“Source to Sink” Sedimentology and Petrology of a Dryland Fluvial System, and Implications for Reservoir Quality, Lake Eyre Basin, Central Australia.

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PART - 3
CHAPTER 8
DIAGENETIC IMPLICATIONS

8.1 REVIEW OF SANDSTONE DIAGENESIS

A better understanding of diagenetic modifications has been of great importance in the exploration and exploitation of hydrocarbons and is essential in determining the original composition of the sediment framework for palaeogeographic and palaeotectonic reconstructions (Helmold, 1985; McBride, 1985). Furthermore, the detrital composition can critically influence reservoir quality of sandstones by conditioning pathways of both physical and chemical diagenesis (Bloch, 1994). Intra-formational variations in detrital composition can cause significant heterogeneity in sandstone reservoir quality. Recognition of changes in composition resulting from changes in provenance has great potential for improving stratigraphic resolution on a regional scale and, hence, reservoir correlation (Morton and Hurst, 1995). This part of the study reviews early diagenetic implications of Umbum Creek sandstones with respect to sand composition and texture, including how early diagenetic processes such as compaction and cementation influence reservoir quality, subsequently this study focuses on the potential early diagenesis of modern Umbum Creek sediments.

The reservoir quality of a buried sandstone is controlled by three factors: (i) depositional porosity and permeability which are strongly influenced by sorting, grain size, grain morphology and sand/mud matrix ratio (depositional environment) (ii) the degree of mechanical and chemical compaction (iii) the amount and type of pore-filling cement; and (iv) geothermal gradient. Early diagenesis (eodiagenesis) includes all processes that occur at or near the sediment depositional surface, where the geochemistry of the interstitial waters is controlled mainly by the depositional environment. Eodiagenesis can also be defined in terms of temperature, geothermal gradient and depth, where the upper temperature limit is <70°C, typically equivalent to about 2 km burial (Morad et al., 2000). The early diagenetic alterations and their impact on reservoir quality evolution of siliciclastic sediments can be constrained mainly by assessing changes in accommodation and sediment supply, which influence the near-surface pore-water chemistry, detrital composition and the ‘residence time’ of a given sediment under a certain set of geochemical conditions (Ketzer et al., 2003) (Fig. 8.1). The eogenetic pore-water chemistry is strongly influenced by local climatic
conditions prevalent during and immediately after deposition. Thus, pore-water chemistry plays an important role in controlling the alteration and dissolution of the detrital grains and the type of clay mineral formed (Dutta and Suttner, 1986) (Fig. 8.1).

The most noticeable feature of sandstone diagenesis is the modification and general reduction of porosity (Fig. 8.2). Compaction, pressure solution and authigenic cementation by mineral reactions are the principal processes contributing to this porosity modification (Fig. 8.1). The rate of sandstone diagenesis is strongly influenced by sediment composition and grain size. The role of climate and depositional environment on formation of eogenetic clay minerals, the presence of detrital clay minerals, inherited clay materials and post-depositional incorporation of detrital clay minerals are all significant factors in the diagenetic processes, for the preservation of porosity and permeability of the sandstone (Morad et al., 2000; Worden and Morad, 2003) (Fig. 8.2).

Sandstone diagenesis is controlled by a maze of interdependent processes, including burial rate, sediment composition and texture, sedimentary and tectonic environment, chemical reaction rates, degree of lithologic variations, and hydrodynamic and geothermal gradients (Hutcheon, 1990). Textural properties are determined by the primary mineralogical composition and the physical processes of sedimentation, but may be affected by subsequent burial history (e.g. physical compaction, mineralogical alteration and cementation) (Pittman, 1979). The earliest stages of diagenesis are dominated by compaction and cementation, processes which primarily control porosity. Cementation is the diagenetic process by which authigenic minerals are precipitated in the pore space of sediments, which thereby become lithified. Compaction typically includes simple grain rearrangement during shallow burial as well as the deformation of soft ductile grains and intergranular matrix (Worden and Burley, 2003).

Diagenetic processes such, as compaction, cementation, recrystallization and replacement are widely recognised porosity-reducing mechanisms. The course of sandstone diagenesis in a given basin is programmed by the preburial, prediagenetic factors of provenance, depositional environments, and tectonic setting. These interrelated factors influence sand composition and texture, which in turn govern mineral reactions and fluid-flow rates (Hayes, 1979). During burial three diagenetic processes are important in modifying intergranular porosity: mechanical compaction, chemical compaction and cementation (Houseknecht, 1987).
Figure 8.1 Illustration of the provenance control on early diagenesis through grain composition (modified from Surdam et al., 1989).
NOTE: This figure is included on page 248 of the print copy of the thesis held in the University of Adelaide Library.

Figure 8.2 The effects of near surface diagenetic process of early diagenesis (modified from Surdam et al., 1989)
8.2 COMPACTION PROCESSES

Compaction in sandstone is defined as the reduction in bulk rock volume that occurs in response to four processes: grain rearrangement, plastic deformation, dissolution, and brittle deformation (Wilson and Stanton, 1994). However, compaction processes are also divided into two main categories: mechanical and chemical. The degree of compaction is strongly influenced by the burial history and lithology of sediments.

Newly deposited loosely packed sediments have a tendency to progress from an open high porosity system, towards a densely packed grain structure during the initial stages of burial through processes such as grain slippage, rotation, bending and brittle fracturing. These reorientation processes are collectively referred to as mechanical compaction (Burley et al., 1985; Giles, 1997). Mechanical compaction and grain breakage change the intergranular volume and the grain surface properties, which determine both the rate of quartz (or carbonate) cementation and the remaining porosity. Sands containing significant volumes of ductile lithic fragments can undergo a total destruction of intergranular volume during mechanical compaction (Fig. 8.1) (Blatt, 1979).

Chemical compaction is the bulk volume reduction caused by the dissolution of framework grains at points of contact. Intergranular volume is reduced as well as the volume of framework grains, causing a reduction in porosity due to closer packing of framework grains (Blatt, 1979). Chemical compaction is driven by thermodynamics and kinetics and is mainly a function of temperature and time, particularly in siliceous sediments (Bjorlykke, 2006). Grain composition and grain size are of particular importance for chemical compaction (Burley et al., 1985).

8.2.1 COMPACTION TRENDS WITH DEPTH

Mechanical compaction usually occurs during early to intermediate burial (0-2.5 km) and involves the rearrangement of grains and the crushing of soft lithoclasts (Burley et al., 1985). Chemical compaction becomes the dominant process during deeper burial (Giles, 1997); it involves the dissolution of material at grain contacts (pressure solution) and its reprecipitation on grain surfaces in adjacent to free pore space. The rate of porosity reduction with depth during deposition in the early stages of compaction for an uncompacted layer is much greater than the decrease in porosity with depth for already compacted layer (Pittman, 1979). Hayes (1979) acknowledged porosity
reduction with depth is not monotonic, and porosity in texturally similar sandstones can be highly variable laterally and areally. It is likely that a simple mechanical compaction model cannot work for deep sediments where complex processes affect the porosity-depth relationship; hence, simple mechanical compaction cannot reflect the complex processes that may have occurred in the sedimentary basins.

8.2.2 INFLUENCE OF SIZE AND SORTING

In sands composed predominantly of non-ductile grains, mechanical compaction does not reduce the volume of framework grains, but is characterised entirely by the reduction of intergranular volume and, therefore, porosity and permeability (Houseknecht, 1987). Mechanical compaction, which includes grain rotation and reorientation, can be greatly influenced by grain size and grain sorting (Burley et al., 1985). In the presence of variable grain sizes within uncompacted sediments, finer grains can significantly reduce the amount of pore space between coarse grains by reorientation during burial. While well-sorted sands can preserve more pore space, angular grains and variations in grain shape allow greater compaction through mechanical processes (Beard and Weyl, 1973; Blatt, 1979; Burley et al., 1985).

Sandstone reservoir quality may be greatly influenced by burial diagenetic processes that are ‘programmed’ by pre-burial depositional texture and framework composition. Angular grain edges cause contacts that facilitate pressure solution and provide a source of quartz or carbonate cement, which speeds up chemical compaction. Whilst sub-rounded grains can resist compaction better and preserve more pore space (Houseknecht, 1987). Crushing of grains not only reduces porosity, but also creates clean fracture surfaces, which provide kinetically favourable sites for quartz precipitation. Grain crushing in the clean sands leads to a loss of porosity; however, it also develops quartz cementation on the fresh grain faces, which helps pressure building and reduces mechanical compaction (Fisher et al., 1999; Chuhan et al., 2002; Chuhan et al., 2003; Bjorlykke, 2006).

8.2.3 INFLUENCE OF GRAIN TYPE

Grain rearrangement leads to compaction when framework grains move into tighter packing configurations, and correlates with the stress transmitted through framework grains (Lander and Walderhaug, 1999). In addition, mineralogical composition of reservoir sandstones is critical to
reservoir quality development, as contrasting framework grains behave differently with burial diagenesis. Whilst composition affects sandstone diagenesis in two ways: the higher the quartz content, the greater the mechanical stability (less compaction) and the higher the variety of minerals, the lower the chemical stability (higher cementation and dissolution). However, sandstones with abundant lithics, feldspar or chert have less occlusion of porosity by quartz overgrowths and more secondary porosity through dissolution of less stable grains (Fig. 8.1). The ratio of quartz to ductile grains is the key to compaction porosity loss (Pittman, 1979; Burley et al., 1985).

