

Authigenic carbonates as natural analogues of mineralisation trapping in CO₂ sequestration: A desktop study

S.D. Golding^a, G. K. W. Dawson^a, C.J. Boreham^b and T. Mernagh^b

^a CO2CRC and School of Earth Sciences, The University of Queensland, QLD 4072, Australia

^b CO2CRC and Geoscience Australia, GPO Box 463, Canberra, ACT 2601, Australia

E-mail addresses: s.golding1@uq.edu.au (S.D. Golding); g.dawson@uq.edu.au (G.K.W. Dawson)

The authors wish to acknowledge financial assistance provided through Australian National Low Emissions Coal Research and Development (ANLEC R&D), Carbon Transport and Storage Corporation (CTSCo) and the CO2CRC. ANLEC R&D is supported by Australian Coal Association Low Emissions Technology Limited and the Australian Government through the Clean Energy Initiative.

Table of Contents

Executive Summary	4
1. Introduction	7
2. Engineered mineral trapping for sequestration of CO ₂	11
2.1. pH and pCO ₂	11
2.2. Fluid supersaturation via addition of reactants	11
2.4. Magnetic field	12
2.5. Microbial activity	12
2.6. Other issues	14
3. Parameters influencing carbonate diagenesis in sandstones	15
3.1. Depositional facies	15
3.2. Detrital mineralogy	16
3.3. Groundwater chemistry	18
3.3.1. Brine composition	18
3.3.2. Cation surface charge density	19
4. Mixing of carbonate waters	20
4.1. The algebraic effect	20
4.2. Salinity and ionic strength effects	21
4.3. pH and pCO ₂	21
4.4. Temperature and pressure effects	23
4.5. The general case	23
5. Methods for reconstruction of basin thermal and fluid flow history	25
5.1. Burial history modelling	25
5.2. Fluid inclusions and calcite cements	28
6. Conclusion	31
References	32

Executive Summary

This desktop study summarizes the known controls on carbonate precipitation in aquifers and the latest methodologies for determination of basin thermal and fluid history. This project has three key components aimed at supporting CO₂ storage projects in Australian sedimentary basins through investigation of the controls on carbonate authigenesis in freshwater aquifers as a natural analogue for mineralisation trapping. The project has a foundation in a literature review and desk top study that synthesises what is known about the controls on carbonate precipitation in aquifers with different chemistries, reservoir temperatures and volumes of CO₂ available. Part I will involve petrological, fluid inclusion and geochemical investigation of authigenic carbonates in Jurassic sandstones of the Eromanga and Surat Basins to determine the conditions and time frame of mineralisation. Parameters derived from Part I will feed into the Part II simulation to produce a model for authigenic carbonate diagenesis that will then be tested experimentally with Precipice and Hutton sandstone samples in Part III of the project. The lab experiments (Part III) will be conducted on fresh cores from the target area of the Wandoan CCS project in Queensland.

Precipitation of carbonate minerals within the pore space of the storage reservoir provides the greatest certainty of long-term storage and eliminates the risk of CO₂ leakage. Modelling studies suggest that significant CO₂ could be sequestered by carbonate formation when CO₂ is injected into sandstone formations with trapping capacity determined largely by cation availability. On the other hand, zones of significant carbonate cementation have also been identified in onshore and offshore shallow clastic aquifers where CO₂ associated with and likely derived from oxidation of hydrocarbons migrating vertically from deeper source rocks or leaky hydrocarbon traps, mixed with local formation water. These carbonates formed close to the naturally-occurring point of shallow subsurface leakage (often a fault) that suggests mineralisation has been rapid relative to the movement of groundwater. Similarly, massive significant scaling of oil wells by calcite precipitation demonstrates that the authigenesis may occur within acceptable time frames for engineered authigenesis. As microbial biodegradation of gas and oil is an active process in reservoir sands of the Bowen and Surat basins, there appears to be no impediment (e.g., nutrients, populations of microbial communities) for the involvement of hydrocarbon degradation processes in carbonate mineralisation in the study area.

All groundwater contains dissolved metal cations (e.g., Ca, Mg, etc.) that could potentially combine with carbonate anions to form carbonate minerals, irrespective of whether reactive minerals phases exist or not. The main parameters determining the extent of mineral trapping in sedimentary formations are pH and pCO₂, brine chemistry and temperature. In natural systems, pH is strongly affected by pCO₂ and the combination of high pH and alkalinity favour carbonate precipitation.

Supercritical CO₂ dissolved in water causes acidic conditions unless the aqueous phase is initially highly basic. An initial fluid pH greater than 9 is required for carbonates to precipitate during the introduction of supercritical CO₂. In spite of the addition of a base to the solution, carbonic acid interactions with both dissolved and solid species can still drive pH lower if high partial pressures of CO₂ are maintained, unless the solution is buffered. Brines buffered with borate are much better able to sustain basic conditions suitable for optimal carbonate precipitation than phosphate buffers.

The mixing of solutions with different chemical compositions can produce undersaturated or supersaturated conditions for a particular mineral depending on the original compositions and temperatures even where the original groundwaters were saturated with the mineral in question. The system may also evolve with time and the degree of mixing such that undersaturation prevails in more acidic and saline parts of the system and supersaturation in the more basic and dilute region of the system. Calcite solubility increases with NaCl concentration up to 2 molar but decreases with further increases of NaCl concentration, which is likely due to the solubility enhancement effect of chloride complexation being dominant at lower concentrations of NaCl, and the reduced solubility of CO₂ having a greater effect upon calcite solubility at higher solution molarities. Solution temperature strongly affects both ion solubility and precipitation rates. Calcite solubility is inversely proportional to temperature and directly proportional to pressure. Aside from the influence of system pressure upon pCO₂, it is not as important as the other factors affecting calcite precipitation.

Carbonates precipitated as part of microbial processes are commonly found associated with seafloor methane seeps, and concurrent microbial sulphate reduction intensifies the carbonate formation. Micro-organisms that produce and/or live within a protective biofilm attached to a geological substrate are resilient to supercritical CO₂ exposure, whereas free-floating vegetative micro-organisms are generally not able to remain viable under such conditions. Bacterial hydrolysis of urea can generate solution oversaturation with respect to calcite, and the bacteria themselves may enhance calcite nucleation.

The timing of oil and gas generation, expulsion and migration provided by burial history modelling enables better constraints on the compositions, displacement and entrapment of fluids. At Gidegalpa-16 (Cooper-Eromanga), the Permian source rocks entered the oil window during the mid-Cretaceous with the majority of the gas and oil being generated and expelled over a ~15Ma year window up to around 85 Ma. This narrow timeframe places strict constraints on total fluid movement in response to petroleum generation in the vicinity of this well. The Wandoan-1 well locality (Bowen-Surat) has experienced a more complex petroleum generation history primarily due to the much deeper burial of the Permian source rocks. A minor phase of petroleum generation and

expulsion occurred during the latest Permian-earliest Triassic times with the main phase occurring between the early Jurassic to mid Cretaceous. This ~40 Ma window at Wandoan-1 represents a much wider period of total fluid movement compared to that at Gidgealpa-16, potentially enabling longer residence times for fluid-rock interactions.

Little is currently known about the genesis of calcite-cemented zones that occur in the Eromanga and Surat basins. Early workers considered calcite-rich sequences in the Hutton Sandstone to be near-surface low temperature calccrete horizons formed between intermittent sedimentation episodes. However, on the basis of oxygen isotope data, it has been suggested that the carbonate cements precipitated at elevated temperatures of 55–121 °C. The carbon isotope composition of the carbonates was similar to that of Cooper Basin carbon dioxide and was not similar to the expected carbon isotope composition of CO₂ derived from microbial oxidation of hydrocarbons.

A previous apatite fission-track study of samples from the Bowen and Surat basins indicates that certain samples of the Precipice Sandstone experienced paleotemperatures > 80 °C. The Hutton Sandstone experienced paleotemperatures ≥ 110 °C and the Injune Creek Group had paleotemperatures ≥ 70 °C based on samples from the Cabawin-1, Wandoan-1, Flinton-1 and Macintyre 1 wells. The thermal history modelling of the apatite fission-track parameters suggests that cooling occurred during the interval 100–80 Ma. The magnitude of cooling was in the order of 25–60 °C, being the greatest in the northern part of the trough and relatively less in the southern part of the trough. The proposed fluid inclusion studies will provide better constraints on the paleotemperatures estimated from other indirect methods and at the same time measure the salinity of the fluids associated with carbonate precipitation. The origin of carbonates can be inferred indirectly from the carbon isotopic composition of CO₂ trapped within the fluid inclusions and directly from the carbon isotope composition of the authigenic carbonates.

1. Introduction

When CO₂ is injected into a siliclastic (or carbonate) reservoir the trapping mechanisms evolve over time (Figure 1) with containment of CO₂ dominated by structural, stratigraphic and/or hydrodynamic traps over the 30-35 year injection stage of the project. A number of geochemical reactions also occur and become increasingly important after CO₂ injection has finished. CO₂ may be partially contained via residual trapping as the plume moves away from the wellbore and also mixes with and dissolves in the formation water at the leading and trailing edges of the plume (solubility trapping). Dissociation of the CO₂ dissolved in the formation water creates acidity that reacts with minerals in the formation and may dissolve fast reacting carbonate minerals (if present) in the acidified zone surrounding the injection well leading to an increase in dissolved bicarbonate (so-called ionic trapping). In the longer term dissolution of silicates such as plagioclase and chlorite causes pH to increase and carbonates may precipitate in the previously acidified zone as CO₂ partial pressure declines (mineral trapping).

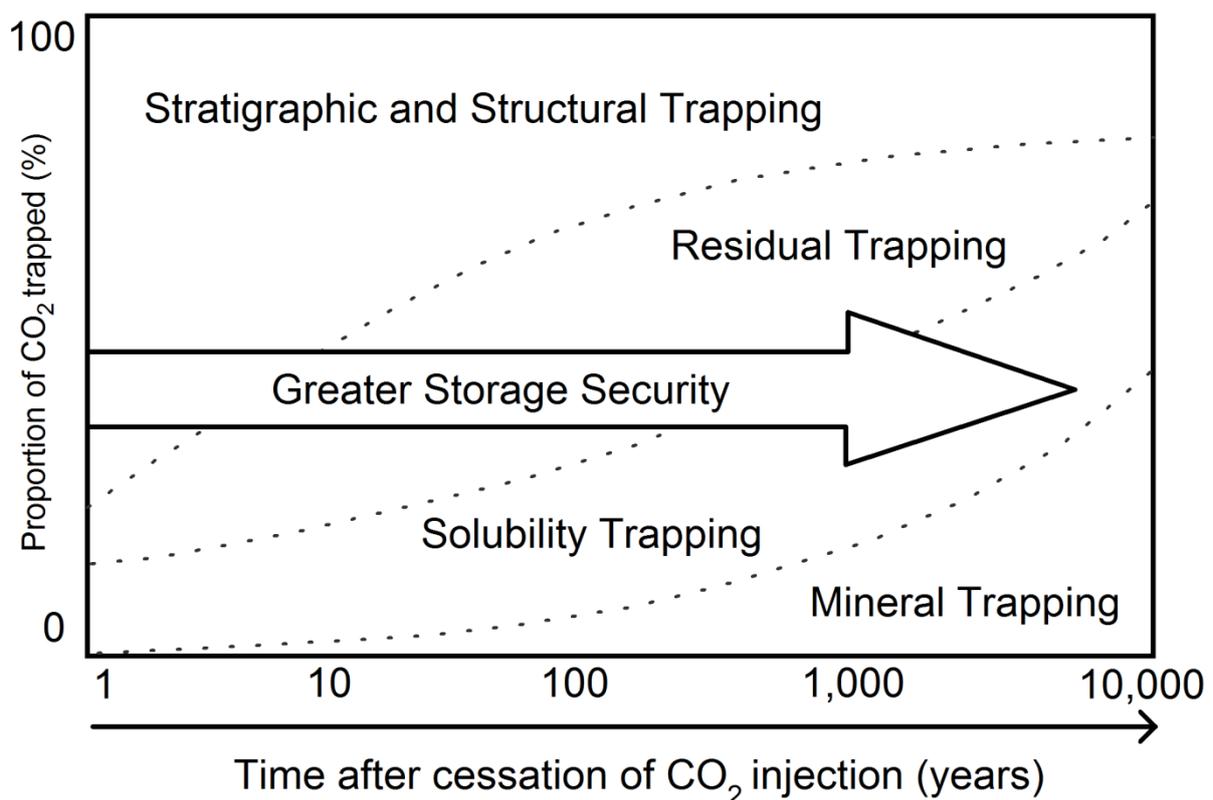


Figure 1. Schematic representation of the change of trapping mechanisms and increasing CO₂ storage security over time (modified after Class *et al.*, 2009; IPCC, 2005).

Precipitation of carbonate minerals within the pore space of the storage reservoir provides the greatest certainty of long-term storage and eliminates the risk of CO₂ leakage. CO₂, in mineralised form, may fill all of the available pore space and thereby be the most efficient use of pore storage capacity and minimise the volumetric impact of storage on aquifers. For these reasons, we are investigating how significant mineralisation trapping might occur (or be engineered to occur) over shorter time periods and under what conditions. Modelling studies suggest that significant CO₂ can be sequestered by carbonate formation when CO₂ is injected into sandstone formations, with trapping capacity determined largely by cation availability (Newell *et al.*, 2008; Xu *et al.*, 2005; Xu *et al.*, 2007). Cations for carbonate precipitation in these simulations come mainly from dissolution of chlorite and calcic plagioclase that are uncommon in many reservoir sandstones as are other reactive phases like volcanic rock fragments. This may explain the lack of evidence for mineral trapping in high CO₂ gas fields where dissolution of CO₂ in formation water (solubility trapping) is the dominant sequestration mechanism (Gilfillan *et al.*, 2009). On the other hand, there is ample evidence for the presence of reactive minerals and carbonate formation through fluid-rock interaction processes in the Bowen-Gunnedah-Sydney (BGS) basin system (natural analogues) with many sandstones having carbonate cement contents in excess of 10% (Baker *et al.*, 1995; Uysal *et al.*, 2011; Uysal *et al.*, 2000). Moreover, Eromanga Basin sandstones may have up to 80% of pore space filled with authigenic carbonate (over 100's of metres of vertical extent and km's of lateral extent), where located above major gas and oil fields. The formation of dawsonite in the BGS seems to be linked to influx of magmatic/mantle CO₂ into sandstones that contained detrital plagioclase and/or volcanic rock fragments (Baker *et al.*, 1995; Uysal *et al.*, 2011). More broadly, calcite-ankerite-siderite mineralisation in the BGS basin system appears to have formed under high fluid-rock ratio conditions in response to Mesozoic hydrothermal activity. This suggests that injection of CO₂ into structural lows and the long distance lateral and vertical migration of this CO₂ provides the best opportunity for maximising mineral trapping (cf. Golding *et al.*, 2011). The dominant initial trapping mechanism in this scenario is residual gas saturation trapping of CO₂ left behind by the migrating plume that then dissolves in the formation water and ultimately precipitates as carbonate.

