth (Figure 5c). This indicates that kaolinite post-dates the quartz overgrowths. Significant intercrystalline microporosity is preserved in the authigenic kaolinite. Also, illite and chlorite were precipitated on the quartz overgrowth in other samples, interpreting that they are late diagenetic stage.

Late siderite and ankerite cement

Carbonate cementation, particularly siderite and ankerite, also occurred during the late stages of diagenesis. Siderite and ankerite cement exist as grain-coatings on quartz overgrowths. This indicates that they post-date the quartz overgrowths (Figures 6c-6d). Euhedral crystals of siderite are uncommon in some samples but confirm a late phase origin. Also, later compaction is prevented by carbonate cementation. Mg and Ca are more abundant in late diagenetic siderite [21]. New siderite cement may be re-precipitated in some samples after dissolution of early carbonate cement (Figure 8b). This may be the interpretation of the occurrence of late diagenetic siderite cement.

In conclusion, the chronological order of the diagenetic phases is as follows;

1) Mild compaction.

2) Authigenic clay minerals.

3) Carbonate cementation.

4) Dissolution/alterations of detrital grains.

5) Secondary silica overgrowths.

6) Precipitation of authigenic kaolinite followed by siderite and ankerite cement.

Pore Types

Primary porosity

Porosity is mostly primary (Figures 5a and 8c), varying between 0% and 16.5% (Appendix 1) and ranges from 30 to 356 µm in size.

Secondary porosity

Secondary porosity is less abundant than primary porosity in the Hawkesbury Sandstone (Figures 5b and 8a-8b). It occurs up to a maximum of 4.3% (Appendix 1). Secondary pores range in size between 20 and 220 μm in the Hawkesbury Sandstone.

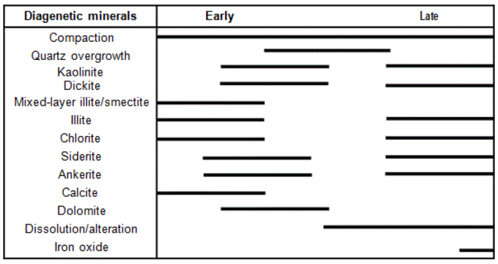

Figure 7: Paragenetic sequence of the diagenetic alterations in the Hawkesbury Sandstone.

The Influence of Diagenetic Alteration and Composition on Reservoir Quality

Compaction

In the Hawkesbury Sandstone, compaction dominates the porosity reduction during the early diagenetic phase. This porosity is unrecoverable [18]. Also, long, concavo-convex and sutured contacts produced by pressure solution and chemical compaction are observed commonly in the Hawkesbury Sandstone and contribute to primary porosity loss.

The role of chemical compaction in primary porosity reduction occurs during mid to late diagenesis. Carbonate cement is rare to absent in most of the Hawkesbury Sandstone, thus the role of chemical compaction to reduce primary porosity is significant, as shown by Kim and Lee [36].

Mechanical compaction occurs in the Hawkesbury Sandstone but had less influence on porosity than chemical compaction. This is because of the lack of ductile grains and grain deformation in the Hawkesbury Sandstone. Thus, the presence of rigid grains plays a role in obstructing the importance of mechanical compaction since rigid grains increase the stability of the framework and thus contributes to the preservation of primary porosity as shown by Sager [37].

Thus some primary porosity was preserved in the Hawkesbury Sandstone. Also, the moderately open framework packing is evidence that primary porosity was not greatly affected by mechanical compaction in this unit [38]. These factors indicate that the remaining primary porosity was preserved after mechanical compaction and it decreased with the occurrence of cementation.

Quartz overgrowths

Deposition of quartz overgrowths is recognised in many studies as a mechanism for porosity loss in sandstones [34,39-41]. In quartzose sandstone, porosity is strongly influenced by the amount of quartz dissolution and cementation.

This influence occurs during mid diagenesis at temperatures of 80°C or more [42,43]. The porosity reduction resulting from precipitation of authigenic quartz is associated with increased temperature in several studies [44,45].