8.2.4 INFLUENCE OF MATRIX CONTENT

The matrix in grain-supported sandstones does not compact significantly, but matrix-supported sandstones compact considerably according to the nature of the matrix material (Pittman, 1979; Burley et al., 1985; Pittman and Larese, 1991). In some sandstone, much of the matrix is actually formed by the compaction and alteration of unstable grains to form a secondary matrix or pseudo-matrix. During compaction, a matrix that is comprised of mainly phyllosilicate minerals is subjected to a high degree of chemical compaction. In addition, the presence of a small amount of clay in carbonates and sandstones has a large influence on their physical properties and reduces the mobility of reservoir fluids. Furthermore, sandstones with early quartz and carbonate cement may stabilise the grain framework and reduce later porosity loss by compaction, however, the early formation of cements reduces the permeability (Bjorlykke, 2006).

8.3 CEMENTATION PROCESSES

There are three main early cementation processes in sandstones which involve carbonate cements, clay cements (early grain coating), and quartz (quartz) cements.

8.3.1 EARLY CEMENTS (CARBONATES)

Carbonate cements are common in clastic reservoirs and typically form low porosity and permeability layers or lenses that serve as barriers to fluid flow. Sandstones that are rich in clasts from mafic volcanic and igneous rocks represents a source of Ca²⁺ for the growth of carbonate cements (Boles and Ramseyer, 1987). However, the early precipitation of calcite inhibits later quartz overgrowth formation and feldspar alteration to clays, but can result in total porosity and permeability loss (Fig. 8.2). Apart from filling pores, calcite and other carbonates may also replace
grains. Generally quartz grains cemented by calcite are commonly corroded and etched at their margins. Occurrence of feldspar grains can be replaced, with incipient alteration taking place along twin and cleavage planes (Morad, 1998). In addition, mainly dolomite cements vary from pore-filling microcrystalline rhombs to coarse anhedral mosaics and large poliklotopic crystals. Generally early dolomitic precipitation may be related to near-surface evaporation.

8.3.2 EARLY GRAIN COATINGS (CLAY)

Grain coating may stop or delay cementation and thereby preserve porosity during deep burial and high temperatures, but reduce permeability at pore throats. The preservation potential depends on factors such as type of coating, coating thickness and grain coverage (Jahren, 2006). The most common mineral coatings are chlorite and microcrystalline quartz but coatings such as detrital clay and Fe-oxyhydroxides are also significant. The role of partial cementation and overpressuring are important in limiting compaction, whereas clay coatings are effective in preventing quartz cementation (Fig. 8.2) (Burley et al., 1985). It is important to note that the near-surface eogenetic interaction of meteoric waters with sandstone results in dissolution of detrital silicates, primarily feldspars (Pittman, 1979).

During early diagenesis, the formation of clay grain coatings covers potential nucleation sites that inhibit the growth of quartz cement. However, the growth of quartz cement may be more influenced by grain size (Ehrenberg, 1989; Worden and Morad, 2000). Chemical weathering of source rocks under semi-arid conditions accounts for the presence of infiltrated clays and their association with iron oxides (Worden and Morad, 2003). Hematite is often associated with early diagenetic clay mineral grain coatings. It probably transformed from various Fe-hydroxides and Fe-oxides, which typically precipitate in near-surface conditions of semi-arid clastic deposits (Bullard and White, 2002).

8.3.3 QUARTZ CEMENTATION

Quartz cement grows via both homogeneous and heterogeneous nucleation mechanisms. Heterogenous nucleation is the most common process evidenced by the domination of syntaxial quartz overgrowths relative to the crystallisation of pore-filling, discrete quartz crystals. A number of quartz cementation mechanisms have been proposed for quartzose sandstones, including coupled cementation and compaction arising from pervasive intergranular pressure solution,
precipitation of quartz cements from cooling fluids, and the diffusion-controlled derivation of quartz cement from nearby shales. These quartz cementation on the grain surfaces ultimately destroy the permeability within the sandstones (Burley et al., 1985; Lander and Walderhaug, 1999).

Silica in quartz cement has no single source that can be universally predicted. It can be sourced on a large scale by feldspar alteration reactions, pressure dissolution at grain contacts and stylolites, dissolution of biogenic silica and volcanic fragments, and from the illitization of smectite. Quartz cementation is favoured by high concentrations of silica in pore waters and by low temperatures. Fine-grained sandstones tend to have pervasive quartz cementation reactions, which causes porosity occlusion by precipitation. Houseknecht, (1987) demonstrated that little primary porosity is conserved in finer grained sandstones even if they contain small total volumes of quartz cement. Substantial primary porosity may be retained by coarser grained sandstones regardless of the larger absolute volumes of quartz cement these sediments may contain (Lander and Walderhaug, 1999). Grain size and temperature also significantly influence intergranular pressure solution, quartz cementation, and porosity evolution. In the study of Houseknecht, (1987) illustrates that a negative linear relationship exists between the mean grain size and the volume of quartz dissolved by intergranular pressure solution, and a positive relationship exists between mean grain size and porosity.

8.4 POTENTIAL DIAGENESIS OF UMBUM CREEK SANDS

The study of the potential diagenesis of Umbum Creek sands mainly considers the modern sediments deposited in the terminal splay complex, focusing on sample location 1 which in cooperates 6 sample points. This is because the sample location 1 and six sample points represents the ‘sink’ depositional area and environments with respect to the entire ‘source’ modern sediments of Umbum Creek network. A summary of texture, mineralogy and petrographic characteristics of the modern sediments (six samples) from sample location 1 is presented in Table 8.1. During early diagenesis (eodiagenesis), the prevailing arid to semi-arid climatic conditions in the study area exert a profound control on the position and chemistry of pore and groundwater, which in turn, influence the mineralogy and overall pattern of the cement distribution in the sandstones.
8.4.1 DUCTILE GRAIN CONTENT

The rapid loss of permeability with decreasing porosity is a result of the compaction of ductile grains being squeezed between rigid quartzose grains, blocking pore-throats and leaving isolated, ineffective porosity. The type of ductile content and grain size depends upon the conditions of the depositional system and the climate (Worden et al., 2000). The role of lithic grains on compactional porosity loss has been recognised for a long time; however, lithic grains only exacerbate the rate of porosity loss with depth if they are ductile-lithic or plastically deformable grains (Worden et al., 2000). Typically ductile-lithic sand grains, such as mud intraclasts, mica, and Fe-Mg-rich rock grains behave differently from the rigid grains. Furthermore, the observation of Worden et al., (92000) suggests that the highest permeabilities are found in sandstones with the lowest ductile-lithic grain content. Mechanically unstable rock components, such as soft lithics, contribute to porosity reduction during burial. However, the influence of soft detritus seems to be small as long as there is sufficient detrital quartz (>50%) present to stabilise the rock framework (Burley et al., 1985).

The ductile-lithic grains present in the Umbum Creek modern sand comprise silcretes, as well as sedimentary and metamorphic rock fragments. The silcretes were subdivided into ductile-lithic and rigid silcrete grains according to texture and compositional qualities. Ductile-lithic silcretes include clay-rich (RSEXc), sand-sized (RSEXs) and silt-sized microclasts (RSEXt). Rigid silcretes (non-ductile) include non-opaque (RSEXn) and opaque (RSEXo) siliceous grains (Appendix 9). Sedimentary rock fragments classified as ductile-lithic grains (RSCL) are clay-rich rock fragments or carbonate rock fragments (RSCB, RSCBr and RSCBc). The ductile-lithic grains amongst the metamorphic rock fragments component are mica-rich (RMMRm-g). Among the other metamorphic grain categories include mica-poor metamorphic rock fragments, such as muscovite mica-poor (RMMPm), biotite mica-poor (RMMPb) and garnet mica-poor (RMMPg) (Appendix 9).