Central to any attempt to engineer accelerated mineralisation for sequestration of CO₂ is an understanding of the conditions under which relatively rapid carbonate mineralisation has formed both in present hydrocarbon extraction activities (e.g., in-well bore hole rapid scale formation), and in the geological past. In the context of past significant mineralisation, carbonate-cemented zones (primarily calcite) have been found within all hydrocarbon reservoir units of the Eromanga Basin (Anderson, 1985; Menhennitt, 1985; Schulz-Rojahn, 1993; Staughton, 1985; Wall, 1987), and in places have sufficient seismic impedance contrast with adjacent units to be mapped during seismic

surveys (e.g. Schulz-Rojahn *et al.*, 2009). However, the reservoir units are not uniformly cemented throughout the basin (Table 1) and in places hydrocarbons occur within them in the absence of carbonate cementation (Schulz-Rojahn, 1993; Staughton, 1985). Unpublished studies show a close correlation between the amount of authigenic carbonate and the volume of hydrocarbons trapped. Other unpublished work shows some thick carbonates along the migration pathway to certain petroleum fields in which there is no evidence of carbonate in the wells within the pool limits (Rob Heath, private communication, March 2013). Within the Gidgealpa Field of the Eromanga Basin, significant carbonate-cemented zones occur around major structural crests above breaches of regional seals (Schulz-Rojahn *et al.*, 2009), and indeed many hydrocarbon accumulations within the Eromanga Basin are presently leaking (Boult *et al.*, 1997). In many cases, these carbonates cements formed close to (and stratigraphically above) the inferred naturally-occurring point of injection in a shallow reservoir zone (for example where brine, hydrocarbons and associated CO₂ migrate up leaking faults and emerge into a shallow aquifer system), which suggests that mineralisation has been rapid relative to the movement of groundwater. The carbonate cemented zones are of varying thickness within these wells and detailed correlation is not possible nor meaningful given the authigenesis is a post-depositional imprint. The key issues here are why carbonates precipitated within some units but not others, or for the case of the same unit precipitated within one locality but not another. Hence the primary focus of this desktop study is a better understanding of the controls on the formation of authigenic carbonates in low salinity, siliclastic aquifers of the Surat and Eromanga Basins as a natural analogue of mineralisation trapping in CO₂ geosequestration.

Table 1. Variability of selected geological elements observed during a survey of lithological descriptions of sixteen wells drilled through the Eromanga and Cooper Basins.*

Geological time zone	Unit of interest	Dominant Inferred Depositional Environments	Sometimes:		May be present:				Sometimes cemented with:						
			Unit absent	No cement	Oil	Coal	Sea shells	Lime-stone	Calcite	Silica	Clay	Pyrite	CaSO ₄		
Cenozoic	Consolidated, undefined	Shallow marine & paralic to continental interior													
Early – Late Cretaceous	Winton Fm.	Meandering fluvial to paralic & shallow marine													
Early Cretaceous	Mackunda Fm.	Marginal marine to paralic													
	Allaru Mudstone	Shallow marine to paralic													
	Toolebuc Fm.	Restricted marine to paralic													
	Wallumbilla Fm. (equiv. Oodnadatta Fm.)	Shallow marine													
	Coorikiana Sandstone (equiv. Wallumbilla Fm.)	Nearshore / shoreface													
	Bulldog Shale (equiv. Wallumbilla Fm.)	Shallow marine to paralic													
	Cadna-Owie Fm.	Wyandra Sandstone (Transition Beds)	Beach												
		Murta Fm. (equiv. Hooray Sandstone)	Meandering fluvial to lacustrine & shallow marine												
Late Jurassic to Early Cretaceous	Namur Sandstone (equiv. Hooray Sandstone)	Braided to meandering fluvial & paralic													
	Westbourne Fm.	Meandering fluvial to lacustrine & deltaic													
Late Jurassic	Adori Sandstone	Braided stream to meandering fluvial to lacustrine													
Middle Jurassic	Birkhead Fm.	Meandering fluvial to lagoon-lacustrine & lower delta plain													
Early – Middle Jurassic	Hutton Sandstone	Braided fluvial													
Early Jurassic	Poolowanna Fm. (a.k.a. 'Cuttapirrie Beds' & 'Basal Jurassic')	Fluvial & lacustrine			gas										
Late Permian to Early – Middle Jurassic	Nappamerri Group	Fluvial & lacustrine, minor evaporates, & shallow marine						MgCa Dolostone							
Middle Permian	Toolachee Fm.	Braided floodplain to lacustrine, fluvial deltaic & coal swamp													
Early – Middle Permian	Daralingie Fm.	Fluvio-deltaic													
	Roseneath Shale	Lacustrine			gas										
	Epsilon Fm.	Floodplain, lacustrine, coal swamps													
	Murteree Shale	Fluvial deltaic to lacustrine													
Early Permian	Patchawarra Fm.	Lacustrine, fluvial-deltaic and coal swamps			gas										
	Merrimelia Fm.	Fluvio-glacial and braided fluvial													
Pre-Permian	Various	Various						Ca & CaMg							

* The darkness of shading within a column indicates relative abundance of a geological element within a specific unit (dark – abundant, light – trace). Thick borderline indicates approximate basin boundary. Geological information summarized from petroleum well completion reports (Brown, 1984; Burnett and Darling, 1986; Fawcett, 1983; Harrison and Higginbotham, 1964; Jenkins, 1984; Nugent, 1988; O'Neill, 1985; Ostler, 1989; Rudd and Ties, 1987; Short and Harris, 1986a, b; Surka and Rouse, 1984; Taylor, 1985; Thornton, 1984; Thornton and Elliott, 1982; Ties and Rudd, 1986).

2. Engineered mineral trapping for sequestration of CO₂

Mineral trapping is the most secure form of CO₂ storage; however, these reactions are likely to be very slow, relative to the time frame of the injection period (i.e., may require 1000's of years) and are most likely to occur where a basic silicate mineral such as feldspar or clay is present. An accurate model able to predict the conditions required for acceleration of mineralisation trapping in particular storage reservoirs is the first step towards engineering to maximise storage security and efficiency. This could be conceived either as a primary storage enhancement strategy within the storage complex or as a mitigation option were CO₂ leakage to occur into a shallower aquifer. Our ability to influence what proportion of injected CO₂ will ultimately be fixed in carbonate minerals, and to potentially decrease the time required for mineral sequestration, is limited by our knowledge of subsurface mineralisation processes related to CO₂ – rock reactions. It is necessary, therefore, to determine whether there are differences in groundwater composition or reservoir conditions that encourage rapid mineralisation of CO₂, and if so, what are the key parameters. All groundwater contains dissolved metal cations (e.g., Ca, Mg, etc.) that could potentially combine with carbonate anions to form carbonate minerals, irrespective of whether reactive mineral phases exist or not. Some parameters that other studies have altered in an effort to induce accelerated carbonate precipitation are as follows:

2.1. pH and pCO₂

Supercritical CO₂ dissolved in water causes acidic conditions unless the aqueous phase is initially highly basic. Precipitation rate and yield are actually greater for calcite formed under supercritical CO₂ conditions than for liquid or dense vapour CO₂ conditions, if the solution pH is engineered to be basic (Domingo *et al.*, 2006; Druckenmiller and Maroto-Valer, 2005; Montes-Hernandez *et al.*, 2007). An initial fluid pH greater than 9 is required for carbonates to precipitate during the introduction of supercritical CO₂ (Druckenmiller *et al.*, 2005; Liu and Maroto-Valer, 2011b; Soong *et al.*, 2004). In spite of the addition of a base to the solution, carbonic acid interactions with both dissolved and solid species can still drive pH lower if high partial pressures of CO₂ are maintained, unless the solution is buffered. Brines buffered with borate are much better able to sustain basic conditions suitable for optimal carbonate precipitation than phosphate buffers (Liu and Maroto-Valer, 2011a).

2.2. Fluid supersaturation via addition of reactants

McGrail *et al.* (2001) suggested that Ca(OH)₂ dissolved out of crushed concrete in demolition waste by rain or irrigation water could be injected into a formation in which CO₂ is then injected, resulting in precipitation of calcite when the groundwater becomes supersaturated with respect to the ions

that form this mineral. To avoid formation damage and poor reservoir utilisation resulting from inopportune calcite precipitation (McGrail *et al.*, 1999; Renard *et al.*, 1998; Saripalli *et al.*, 2000; Steefel and Lichtner, 1998), reactants could be injected at different points in the reservoir (McGrail *et al.*, 2001). Co-contaminant injection (e.g., co-injecting minor SO₂ or O₂ within the CO₂ stream) has been predicted by reactive transport models to increase or accelerate long term CO₂ mineral trapping by carbonate precipitation (CO₂_Capture_Project, 2013; Knauss *et al.*, 2005; Xu *et al.*, 2007). Enhanced dissolution of silicates, and reduction of Fe³⁺ by dissolved SO₂ has been shown experimentally to result in greater availability of divalent cations for long term carbonate precipitation than in the case of pure CO₂ storage (Garcia *et al.*, 2012; Pearce *et al.*, 2013; Wilke *et al.*, 2012).

2.3. Solvents

The presence of 10% (per volume) ethanol, isopropanol, or diethylene glycol can increase the precipitation rates of both calcium carbonate and calcium phosphate by an order of magnitude (Manoli and Dalas, 2000). This is unlikely to be practical generally or environmentally acceptable for *in situ* CO₂ geosequestration but may be useful as a mitigation option for detected leakage and has potential for application to *ex situ* CO₂ geosequestration.

2.4. Magnetic field

The presence of a strong stationary magnetic field greatly enhances nucleation, precipitation rate and yield of calcium carbonate, either by increasing the second ionization constant of carbonic acid by several orders of magnitude (causing enhanced production of carbonate anions) and/or accelerating intermediate phase interactions necessary for ultimate carbonate precipitation (Fathi *et al.*, 2006; Higashitani *et al.*, 1993; Lundager Madsen, 2004; Madsen, 1995). Whilst potentially quite useful and as yet unexplored for application to *ex situ* CO₂ mineral trapping, artificial magnetic field treatment is unlikely to be practical for *in situ* CO₂ geosequestration.

2.5. Microbial activity

Microorganisms have been found living at least five kilometres below the Earth's surface (e.g. Pedersen, 2000). Bacterial hydrolysis of urea can generate a solution oversaturation with respect to calcite, and the bacteria themselves may enhance calcite nucleation (Lippmann, 1973; Lumsden *et al.*, 1989; Mucci and Morse, 1983; Reddy and Wang, 1980; Zhang *et al.*, 1999; Zhang *et al.*, 2001). If such microbes are able to survive at depth then they may be able to play a role in engineered accelerated mineral trapping of CO₂. Below approximately 800 m, CO₂ becomes a supercritical fluid which is an extremely strong organic solvent. Micro-organisms that produce and/or live within a

protective biofilm attached to a geological substrate have been found to be resilient to supercritical CO₂ exposure, whereas free-floating vegetative micro-organisms may not be able to remain viable under such conditions (Lumsden *et al.*, 1989). Even so, significant carbonate cementation is known to be associated with microbial activity within aquifers (e.g., O'Brien *et al.*, 1999).

Carbonate precipitated as part of microbial processes is commonly found associated with seafloor methane seeps, and concurrent microbial sulphate reduction intensifies the carbonate formation (Fujita *et al.*, 2000; Hammes *et al.*, 2003; Romanek *et al.*, 2003; Warren *et al.*, 2001). Bacterial oxidation of hydrocarbons within shallow aquifers liberates CO₂ that can eventually transform into significant carbonate cementation with a light stable isotopic signature, which may have enough acoustic impedance contrast with adjacent uncemented sands to be mapped seismically (O'Brien *et al.*, 1999). Sulphate reducing bacteria mediate and likely facilitate Ca-dolomite precipitation via removal of the sulphate ion (which strongly inhibits dolomite formation) from solution whilst also potentially acting as a nucleation catalyst for this otherwise generally slow precipitation reaction (Boetius *et al.*, 2000; Ferris *et al.*, 1997; Hovland, 1990; Rollet *et al.*, 2006; Stocks-Fischer *et al.*, 1999). Iron reducing bacteria of both the mesolithic and thermophilic kinds can produce siderite as part of their metabolic processes (Deleuze and Brantley, 1997; Montes-Hernandez *et al.*, 2007; Mucci, 1987; Vasconcelos *et al.*, 1995), and greatly enhance the rate of siderite formation relative to the inorganic pathways (Vasconcelos *et al.*, 1995).

Methane-derived authigenic carbonates (MDACs) or, more broadly, hydrocarbon-related diagenetic zones (HRDZs) have been well documented (e.g., Rollet *et al.*, 2006). In a young proto-foreland basin of the Timor Sea, HRDZs occur as lenses along *en echelon* Mio-Pliocene faults that were likely the result of riedel shearing during reactivation of underlying Mesozoic and older extensional faults (O'Brien *et al.*, 1999). Fluid inclusion and apatite fission track data indicate that brines with a salinity of greater than 200,000 ppm and sourced from Palaeozoic evaporate deposits buried up to 10 km deep migrated up re-activated faults (Eadington and Hamilton, 1990; O'Brien and Woods, 1995; O'Brien *et al.*, 1999), and possibly dykes (Rollet *et al.*, 2006). The fluids were still over 100°C when they reached the syntectonic Mio-Pliocene faults and co-migrated with escaping hydrocarbons into shallow aquifers, such as Eocene aged sands, or reached the sea floor (Eadington and Hamilton, 1990; O'Brien and Woods, 1995; O'Brien *et al.*, 1999). Bacterial oxidation of hydrocarbons within shallow aquifers and seafloor sediments may have resulted in authigenic carbonate precipitation (O'Brien *et al.*, 1999), and was possibly coupled with bacterial sulphate reduction (Boetius *et al.*, 2000; Rollet *et al.*, 2006).