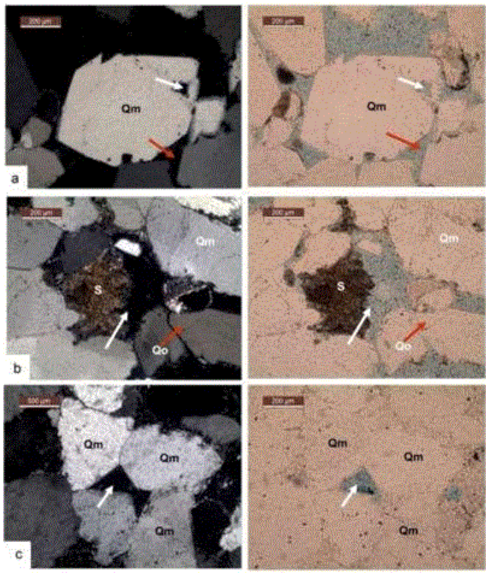

Figure 8: a) Secondary porosity (white arrow) is formed by dissolution of silica. Primary porosity (red arrow) also occurs in the Hawkesbury Sandstone. b) Secondary porosity (white arrow) results from dissolution of siderite (S) cement. Margins of quartz grains are coated by siderite (S) cement or quartz overgrowths (Qo) in the Hawkesbury Sandstone. c) Primary porosity (white arrow) occurs between monocrystalline quartz (Qm) grains in the Hawkesbury Sandstone.

In the Hawkesbury Sandstone, there is a very low positive correlation between quartz overgrowths and porosity. This relationship indicates that porosity is present when the pores are clean enough for quartz overgrowths. Porosity can be observed at the termination points of quartz overgrowth cements in this unit [46]. Primary porosity is preserved in the Hawkesbury Sandstone by the mechanism of quartz cementation, which inhibits collapse of the grain framework [18].

Quartz overgrowths in some samples of Hawkesbury Sandstone help cement the framework and obliterate chemical compaction. In these cases, primary porosity was preserved in these samples, supported by quartz overgrowths [24]. However, the relationship between quartz overgrowths and secondary porosity also shows a very low positive value in the Hawkesbury Sandstone, indicating that secondary porosity can increase with increasing quartz overgrowths in this porous sandstone. This could suggest that quartz overgrowths post-date the dissolution of carbonate cement [47]. Porosity gain from feldspar dissolution could also add to the low positive correlation between quartz cement and secondary porosity in the Hawkesbury Sandstone [48].

Quartz cement is a mid to late stage diagenetic mineral that was derived from pressure solution leading to the reduction of porosity. This indicates continuous compaction in the sediment at least until the time of quartz cementation. In general, quartz overgrowths are observed as pore-filling cements that destroy porosity in the Hawkesbury Sandstone (Figure 3f) [49]. This unit is poor in ductile grains and carbonate cement. Thus, quartz cement is the main reason for porosity loss in the Hawkesbury Sandstone [39].

The rarity of grain-coating clay in the Hawkesbury Sandstone indicates clearly that the development of quartz overgrowths continued after the clay precipitation and caused the main reduction of porosity in this unit [34]. In a few samples, clay minerals such as chlorite exist as grain-coatings around quartz grains. In these cases, the clays effectively prevent the precipitation of quartz overgrowths and support the preservation of porosity [34,41,50].

In the Hawkesbury Sandstone, the development sites for quartz overgrowths are subject to obliteration by grain-coating illite, thus this process can support the preservation of porosity in this unit [19,51]. Several studies have shown that quartz overgrowths are prevented by the presence of microcrystalline quartz rims on detrital quartz grains [52,53].

In a few samples of Hawkesbury Sandstone, microcrystalline quartz rims are important and contribute to the development of reservoir quality where they prevent the growth of quartz overgrowths and pressure dissolution. The distinction of microcrystalline quartz coatings in thin section is not easy due to the very small crystal size whereas their distinction by scanning electron microscope is easy. Low abundance of quartz overgrowths and high porosity occur clearly in sandstone with abundant microcrystalline quartz coatings.

Authigenic clay minerals

Authigenic clay minerals occur as pore-filling cement and are one of the main reasons for porosity reduction in the Hawkesbury Sandstone.

Vermicular booklets of kaolinite crystals are the most common authigenic clay minerals and fill both primary and secondary pores, reducing total porosity in the Hawkesbury Sandstone (Figures 5a-5b). In some samples, kaolinite is deformed and generates pseudomatrix that effectively decreases porosity. Pore-filling illite is present and prevents the developed porosity in the Hawkesbury Sandstone (Figure 5d).

Pore-filling chlorite is rare but also reduces porosity in the Hawkesbury Sandstone [22]. A comparison between the influences of pore-filling kaolinite, pore-filling illite and pore-filling chlorite on porosity indicates that pore-filling kaolinite has the greatest influence, followed by pore-filling illite and then pore-filling chlorite, which has the least influence.