Ductile lithic grains are more concentrated in the proximal end of the terminal spay complex. The total ductile-lithic content in the terminal splay complex comprises ~ 7%, in which silcrete ductile grains constitutes ~ 4%, sedimentary clay-rich ductile grains constitutes ~ 2% and sedimentary carbonate lithic comprises ~ 1% in the whole framework (Appendix 10). Metamorphic ductile-lithic grains are <1% in the terminal splay complex areas.
Table 8.1: Summary of texture, mineralogy and petrographic characteristics of modern Umbum Creek terminal splay complex sediments.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texture</td>
<td></td>
</tr>
<tr>
<td>Grain size</td>
<td>Upper medium to upper coarse, poly-modal grain size distribution</td>
</tr>
<tr>
<td>Sorting</td>
<td>Moderate</td>
</tr>
<tr>
<td>Roundness</td>
<td>Angular to well rounded</td>
</tr>
<tr>
<td>Mineralogy</td>
<td></td>
</tr>
<tr>
<td>Composition</td>
<td>Quartz: monocrystalline (50-65%) and polycrystalline (13-16%), Feldspar (3%), and lithics, sedimentary (20-25%), metamorphic (8-10%), and volcanic (0%).</td>
</tr>
<tr>
<td>Provenance</td>
<td>Quartzose recycled and transitional recycled</td>
</tr>
<tr>
<td>Quartz grain - provenance</td>
<td>Plutonic (47-52%), volcanic (3%), and metamorphic (45-56%).</td>
</tr>
<tr>
<td>Ductile-lithic grain content</td>
<td>Silicate (4%), sedimentary clay rich (2%) and lithic carbonate (1%).</td>
</tr>
<tr>
<td>Silt + Clay fraction mineralogy</td>
<td>Quartz, sandine, albite, kaolinite, hematite, gypsum and halite.</td>
</tr>
<tr>
<td>Other Variables</td>
<td></td>
</tr>
<tr>
<td>Climate</td>
<td>Semi-arid to arid climate, dry seasonal</td>
</tr>
<tr>
<td>Transportation distance</td>
<td>90-100kms</td>
</tr>
<tr>
<td>Residence time during transportation</td>
<td>Long residence time (1000’s years) in distal end (&lt;0.1' relief) and moderate (100’s years) in medial (1-2' relief)</td>
</tr>
<tr>
<td>Depositional environment</td>
<td>Terminal splay complex with fluvio-aeolian interactions</td>
</tr>
<tr>
<td>Rate of sedimentation</td>
<td>Slow, because rate of subsidence and rate of hinterland uplift are slow</td>
</tr>
<tr>
<td>Temperature - depositional area</td>
<td>Temperature ranges from - 4 to 10°C during winter and 30-60°C in summer</td>
</tr>
<tr>
<td>Reworked detrital grains</td>
<td>Around 60-70% of quartz, and &lt;10% feldspar mostly from Mesozoic and Cainozoic deposits. 10-20% metamorphic rock fragments from Cenozoic deposits.</td>
</tr>
<tr>
<td>Organic matter</td>
<td>Accumulation of total organic matter ranges 4-10% in terminal splay complex</td>
</tr>
<tr>
<td>Origin (source) of clay minerals</td>
<td>Mudstone deposits from Mesozoic and Cainozoic formations in the hinterland area.</td>
</tr>
<tr>
<td></td>
<td>Inherited clay coats on aeolian sand grains. Infiltration of clay and as coating on sand grains typically in semi-arid climates.</td>
</tr>
<tr>
<td>Dissolution of detrital grains</td>
<td>Feldspar grains and feldspar content in rock fragments, carbonate/calcite grains</td>
</tr>
<tr>
<td>Pore water/fluid availability</td>
<td>Mixing between the fresh water and saline water. Precipitation of gypsum and halite from the ground water available within the terminal splay complex</td>
</tr>
<tr>
<td>Grain coating material</td>
<td>Clay minerals: alumino-silicate, hematite and titanium oxides, and kaolin clay.</td>
</tr>
<tr>
<td>Rate of compaction</td>
<td>Slow early compaction, because of low sedimentation rate.</td>
</tr>
<tr>
<td>Elimination of detrital grains</td>
<td>Feldspar, volcanic, metamorphic, and carbonate/calcite rock fragment by leaching and disintegration</td>
</tr>
<tr>
<td>Early Cements</td>
<td>Quartz cements, quartz overgrowth, halite and gypsum cements.</td>
</tr>
</tbody>
</table>
The high-relief hinterland of the Umbum Creek proximal river network originally introduces medium to high ductile-lithic grains into the network system with respect to other parts, although the ductile-lithic content is reduced in the low-relief medial and distal parts by mechanical and chemical weathering. Arid to semi-arid climatic conditions allow more residence time during transportation, leading to leaching and dissolution of ductile-lithic grains, which are consequently eliminated from the final depositional system. Thus, the availability of ductile-lithic grains in the Umbum Creek terminal splay complex area is restricted by sediments generated from multiple reworked sedimentary provenances, arid to semi-arid climatic conditions, long temporary residence times during the transportation, and mechanical and chemical weathering via fluvio-aeolian interaction.

8.4.2 QUARTZ CEMENT

At surface conditions, a direct relationship exists between the degree of cementation and sandstone porosity, due to the presence of a certain volume of cement reduces the porosity by an approximately equal volume. As if cementation takes place in the subsurface, porosity reduction will be caused by both cementation and compaction (Scherer, 1987). However, early clay coatings can prevent quartz cement from growing and thereby preserve porosity. Where by quartz cement is more abundant on clean quartz surfaces than on unclean and clay-coated surfaces (Ehrenberg, 1989).

In the modern Umbum Creek sands, quartz from the metamorphic provenance of the Peake and Denison Inliers has the cleanest surfaces for quartz cementation because these quartz grains have been unaffected by any previous diagenetic processes. Results from this study have shown that metamorphic quartz yield from the Peake and Denison Inliers is mostly concentrated in the proximal and distal parts of the system (Fig.7.1). Plutonic quartz grains are also expected to have a high potential for quartz cementation because they have clean surfaces if they are directly generated from the plutonic terrain. However, the plutonic quartz available in Umbum Creek sediments is mainly generated from reworked grains from the Mesozoic and Cenozoic sedimentary deposits, which have already undergone diagenetic processes. These quartz grains typically show dirty surfaces and previously formed quartz overgrowths, which inhibit rapid quartz cementation at the early diagenesis. In addition, the quartz grains derived from plutonic and metamorphic provenance in the terminal splay complex is nearly equal (~ 50%) and comprises ~ 65% of the total sand content.
Angular quartz sand allows for rapid quartz cementation, if the surfaces of the detrital grains are clean. Most of the angular to sub-angular grains introduced to the Umbum system are from the proximal and medial parts. The angularity of the modern sediments in the terminal splay complex ranges from angular to well-rounded where approximately half of the grains in these sediments are angular to sub-angular (Appendix 9).

In modern Umbum Creek sediments inherited clay coats are interpreted to have been derived from the clay material which adheres to moist sand grains during fluvio-aeolian interactions. Furthermore, it has been noted that the most of the inherited clay-coated sand grains are contributed from aeolian deposits. Within the majority of clay-coated grains are to be found in the distal part of the river network because of the increased fluvio-aeolian action. Hot and dry climatic environments are highly oxidizing and iron remains in the ferric state and coats minerals in a hydroxide or sesqui-oxide form, leading to the characteristic red colouration of sediments (Pittman, 1979). Hematite is therefore often associated with early diagenetic clay mineral grain coatings which are in turn responsible for the red colour in sediments such as aeolian grains (Fig. 6.27). Generally however, the inherited clay coats seen in the terminal splay complex modern sediments are alumino-silicate (clay) with ferric hydroxide or sesqui-oxide coats (hematite) are sub-ordinate.

The playa depositional setting of the Umbum Creek terminal splay complex is characterised by arid to semi-arid climatic conditions and episodic major flooding (averaging once in 25 years) that enhances the infiltration of suspended clay particles and the formation of coatings around framework grains in sediment deposits. Worden and Morad, (2003) emphasise that clay minerals formed by weathering processes in the hinterlands which are subjected to arid to semi-arid climatic conditions are expected to be dominated by smectite, as are infiltrated clays, clay pseudomatrix and mudstones. However, the X-ray diffraction results from the Umbum Creek sediments indicate an absence of smectite in the system. Either the formation of palygorskite with smectite from the dryland environmental conditions or the deflation of smectite clay is interpreted as the cause for the absence of smectite in the terminal splay complex. Furthermore, near-surface eogenetic interaction of meteoric waters with detrital minerals results in the formation of kaolinite at the expense of detrital feldspar and micas whose alteration products are typically smectitic. Eogenetic kaolinite is probably formed during periods of increased rainfall.
The early diagenetic clay coats found in the terminal splay complex sediments support kaolinite formation, because of the wet-dry seasons experienced in the region. The medial part of the system also favours kaolinite formation, but not as strongly as the distal part. The other early cements such as quartz overgrowth and halite are concentrated in the distal part of the system most likely related to the dominantly evaporitic conditions (Fig. 6.25). Quartz nodule overgrowths are also seen as grain coats in the terminal splay complex sediments and are formed by quartz precipitation due to the arid climate and playa environment conditions (Fig. 6.25).

8.4.3 CARBONATE/ EVAPORITE CEMENT

Pedogenesis in arid continental environments mostly leads to non-ferroan calcrete and dolocrete with an abundance of biogenic calcite and dolomite cement fabrics (Morad, 1998). The presence of carbonate intraclasts in the sediments typically results in carbonate re-cementation in arid or semi-arid successions (Burley et al., 1985). In sub-aerial, arid, hot (tropical to sub-tropical) environments sediments typically undergo minimal chemical weathering because of the reduced rainfall. The resulting interstitial waters are alkaline and concentrated (Worden and Burley, 2003). However, in contrast, chemical weathering processes are facilitated in Umbum Creek sediments by temporary sediment storage periods which occur during transportation of sediments along the system. As a result, carbonate intraclasts are more prevalent in proximal sediments, but are of very low content in the terminal splay complex region.