2.6. Other issues

Changing the groundwater chemistry of a formation can potentially result in undesirable consequences. Smectite clays may react adversely to changes in groundwater specific ionic activity and total salinity, leading to blocking of pore-throats due to smectite swelling (Almon and Davies, 1981; Morad *et al.*, 2010). Acid stimulation of chlorite-containing sandstones can result in the formation of pore-blocking iron hydroxide precipitation (Almon and Davies, 1981), unless chelating chemicals are added to limit this (Almon and Davies, 1981; Eslinger and Pevear, 1988; Pittman, 1989). It is possible to limit such adverse effects provided that reservoir properties such as mineralogy and groundwater chemistry are well known, and appropriate injection strategies are used (e.g., McGrail *et al.*, 2001).

3. Parameters influencing carbonate diagenesis in sandstones

3.1. Depositional facies

Eogenetic, shallow-marine carbonate cement is often magnesium-rich (Morad, 2009), and has the stable isotope composition of global average ocean carbonate. Sandstones and adjacent channel-lag deposits of Parasequence Boundaries (PB), Transgressive Surfaces (TS), and Maximum Flooding Surfaces (MFS) are conducive for the formation of significant calcite, dolomite, siderite, and/or pyrite cementation (Al-Ramadan *et al.*, 2005; Ketzer *et al.*, 2003; Morad *et al.*, 2010). Poikilotopic calcite cementation is a feature of sediments deposited in forced regressive wedge systems tracts (FRWST). Some of the associations between stratigraphic surfaces/systems tracts and diagenetic carbonate mineralisation are given in Table 2.

Table 2: Depositional facies and potential diagenetic carbonate mineralisation modified after Morad *et al.* (2010).

Stratigraphic Term	Potential Diagenetic Carbonate Mineralisation
Lowstand systems tract (LST)	Calcrete and dolocrete
Transgressive systems tract (TST)	Microcrystalline calcite and dolomite
Highstand systems tract (HST)	Calcrete, dolocrete, siderite
Regressive surface of marine erosion (RSE)	Poikilotopic calcite
Transgressive surface of marine erosion (TSE)	Microcrystalline calcite, dolomitization
Parasequence boundary systems tracts (PB)	Carbonate cementation
Sharp-based shoreface (SBS)	Calcite cementation of shore-lags

Strong carbonate cementation may occur within transgressive system tract (TST) sandstones and is related to organic matter and carbonate bioclasts, which are concentrated due to low apparent clastic sedimentation rates, and heavily wave-reworked and bioturbated due to a long shallow-seafloor residence time (Caja *et al.*, 2010; Kantorowicz *et al.*, 1987; Ketzer *et al.*, 2002; Morad *et al.*, 2010). In this context, fluvial- and wave-dominated delta front sands can have laterally extensive carbonate cementation associated with flooding surfaces, with later shoreface deposits having less pervasive carbonate in the form of concretions around bioclasts deposited within finer grained material (Al-Ramadan *et al.*, 2005; Morad *et al.*, 2010; Walderhaug and Bjørkum, 2009). Turbidite deposits also may have carbonate concretions, especially along sandstone-mudstone contacts, and if thin are more likely to be heavily carbonate cemented (Bruhn and Walker, 1997; Carvalho *et al.*, 1995; Fetter *et al.*, 2009; Mansurbeg *et al.*, 2009; Morad *et al.*, 2010). Extensive calcite cementation also occurs within shallow-marine tempestites containing abundant bioclasts (Walderhaug and Bjørkum, 2009). Generally, any deposit containing abundant bioclastic carbonate is likely to become strongly cemented with carbonates. Moreover, later thermal maturation of organic matter releases

organic acids and CO₂, causing dissolution of carbonates and other unstable minerals, eventually resulting in re-precipitation of carbonates. Shale dewatering also plays a role in diagenesis of interbedded sandstones (Hayes, 1979). Knowing the temperature of authigenesis, e.g., via studies of carbonate fluid inclusions, relative to the temperature at the time of deposition of the cemented lithology can help to address how and when cementation is likely to have occurred.

Meteoric water percolation through sandstones containing carbonate clasts results in first dissolution of carbonate (due to the slightly acidic nature of meteoric water as a result of dissolved CO₂) and later precipitation of carbonate cement (Al-Ramadan *et al.*, 2005). Carbonate accumulations eroded during episodic floods or by channel avulsion may be deposited as clasts together with mud intraclasts in fluvial channel lag sands, which ultimately become tightly cemented by calcite (Morad *et al.*, 2010; Sarkar, 1988; Tandon and Narayan, 1981). Eogenetic, near-pure siderite mineralisation of flood-plain deposits, and low-Mg-calcite cementation of channel sands, tends to occur within meandering fluvial systems in semiarid climates (Dutta and Suttner, 1986; Garcia *et al.*, 1998; Morad, 2009; Morad *et al.*, 2010; Morad *et al.*, 2009; Morad *et al.*, 2000; Mozley, 1989). Sequence boundaries in arid climates may contain either calcrete or dolocrete layers, and microcrystalline dolomite and magnesite may form within interdune deposits via evaporation of pore water already depleted in calcium and sulfate ions due to prior precipitation of anhydrite and gypsum (Amthor and Okkerman, 1998; Morad *et al.*, 2010; Parry *et al.*, 2009; Purvis, 1992).

Notwithstanding the important control of depositional facies and sedimentation rate on carbonate diagenesis in clastic rocks, ankerite, anhydrite, barite, and Mg-siderite cementation is often related to systems in which basinal fluids have been in a state of flux, primarily associated with faults (Morad *et al.*, 2010).

3.2. Detrital mineralogy

CO₂ released via decay of non-carbonate organic matter can form carbonic acid that in turn dissolves carbonate bioclasts, leading to localised supersaturation of pore waters with respect to carbonate minerals, resulting in carbonate cementation. Sandstones containing abundant lithic clasts, especially igneous clasts, as well as detrital organic matter, tend to undergo diagenetic alteration to form chlorite, smectite, opal, microquartz, zeolites, and some degree of carbonate cement (Morad *et al.*, 2010). Biotite may react to form a mixture of carbonates and hydrous clays prior to sediment compaction (Hayes, 1979).

The open file well completion reports of more than sixty hydrocarbon wells in the Great Artesian Basin have been examined for the presence of abundant carbonate cemented sandstone, and

possible factors contributing to the cementation observed (Adamson and Dorsch, 1988; Anon., 1964, 1969, 1970, 1982, 1994, 2001, 2008; Baily, 1996; Battrick *et al.*, 1985; Brown, 1984; Burnett and Darling, 1986; Espiritu and James, 1999; Estensen *et al.*, 1986; Fawcett, 1983; Freeman, 1967; French, 1989; Green, 1963; Hall and Gagen, 1989; Harrison and Higginbotham, 1964; Jacque *et al.*, 1968; Jenkins, 1984; Knauer and Delbaere, 1992; Kyranis, 1963; Laing, 1966, 1967; Lane and Putnam, 1982; Longley *et al.*, 1986; Longley and Batt, 1985a, b; Lowman, 2003; Meyers, 1965; Moore, 1981; Nguyen *et al.*, 1996; Nugent, 1988; O'Neill, 1985; Ostler, 1989; Pinder, 2007; Pyle, 1962, 1965a, b, 1966a, b, c, d; Pyle *et al.*, 1963; Pyle and Dabney, 1963; Robbie and Mitchell, 1996; Rudd and Ties, 1987; Salomon *et al.*, 1990; Short and Harris, 1986a, b; Slijderink, 1998; Surka and Rouse, 1984; Taylor, 1985; Thornton, 1984; Thornton and Elliott, 1982; Ties and Rudd, 1986; Titheridge, 2010; Tolliday and How, 1986; Turk and Pyle, 1962). The locations of some of the wells assessed are plotted in Figure 2.

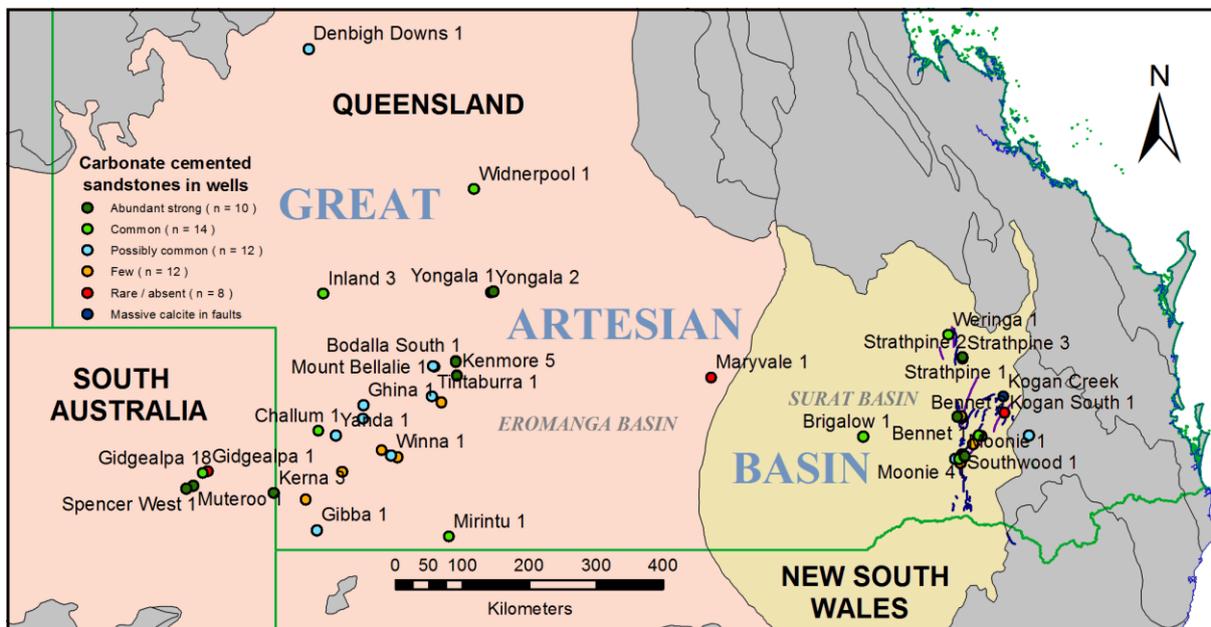


Figure 2. Australian sedimentary basins map excerpt showing locations of selected hydrocarbon wells of the Great Artesian Basin that were examined for the presence of strongly carbonate cemented sandstones. The relative abundance of such sandstones found within the wells is indicated by the colour of the well location points: abundant strongly carbonate cemented = dark green; common = light green; possibly common (well report not sufficient for high confidence determination) = light blue; few = orange; rare / absent = red. Chimney-style massive carbonate and sulfide mineralisation found within faults = dark blue location point.

Broadly, there appear to be three major lithological contexts for massive authigenic carbonate occurrences within the Great Artesian Basin; 1) obviously marine-influenced glauconitic sandstones proximal to limestone/dolomite and often also containing oolitic limestone and shell fragments, 2) lithic, feldspathic, micaceous, and argillaceous sandstones with potentially reactive mineralogies and not obviously marine-influenced, and 3) significantly calcite-cemented quartzose sandstones not proximal to limestone/dolomite and shell fragments (this is the least prevalent of the three

contexts). Silica cement occurs together with abundant calcite in some wells, but not others for given rock units, just as a unit may be calcite cemented in one well but not in an adjacent well. Horizons in which massive carbonate cementation occurs, as well as the presence of other factors such as other carbonate cements, silica cement, clay cement, sea shells, limestone, oil, and coal have been informally compared and contrasted both laterally and vertically for all of the wells examined, in an ongoing effort to understand the context of the mineralisation and which locations/horizons are the best to sample for additional laboratory analyses.

3.3. Groundwater chemistry

3.3.1. Brine composition

Changes in the chemical composition of formation waters due to sea-level fluctuations have a strong influence upon eogenetic diagenesis (Morad *et al.*, 2000). Carbonate precipitation rates tend to be proportional to the square of apparent solution supersaturation with respect to a given carbonate mineral (Wajon *et al.*, 1985). If two carbonate-bearing groundwaters that are individually saturated with respect to carbonate minerals are mixed, the resultant fluid may either be supersaturated or strongly undersaturated depending upon the original partial pressures of CO₂, the temperatures, and the chemical compositions of the individual waters (Chong and Sheikholeslami, 2001; Dawe and Zhang, 1997; Domingo *et al.*, 2006; Wigley and Plummer, 1976; Zuddas and Mucci, 1998). This is discussed further in a subsequent section.

For NaCl concentrations from 0 up to 2 molar calcite solubility increases, but then decreases with further increases of NaCl concentration (Duan and Li, 2008), at which point calcite precipitation rate can increase by two orders of magnitude in response to the ionic strength of solution being increased by just 50% (Zuddas and Mucci, 1998). This is likely due to the solubility enhancement effect of chloride complexation being dominant at lower concentrations of NaCl, and the reduced solubility of CO₂ having a greater effect upon calcite solubility at higher solution molarities (Dawson, 2012).

Both magnesium (Mitchell *et al.*, 2010) and sulphate ions in solution can greatly inhibit the precipitation rate of calcite at a given ionic strength (Mucci, 1988). In fact, the presence of aqueous sulphate can increase the solubility product of calcite by at least an order of magnitude (Dromgoole and Walter, 1990), and also inhibits magnesium incorporation into calcite (Mackenzie *et al.*, 2006). Similarly, aqueous strontium can marginally slow the precipitation rate of calcite (Lumsden *et al.*, 1989). Manganese negatively affects strontium but positively influences sodium incorporation in calcite (Jimenez-Lopez and Romanek, 2004), and manganese incorporation into calcite is affected by

magnesium concentration (Zuddas *et al.*, 2003). Manganese can reduce the precipitation rate of dolomite (Duan and Li, 2008; Dupraz *et al.*, 2009). Aqueous iron, if three orders of magnitude more saturated than calcium, significantly decreases calcite formation kinetics (Van Lith *et al.*, 2003; Vasconcelos *et al.*, 1995; Wright, 1999; Zuddas *et al.*, 2003). Otherwise, the precipitation rate of siderite is generally eight orders of magnitude slower than for calcite (Vasconcelos *et al.*, 1995). Humic acid inhibits calcite precipitation via interference with active crystal growth (Wright and Wacey, 2005).