Quartz cementation is affected by grain-coating kaolinite, grain-coating illite and grain-coating chlorite which preserve primary porosity in the Hawkesbury Sandstone (Figures 5b-5c and 5e) [54]. Grain-coating kaolinite is more common, thus its influence is stronger on quartz overgrowths (Figures 5b, 5c and 5e). Thus grain-coating kaolinite contributes significantly to the preservation of primary porosity in the Hawkesbury Sandstone. Also, grain-coating illite around quartz overgrowths is observed, thus it retains primary porosity in the Hawkesbury Sandstone [19].

The influence of grain-coating kaolinite and illite on quartz overgrowths is stronger than grain-coating chlorite because they occur as thick and continuous layers between detrital grains and intergranular pore space. These features support the importance of grain-coating kaolinite and illite to inhibit quartz overgrowth and preserve primary porosity in the Hawkesbury Sandstone. Clay coatings affect porosity and are associated with rare compaction in some samples. The influence of patchy detrital clay rims on quartz overgrowth precipitation is much less than the influence of authigenic clays coatings which are continuous [45].

Carbonate cementation

In the Hawkesbury Sandstone, carbonate cement is a rare component in some samples, thus its influence on reservoir quality is low or absent. Pore-filling carbonate cement, represented by siderite and ankerite cement, occurs as an early diagenetic mineral and contributes to the porosity reduction in the Hawkesbury Sandstone (Figure 6b).

Dissolution

In the Hawkesbury Sandstone, dissolution of the rare unstable grains, such as feldspars and lithic grains, is not significant whereas dissolution of carbonate cement is absent. This indicates that secondary porosity is uncommon in the Hawkesbury Sandstone, which is characterised by primary porosity. Compaction is the main mechanism in the reduction of secondary porosity [55]. Carbonate cement is rare in the Hawkesbury Sandstone, thus compaction has more influence on secondary porosity. The presence of carbonate cement prevents compaction. Dissolution of feldspar is low but when it is present, it does not enhance porosity in the Hawkesbury Sandstone because it is incomplete.

Reservoir Potential of the Southern Sydney Basin

The Hawkesbury Sandstone is characterized by medium to coarse-grained sandstone with a lesser presence of fine sandstone, siltstone and shale. This unit has thin section porosity ranging from 0 to 19.3%. Reservoir quality is lost by quartz overgrowths which are present as pore-filling cement. This indicates that quartz overgrowths reduce porosity and permeability, thus they reduce the amount of available groundwater in the Hawkesbury Sandstone.

The environment of deposition in the Hawkesbury Sandstone mainly is not different from the environments of typical fluvial aquifer and hydrocarbon traps. Medium and coarse-grained sandstone are common in the Hawkesbury Sandstone whereas siltstone and shale are rare. Well logs showed that medium and coarse-grained sandstone contains porosity whereas siltstone and shale are poor. This indicates the importance of facies and environment in the determination of available space for groundwater.

The results indicated that the Hawkesbury Sandstone is moderate to poor reservoir and may contain groundwater. It is unlikely that the Hawkesbury Sandstone is the potential source for oil or gas since the included shales would only provide local seal potential.

Thin section porosity is high in the Hawkesbury Sandstone which is near the land surface and is recognized as having good groundwater potential. In this study, the Hawkesbury Sandstone is not a homogeneous aquifer as result of local variations in the porosity percentages [10,56,57]. Rainfall is the main source of groundwater in the Hawkesbury Sandstone, which is recharged by direct infiltration. This shows the presence of a positive relationship between porosity and aquifer potential. It also indicates that primary and secondary porosity allow groundwater flow and forms the paths for water movement in the Hawkesbury Sandstone [58]. In this study, groundwater flow is affected by primary porosity more than by secondary porosity. Also, changes in facies and grain size play a role in influencing groundwater movement. Freeze and Cherry showed that the hydraulic gradient is changed in aquifers as a result of the variations in facies [59]. In this study, two types of units are determined based on reservoir quality in the Hawkesbury Sandstone. They are coarse-grained deposits and fine-grained deposits, with the former being more common than the later.

The medium and coarse-grained sandstone units are thick, massive and trough cross-bedded. These units are mainly composed of quartz grains and are represented by coarsening upwards and fining upwards trends. The sandstone mainly consists of well sorted, rounded to sub-rounded grains. Thus, medium and coarse-grained sandstone units are characterized by containing visible thin section porosity. In general, medium and coarse-grained sandstone units are probably characterized by moderate to good groundwater storage and flow potential.