There are a number of possible primary sources of the components (mainly Ca$^{2+}$, Mg$^{2+}$ and bicarbonate) of eogenetic carbonate cements in continental sedimentary rocks. The main mechanisms for near-surface carbonate accumulation can be divided into organic and inorganic processes. There is no evidence of eogenetic carbonate cements developed from organic sources in the terminal splay complex. Inorganic sources for carbonate cements are formed by the supersaturation of water with carbonate minerals and the evaporation of the increased concentration of aqueous solutes to the point of mineral precipitation. However, the low content (~1%) of carbonate lithic grains in Umbum Creek terminal splay sands does not favour this process. Carbonate cements from early diagenesis are removed during burial diagenesis, which leads to their dissolution, recrystallization or replacement by other carbonates.
Gypsum cements resulting from early diagenetic process are related to evaporitic conditions at the
time of sedimentation, conditions which are typical of the arid to semi-arid climate and the playa
environment of the terminal splay complex of Umbum Creek. In this environment, the final stage of
progressive evaporation leads to highly saline water. Gypsum saturation is reached through
evaporation of > 90% of the original water mass, leading to the growth of gypsum in siliciclastic
sediments. Gypsum and anhydrite cement removal during the evaporite dissolution and
calcitisation reactions only takes place where sediments are flushed with meteoric fluids (Boles
and Ramseyer, 1987).

8.5 PREDICTION OF DIAGENESIS FROM TERMINAL SPLAY COMPLEX
SAND

Predicting early diagenesis requires an estimate of diagenetic processes and results based on
composition, texture, climate, pore-water chemistry, and depositional environment (Table 8.1). In
the modern Umbum Creek sediments, petrogenesis is accelerated by the arid climatic conditions.
Other significant factors include chemical weathering influenced by meteoric waters and
mechanical weathering controlled by the abrasion and sorting of sediments during transportation
processes, factors which impact on texture, bulk composition and mineralogy.

Early diagenesis of Umbum Creek sediments involves various combinations of early cementation,
infiltration and deposition by clay-rich surface waters, as well as the dissolution of unstable clasts
by groundwater and meteoric waters. The playa environment facilitates these early diagenetic
events and also contributes to the alteration of infiltrated clay to kaolinite, the formation of
evaporites (gypsum and anhydrite) and the formation of authigenic clays.

Low percentage of mechanical compaction would be expected when the sand composition is
considered: 70-90% quartz, <5% feldspar, and <15% rock fragments, of which ~ 7% are ductile
lithic grains (whole rock %). The high quartz content increases mechanical stability. An
examination of the texture of terminal splay sediments (upper medium to upper coarse grainsize,
angular to well-rounded shape and moderate sorting) supports low to moderate compaction. Grain
crushing is unlikely as only about half of the grains in the terminal splay complex are medium-
coarse in size and angular to sub-angular in shape, and the rate of sedimentation is low. The
influence of the matrix content during compaction is predicted to be low, as the sand contains few ductile lithic fragments, has a low clay content and is not matrix supported.

Several elements combine to affect the prediction of chemical diagenesis in Umbum Creek sediments. For example, the chemical compaction rate in these sediments is expected to be low because of the low content of feldspar and ductile lithic fragments. However, on the other hand, the angular to sub-angular grains would be subjected to grain contacts interactions during compaction, a process which facilitates contact pressure dissolution and can accelerate chemical compaction and authigenic cement generation. During compaction, the initial pressure dissolution rates of the quartz grains would be low, because of the absence of mica lithics in the sand. The limited variety of minerals in the Umbum Creek sediments leads to higher chemical stability and therefore less cementation and dissolution. Preservation of porosity in the terminal splay complex sediments is predicted to be high, as porosity loss during compaction of coarse-grained sands would be limited due to interlocking of the framework grains, which form a rigid rock framework.

Early carbonate cements have little influence on terminal splay complex sediments as the content of carbonate intraclasts in is only ~ 1%. However, the high evaporation conditions in the playa environment lead to the growth of gypsum and anhydrite cements in these sediments. The early grain coatings of alumino-silicate, microcrystalline quartz and Fe-oxyhydroxides on the terminal splay complex sands would be expected to inhibit initial quartz cementation process. The presence of grain coatings on the fluvio-aeolian grains reduces and delays thermally-activated quartz cement growth (Jahren, 2006). Furthermore the low feldspar content and the precipitation of quartz during feldspar dissolution is a negligible factor in the facilitation of quartz cementation. Processes such as the diffusion-controlled derivation of quartz cements from the low content of ductile lithics and dissolution of volcanic fragments could also release quartz and improve quartz cementation in these sands. These processes are not relevant however, due to the high salinity waters within the arid to semi-arid climatic conditions of the Umbum Creek terminal splay complex. As a result of all the above factors, the rate of quartz cementation during early diagenesis on the terminal splay complex sand is predicted to be low to moderate.
CHAPTER 9

DISCUSSION AND CONCLUSIONS

The aim of this study was to assess ‘source’ to ‘sink’ sedimentation in a modern dryland fluvial system analogue within a continental interior basin in order to improve prediction of reservoir quality in comparable ancient successions. In accordance with this aim, modern Umbum Creek sediments were studied in relation to their provenance lithotype regions. The research was based on extensive petrographical analysis of provenance lithotypes from the Proterozoic to Cenozoic meta-sedimentary and sedimentary successions in pertinent basins and on modern sediment provenance analysis. This study also involved the estimation and prediction of early diagenetic implications of terminal splay complex modern sediment deposits. Because sandstone reservoir quality prediction requires an accurate assessment of original composition, texture and subsequent diagenesis (Burley et al., 1985), the study of a modern drainage system from 'source' to 'sink' can be of vital importance in the prediction of subsurface composition and texture of reservoir sandstones.

The objectives of this study were to answer three main questions:

1. How have Umbum Creek sediment sources and dispersal paths evolved through time?

2. To what extent does the present Umbum Creek sediment population reflect changes in tectonic, climatic and depositional settings from 'source' to 'sink'?

3. What are the implications for predicting reservoir quality?

The most significant conclusions arising from these questions are discussed below.

9.1 SEDIMENTARY BASIN EVOLUTION

The sedimentary basin evolution of the western Lake Eyre sedimentary basin was analysed through the study of the isopach maps and the petrographic evaluation of various provenances of different sedimentary basin lithotypes. Provenance studies evaluate the lithology and tectonic evolution of sediment source regions in relation to basin development (Dickinson et al., 1983; DeCelles and Giles, 1996). These techniques were used in this study to constrain the timing of the
uplift and the erosion of the hinterland of Umbum Creek. The geometrical and structural relationships of source areas and the receiving sedimentary basins can be established through the appraisal of sediment generation from the sediment ‘source’ to sediment ‘sink’ (Cavazza et al., 1993; DeCelles and Giles, 1996; Critelli et al., 2003). In addition, the amount of reworked sediments, cycling from the older through to the younger sedimentary basins can also be determined (Giulio et al., 2003).

Qt-F-L and Qm-F-Lt ternary diagrams of the Proterozoic to the Cenozoic provenance lithotypes indicate reworking of sediments throughout basin development from the Officer Basin through to the present western Lake Eyre Basin. The provenance lithotype characterisation studies provided evidence of the evolutionary history and provenance of the sediments from each formation within these basins. This lithotype characterisation was then used to quantify the extent and character of each sediment provenance lithotype region, information needed to understand the modern sediments of Umbum Creek in relation to western Lake Eyre Basin evolution. An estimate of the contribution of sediment from different hinterland sources was possible when younger sediments were fingerprinted to their provenance lithotype and evaluated with sediment mixing models. This multiple provenance concept approach has been well documented by Zuffa, (1987), Critelli et al., (1997), Weltje et al., (1998) and Arribas et al., (2000).

The isopach maps showed that each basin was controlled by northeast and northwest-trending structures, which were tectonically active during sedimentation over the Troughs and in erosion from the palaeohighs (Table 4.2). The Wintinna, Manya and Boorthanna Troughs controlled depocentre distribution and accommodation patterns within the Officer Basin. The Arckaringa Basin was characterised by the migration and apparent rotation of the Officer Basin depocentres along the northeast structural elements and the creation of new depocentres. Although the Arckaringa Basin was not within the Umbum Creek modern study area, reworked sediments from the Arckaringa Basin are recognised in the younger Eromanga Basin deposits. The isopach maps were used to infer the removal and subsequent redeposition of sediment from the Arckaringa in to the Eromanga Basin, and indicated the thickness and distribution of Arckaringa sediments throughout the study area. The petrographic results reveal that provenance of Eromanga Basin sandstones of the Algebuckina Sandstone, Cadna-owie Formation, Bulldog Shale sandstone units as well as the Coorikiana Sandstone also indicated reworking of Arckaringa Basin deposits.
The early Jurassic to late Cretaceous stratigraphic signature of the Eromanga Basin and the hierarchy of the sedimentary successions are significant as provenance for the development of the Lake Eyre Basin sediment during the Palaeogene and Neogene. The isopach maps for the Eromanga Basin show a thin, blanket-like and widespread preserved sedimentary succession. The northeast-trending Karari Fault Zone and the northwest trending fault-bounded Mulgathing Trough were shown to control Eromanga sedimentation patterns in the study area. The Denison-Willouran Divide and the folded Stuart Range also imposed a structural grain on the Mesozoic sediments by controlling palaeo-current directions and the channel alignments of fluvial deposits which consistent with Rankin et al., (1989). Furthermore, this study confirmed the significance of the Denison and Willouran Divide during deposition of the Algebuckina Sandstone, Mount Anna Sandstone and Cadna-owie Formation in the study area. It has been demonstrated that the depocentres migrated from northwest to southeast, but the sediment accumulation pattern remained essentially the same, controlled by the tectonic setting and the palaeo-drainage pattern. In addition the uplift of the Gawler Craton, according to Drexel and Preiss, (1995) provided the clastic input into the subsiding fault-controlled western margin of the Eromanga Basin in the early Jurassic to early Cretaceous.