3.3.2. Cation surface charge density

Carbonate precipitation rates tend to be inversely proportional to cation surface charge density (Deleuze and Brantley, 1997; Druckenmiller and Maroto-Valer, 2005; Druckenmiller *et al.*, 2005; Liu and Maroto-Valer, 2011b; Manoli and Dalas, 2000; Mucci, 1987; Mucci and Morse, 1983; Reddy and Wang, 1980; Soong *et al.*, 2004; Vasconcelos *et al.*, 1995). The distribution of charge over the surface of a small diameter cation such as Fe^{2+} is of a higher density than for a larger diameter cation such as Ca^{2+} . Because of this, greater energy is required to dehydrate small cations than large cations upon the surface of a nucleating crystal such as a carbonate mineral (Jimenez-Lopez and Romanek, 2004; Lippmann, 1973). This is likely why there is a much greater activation energy required for inorganic siderite precipitation than calcite precipitation (Jimenez-Lopez and Romanek, 2004; Vasconcelos *et al.*, 1995).

4. Mixing of carbonate waters

The concentration of Ca and Na in formation waters is controlled largely by equilibration with minerals, particularly calcite and calcic plagioclase although high cation concentrations in brines may exceed the buffering capacity of the sediments (Houston *et al.*, 2011). Three different trends in the relative concentrations of Ca and Na in formation waters have been identified that reflect fluid-rock interaction processes and the original chemistry of the system.

- 1) Low salinity formation waters are similar to shallow groundwater and dominated by dissolved calcium bicarbonate with the Ca/Mg ratio largely determined by the equilibrium carbonate in the system (Houston *et al.*, 2011).
- 2) The most common trend for more saline formation waters is one where the relative molar fraction of Ca increases with salinity such that Ca becomes the dominant cation at high salinity (high-Ca trend). This trend is interpreted to reflect buffering of NaCl brines through equilibration with Ca and Na minerals (Hanor and McIntosh, 2007; Houston *et al.*, 2011).
- 3) In contrast, a subset of higher salinity brines show little or no increase in the relative molar fraction of Ca with salinity (low-Ca trend) that likely results from dissolution of halite. In the latter case, the relative molar fraction of Na and Ca in the formation water reflects their concentrations in the host rock and the extent of halite dissolution rather than mineral buffering (Houston *et al.*, 2011).

Carbonate mineral buffering is important for two of the three trends in formation water chemistry discussed above such that the majority of formation waters and more evolved shallow groundwaters are near saturation with respect to calcite. The mixing of such carbonate waters may lead to supersaturated or undersaturated conditions for particular carbonate phases depending on the nature of the original fluids and whether the system is open or closed with respect to CO₂ gas (cf. Wigley and Plummer, 1976). Total carbonate is conserved under closed system conditions, whereas exchange of CO₂ between the fluid and gas phases occurs under open system conditions. The situation is more complex where the system is open to CO₂ but can often be approximated in the mixing zone by closed system conditions because the exchange of gaseous CO₂ with water is a slow process (Wigley and Plummer, 1976).

4.1. The algebraic effect

Mixing of two fluids saturated with calcite but with different Ca concentrations under closed system conditions typically produces a fluid that is supersaturated with calcite because of the algebraic effect first described by Wigley and Plummer (1976). This occurs because fluids equilibrated with

calcite that have different Ca concentrations also have different carbonate activities (Corbella *et al.*, 2003). The extent of supersaturation increases with difference in the cation chemistry and reaches a maximum when equal proportions of the two fluids mix (Corbella *et al.*, 2003; Wigley and Plummer, 1976).

4.2. Salinity and ionic strength effects

Mixing of two fluids saturated with calcite and chemically similar except for their differing salinities results in a fluid that is undersaturated in calcite and may lead to dissolution of carbonates in carbonate rocks and bioclasts and authigenic carbonates in siliclastic reservoirs (Corbella *et al.*, 2003). This occurs because calcium activity is lower in solutions of intermediate salinity than in solutions with a very high or low salinity. Significant undersaturation also results when calcite saturated solutions of very different ionic strength are mixed (Wigley and Plummer, 1976).

4.3. pH and ρCO_2

Fluid pH is the most significant governor of carbonate precipitation (Liu and Maroto-Valer, 2011a). In natural systems pH is strongly affected by ρCO_2 , and the combination of high pH and alkalinity favour carbonate precipitation. Mixing of fluids with similar Ca concentration but different pH and ρCO_2 produces non linear trends in pH because of the low buffering capacity of the system when the ρCO_2 is low (Corbella and Ayora, 2003; Corbella *et al.*, 2003). Depending on the composition of the end members, this may result in a solution with acidic to neutral pH that is undersaturated with respect to calcite. Calcite saturation tracks the CO_3^{2-} concentration that also varies in a non linear way because the speciation of carbon is pH dependent. Because the majority of rock-brine systems exhibit some carbonate buffering, it is important to accurately determine the *in situ* aqueous geochemistry to allow accurate modelling and prediction of mineral dissolution and precipitation in response to mixing of carbonate waters in the natural environment or injection of CO_2 into siliclastic or carbonate reservoirs (cf. Newell *et al.*, 2008).

Carbonate precipitation requires alkaline pH conditions, whereas groundwater proximal to a plume of CO_2 will be moderately acidic. The supercritical CO_2 dominated phase itself will almost always contain some dissolved water, which as a consequence of exposure to very high ρCO_2 would be highly acidic. This would react with any labile mineralogies encountered, producing abundant ions within the small amounts of water dissolved within CO_2 which would consequently cause carbonate precipitation, and this could potential help to “self-seal” formations like mudstone caps. There will almost always be a transition zone between CO_2 -only and water-only zones, and it is this aqueous transition that we are most concerned with as that is where majority of chemistry will occur. CO_2 on

its own does not appreciably react/interact chemically with other species underground, except for any organic compounds present.

Natural systems with quantities of CO₂ sufficient to affect groundwater pH on a similar scale to CO₂ geosequestration may include natural gas plays, coal measures, mantle degassing, igneous intrusions and related geothermal activity. For all of these, proximal groundwater with high pCO₂ will be acidic and leach ions from minerals, whereas distal groundwater containing lower pCO₂ and sufficient concentrations of dissolved cations will precipitate carbonate minerals. Sulfur is also present as a significant component of such systems; however, for natural gas and coal measures not exposed to oxygen, the dominant volatile sulfur species is H₂S, whereas for igneous activity related systems sulfur is predominantly present as SO₂.

After water vapour and CO₂, SO₂ is the most abundant volatile component of all igneous-related fluids, and it dissolves completely within water. This is important, as unlike H₂S, sulphurous acid is formed by SO₂ dissolved under anaerobic conditions, and this causes pH to be significantly more acidic than when CO₂ alone is present. Greater quantities of ions will have been dissolved and therefore later become available for mineral trapping within a system containing both SO₂ and CO₂ than just CO₂ alone. As igneous-related fluids have had widespread influence throughout Australia's geological history, many natural carbonate mineralisation occurrences could be related to periods of enhanced geothermal activity. Methods to test the origins of the carbonate and related mineralisation present within a geological formation include stable isotopes analysis, REE-analysis, and mineral assemblage recognition, such as the presence of vein quartz and sulfides, barium carbonate, barite, anhydrite, and multiple carbonate species (with calcite being most abundant) all occurring together often within specific zones of igneous/geothermal-related mineralisation (cf. Dawson et al., 2012). High temperatures are not required for such mineralisation to occur, and igneous-influenced groundwaters are known to have migrated laterally far from the source of the volatiles within them. Fluid inclusion analysis can help to determine both the temperature of the mineralising fluid and its composition.

Natural analogues for mixed CO₂-SO₂ effects upon geological systems are important, as co-contaminant gases including SO₂, NO_x, and O₂ are present in gas streams from oil or coal burning and oxy fuel power plants planned for commercial CCS utilization (Pearce *et al.*, in prep). Eliminating the SO₂ scrubbers in a CCS retrofit has been suggested to result in a 13% reduction in capital costs and 8% reduction in annual operating expenses (based on an amine capture system)(Glezakou *et al.*, 2012). Co-contaminant injection (e.g., minor SO₂ within CO₂) could aid eventual enhanced carbonate precipitation; initial dissolution of silicates and reduction of transition metals by aqueous SO₂ would

result in more divalent cations available for carbonate precipitation than were originally present within formation waters. An experiment involving carbonate cemented sandstone exposed to just 0.16% SO₂ mixed with CO₂ experienced a pH increase from < 2 up to > 6 and significant mineral precipitation within less than two weeks (Pearce *et al.*, in prep.), whereas obvious visible mineral precipitation was not observed for a concurrent experiment with a sister sample exposed to only CO₂ and water (Farquhar *et al.*, in prep). Whether or not co-contaminant injection is an option for Australia that would be both commercially and environmentally acceptable is beyond the scope of this scientific study, but we note that geosequestration of other acid gases such as H₂S has been successful in Canada since 1989 (Bachu and Gunter, 2004), and naturally occurring sulfur species are often found in the subsurface.

4.4. Temperature and pressure effects

Solution temperature strongly affects both ion solubility and precipitation rates and has a greater effect on final pH than pressure (Liu and Maroto-Valer, 2011b). Calcite solubility is inversely proportional to temperature and directly proportional to pressure (Roberts *et al.*, 2004). Increasing temperature increases the incorporation of iron, manganese (Zuddas *et al.*, 2003), and strontium (Lumsden *et al.*, 1989) in calcite. Mixing of fluids saturated with calcite but with different temperatures may result in a solution that is undersaturated or oversaturated with respect to calcite depending on the chemistry of the end members (Corbella *et al.*, 2003; Wigley and Plummer, 1976). The temperature effect is relatively minor except where there is a significant temperature difference between the fluids such as occurs when a hot geothermal fluid mixes with shallow groundwater or seawater, or a deeper basinal fluid is able to migrate relatively quickly to a shallower unit, for example, up a fault from the Cooper Basin into the Eromanga Basin.

4.5. The general case

For the more general case of mixing between fluids with different physico-chemical characteristics, a combination of the effects described above may result in either undersaturation or supersaturation with respect to calcite and other carbonates (Corbella *et al.*, 2003; Wigley and Plummer, 1976). The system may also evolve with time and the degree of mixing such that undersaturation prevails in more acidic and saline parts of the system and supersaturation in the more basic and dilute region of the system. By way of example, Figure 3 shows the minerals that form and those that dissolve when a more and less saline fluid mix in varying proportions in a sandstone formation that contains quartz, potassium feldspar, muscovite (illite) and dolomite (ankerite). Dolomite precipitates as the fluids mix and muscovite and quartz form at the expense of potassium feldspars.

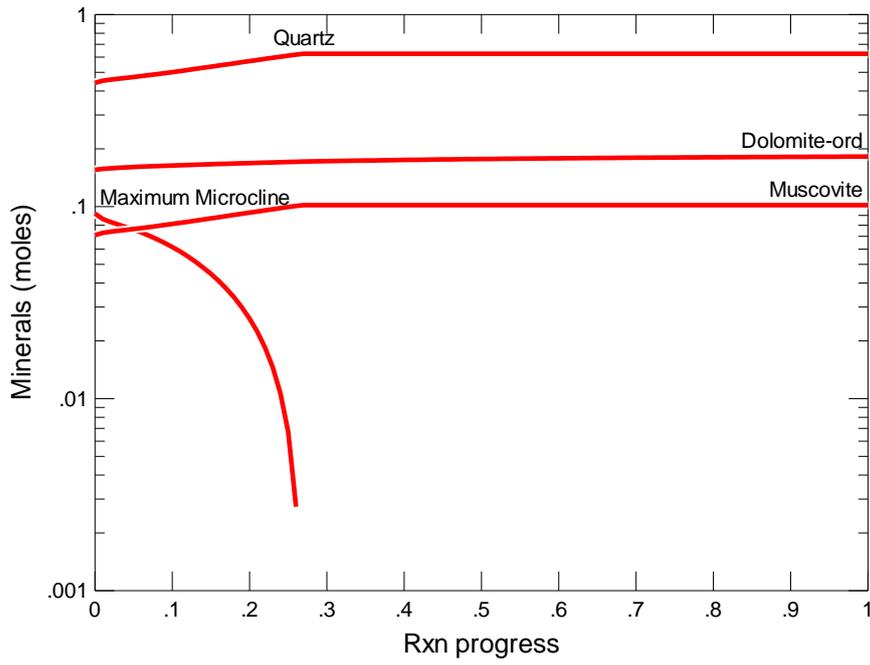


Figure 3. Mineralogical effect of mixing a more and less saline fluid at 50°C in the presence of quartz, potassium feldspar, muscovite (illite) and dolomite. Reaction modelling undertaken with the Geochemist's Workbench Release 8.0.

5. Methods for reconstruction of basin thermal and fluid flow history

5.1. Burial history modelling

Dynamic fluid flow is a critical component of fluid-rock interaction as it provided a means to bring the two together as well as replenishing reactants in the mineralisation process. The timing of petroleum (gas and oil) generation, expulsion and migration provided by burial history modelling enables better constraints on the compositions, displacement and entrapment of fluids (petroleum and CO₂). Furthermore, compositional analyses on natural gases and dissolved gaseous hydrocarbons in formation waters can be used to identify genetic relationships between the encapsulated fluid inclusion gases and free gases. The latter also provide a calibration point in petroleum system modelling.

Previous thermal modelling by Deighton and Hill (1998) and Deighton (2003) indicated that generation and expulsion of hydrocarbons from Cooper and Eromanga source rocks in the Patchawarra Trough occurred primarily during the Mid Cretaceous. Vertical migration of oil from Permian (Cooper Basin) terrestrial source rocks has been widely accepted as the principal source of most Eromanga reservoir oil. However, organic geochemistry studies have established the possibility that source rocks within both the Eromanga and underlying Cooper Basin sequences have contributed, to varying degrees, to oil accumulations in Eromanga Basin reservoirs (Summons *et al.*, 2002 and references therein). On the other hand, the origin of the reservoir oils in the Bowen and overlying Surat basins is almost exclusively from Bowen Basin Permian source rocks, which continued generating and expelling petroleum over a wide age range (Al Arouri *et al.*, 1998; Boreham *et al.*, 1996). Natural gases from both regions are sourced from Permian coals and carbonaceous shales (Boreham, 1995; Boreham, 2001).