Good aquifer can be indicated by well sorted and coarse grains which preserve a greater quantity of primary porosity [60]. In the Hawkesbury Sandstone, medium to coarse-grained sandstone is characterized by these features. Also, water flow rates are probably increased by the abundance of primary porosity in these well sorted and coarse-grained sandstones according to the interpretation of Freed [10]. Diagenetic alteration such as chemical compaction, quartz overgrowths, authigenic clays and carbonate cement are recorded as potential barriers to flow and may reduce water quality in the medium to coarse-grained sandstone.

Cement fills many space pores and is present as a barrier to the development of porosity and permeability. Also, packing and compaction reduce porosity and permeability. This indicates that these factors, particularly pore-filling cement and the tightly packed nature of the grains, affect the movement and storage of water in medium and coarse-grained sandstone [15].

Water quality is affected by clays which may include dispersed clay and structural clay. Dispersed clays fill some pore spaces and have a strong influence on sandstone permeability. Structural clays exist as clay grains and are present between grain contacts. The influence of clay grains on water quality is very low [61]. Also, iron oxide can affect porosity in the Hawkesbury Sandstone and is present as potential barriers to flow [62-67].

Thin section porosity is completely absent in shale and siltstone units in the Hawkesbury Sandstone which are poorly sorted and fine-grained. Clays represented by kaolinite, mixed layer illite/smectite and illite are observed in most shale and siltstone beds according X-ray diffraction and scanning electron microscope. Thus, shale and siltstone beds are less porous and permeable, and they form groundwater-poor confining layers in the Hawkesbury Sandstone. Grain size, mineralogy and well logs contribute to the determination of impermeable shale beds in the Hawkesbury Sandstone.

The groundwater movement may be affected by synclines and faults in the Hawkesbury Sandstone. Faults can prevent free groundwater movement and can form semi-isolated groundwater potential. This indicates that the presence of faults probably changes the path of groundwater movement in the Hawkesbury Sandstone. Also, faults are probably present as potential barriers. Synclines can be recognized as places for water accumulation.

Conclusion

The Hawkesbury Sandstone is rich in quartz and falls in quartzarenite to sublitharenite fields. The Hawkesbury Sandstone shows a craton interior to quartzose recycled provenance. Thecratonic Lachlan Orogen is the main source of the quartz grains. Petrographic data demonstrated that the Hawkesbury Sandstone is characterized by quartz grains. Feldspar grains are least common in the Hawkesbury Sandstone.

Quartz includes monocrystalline and polycrystalline quartz grains whereas feldspar grains consist of K-feldspar and plagioclase. Rock fragments are volcanic or sedimentary, with an absence of volcanic rock fragments in the Hawkesbury Sandstone. Mica includes more common muscovite than biotite. The heavy minerals comprise hematite, hornblende, rutile, zircon and tourmaline in trace percentages.

Thin section and scanning electron microscope analyses were used to describe the alteration and diagenesis in the southern Sydney Basin. Results showed that quartz overgrowths are the dominant cement in the Hawkesbury Sandstone.

Thin section porosity is high in the Hawkesbury Sandstone. The study noted the presence of two types of porosity. They are primary and secondary porosity. Primary porosity is more common than secondary porosity in the Hawkesbury Sandstone. Chemical compaction has a greater effect on thin section porosity than mechanical compaction.

The Hawkesbury Sandstone is rich in the quartz grains, and hence quartz overgrowths are more common. Thus, thin section porosity is more affected by quartz overgrowths. In contrast, carbonate cement is rare, thus its influence on thin section porosity in this formation is low. In the Hawkesbury Sandstone, pore-filling clays are present and reduce thin section porosity. Also, grain-coating clays preserve thin section porosity in this unit. Lithic and feldspar grains are rare, thus secondary porosity caused by unstable grain dissolution is absent in the Hawkesbury Sandstone.

Good porosity aquifers are recorded in the Hawkesbury Sandstone as result of the presence of both primary and secondary porosity in these beds. The Hawkesbury Sandstone has high thin section porosity in most units, thus it has a good groundwater potential. The common thin section porosity occurs in well sorted medium and coarse-grained sandstone units which are rich in quartz. These sandstone units may coarsen upwards or fine upwards and thus show vertical variations in porosity.

These features indicate that medium- and coarse-grained sandstone units are probably characterized by moderate to good groundwater storage and flow potential. Fine-grained deposits represented by impermeable shale and siltstone units are poorly sorted and are very poor in thin section porosity. Thus, they are recognized as confining layers and provide very poor groundwater storage in the Hawkesbury Sandstone. These shale and siltstone beds form local vertical permeability seals in the Hawkesbury Sandstone.

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