Petrographic studies and isopach map analysis indicated that the western Lake Eyre Basin evolution was controlled predominantly by the northeast and northwest trending structural elements. These structures were influential in the formation of the older basins in the area and continued to play an important role during the Cenozoic development of the Western Lake Eyre Basin. To the northwest, the uplift of the Peake and Denison Inliers was a major structural development during the Early Palaeogene, which had a significant impact on western Lake Eyre Basin evolution and provenance changes which agrees with the observations of Callen et al., (1995). There were no major changes in the provenance of the Lake Eyre Basin sediments prior to this event. However, the input of meta-sedimentary lithotypes mainly from the uplifted Peake and Denison Inliers modified detritus source regions (provenance) of later Lake Eyre Basin deposits.

The sedimentary basin evolution study provided constraints regarding the provenance of Umbum Creek sediments and the controls exerted by tectonics on sedimentation in the study area. Most importantly the study highlighted the significance of reworked sediments through the Umbum Creek network system, emphasising the relevance of the multiple sediment provenances with input
from various hinterland sources derived from older sedimentary basin deposits through to the
western Neogene Lake Eyre Basin (Fig. 9.1).

In summary, the major conclusions drawn from the sedimentary basin evolution study are outlined
below:

- Northeast and northwest trending structural elements played a prominent role in the
development of the sedimentary basins in the study area from the first phase Officer Basin
sedimentation through to present day sediment deposition in the western Lake Eyre Basin.

- Gawler Craton (plutonic source rocks) was interpreted as the main provenance region for
sedimentary deposits during the Palaeozoic (Arckaringa Basin) and the Mesozoic
(Eromanga Basin). During the Cenozoic, the uplift of the Peake and Dennison Inliers
(meta-sedimentary rocks) resulted in changes in provenance for sedimentary deposits in
the Lake Eyre Basin from the Late Neogene to the present.

- The following sediment source areas were identified for modern sediments of the western
Lake Eyre Basin: Plutonic detritus originated from the Gawler Craton, but is currently
supplied from Mesozoic Eromanga Basin deposits. The Peake and Dennison Inliers are
the source of metamorphic grains in the system. These also originated in the Gawler
Craton but were metamorphosed. Volcanic and carbonate detritus are derived from the
Peake and Dennison Inliers.

- The Gawler Craton provenance has influenced deposits of the older sedimentary basins
such as Officer, Arckaringa, Eromanga and Lake Eyre basins in the study area. These
older sedimentary deposits were reworked through the system and are represented in
modern Umbum Creek sediments, highlighting the importance of reworked sediments and
their provenance both for younger sedimentary deposits and for determination of early
diagenetic modification. Consequently, identifying reworked sediments and their
provenance has significance for assessing sediment composition and texture which has
implications for subsequent burial diagenesis then to reservoir quality.
Figure 9.1 Sediment provenance diagram illustrating the influence of basin development and the contribution of sediment supply with respect to the analysis of isopach thickness map and petrographic analyses.
9.2 MODERN SEDIMENTS

The sediment yield and mixing effect from hinterland and local sediment sources along the Umbum Creek network were evaluated via a triangular sampling model, providing key information about the effects of grain size modality, variation in composition, transportation and weathering patterns. This sampling revealed essential differences in fluvio-aeolian transportation processes and grain-size distributions between differing sediment framework lithology types.

In the proximal part of the river network, changes in grain size distribution were erratic because of the influence of mixing from local sources and the joining of other tributaries to the mainstream, however, the overall grain-size trend from each tributary to the mainstream suggests that grain size apparently increases downstream. In the proximal and medial part of the network, grain size varies through the addition of coarser sediments from the tributaries and the coarser sediment supply from the older sedimentary formations. Sub-angular to sub-rounded grains are characteristic of the proximal end of the network. The more rounded grains are due to the reworked grains from older sandstone and siltstone sources in the hinterland.

In summary grain size variation depends on mechanical and chemical weathering as well as lateral sediment influx from confluences and aeolian reworking. In contrast rounded to well-rounded grains have been strongly influenced by aeolian processes and show evidence of multiple reworking through both fluvial and aeolian transportation.

Although general downstream fining of grain size is commonly observed in river sediments worldwide, Umbum Creek sediments shows a contrasting pattern of downstream coarsening. The modern Umbum Creek sediments study has indicated that downstream coarsening is due to several factors. These are:

- Coarse–grained sediment mixing from tributaries
- Input from older coarse-grained Mesozoic and Cenozoic formations
- High influx of resistant silcrete fragments from the distal part of Umbum Creek network
- Input from coarse-grained gibber-plain sediments during the flooding season as the net effect of surface run-off,
- Coarse-grained sediment remaining from aeolian deflation phases.

This study has indicated that grain-size variation in modern Umbum Creek sediments (sand fraction) is highly controlled by the sediment yield from reworked older sedimentary deposits throughout the drainage system and wind ablation mainly in medial and distal parts of the network. Mechanical weathering due to fluvial and aeolian transportation also impacts on grain size variation.

The compositional variation determined by petrographic modal analysis forms a quantitative dataset whereby grain composition analysis was based on 72 grain lithology categories. This high resolution study has resulted in the recognition of the original provenance lithotype rocks in the Umbum Creek hinterland (Fig. 9.2).

The modern Umbum Creek sands consist largely of detrital grains, derived from the old sedimentary deposits rocks (Fig. 9.2). The compositional variation of sediments is often attributed to the physical mixing of sediments from multiple sources, which is recognised as one of the factors that quantify the contribution of each source to the total sediment deposition in the basin. Downstream variations in Umbum Creek modern sand composition are characterised by trends of increasing quartz/feldspar ratios, decreasing abundance of unstable fragments and increasing stable monocrystalline quartz. The high quartz content in the system indicates supply from reworked quartz-rich bedrock sources (Fig. 9.2). Because of sediment generation from meta-sedimentary and sedimentary rocks, it is suggested that compositional variation in modern sediments along Umbum Creek is a function of sediment input and sediment mixing from the entire ‘source’ and drainage pattern (Figs 6.12, 6.13, 6.14, 6.15 and 6.16).
Figure 9.2 Schematic diagram showing the major provenances for the modern Umbum Creek sand generation. The arrows are indicating the influence of respective provenance lithotype (formations) sediment input from the hinterland 'source' areas to the Umbum Creek modern sand.
This study provided evidence that provenance lithotypes played a major role in contributing monocrystalline quartz into the system (Fig. 7.1). The sedimentary provenance lithotypes, which were either, derived from the Gawler Craton or from the combined sediments from Gawler Craton and a meta-sedimentary source (the Peake and Denison Inliers), supplied plutonic quartz grains to the modern sediments. The proximal samples from locations 12, 13 and 14 showed an abundance of both plutonic and metamorphic quartz grains, which indicated that Gawler Craton sediments and meta-sedimentary grains from the Peake and Denison Inliers contributed to the abundance of plutonic and metamorphic quartz grains in the modern sediments. The medial samples showed an abundance of plutonic quartz grains, which suggested recycled plutonic quartz from an older Mesozoic sedimentary lithotype, which were originally derived from the Gawler Craton. This provides evidence that the Gawler Craton was a major source of sediments to the Mesozoic Eromanga Basin sedimentary deposits.

The distal network samples show the highest percentages of metamorphic quartz grains in the modern sediments, indicating the influence of recycled metamorphic grains from outcropping Cenozoic sedimentary rocks, which were originally derived from the uplift of the Peake and Denison Inliers. The disintegration of ductile lithic fragments was also observed across the entire Umbum Creek drainage system (Fig. 9.2).

Proximal network samples show litharenites to sublitharenites on the QFL ternary diagram, and ‘quartzose recycled’ and ‘transitional recycled’ according to the QmFLt ternary. The mixing of mostly Mesozoic sediments from the interfluves of George Creek, Hope Creek and Davenport Creek increases the mature grains in the Umbum Creek ‘medial’ sediments. However, composition varies only minimally even with the influence of sediment influx, the mixing effect from the supplying interfluves and weathering effects in the medial part. The medial network samples shown to be sublitharenites on the QFL and QmFLt ternary diagrams suggest that the provenance of all samples was ‘quartzose recycled’. Significant compositional changes were evident in the medial part of the Umbum Creek network, including the very low lithics content (carbonate grains), low plutonic quartz grains, and the increase in proportions of sedimentary and metamorphic lithics.