Here we present the results of 1D-burial history modelling for one well each in Cooper-Eromanga and Bowen-Surat using the regional models of Deighton and Hill (1998) and Boreham *et al.* (1996), respectively. The Gidegalpa-16 (Cooper-Eromanga) and Wandoan-1 (Bowen-Surat) wells were selected to complement the initial core sampling in each of these fields. At Gidegalpa-16 the Permian source rocks entered the oil window during the mid-Cretaceous (Figure 4) with the majority of the gas and oil being generated and expelled over a ~15Ma year window up to around 85 Ma (Figure 5). Such a narrow timeframe places strict constraints on total fluid movement in response to petroleum generation in the vicinity of this well. However, the Eromanga reservoir oils in the Gidegalpa Field have been thought to be sourced from the Birkhead Formation (Boult *et al.*, 1998), although the extent of Eromanga source contribution remains controversial (Rob Heath, private

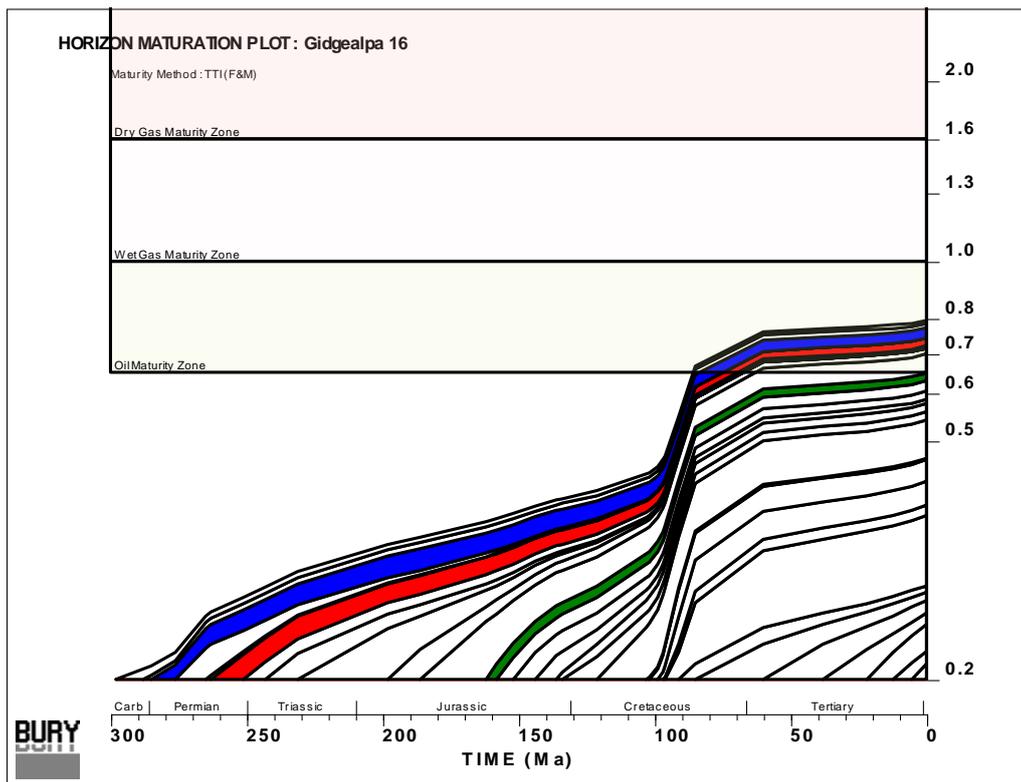


Figure 4. Modelled maturity (vitrinite reflectance – VR) versus time (Ma) for Gidgealpa-16. The potential source rocks are shown for the Permian Patchawarra (blue) and Toolachee (red) formations and the Jurassic Birkhead Formation (green).

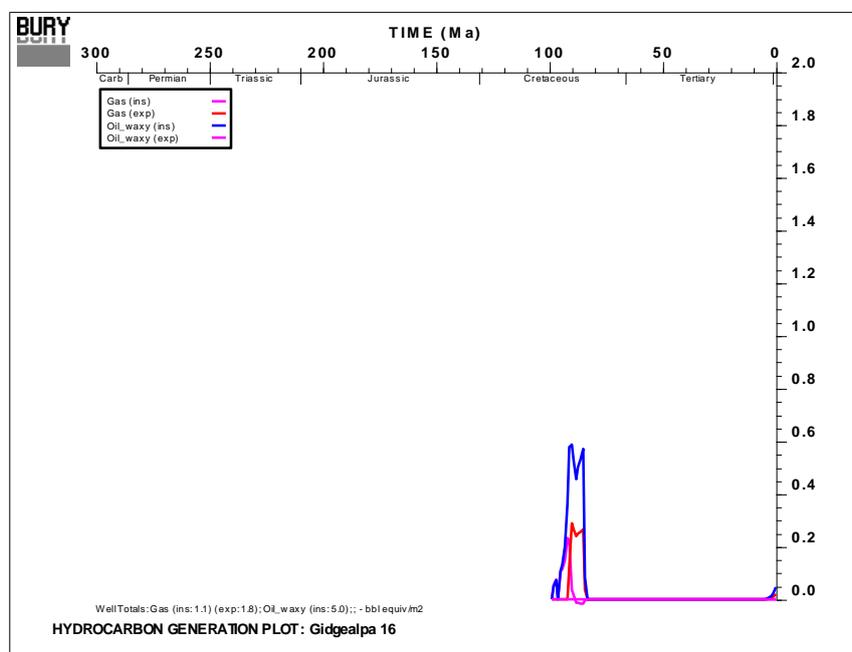


Figure 5. Rate of petroleum (gas and oil) generation that remains within (in-situ – Ins) and migrated (expelled –Exp) from the source rock in the Gidgealpa-16 well.

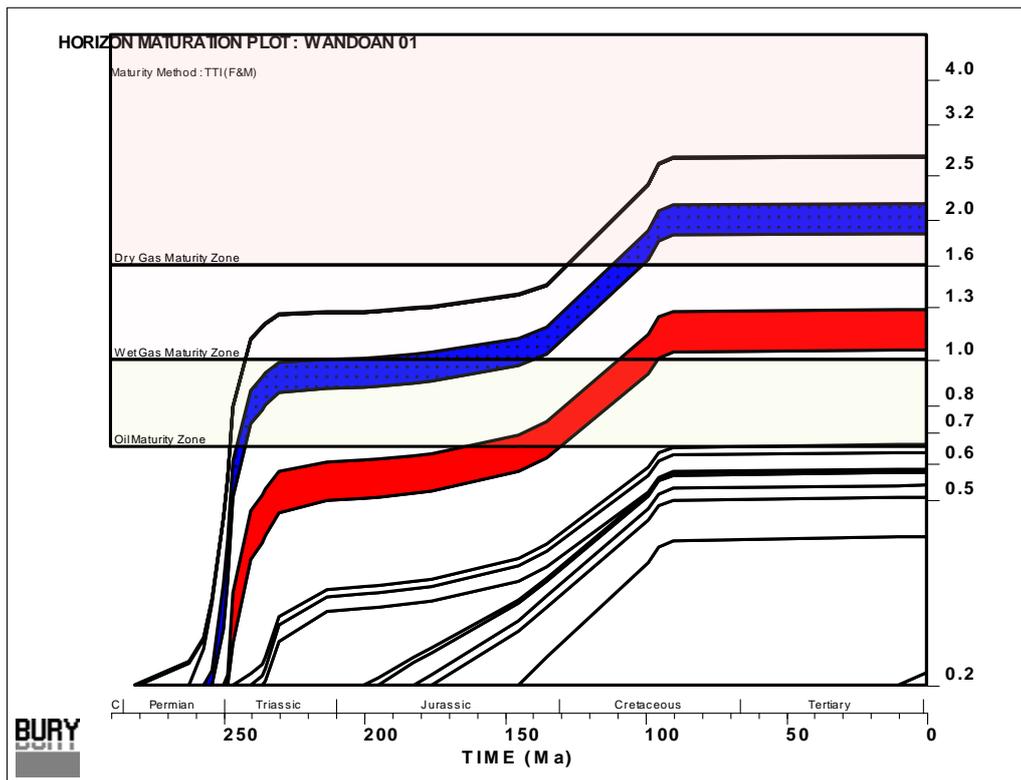


Figure 6. Modelled maturity (vitrinite reflectance – VR) versus time (Ma) for Wandoan-1. The potential source rocks are shown for the Permian Baralaba Coal Measures (reds) and Burunga Formation (Scotia Coal Member; blue).

communication, March 2013). As the Birkhead Formation is of low maturity around Gidgealpa-16 (Figure 4), this may imply migrating oil has either come from afar or else deeper units.

Using the preferred burial history model presented here, the Wandoan-1 well has experienced a more complex petroleum generation history from the Permian source rocks, primarily due to much deeper burial compared to similarly aged source rocks at Gidgealpa 16. Presently, the Permian source rocks are overmature for oil generation (Figure 6). A minor phase of petroleum generation and expulsion occurred during the latest Permian-earliest Triassic times with the main phase occurring between the Early Jurassic to Mid Cretaceous (Figure 7; Al Arouri *et al.*, 1998). This ~40 Ma generation/expulsion window at Wandoan-1 represents a much wider period of total fluid movement compared to that at Gidgealpa-16, potentially enabling longer residence times for fluid-rock interactions. Oil generation from the Late Permian Baralaba Coal Measures (Figure 6) is synchronous with dry gas generation from older Permian source rocks (e.g., Scotia Coal Member; Figure 6), enabling gas mobilisation of liquids and potentially extending the range and influence of migrating fluids (Boreham *et al.*, 1996).

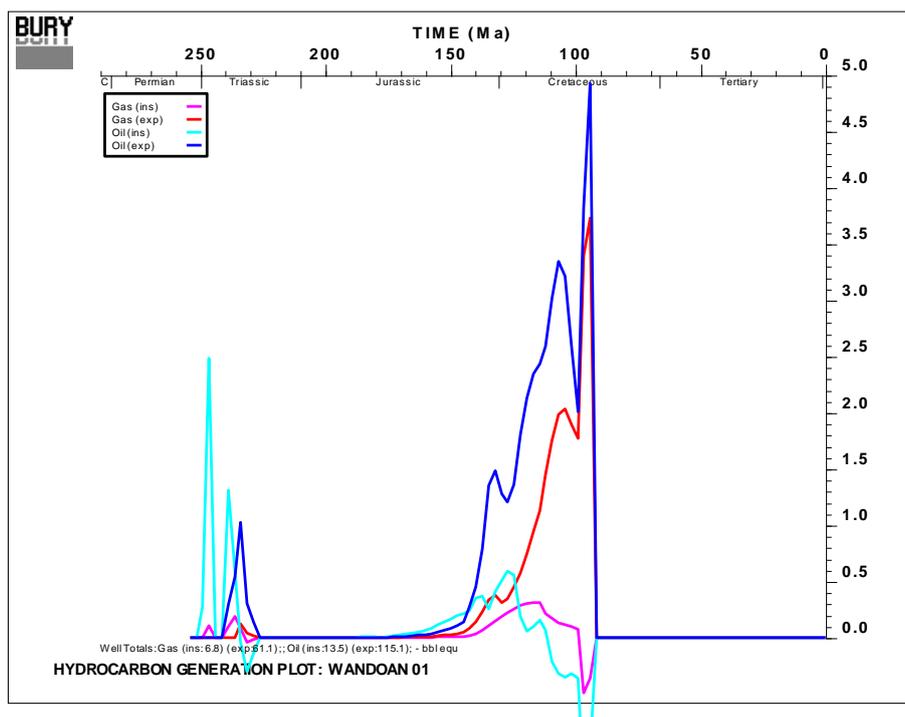


Figure 7. Rate of petroleum (gas and oil) generation that remains within (in-situ – Ins) and migrated (expelled – Exp) from the source rock in Wandoan-1 well.

5.2. Fluid inclusions and calcite cements

Little is currently known about the genesis of calcite-cemented zones that occur in the Eromanga and Surat basins. Conflicting ideas have been put forward by different workers. (Gravestock *et al.*, 1983) considered calcite-rich sequences in the Hutton Sandstone to be early diagenetic calcrete horizons (“duricrusts”) formed between intermittent episodes of sandy fluvial sedimentation. However, on the basis of oxygen isotope data, Wall (1987) suggested that the carbonate cements precipitated at elevated temperatures of 55–121 °C. The carbon isotope composition of the carbonates was similar to that of Cooper Basin carbon dioxide (Rigby and Smith, 1981; Vincent *et al.*, 1985) and was not similar to the expected carbon isotope composition of CO₂ derived from microbial oxidation of hydrocarbons (Schulz-Rojahn, 1993). Only small amounts of CO₂ (Armstrong and Barr, 1986; Vincent *et al.*, 1985) and lighter hydrocarbons remain within oil-dominated Eromanga Basin reservoir units, with the majority of the gases presumably having been lost during geological time (Heath *et al.*, 1989). This makes it difficult to test a new hypothesis that the CO₂ was enriched in heavier isotopes relative to an originally microbial hydrocarbon oxidation derived CO₂ source, via microbial reduction of the CO₂ to form methane gas that has since been lost, thus producing residual CO₂ that precipitated as calcite with a much less negative carbon isotope composition than the associated hydrocarbons. The process of microbial reduction of CO₂ to form methane was not considered by Schulz-Rojahn (1993). Even so, if CO₂ comigrated with hydrocarbons from the Cooper

Basin up faults into the Eromanga Basin, and carbonic acid formed by CO₂ dissolution was buffered by the anions of organic acids formed during initial kerogen thermal maturation (Kharaka *et al.*, 1986; Surdam *et al.*, 1984; Surdam *et al.*, 1989), and/or reaction of aluminosilicates with carbonic acid to form dissolved silica, significant carbonate mineralisation could have resulted from migrating CO₂ dissipation through Eromanga Basin units (Schulz-Rojahn, 1993).

One important distinction between the two petroleum provinces is the much stronger impact that microbial alteration (biodegradation) has had on petroleum in the Bowen-Surat basins (Boreham, 1995), wherein aqueous fluid flow, supplying nutrients and potentially allochthonous microbial communities, has played a major role at least since post hydrocarbon emplacement times. Biodegradation provides more local source of CO₂, together with CO₂ from an organic source associated with petroleum generation and deeper inorganic sources (Boreham *et al.*, 2001). Stienstra (1992) has suggested that the early carbonates of the Eromanga Basin precipitated from mineralised groundwater and a later phase of carbonate precipitation was controlled by CO₂ produced from the reduction of acetic acids generated from the same kerogens that sourced oil found in the Jurassic section.