The composition of the ‘distal’ samples reveals sublitharenites in the QFL ternary diagram. The QmFLt ternary diagram indicates the provenance as ‘quartzose recycled’ and ‘transitional recycled’ which agrees the observations of Dickinson, (1985). The large amounts of Mesozoic and Cenozoic
deposits in the distal reworked sediments promote mature polymodal and rounded grains. However, the dry and wet seasonal climatic conditions provide more fluvio-aeolian sediments reworked from meta-sedimentary and sedimentary Palaeogene and Neogene deposits into the medial part of system, which enhances the metamorphic and sedimentary lithic composition. In addition, the presence of abundant quartz, sedimentary to meta-sedimentary lithic fragments, along with the lack of feldspar, is consistent with derivation of sediments from older sedimentary rocks.

According to Weltje and von Eynatten, (2004) chemical alteration and mechanical breakdown of sediment source rock, followed by sorting of particles during transport and deposition, leads to preferential enrichment of specific materials in certain grain-size fractions, and hence, sediment composition tends to be a function of grain size. As discussed previously, sands generated from Umbum Creek and the tributaries are from mixed deposits of variety source rocks. The quantification of the abundance of the different source rock types in Umbum Creek drainage system permitted comparison with petrographic data from the sands. Because lithic grains are unequivocally related to their ‘source’, the contrast between their abundance in the sand and the aerial extent of the ‘source’ lithology within the drainage basin, allowed an evaluation of the amount to which each grain type is representative of specific sediment sources, which agrees with technique used and observation made by Arribas and Tortosa, (2003).

The compositional variation of the modern Umbum Creek sand indicated changes associated with the tributary sediment supplies, as well as changes in source lithology in the drainage basin (Figs 6.12, 6.13, 6.14, 6.15 and 6.16). Thus, compositional variation has a direct relationship with the aerial extent of the sources. For example, the quartz grain percentages throughout modern Umbum Creek sediments depend on the total amount of lithic grains generated from outcropping sediment sources. However, the result of this study (Appendix 9 and 12) indicated that the percentage of metamorphic lithic grains exceeded the relative proportion of these lithologies in the source area. This implies that metamorphic detritus concentrates in the lithic grain population, over-representing the proportion of this framework grain lithology with respect to the original sediment source area (sample points 14-2, 13-2 and 12-1).

In contrast, sedimentary lithic grains were observed to concentrate in the medial and distal part of Umbum Creek drainage system. This variation in grain types appears to correlates with the
tectonic setting of the ‘source’ (provenance) terrains. In addition, the total compositional trends show that the modern sands are substantially affected by chemical weathering during the course of the network in the medial and distal parts, which reduces the content of feldspar and lithic grains of carbonate and volcanics.

The rate and nature of sediment supply to aeolian systems from fluvial systems is not only the function of sediment production and sorting but also strongly depends upon the nature of the channel through which sediment is transported (Blair and McPherson, 1994). Within this context, the Umbum Creek system discharges mainly onto the exposed playa lakebed in the form of a subaerial terminal splay complex. As the Umbum Creek fluvial system changes from the braidplain environment to the terminal splay (playa) complex in the distal area, it passes through an aeolian dune field system which augments the fluvio-aeolian grains in the system. During periods of reduced runoff, wind erosion of fluvial deposits occurs, with fluvial-derived sand reworked into expanding aeolian dune fields. In the wet phase, increased runoff results and sediment is supplied from the adjacent dune fields to the fluvial system. After drying out, the delta is subjected to intense aeolian reworking, and much of the fine-grained sands and silts on the delta front are either blown away or moulded into shadow bars on the delta front and on the delta plain (Lang et al., 2004). The wind also reworks the upper surface of the in-channel bars, resulting in well-sorted, coarse-grained sediments in the system. Deflation is prominent in the terminal splay area of Umbum Creek today. One of the reasons for the apparent coarsening downstream trend observations is due to the wind erosion at the terminal splay removing fine grains and clay fraction sediment.

The majority of the modern sands were deposited in areas where fluvio-aeolian processes are dominant. The study highlighted that the key areas of sediment accumulation in the distal part of the system were in the terminal splay complex, including the floodplain, channels and the fan delta area ('sheet' of sand deposition). In addition to these depositional areas, Umbum Creek modern sand has temporal storage areas in the medial part of the system. Sediment is ultimately deposited in a setting where it is buried and isolated from the weathering environment. The rapidity with which sediment is isolated from weathering is important in determining its composition, especially where exposure to the weathering environment has been brief during pedogenesis and transport. Temporal storage during transportation facilitates the decrease in feldspar and carbonate grain content. Fluvial mechanical and chemical weathering processes as well as aeolian abrasion
contribute to the high percentage of quartz and the disintegration of lithics in the Umbum Creek modern sands. Fluvial, aeolian and fluvio-aeolian transportation processes directly control depositional processes in the western Lake Eyre Basin, and also modify composition, grain texture, sorting, grain size and early diagenesis (grain coating, cementation and overgrowth). Thus, the compositional and textural maturity of Umbum Creek modern sediments develops as they travel from the proximal to distal part of the system.

Forward modelling characterised the composition and texture in the evolution of sediments at the main stage of sediment generation from the ‘source’ rocks. The extent to which generated sediment differs from the provenance lithotypes depends on the intensity and duration of weathering processes, which in turn depends primarily on climate (for intensity) and topography (for duration) (Heins, 1993; Heins and Kairo, 2006). The Umbum Creek modern sediment generation was predicted according to controlling factors such as drainage pattern, relief, transport process, mixing effect and source rocks. The predicted dataset was calibrated with the observed dataset from the modern sediment modal analysis.

The main differences between the predicted and observed data set of quartz monocrystalline and polycrystalline grain categories were due to later modifying factors such as mechanical and chemical weathering, as well as the recycling of quartz grains from younger sedimentary rocks. There was however a good correlation between the predicted data set of the limited grid and translator and the observed sand composition. In contrast, the full grid was used the predicted sand data showed similarities to the observed sand categories in half of the sediment samples (Table 7.8 and 7.9). This discrepancy is most likely due to the mixing effect in the upstream sediments being more subdued than modelled. However, the local drainage pattern and the local source rocks have a greater influence on sediment yield to the sample points more than the mixing effects from further drainage patterns due to the climatic conditions of the catchment area. The dry seasonal climate does however, reduces transportation of materials through the river network.

There were similarities and dissimilarities in the predicted and observed grain categories among the samples from the proximal to the distal part of the Umbum Creek catchment. Differences were due to factors such as the recycling of quartz grains and the mechanical and chemical disintegration of metamorphic and sedimentary rock fragments. However, petrographic observations agreed with the predicted sorting properties, but differed with respect to grain size
ranges. This latter disparity was probably due to aeolian deflation in the distal end, especially in the terminal splay complex of Umbum Creek. The results of the predicted and observed grain categories supported the importance of modelling multiple sand characteristics as a function of many environmental controls, including tectonic setting, provenance lithotype abundance, climate, regional topographic gradient, hinterland transport distance, basin transport distance, basin subsidence rate, and depositional environment.

The study of modern sediments quantitatively demonstrated how the sediment yield from Umbum Creek is derived from multiple provenances. Umbum Creek receives sediments from the entire catchment area, including sediment generated from the uplifted Davenport Ranges, particularly in the proximal areas, and from Mesozoic and Cenozoic deposits in the medial and distal areas (Fig. 9.3). This means that the river network captures sediments from a large source area of older rocks and deposits them into a comparatively small sink area. The volumes of sediment supplied from within the larger drainage pattern are transported into a relatively small basin.
Figure 9.3 A map showing the multiple provenance regions with respect to modern Umbum Creek sediments from a larger 'source' area (red colour) whereas the sediment 'sink' area is comparatively small (yellow colour). There has been no sediment 'source' bypasses occur during any geologic time.
The transportation processes—fluvial, aeolian, fluvio-aeolian—that influence sediments as they progress through the Umbum Creek system were detailed in Chapter 7. By the time sediments are deposited in the terminal splay complex, sediments have been deflated to a stable residue of medium to coarser grains. The most significant process for redistributing and sorting sand is the fluvio-aeolian interaction. Aeolian processes rework channel deposits as well as those in the surrounding floodplain and terminal splay complex during the long intermission between flood events. These processes can rework grain size up to lower coarse-grained sand, which may then be redeposited anywhere in the depositional system. Fluvial transportation carries the aeolian sediments from the adjacent dune systems during the major flood events. Because the grain coatings developed during dryland fluvio-aeolian interactions have the potential to preserve or destroy reservoir quality in sandstone deposits (see section 9.3), the study of the fluvio-aeolian processes in the Umbum Creek terminal splay has great significance for reservoir quality analysis.

Ephemeral sandy fluvio-aeolian dominated terminal splays associated with dryland depositional environments are important intracratonic reservoirs in many basins around the world. For example, the Permian Upper Rotliegend Group of northern Europe records complex interactions between aeolian, fluvial and playa environments in a basin (Bjørlykke, 1998), and fluvio-aeolian reservoirs of Jurassic Norphlet Formation sandstone reservoirs in Mobile Bay of Alabama, USA. The other significant examples are from the aeolian and alluvial deposition within the Mesozoic Etjo Sandstone Formation, northwest Namibia (Mountney et al., 1998), the Lower Cretaceous Avile Sandstone Member of the Agrio Formation consists of aeolian and fluvial deposits of Neuquen Basin in Argentina, and the semiarid aeolian-fluvial succession of the Upper Jurassic Guara Formation of southern Brazil.