Toupin *et al.* (1997) reported fluid inclusion salinity and temperature data for the Cooper and Eromanga basins. Homogenisation temperatures of aqueous inclusions in diagenetic quartz overgrowths from the Cooper Basin ranged between 92° and 158°C. Toupin *et al.* (1997) also reported present day salinities of around 3,300 ppm in the Hutton Sandstone, which is consistently lower than paleosalinity data from fluid inclusions.

Scorer (1966) gave a preliminary discussion of the hydrodynamics of the Surat Basin based on pressure and fluid data from various wells drilled in the basin. He reported that the Mesozoic waters of the Surat Basin are generally fresh to salty, with a total dissolved solids content ranging from as low as 340 to a maximum of about 7,000 ppm. The predominance of bicarbonate over chloride in almost every analysis was thought to indicate that most of the water was in fact meteoric but could also reflect contamination with drilling fluids.

Raza *et al.* (2009) carried out an apatite fission-track analysis of samples from the Bowen and Surat basins. Results from the Rockwood-1 well indicate that the Precipice Sandstone experienced paleotemperatures > 80 °C. Samples from the Cabawin-1, Wandoan-1, Flinton-1 and Macintyre 1 wells indicate that the Hutton Sandstone experienced paleotemperatures ≥ 110 °C and the Injune Creek Group had paleotemperatures ≥ 70 °C. The thermal history modelling of the apatite fission-track parameters (Raza *et al.*, 2009) suggests that cooling from T_{peak} occurred sometime during the

interval 100–80 Ma. The magnitude of cooling was in the order of 25–60 °C, being the greatest in the northern part of the trough and relatively less in the southern part of the trough. This agrees well with the burial history graphs which indicate a gradual increase in temperature up until the mid Cretaceous and a corresponding expulsion of oil around the time of T_{peak} (see Figures 3-7). There is little change in vitrinite reflectance after this T_{peak} time in the Precipice and Hutton Sandstones (see Figure 6, Raza *et al.*, 2009), which indicates the onset of cooling.

The proposed fluid inclusion studies will provide better constraints on the paleotemperatures estimated from other indirect methods and at the same time measure the salinity of the fluids associated with carbonate precipitation. The origin of carbonates can be inferred indirectly from the carbon isotopic composition of CO₂ trapped within the fluid inclusions and directly from the carbon isotope composition of the authigenic carbonates. Combined with petrographic and experimental studies this will enable us to determine the changes in fluid composition and porosity evolution of the selected basins over time.

6. Conclusion

Depositional facies has a strong control over the presence, distribution, and abundance of biogenic and evaporation derived carbonate minerals, and associated eogenetic cementation. Detrital mineralogy, aside from influencing reservoir quality, can determine the degree of mesogenetic carbonate mineralisation likely to occur, for example volcanolithics and mafic igneous mineral grains are far more likely than quartzose sandstone to react with migrating CO₂-rich fluids to form carbonate mineralisation. In certain cases, minor natural SO₂ together with CO₂ associated with geothermal or igneous activity has likely leached significant quantities of ions from host rocks resulting in relatively rapid pH neutralisation and massive carbonate and other mineral precipitation. Burial history and fluid migration modelling, using measured parameters including those from studies of fluid inclusions, carbonate stable isotope chemistry, cathodoluminescence, vitrinite reflectance, and apatite fission tract analysis can help determine the conditions under which past carbonate mineralisation occurred within basins.

For accelerated precipitation of carbonate minerals, factors that can be artificially modified include pH, type of buffers, pCO₂, concentration and species of dissolved ions, micro-organisms (e.g., sulfate reduction to promote carbonate precipitation), solvents, temperature, and an applied magnetic field. Of these, the most easily manipulated would likely be pH via addition of minor SO₂, buffers and modification of pCO₂, followed by injection of a solution with cations capable of reacting with CO₂, and targeted injection of an organic solvent to potentially help plug a leak. Other potential methods require much further thought as to how they could be applied most effectively.

Carbonate mineral yields are greater under supercritical CO₂ conditions than for subcritical CO₂, provided that the solution is buffered to a pH more alkaline than 9; otherwise, water exposed to supercritical CO₂ is too acidic for carbonate minerals to be stable. Calcite precipitates faster than other carbonate minerals such as dolomite and siderite, due to the lesser amount of energy required to dehydrate the relatively large calcium cations compared with smaller magnesium and iron cations, enabling them to combine with carbonate anions. The mixing of solutions with different chemical compositions can produce undersaturated or supersaturated conditions for a particular mineral depending on the original compositions and temperatures even where the original groundwaters were saturated with the mineral in question. Mixing of waters saturated with calcite but with very different chemistries is most likely to lead to supersaturated conditions and calcite precipitation under closed system conditions. On the other hand, mixing of saturated waters with different partial pressures of CO₂ or temperatures will produce undersaturated mixtures able to dissolve calcite under closed system conditions.

References

- Adamson, M., Dorsch, C., 1988. A-P 244P, SOC Deep Crossing 1, Final Well Report (#19919). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Al-Ramadan, K., Morad, S., Proust, J.N., Al-Aasm, I., 2005. Distribution of diagenetic alterations in siliciclastic shoreface deposits within a sequence stratigraphic framework: Evidence from the Upper Jurassic, Boulonnais, NW France. *Journal of Sedimentary Research* 75, 943-959.
- Al Arouri, K., Boreham, C.J., McKirdy, D.M., Lemon, N.M., 1998. Modeling of thermal maturation and hydrocarbon generation in two petroleum systems of the Taroom Trough, Australia. *AAPG Bulletin* 82, 1504-1527.
- Almon, W.R., Davies, D.K., 1981. Formation damage and the crystal chemistry of clays. *Clays and the Resource Geologist*. Mineralogical Association of Canada, Short Course Handbook 7, 81-103.
- Anthor, J.E., Okkerman, J., 1998. Influence of early diagenesis on reservoir quality of Rotliegende sandstones, northern Netherlands. *AAPG Bulletin* 82, 2246-2265.
- Anderson, A., 1985. A geoseismic investigation of carbonate cementation of the Namur Sandstone of the Gidgelpa Field, Eromanga Basin, B.Sc. (Hons.) Thesis. University of Adelaide, Australia, p. 47 (unpublished).
- Anon., 1964. Preliminary Final Report Union - Kern - AOG Brigalow Creek 1, A-P 57P, QLD (#1248). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Anon., 1969. A-P 145P, QLD, Union - Tenneco - AOG Dilbong 1, Well Completion Report (#2909). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Anon., 1970. A-P 145P, UOD Bennett 4, Well Completion Report (#3126). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Anon., 1982. IOL Moonie 37, Well Completion Report (#10806). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Anon., 1994. EPP 522, IOD Moonie Corner 1, Well Completion Report (#27720). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Anon., 2001. A-P 676P, QGC Wyalla 1, Well Completion Report (#32867). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.

- Anon., 2008. A-P 269P, BPL Warragon 1, Well Completion Report (#50586). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Armstrong, J., Barr, T., 1986. The Eromanga Basin. An overview of exploration and potential. Contributions to the geology and hydrocarbon potential of the Eromanga Basin, Geological Society of Australia Special Publication No. 12, 25-28.
- Bachu, S., Gunter, W.D., 2004. Acid-gas injection in the Alberta basin, Canada: a CO₂-storage experience. Geological Society, London, Special Publications 233, 225-234.
- Baily, T.A., 1996. A-P 548P, IOR Inland 3, Well Completion Report (#28852). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Baker, J.C., Bai, G.P., Hamilton, P.J., Golding, S.D., Keene, J.B., 1995. Continental-scale magmatic carbon dioxide seepage recorded by dawsonite in the Bowen-Gunnedah-Sydney Basin system, eastern Australia. *Journal of Sedimentary Research* 65, 522-530.
- Battrick, M.A., Ulmer, B., Slater, D.J., 1985. A-P 269P, HOA Bodalla South 1, Well Completion Report (#13872). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Boetius, A., Ravenschlag, K., Schubert, C.J., Rickert, D., Widdel, F., Gieseke, A., Amann, R., Jorgensen, B.B., Witte, U., Pfannkuche, O., 2000. A marine microbial consortium apparently mediating anaerobic oxidation of methane. *Nature* 407, 623-626.
- Boreham, C., Hope, J., Hartung-Kagi, B., 2001. Understanding source, distribution and preservation of Australian natural gas: A geochemical perspective. *APPEA Journal* 41, 523-547.
- Boreham, C.J., 1995. Origin of petroleum in the Bowen and Surat Basins: Geochemistry revisited. *APPEA Journal* 35, 534-567.
- Boreham, C.J., Korsch, J., Carmichael, D.C., 1996. The significance of mid-Cretaceous burial and uplift on the maturation and petroleum generation in the Bowen and Surat basins, eastern Australia, Mesozoic Geology of Eastern Australia Plate Conference. Geological Society of Australia Inc. Extended Abstracts, pp. 104-113.
- Boreham, C.J.H., J. M.; Hartung-Kagi, B., 2001. Understanding source, distribution and preservation of Australian natural gas: A geochemical perspective. *APPEA Journal* 41, 523-547.
- Boult, P.J., Lanzilli, E., Michaelsen, B.H., McKirdy, D.M., Ryan, M.J., 1998. A new model for the Hutton/Birkhead reservoir/seal couplet and the associated Birkhead-Hutton petroleum system. *APPEA Journal* 38, 724-744.

- Boult, P.J., Ryan, M.J., Michaelsen, B.H., McKirdy, D.M., Tingate, P.R., Lanzilli, E., Kagya, M.L., 1997. The Birkhead-Hutton Petroleum System of the Gidgealpa Area, Eromanga Basin, Australia.
- Brown, N.C., 1984. Kerna 3 Well Completion Report (# 5573). PEPS - SA, Energy Resources Division, Department for Manufacturing, Innovation, Trade, Resources and Energy (DMITRE), State Government of South Australia, Adelaide, Australia.
- Bruhn, C.H.L., Walker, R.G., 1997. Internal architecture and sedimentary evolution of coarse-grained, turbidite channel-levee complexes, Early Eocene Regência Canyon, Espírito Santo Basin, Brazil. *Sedimentology* 44, 17-46.
- Burnett, P.J., Darling, R.A., 1986. A-P 267P, Eromanga Basin, PPL Winna 1, Well Completion Report (#15916). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Caja, M.A., Marfil, R., Garcia, D., Remacha, E., Morad, S., Mansurbeg, H., Amorosi, A., Martínez-Calvo, C., Lahoz-Beltrá, R., 2010. Provenance of siliciclastic and hybrid turbiditic arenites of the Eocene Hecho Group, Spanish Pyrenees: Implications for the tectonic evolution of a foreland basin. *Basin Research* 22, 157-180.
- Carvalho, M.V.F., De Ros, L.F., Gomes, N.S., 1995. Carbonate cementation patterns and diagenetic reservoir facies in the Campos Basin cretaceous turbidites, offshore eastern Brazil. *Marine and Petroleum Geology* 12, 741-758.
- Chong, T.H., Sheikholeslami, R., 2001. Thermodynamics and kinetics for mixed calcium carbonate and calcium sulfate precipitation. *Chemical Engineering Science* 56, 5391-5400.
- Class, H., Ebigbo, A., Helmig, R., Dahle, H., Nordbotten, J., Celia, M., Audigane, P., Darcis, M., Ennis-King, J., Fan, Y., Flemisch, B., Gasda, S., Jin, M., Krug, S., Labregere, D., Naderi Beni, A., Pawar, R., Sbaji, A., Thomas, S., Trenty, L., Wei, L., 2009. A benchmark study on problems related to CO₂ storage in geologic formations. *Computational Geosciences* 13, 409-434.
- CO₂ Capture Project, 2013. Available at; URL: <http://www.co2captureproject.com/> (accessed 20/02/2013).
- Corbella, M., Ayora, C., 2003. Role of fluid mixing in deep dissolution of carbonates. *Geologica Acta* 1, 305-313.
- Corbella, M., Ayora, C., Cardellach, E., 2003. Dissolution of deep carbonate rocks by fluid mixing: A discussion based on reactive transport modeling. *Journal of Geochemical Exploration* 78-79, 211-214.
- Dawe, R.A., Zhang, Y., 1997. Kinetics of calcium carbonate scaling using observations from glass micromodels. *Journal of Petroleum Science and Engineering* 18, 179-187.

- Dawson, G.K.W., 2012. Carbon dioxide sequestration in coal: The relationships between coal structure, texture, and mineralogy, and the role of mineral reactivity with carbonic acid, School of Earth Sciences. The University of Queensland, Brisbane, p. 235.
- Dawson, G. K.W., Golding, S.D., Esterle, J.S., Massarotto, P., 2012. Occurrence of minerals within fractures and matrix of selected Bowen and Ruhr Basin coals. *International Journal of Coal Geology* 94, 150-166.
- Deighton, I., Draper, J.J., Hill, A.J., Boreham, C.J., 2003. A hydrocarbon generation model for the Cooper and Eromanga Basins. *APPEA Journal* 43, 433-451.
- Deighton, I., Hill, A., 1998. Thermal and burial history. *The Petroleum Geology of South Australia, Cooper Basin* 4, 143-155.
- Deleuze, M., Brantley, S.L., 1997. Inhibition of calcite crystal growth by Mg²⁺ at 100°C and 100 bars: Influence of growth regime. *Geochimica et Cosmochimica Acta* 61, 1475-1485.
- Domingo, C., Loste, E., Gómez-Morales, J., García-Carmona, J., Fraile, J., 2006. Calcite precipitation by a high-pressure CO₂ carbonation route. *The Journal of Supercritical Fluids* 36, 202-215.
- Dromgoole, E.L., Walter, L.M., 1990. Iron and manganese incorporation into calcite: Effects of growth kinetics, temperature and solution chemistry. *Chemical Geology* 81, 311-336.
- Druckenmiller, M.L., Maroto-Valer, M.M., 2005. Carbon sequestration using brine of adjusted pH to form mineral carbonates. *Fuel Processing Technology* 86, 1599-1614.
- Druckenmiller, M.L., Maroto-Valer, M.M., Hill, M., 2005. Investigation of Carbon Sequestration via Induced Calcite Formation in Natural Gas Well Brine. *Energy & Fuels* 20, 172-179.
- Duan, Z., Li, D., 2008. Coupled phase and aqueous species equilibrium of the H₂O–CO₂–NaCl–CaCO₃ system from 0 to 250°C, 1 to 1000 bar with NaCl concentrations up to saturation of halite. *Geochimica et Cosmochimica Acta* 72, 5128-5145.
- Dupraz, C., Reid, R.P., Braissant, O., Decho, A.W., Norman, R.S., Visscher, P.T., 2009. Processes of carbonate precipitation in modern microbial mats. *Earth-Science Reviews* 96, 141-162.
- Dutta, P.K., Suttner, L.J., 1986. Alluvial sandstone composition and paleoclimate; II, Authigenic mineralogy. *Journal of Sedimentary Research* 56, 346-358.
- Eadington, P., Hamilton, P., 1990. Fluid migration and thermal history of Tithonian sandstones, Lower Swan Formation, Octavius 1 borehole, Timor Sea. Unpublished CSIRO Report.
- Eslinger, E., Pevear, D.R., 1988. Clay minerals for petroleum geologists and engineers. SEPM.
- Espiritu, E., James, A., 1999. A-P 610P, EAE Strathpine 3, Well Completion Report (#30941). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.

- Estensen, A., Longley, I., Griffiths, P., Knuckley, E., Batt, E., 1986. A-P 269P (1), LEA Kenmore 5, Well Completion Report (#15553). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Farquhar, S.M., Dawson, G.K.W., Pearce, J.K., Golding, S.D., in prep. (Draft) Experimental investigation of CO₂-water-rock interactions under simulated *in situ* conditions. To be submitted to Chemical Geology in 2013.
- Fathi, A., Mohamed, T., Claude, G., Maurin, G., Mohamed, B.A., 2006. Effect of a magnetic water treatment on homogeneous and heterogeneous precipitation of calcium carbonate. Water Research 40, 1941-1950.
- Fawcett, W.R., 1983. DIO Jackson South 1 Well Completion Report (# 11687). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Ferris, F., Stehmeier, L., Kantzas, A., Mourits, F., 1997. Bacteriogenic mineral plugging. Journal of Canadian Petroleum Technology 36.
- Fetter, M., De Ros, L.F., Bruhn, C.H.L., 2009. Petrographic and seismic evidence for the depositional setting of giant turbidite reservoirs and the paleogeographic evolution of Campos Basin, offshore Brazil. Marine and Petroleum Geology 26, 824-853.
- Freeman, R.N., 1967. A-P 117P, Area 1, OOC Maryvale 1, Final Report (#2068). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- French, J.V., 1989. BUO Denbigh Downs 1, Well Completion Report (#17999). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Fujita, Y., Ferris, F.G., Lawson, R.D., Colwell, F.S., Smith, R.W., 2000. Subscribed Content Calcium Carbonate Precipitation by Ureolytic Subsurface Bacteria. Geomicrobiology Journal 17, 305-318.
- Garcia, A., Morad, S., De Ros, L., Al-Aasm, I., 1998. Paleogeographical, paleoclimatic and burial history controls on the diagenetic evolution of Lower Cretaceous Serraria sandstones in the Sergipe-Alagoas Basin, NE Brazil. Carbonate cementation in sandstones: International Association of Sedimentologists Special Publication 26, 107-140.
- Garcia, S., Rosenbauer, R.J., Palandri, J., Maroto-Valer, M.M., 2012. Sequestration of non-pure carbon dioxide streams in iron oxyhydroxide-containing saline repositories. International Journal of Greenhouse Gas Control 7, 89-97.

- Gilfillan, S.M.V., Lollar, B.S., Holland, G., Blagburn, D., Stevens, S., Schoell, M., Cassidy, M., Ding, Z., Zhou, Z., Lacrampe-Couloume, G., Ballentine, C.J., 2009. Solubility trapping in formation water as dominant CO₂ sink in natural gas fields. *Nature* 458, 614-618.
- Glezakou, V.-A., Peter McGrail, B., Todd Schaef, H., 2012. Molecular interactions of SO₂ with carbonate minerals under co-sequestration conditions: A combined experimental and theoretical study. *Geochimica et Cosmochimica Acta* 92, 265-274.
- Golding, S.D., Uysal, I.T., Boreham, C.J., Kirste, D., Baublys, K.A., Esterle, J.S., 2011. Adsorption and mineral trapping dominate CO₂ storage in coal systems. *Energy Procedia* 4, 3131-3138.
- Gravestock, D.I., Griffiths, M., Hill, A., 1983. The Hutton Sandstone – Two separate reservoirs in the Eromanga Basin – South Australia. *APPEA Journal* 23, 109-119.
- Green, D.C., 1963. Phillips Sunray QLD American, Kogan South 1, Well Completion Report (#1026). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Hall, R., Gagen, S., 1989. AMX Widnerpool 1, Well Completion Report (#20102). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Hammes, F., Boon, N., De Villiers, J., Verstraete, W., Siciliano, S.D., 2003. Strain-specific ureolytic microbial calcium carbonate precipitation. *Applied and environmental microbiology* 69, 4901-4909.
- Hanor, J.S., McIntosh, J.C., 2007. Diverse origins and timing of formation of basinal brines in the Gulf of Mexico sedimentary basin. *Geofluids* 7, 227-237.
- Harrison, J., Higginbotham, G.T., 1964. Gidgealpa 1 Well Completion Report (# 363). PEPS - SA, Energy Resources Division, Department for Manufacturing, Innovation, Trade, Resources and Energy (DMITRE), State Government of South Australia, Adelaide, Australia.
- Hayes, J.B., 1979. Sandstone diagenesis - The hole truth. *SEPM Special publication*, 127-139.
- Heath, R., McIntyre, S., Gibbins, N., 1989. A Permian origin for Jurassic reservoir oil in the Eromanga Basin. *The Cooper and Eromanga basins, Australia: Adelaide, Petroleum Exploration Society of Australia, Society of Petroleum Engineers, Australian Society of Exploration Geophysicists*, 405-415.
- Higashitani, K., Kage, A., Katamura, S., Imai, K., Hatade, S., 1993. Effects of a magnetic field on the formation of CaCO₃ particles. *Journal of Colloid and Interface Science* 156, 90-95.
- Houston, S., Smalley, C., Laycock, A., Yardley, B.W.D., 2011. The relative importance of buffering and brine inputs in controlling the abundance of Na and Ca in sedimentary formation waters. *Marine and Petroleum Geology* 28, 1242-1251.

- Hovland, M., 1990. Do carbonate reefs form due to fluid seepage? *Terra Nova* 2, 8-18.
- IPCC, 2005. Special report on carbon dioxide capture and storage. Technical report, intergovernmental Panel on Climate Change (IPCC), prepared by Working Group III.
- Jacque, M., Sweeney, P.J., Tricot, P., 1968. A-P 66P & 67P, QLD, TEA Tickalara 1, Well Completion Report (#2619). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Jenkins, C.C., 1984. DIO Yanda 1, Well Completion Report, A-P 259P (#13483). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Jimenez-Lopez, C., Romanek, C.S., 2004. Precipitation kinetics and carbon isotope partitioning of inorganic siderite at 25°C and 1 atm. *Geochimica et Cosmochimica Acta* 68, 557-571.
- Kantorowicz, J.D., Bryant, I.D., Dawans, J.M., 1987. Controls on the geometry and distribution of carbonate cements in Jurassic sandstones: Bridport Sands, southern England and Viking Group, Troll Field, Norway. *Geological Society, London, Special Publications* 36, 103-118.
- Ketzer, J.M., Holz, M., Morad, S., Al-Aasm, I.S., 2003. Sequence stratigraphic distribution of diagenetic alterations in coal-bearing, paralic sandstones: evidence from the Rio Bonito Formation (early Permian), southern Brazil. *Sedimentology* 50, 855-877.
- Ketzer, J.M., Morad, S., Evans, R., Al-Aasm, I.S., 2002. Distribution of diagenetic alterations in fluvial, deltaic, and shallow marine sandstones within a sequence stratigraphic framework: evidence from the Mullaghmore Formation (Carboniferous), NW Ireland. *Journal of Sedimentary Research* 72, 760-774.
- Kharaka, Y.K., Law, L.M., Carothers, W.W., Goerlitz, D.F., 1986. Role of organic species dissolved in formation waters from sedimentary basins in mineral diagenesis, in: Gautier, D.L. (Ed.), *Roles of Organic Matter in Sediment Diagenesis*. Society of Economic Palaeontologies and Mineralogists Special Publication, pp. 111-122.
- Knauer, K., Delbaere, M., 1992. A-P 374P Block A, Surat Basin, PSA Strathpine 1, Well Completion Report (#24344). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Knauss, K.G., Johnson, J.W., Steefel, C.I., 2005. Evaluation of the impact of CO₂, co-contaminant gas, aqueous fluid and reservoir rock interactions on the geologic sequestration of CO₂. *Chemical Geology* 217, 339-350.
- Kyranis, N., 1963. A-P 71P, Kogan 1, Well Completion Report (#1006). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.

- Laing, A.C.M., 1966. A-P 98P, QLD, AOD Yongala 1, Well Completion Report (#2017). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Laing, A.C.M., 1967. A-P 98P, AOD Yongala 2, Well Completion Report (#2257). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Lane, C., Putnam, K., 1982. A-P 269P, HOA Eromanga 1, Well Completion Report (#11049). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Lippmann, F., 1973. Sedimentary carbonate minerals. Springer-Verlag, Berlin, New York.
- Liu, Q., Maroto-Valer, M.M., 2011a. Investigation of the effect of brine composition and pH buffer on CO₂-brine sequestration. *Energy Procedia* 4, 4503-4507.
- Liu, Q., Maroto-Valer, M.M., 2011b. Parameters affecting mineral trapping of CO₂ sequestration in brines. *Greenhouse Gases: Science and Technology* 1, 211-222.
- Longley, I., Griffiths, M., Knuckley, E., Batt, E., 1986. A-P 269P (1), LEA Kenmore 6, Well Completion Report (#15673). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Longley, I.M., Batt, E., 1985a. A-P 269P, HOA Bodalla South 2, Well Completion Report (#14142). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Longley, I.M., Batt, E., 1985b. A-P 269P, HOA Mount Bellalie 1, Well Completion Report (#14566). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Lowman, R., 2003. PL 1, SSL Moonie 40, Well Completion Report (#35693). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Lumsden, D.N., Shipe, L.G., Lloyd, R.V., 1989. Mineralogy and Mn geochemistry of laboratory-synthesized dolomite. *Geochimica et Cosmochimica Acta* 53, 2325-2329.
- Lundager Madsen, H.E., 2004. Crystallization of calcium carbonate in magnetic field in ordinary and heavy water. *Journal of Crystal Growth* 267, 251-255.
- Mackenzie, F.T., Lerman, A., Mackenzie, F., 2006. Mineralogy, chemistry, and reaction kinetics of the major carbonate phases, *Carbon in the geobiosphere — Earth's outer shell —*. Springer Netherlands, pp. 89-121.

- Madsen, H.E.L., 1995. Influence of magnetic field on the precipitation of some inorganic salts. *Journal of Crystal Growth* 152, 94-100.
- Manoli, F., Dalas, E., 2000. Spontaneous precipitation of calcium carbonate in the presence of ethanol, isopropanol and diethylene glycol. *Journal of Crystal Growth* 218, 359-364.
- Mansurbeg, H., Caja, M.A., Marfil, R., Morad, S., Remacha, E., Garcia, D., Martín-Crespo, T., El-Ghali, M.A.K., Nystuen, J.P., 2009. Diagenetic Evolution and Porosity Destruction of Turbiditic Hybrid Arenites and Siliciclastic Sandstones of Foreland Basins: Evidence from the Eocene Hecho Group, Pyrenees, Spain. *Journal of Sedimentary Research* 79, 711-735.
- McGrail, B.P., Lindenmeier, C.W., Martin, P., 1999. Characterization of pore structure and hydraulic property alteration in pressurized unsaturated flow tests, MRS Proceedings. Cambridge Univ Press.
- McGrail, B.P., Martin, P.F., Saripalli, K.P., Bryant, S.L., Sass, B.M., 2001. Use of forced mineral trapping for sequestration of CO₂. Pacific Northwest National Laboratory (PNNL), Richland, WA (US).
- Menhennitt, C.E., 1985. Diagenesis and its influence on the reservoir sandstones of the Jackson Oilfield, B.Sc (Hons.) Thesis, Department of Earth Sciences. Monash University, Melbourne, Australia, p. 112 (unpublished).
- Meyers, N.A., 1965. A-P 71P, QLD, Phillips - Sunray Tipton 1, Well Completion Report. QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Mitchell, A.C., Dideriksen, K., Spangler, L.H., Cunningham, A.B., Gerlach, R., 2010. Microbially enhanced carbon capture and storage by mineral-trapping and solubility-trapping. *Environmental Science & Technology* 44, 5270-5276.
- Montes-Hernandez, G., Renard, F., Geoffroy, N., Charlet, L., Pironon, J., 2007. Calcite precipitation from CO₂-H₂O-Ca(OH)₂ slurry under high pressure of CO₂. *Journal of Crystal Growth* 308, 228-236.
- Moore, P.S., 1981. DIO Morney 1, Well Completion Report (#9551). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Morad, S., 2009. Carbonate cementation in sandstones: Distribution patterns and geochemical evolution, Carbonate cementation in sandstones. Blackwell Publishing Ltd., pp. 1-26.
- Morad, S., Al-Ramadan, K., Ketzer, J.M., De Ros, L.F., 2010. The impact of diagenesis on the heterogeneity of sandstone reservoirs: A review of the role of depositional facies and sequence stratigraphy. *AAPG Bulletin* 94, 1267-1309.