The modern sediments study of the Umbum Creek network provided a modern fluvio-aeolian petrological and depositional analogue of a dryland basin which offers insights into these types of reservoirs, particularly regarding framework mineralogy, grain-size, roundness and sorting, and provenance of the framework grains. Reservoir quality composition and texture of sub-surface sediment is predominantly influenced by the provenance of the sediment and the depositional environment. For example, in the Umbum Creek modern sands, potential reservoir quality is favourably impacted by the presence of metamorphic quartz from the Peake and Denison Inliers, plutonic quartz from reworked Mesozoic deposits, low content of ductile lithic fragments, low
feldspar, and fluvio-aeolian depositional processes. These issues are further discussed in section 9.3.

In summary, the major conclusions drawn from the study of modern sediments are presented below:

- Five different provenance lithotype grains were identified in modern Umbum Creek sediments:
  1. Gawler Craton plutonic/basement provenance (recycled)
  2. Proterozoic volcanic provenance from Gawler volcanics and Peake and Dennison Inliers volcanics (recycled)
  3. Metamorphic provenance of Peake and Dennison Inliers
  4. Mesozoic (Eromanga Basin) sedimentary provenance
  5. Cenozoic (Lake Eyre Basin) sedimentary provenance.

This underlines the importance of multiple provenance lithotypes in Umbum Creek modern sediments.

- Modern sediments in the Umbum Creek network are sourced from the drainage hinterland as well as the entire catchment area. Multiple provenances supply sediments from a significantly larger ‘source’ area to a comparatively small ‘sink’ area.

- Provenance lithotype control on modern sediments is mainly due to sediment generation from relief-controlled interfluve drainage networks and the mixing effect of sediment during the course of the river network through fluvio-aeolian interactions.

- Prediction of grain size and composition largely depends on sediment input from the tributaries as they capture sediment from both the hinterland and lateral sources.

- A general downstream coarsening pattern is observed through the Umbum Creek network.

- Multiple reworking of sediments from older deposits, originally sourced from Gawler Craton, strongly influences the composition of the modern sediments.

- Provenance interpretation of quartz grains based on petrographic examination correlates well with cathodoluminescence imaging.

- The observed modern sand composition correlates well with the predicted data set using the limited grid and translator 1 in the forward modelling of sand composition and texture.
• Features of the dryland fluvial setting which are of relevance to analogue studies and reservoir quality estimations are:
  1. grain size and texture changes due to fluvio-aeolian interactions
  2. wet and dry phase effects on grain compositional modifications
  3. cementation and coatings on the grains due to climatic conditions
  4. variations in clay mineralogy due to wind ablation.

• The compositional and textural maturity of terminal splay complex sand is due to:
  1. reworked plutonic quartz grains
  2. dissolution and disintegration of feldspar and carbonate grains during transportation
  3. breakdown of lithic fragments because of fluvial and aeolian accelerated mechanical weathering and chemical weathering from fluid contacts.

9.3 DIAGENESIS AND IMPLICATIONS FOR RESERVOIR QUALITY

Subsurface porosity and permeability of sandstones determine reservoir quality. These features are strongly related to initial texture and composition of grains, depositional environment and diagenesis (Blatt, 1979; Hayes, 1979; Burley et al, 1985). Provenance determines sand grain mineralogy and sediment maturity. Mechanical and chemical weathering processes can alter the texture and composition of sediment during transportation. This means that sediment texture and composition, which are of critical importance in determining ultimate reservoir quality, are controlled by factors such as provenance lithotype, climatic conditions, and transport distance and medium within the sedimentary basin.

The early diagenesis of the modern Umbum Creek sediments is influenced by the arid to semi-arid climatic conditions, in which meteoric water supports chemical weathering whilst fluvio-aeolian transportation processes controls mechanical weathering. The fluvio-aeolian depositional environment facilitates the clay coating process as well as maintaining low content of clay material within the deposits. Early diagenetic processes consist of various combinations of early cementation, infiltration and deposition by clay-rich surface waters, and the dissolution of unstable (ductile) clasts by groundwater and meteoric waters. The playa environment facilitates these early
diagenetic events as well as the alteration of infiltrated clay to kaolinite, the formation of evaporites (gypsum and anhydrite) and the formation of authigenic clays.

Other diagenetic factors, which control the reservoir quality of the Umbum Creek modern sediments are detrital composition and provenance, texture, sorting, clay coating and clay composition within the deposits. Diagenetic processes such as compaction, cementation, recrystallisation and replacement are widely recognised porosity-reducing mechanisms. Porosity loss, in general, results from the compaction of grains, the pressure solution of grains and the growth of authigenic minerals (cements). The loss of porosity is higher where there is a higher content of volcanic rock fragments, feldspar and other immature or chemically less stable constituents than where sediments comprise meta-sedimentary fragments and less feldspar and lithic fragments (Hutcheon, 1990), such as occurs in the modern Umbum Creek sands.

Preservation of the porosity in the Umbum Creek terminal splay complex sands was predicted to be high, because porosity loss during the compaction in angular to well-rounded, upper medium to coarse-grained sands is low, which consistent with the observations with Pittman, (1979). A low mechanical compaction is expected when the modern Umbum Creek sediment composition consists of 70-90% quartz, <5% of feldspar, and <15% of rock fragments, in which ~ 7% are ductile lithic grains. The chemical compaction rate is also expected to be low in the Umbum Creek terminal splay complex sediments, due to the low content of feldspar, carbonate and ductile-lithic grains. The reduced rate of chemical compaction has the effect of enhance porosity and permeability. In addition, low proportion of ductile grains reduces the total destruction of intergranular volume during mechanical compaction. The reduction of ductile-lithic grains in terminal splay complex sediments results from the multiple reworking of sediment and the elimination of these grains from the final depositional system by mechanical and chemical weathering.

The rate of quartz cementation during early diagenesis in the terminal splay complex sand was predicted to be low to moderate based on the following criteria. The constraints on quartz cementation in these sands are largely due the detrital mineralogy with the following factors exerting strong influence:

- Lack of feldspar dissolution
- Low ductile lithic content
- Lack of volcanic fragment dissolution (to release silica), and
- Early clay coatings on the grains such as anatase coating, alumino-silicates and fe-oxyhydroxides, which inhibits quartz overgrowths.

However, other factors present at the Umbum Creek terminal splay act to accelerate quartz cementation in these sands. These factors include high salinity surficial waters and arid to semi-arid climatic conditions. Later in burial compaction, quartz cementation is anticipated from pervasive driven by intergranular pressure solution at grain contacts. Although fresh plutonic grains usually support quartz cementation, the plutonic grains in the Umbum samples do not, because of the 'unclean' surfaces of these reworked grains. Conversely however, angular to well-rounded grains in the modern sands of the terminal splay permit high compaction and result in grain crushing which creates fresh faces for quartz cementation to proceed. These two opposing observations support the prediction of low to moderate rates of quartz cementation. Of the factors mentioned above quartz cementation inhibition by early grain coatings (e.g. anatase), are potentially significant in best preserving reservoir quality of Umbum Creek terminal splay sediments.

Early diagenetic alumino-silicate clay coats were observed as widely present in the terminal splay complex sediments. The medial part of the system favours kaolinite formation, but moderately less than the distal end sediments. The other early cements such as quartz overgrowth and halite are concentrated in the distal part of the system due to the evaporitic conditions of the arid climate (Fig. 6.25). Quartz nodule overgrowths were seen as grain coatings in the terminal splay complex sand and are formed by quartz precipitation under an arid climate within playa depositional environment. The absence of smectite in the distal samples was also noted. It was interpreted that the smectite clay was removed from the system by wind ablation. In addition, the low content of carbonate lithic grains dissolution and the lack of carbonate cements from organic sources do not support the growth of any eogenetic carbonate cements in the modern Umbum Creek terminal splay complex sediments.

The study of diagenesis as applied to the modern Umbum Creek sediments has implications that can be related to other fluvio-aeolian and playa lake depositional environments such as interactions between aeolian, fluvial and playa depositional environments in the Permian Upper
Rotliegend Group of northern Europe. Modification of early diagenetic processes occurs due to the features typical of these environments: fluvio-aeolian interactions, exposure to saline water and exposure to intermittent meteoric waters from major flood events. These resulting characteristics could be expected in the rock records derived from similar dryland environmental conditions:

- Bedded siliciclastic and reworked dune sand
- Hematite, alumino-silicate, and magnesium alumino-silicate coatings
- Halite and gypsum growths and coatings
- Kaolin clay coatings, and
- Quartz growth and quartz cement filling pore systems.

An assessment of the reservoir quality of Umbum Creek terminal splay modern sediments based on texture, mineralogy and petrographic characteristics is presented in Table 9.1. A summary of the impact of the diagenesis of these sands on reservoir quality according to their characteristics and depositional environment is presented in Table 9.2.

A firm understanding of the controls on compositional and the textural maturity is a prerequisite to accurate interpretation of the reservoir quality. In addition, potentially valuable information concerning the sedimentary environment can be obtained if the fluvio-aeolian interactions and processes can be understood. The dryland fluvial-aeolian interactions and resultant terminal splay modern sediments deposits, as described in this study, are distinctive and may be useful as an analogue for similar ancient systems. However, the variability within fluvial-aeolian systems and the understanding of how this variability may be expressed is equally important.

The understanding of the petrology of dryland fluvio-aeolian sediments is desirable in order to evaluate the subsurface porosity and permeability of fluvio-aeolian reservoir sandstones. In dryland arid to semiarid regions, it is common for fluvial and aeolian deposits to be intermixed, with the result that the overall sequence has all the complexities of both fluvial and aeolian processes, plus the complexities produced at the junctions between the two, and by the reworking of one by the other. These observations were also agrees with the conclusions of Mountney et al., (1998). Multiple recycling within the fluvial and aeolian depositional environment with intense chemical weathering seemed essential in order to account for the extreme textural and compositional
maturity observed in Umbum Creek sediments, with the exceptional rounding of many examples pointing to important aeolian abrasion. Other attributes such as very low feldspar grains presence, low proportions of lithic fragments, and elevated concentrations of monocrystalline quartz as well as the ‘breaking’ of polycrystalline quartz are reported in fluvio-aeolian depositional environment (Suttner et al., 1981). The aeolian processes within the Umbum Creek catchment can rework grain sizes up to lower coarse-grained sand, and these may be redeposited anywhere in the depositional system. The fluvial transportation carries the aeolian sediments from the adjacent dune system during the major flood events. According to Langford, (1989) fluvio-aeolian interaction is an important process for redistributing and sorting sand within the depositional environment, which is consistent with the modern Umbum Creek sediments in terminal splay regions.

Provenance exerts a significant influence on reservoir quality by controlling the composition of sediments, which in turn impacts both mechanical properties and chemical diagenetic processes that decrease, preserve or increase porosity and permeability. However, the mechanical and chemical disintegration of the sediments are highly influenced by the medium of transportation and depositional environment. Reservoir quality depends on sand composition, itself a function of hinterland processes: provenance, tectonic setting, sand evolution and transportation, climate, and the depositional environment. Knowing the percentage of mineral composition such as quartz, feldspar and lithics in the subsurface as well as sediment burial history and geothermal gradient, one may be able to predict porosity and permeability of reservoir units as they undergo diagenesis.

The most significant points arising from the study of early diagenesis of the modern Umbum Creek sediments are listed below.

- Modern Umbum Creek sand petrogenesis is accelerated by the dryland environmental conditions.
- Sediment composition and mineralogy are modified by fluvial and aeolian transportation. The wet and dry phases characteristic of the dryland environment facilitates chemical weathering due to contacts with fresh and saline water, consequently modifying sediment composition and texture.
- Playa environments facilitate the alteration of infiltrated clay to kaolinite, the formation of evaporites (gypsum, halite, anhydrite), and the formation of authigenic clays (illite).
Table 9.1: Methods and results, which are significant to Umbum Creek modern sediment reservoir quality.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Results</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sieve Analysis</td>
<td>Grain size - upper medium to upper coarse sand and moderately sorted. Clay fraction - trace amount (&lt; 0.3%) of clay present.</td>
<td>Mechanical compaction is high in coarse grain size, high mechanical compaction leads to high mean effective stresses.</td>
</tr>
<tr>
<td>2. Petrography</td>
<td>Modern sand composition - 60-70% monocrystalline quartz, 10-20% polycrystalline quartz, &lt; 5% feldspar &amp; &lt; 15% lithics. Provenance lithotype - granitic, volcanic, metasediments and sedimentary formations.</td>
<td>The higher the quartz content, the greater the mechanical stability and less compaction. Less lithic grains reduces the initial dissolution rates for quartz over growth adjacent to the lithics. Mono-quartz sand retains porosity in low stress intervals and lose porosity due to grain fracturing. Provenance - individual lithic grains can be fingerprinted to their parent rock.</td>
</tr>
<tr>
<td>4. CL</td>
<td>Provenance of quartz - individual quartz origin identified. Igneous, volcanic, metamorphic and sedimentary origin.</td>
<td>Reworking of quartz grains allows quartz cementation and grain coating. Quartz from igneous and low grade metamorphics undergo less fracturing.</td>
</tr>
<tr>
<td>5. XRD</td>
<td>Bulk mineralogy of clay fraction - quartz and clay minerals with feldspar</td>
<td>Controls the dissolution, fluid flow and clay mineral cementation during diagenesis.</td>
</tr>
<tr>
<td>6. Zoom stereo microscopy</td>
<td>Surface texture - identified as aeolian and fluvial grains.</td>
<td>Moderately well sorted, bimodal, sub-angular to rounded and Clay-poor sands maintain porosities, prior to quartz cementation.</td>
</tr>
</tbody>
</table>
Table 9.2: Early diagenetic processes with respect to Umbum Creek terminal splay complex sand characteristics which lead to the estimation of reservoir quality.

<table>
<thead>
<tr>
<th>Diagenetic processes</th>
<th>Umbum Creek terminal splay complex sediment characteristics</th>
<th>Reservoir quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mechanical compaction</td>
<td>Compaction: low. High quartz content and low ductile grain types</td>
<td>Porosity preserved</td>
</tr>
<tr>
<td>: grain type</td>
<td>Compaction: Low - moderate. Grain size; upper medium to upper coarse allows low compaction, sorting: moderate attribute low - moderate compaction, shape: angular to well rounded tolerate moderate compaction</td>
<td>Mostly porosity preserved, however, moderate compaction permits loss of porosity.</td>
</tr>
<tr>
<td>: size, sorting and shape</td>
<td>Compaction: low. Due to slow rate of sedimentation, the overburden stress is minimum to accelerate angular to sub-angular grain crushing during compaction.</td>
<td>Preserves porosity</td>
</tr>
<tr>
<td>2. Chemical compaction</td>
<td>Compaction: Low - moderate. less feldspar (&lt;5%) and ductile lithic (&lt;7%) allows low compaction, angular to subangular quartz grains permits moderate compaction through contact dissolution for compaction in later burial diagenesis</td>
<td>Initially preserves porosity, but during later burial contact dissolution of Grains destroy porosity.</td>
</tr>
<tr>
<td>3. Cementation</td>
<td>Cementation: Low - moderate. &lt;1% carbonate lithics, high evaporation rate under playa environment accelerate the gypsum and anhydrite cements</td>
<td>Destroys porosity, however develop secondary porosity during late diagenesis as dissolution</td>
</tr>
<tr>
<td>: early carbonate/ evaporite cements</td>
<td>Cementation: Low - moderate. Restrained by early carbonate / evaporite cements, grain coating, and low feldspar content dissolution. Favoured by salinity, low temperatures, pressure dissolution at grain contacts in later burial compaction</td>
<td>Preserve porosity in early diagenesis, but destroying porosity by low rate of quartz cements and in later stages by pressure dissolution quartz cements.</td>
</tr>
<tr>
<td>: quartz cementation</td>
<td>Cementation: Low - moderate. inhibits cementation by enhanced grain coating of alumino-silicate, microcrystalline quartz and Fe-oxyhydroxides.</td>
<td>Preserve porosity, but will reduce permeability and hence reservoir quality.</td>
</tr>
<tr>
<td>: grain coating</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• The composition of modern Umbum Creek sands suggests that low rates of mechanical and chemical compaction upon burial would be expected. The lack of ductile grains in terminal splay sediments reduces the destruction of intergranular volume during mechanical compaction.

• The rate of quartz cementation is predicted to be low to moderate.

• The ‘early’ grain coatings of alumino-silicate, microcrystalline quartz and Fe-oxyhydroxides on fluvio-aeolian sands in the terminal splay complex sediments would be expected to inhibit the quartz cementation process.

9.4 SUMMARY OF CONCLUSIONS

The most interesting issues arising from this ‘source’ to ‘sink’ study in the dryland setting are listed below:

• The importance of multiple provenances with respect to eventual sediment reservoir quality for the sediments delivered into the Umbum Creek drainage system

• Coarsening of grain size downstream

• Compositional variation of sediments with the relatively small area of the Umbum Creek drainage basin

• A larger ‘source’ area depositing into a small basin (‘sink’)

• The significance of fluvio-aeolian interaction on grains and its effects including mechanical and chemical weathering and various grain coatings, and

• The significance of early diagenetic processes with respect to ultimate reservoir quality of dryland siliciclastic sediments.
CHAPTER 10
RECOMMENDATIONS

The following recommendations are made to compliment this study of modern Umbum Creek sediment samples in this thesis:

- A comparative provenance study of the modern sediments of the adjacent Neales River system is recommended. This work could be carried out to provide further support for the multiple provenance concepts and its significance for providing reservoir quality sediment into a dryland basin setting.

- A study of the impact of climate variability and change on fluvio-aeolian interactions in the terminal splay complexes of both Umbum Creek and the Neales River is recommended. This work would help provide a better understanding of grain size and compositional modifications resulting from fluvio-aeolian transportation processes, including clay coating effects and modification of clay mineralogy.

- A specific study focussed on different grain coatings and their relationship to the depositional environment, particularly in a dryland setting, is recommended to further the understanding of the links between reservoir quality and later diagenetic processes.

- A study of spatial and temporal changes in clay mineralogy in the terminal splay complex sands of both Umbum Creek and the Neales River is recommended to assess the effect of climate variation and transportation on this factor which can significantly impact on reservoir quality.