- Morad, S., de Ros, L.F., Nystuen, J.P., Bergan, M., 2009. Carbonate diagenesis and porosity evolution in sheet-flood sandstones: Evidence from the Middle and Lower Lunde Members (Triassic) in the Snorre Field, Norwegian North Sea, Carbonate Cementation in Sandstones. Blackwell Publishing Ltd., pp. 53-85.
- Morad, S., Ketzer, J.M., De Ros, L.F., 2000. Spatial and temporal distribution of diagenetic alterations in siliciclastic rocks: Implications for mass transfer in sedimentary basins. *Sedimentology* 47, 95-120.
- Mozley, P.S., 1989. Relation between depositional environment and the elemental composition of early diagenetic siderite. *Geology* 17, 704-706.
- Mucci, A., 1987. Influence of temperature on the composition of magnesian calcite overgrowths precipitated from seawater. *Geochimica et Cosmochimica Acta* 51, 1977-1984.
- Mucci, A., 1988. Manganese uptake during calcite precipitation from seawater: Conditions leading to the formation of a pseudokutnahorite. *Geochimica et Cosmochimica Acta* 52, 1859-1868.
- Mucci, A., Morse, J.W., 1983. The incorporation of Mg^{2+} and Sr^{2+} into calcite overgrowths: influences of growth rate and solution composition. *Geochimica et Cosmochimica Acta* 47, 217-233.
- Newell, D.L., Kaszuba, J.P., Viswanathan, H.S., Pawar, R.J., Carpenter, T., 2008. Significance of carbonate buffers in natural waters reacting with supercritical CO_2 : Implications for monitoring, measuring and verification (MMV) of geologic carbon sequestration. *Geophysical Research Letters* 35, L23403.
- Nguyen, D.L., Carmody, J.G., Gurney, E.H., 1996. EPP 565, ANU Green Swamp 1, Well Completion Report (#27926). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia
- Nugent, 1988. DIO Dingera 1, Well Completion Report (# 17739). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- O'Brien, G., Woods, E., 1995. Hydrocarbon-related diagenetic zones (HRDZs) in the Vulcan Sub-basin, Timor Sea: Recognition and exploration implications. *APEA Journal* 35, 220-220.
- O'Brien, G.W., Lisk, M., Duddy, I.R., Hamilton, J., Woods, P., Cowley, R., 1999. Plate convergence, foreland development and fault reactivation: Primary controls on brine migration, thermal histories and trap breach in the Timor Sea, Australia. *Marine and Petroleum Geology* 16, 533-560.
- O'Neill, G.J., 1985. Muteroo 1 Well Completion Report (# 6291). PEPS - SA, Energy Resources Division, Department for Manufacturing, Innovation, Trade, Resources and Energy (DMITRE), State Government of South Australia, Adelaide, Australia.

- Ostler, S., 1989. Spencer West 1 Well Completion Report (# 7223/6). PEPS - SA, Energy Resources Division, Department for Manufacturing, Innovation, Trade, Resources and Energy (DMITRE), State Government of South Australia, Adelaide, Australia.
- Parry, W.T., Chan, M.A., Nash, B.P., 2009. Diagenetic characteristics of the Jurassic Navajo Sandstone in the Covenant oil field, central Utah thrust belt. AAPG Bulletin 93, 1039-1061.
- Pearce, J.K., Dawson, G.K.W., Golding, S.D., in prep. (Draft) SO_x and supercritical CO₂ short-term effects upon geological samples under simulated in situ conditions. To be submitted to Chemical Geology in May 2013.
- Pearce, J.K., Golding, S.D., Frank, A., Kirste, D., 2013. SO_x and O₂ Co-contaminant impacts in geological carbon storage. CO2CRC Report, RPT13-4173.
- Pedersen, K., 2000. Exploration of deep intraterrestrial microbial life: Current perspectives. FEMS Microbiology Letters 185, 9-16.
- Pinder, B., 2007. PL 198, ARM Tipton 26/26A, Well Completion Report (#60667). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Pittman, E.D., 1989. Problems related to clay minerals in reservoir sandstones, Oil field development techniques: Proceedings of the Daqing International Meeting: AAPG Studies in Geology, pp. 237-244.
- Purvis, K., 1992. Lower Permian Rotliegend sandstones, southern North Sea: A case study of sandstone diagenesis in evaporite-associated sequences. Sedimentary Geology 77, 155-171.
- Pyle, D.E., 1962. A-P 57P, AOG Moonie 2, Well Completion Report (#931). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Pyle, D.E., 1965a. A-P 57P, QLD, Union - Kern - AOG Bennett 1, Well Completion Report (#1828). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Pyle, D.E., 1965b. A-P 57P, QLD, Union - Kern - AOG Davidson 1, Well Completion Report (#1700). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Pyle, D.E., 1966a. A-P 57P, QLD, Union - Kern - AOG Bennett 2, Well Completion Report (#1836). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.

- Pyle, D.E., 1966b. A-P 57P, QLD, Union - Kern - AOG Bennett North 1, Well Completion Report (#2039). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Pyle, D.E., 1966c. A-P 57P, QLD, Union - Kern - AOG Pring 1, Well Completion Report (#1834). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Pyle, D.E., 1966d. A-P 57P, QLD, Union - Kern - AOG Sussex Downs 1, Well Completion Report (#2018). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia
- Pyle, D.E., Carey, A.R., Jack Jr., J.E., 1963. A-P 57P, QLD, Union - Kern - AOG Southwood 1, Well Completion Report (#1113). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Pyle, D.E., Dabney, L.R., 1963. A-P 57P, UOD Moonie 13, Well Completion Report (#1106). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Raza, A., Hill, K.C., Korsch, R.J., 2009. Mid-Cretaceous uplift and denudation of the Bowen and Surat Basins, eastern Australia: Relationship to Tasman Sea rifting from apatite fission-track and vitrinite-reflectance data. *Australian Journal of Earth Sciences* 56, 501-531.
- Reddy, M.M., Wang, K.K., 1980. Crystallization of calcium carbonate in the presence of metal ions: I. Inhibition by magnesium ion at pH 8.8 and 25°C. *Journal of Crystal Growth* 50, 470-480.
- Renard, F., Gratier, J.P., Ortoleva, P., Brosse, E., Bazin, B., 1998. Self-organization during reactive fluid flow in a porous medium. *Geophysical Research Letters* 25, 385-388.
- Rigby, D., Smith, J., 1981. An isotopic study of gases and hydrocarbons in the Cooper Basin. *Australian Petroleum Exploration Association Journal* 21, 222-229.
- Robbie, S.M., Mitchell, J.A., 1996. PL 31, OCA Bodalla South 9, Well Completion Report (#28847). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Roberts, J.A., Bennett, P.C., González, L.A., Macpherson, G., Milliken, K.L., 2004. Microbial precipitation of dolomite in methanogenic groundwater. *Geology* 32, 277-280.
- Rollet, N., Logan, G., Kennard, J., O'Brien, P., Jones, A., Sexton, M., 2006. Characterisation and correlation of active hydrocarbon seepage using geophysical data sets: An example from the tropical, carbonate Yampi Shelf, Northwest Australia. *Marine and Petroleum Geology* 23, 145-164.

- Romanek, C.S., Zhang, C.L., Li, Y., Horita, J., Vali, H., Cole, D.R., Phelps, T.J., 2003. Carbon and hydrogen isotope fractionations associated with dissimilatory iron-reducing bacteria. *Chemical Geology* 195, 5-16.
- Rudd, G.W., Ties, P., 1987. A-P 267P, Eromanga Basin, PPL Dilkera 1, Well Completion Report (#15974). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Salomon, J.A., Short, D.A., Singley, W., 1990. PL 32, LEA Kenmore 12, Well Completion Report (#22042). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Saripalli, K.P., Sharma, M.M., Bryant, S.L., 2000. Modeling injection well performance during deep-well injection of liquid wastes. *Journal of Hydrology* 227, 41-55.
- Sarkar, S., 1988. Petrology of caliche-derived peloidal calcirudite/calcarenite in the late triassic maleri formation of the pranhita-Godavari valley, South India. *Sedimentary Geology* 55, 263-282.
- Schulz-Rojahn, J., 1993. Calcite-cemented zones in the Eromanga Basin: Clues to petroleum migration and entrapment? *APEA Journal* 33, 63-63.
- Schulz-Rojahn, J., Ryan-Grigor, S., Anderson, A., 2009. Structural Controls on Seismic-Scale Carbonate Cementation in Hydrocarbon-Bearing Jurassic Fluvial and Marine Sandstones from Australia: A Comparison, *Carbonate Cementation in Sandstones*. Blackwell Publishing Ltd., pp. 327-362.
- Scorer, J.D.T., 1966. A summary of Pressure and Fluid Data from Wells Drilled in the Surat Basin, with a Preliminary Discussion of the Hydrodynamics of the Basin. Australian Bureau of Mineral Resources Geology and Geophysics, Record No. 1966/102, p. 218.
- Short, D.A., Harris, R.I., 1986a. A-P 299P (A), QLD, HEP Kooroopa 1 Well Completion Report, (#15070). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Short, D.A., Harris, R.I., 1986b. A-P 299P (A), QLD, HEP Ipundu 1, Well Completion Report, (#15397). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Slijderink, P., 1998. A-P 259P, SSL Ghina 1, Well Completion Report (#30876). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Soong, Y., Goodman, A.L., McCarthy-Jones, J.R., Baltrus, J.P., 2004. Experimental and simulation studies on mineral trapping of CO₂ with brine. *Energy Conversion and Management* 45, 1845-1859.

- Staughton, D.B., 1985. The diagenetic history and reservoir quality evaluation of the Strzelecki hydrocarbon field, Cooper/Eromanga Basins, South Australia, B.Sc. (Hons.) Thesis, Department of Earth Sciences. Monash University, Melbourne, Australia.
- Steeffel, C.I., Lichtner, P.C., 1998. Multicomponent reactive transport in discrete fractures: II: Infiltration of hyperalkaline groundwater at Maqarin, Jordan, a natural analogue site. *Journal of Hydrology* 209, 200-224.
- Stienstra, N., 1992. Hydrocarbon-associated carbonate accumulations within the Middle to Upper Jurassic reservoir sandstones of the Cooper-Eromanga Basins, Central Australia, BSc Honours Thesis, School of Earth Sciences. University of Melbourne, Australia, p. 77.
- Stocks-Fischer, S., Galinat, J.K., Bang, S.S., 1999. Microbiological precipitation of CaCO₃. *Soil Biology and Biochemistry* 31, 1563-1571.
- Summons, R.E., Zumberge, J.E., Boreham, C.J., Bradshaw, M.T., Brown, S.W., Edwards, D.S., Hope, J.M., Natalie, N., 2002. The oils of eastern Australia: Petroleum geochemistry and correlation, Volume 1, Bowen-Surat and Cooper-Eromanga basins. *Geoscience Australia GeoCat* 71431.
- Surdam, R.C., Boese, S.W., Crossey, L.J., 1984. The chemistry of secondary porosity, in: MacDonald, D.A., Surdam, R.C. (Eds.), *Clastic diagenesis*. AAPG Memoir, pp. 127-149.
- Surdam, R.C., Crossey, L.J., Hagen, E.S., Heasler, H.P., 1989. Organic-inorganic interactions and sandstone diagenesis. *AAPG Bulletin* 73, 1-23.
- Surka, E., Rouse, K.R., 1984. HEP Tintaburra No. 1, A-P 299P (A), QLD, Well Completion Report (#13029). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Tandon, S.K., Narayan, D., 1981. Calcrete conglomerate, case-hardened conglomerate and cornstone - a comparative account of pedogenic and non-pedogenic carbonates from the continental Siwalik Group, Punjab, India. *Sedimentology* 28, 353-367.
- Taylor, B.W., 1985. Gidgealpa 18 Well Completion Report (# 5856). PEPS - SA, Energy Resources Division, Department for Manufacturing, Innovation, Trade, Resources and Energy (DMITRE), State Government of South Australia, Adelaide, Australia.
- Thornton, D.A., 1984. A-P 259P, QLD, DIO Challum 1 Well Completion Report (#13528). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Thornton, D.A., Elliott, P., 1982. A-P 259P, DIO Tartulla 1, Well Completion Report (# 10810). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.

- Ties, P., Rudd, G.W., 1986. A-P 267P, Eromanga Basin, PPL Thungo 1, Well Completion Report (#15857). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Titheridge, D., 2010. A-P 788P, PAN Duke S3, Well Completion Report (#63747). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Tolliday, R.G., How, T., 1986. HPP Brigalow 1, Well Completion Report (#12502). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Toupin, D., Eadington, P.J., Person, M., Morin, P., Wieck, J.M., Warner, D., 1997. Petroleum hydrogeology of the Cooper and Eromanga basins, Australia; some insights from mathematical modeling and fluid inclusion data. AAPG Bulletin 81, 577-603.
- Turk, J.N., Pyle, D.E., 1962. A-P 57P, AOG Moonie 1, Well Completion Report (#909). QDEX - Queensland Digital Exploration Reports, Department of Natural Resources and Mines, The State of Queensland, Brisbane, Australia.
- Uysal, I.T., Golding, S.D., Bolhar, R., Zhao, J.-x., Feng, Y.-x., Baublys, K.A., Greig, A., 2011. CO₂ degassing and trapping during hydrothermal cycles related to Gondwana rifting in eastern Australia. *Geochimica et Cosmochimica Acta* 75, 5444-5466.
- Uysal, I.T., Golding, S.D., Glikson, M., 2000. Petrographic and isotope constraints on the origin of authigenic carbonate minerals and the associated fluid evolution in Late Permian coal measures, Bowen Basin (Queensland), Australia. *Sedimentary Geology* 136, 189-206.
- Van Lith, Y., Warthmann, R., Vasconcelos, C., McKenzie, J.A., 2003. Sulphate-reducing bacteria induce low-temperature Ca-dolomite and high Mg-calcite formation. *Geobiology* 1, 71-79.
- Vasconcelos, C., McKenzie, J.A., Bernasconi, S., Grujic, D., Tiens, A.J., 1995. Microbial mediation as a possible mechanism for natural dolomite formation at low temperatures. *Nature* 377, 220-222.
- Vincent, P., Mortimore, I., McKirdy, D., 1985. Hydrocarbon generation, migration and entrapment in the Jackson–Naccowlah area, ATP 259P, southwestern Queensland. *Australian Petroleum Exploration Association Journal* 25, 62-84.
- Wajon, J.E., Ho, G.-E., Murphy, P.J., 1985. Rate of precipitation of ferrous iron and formation of mixed iron-calcium carbonates by naturally occurring carbonate materials. *Water Research* 19, 831-837.
- Walderhaug, O., Bjørkum, P.A., 2009. Calcite Cement in Shallow Marine Sandstones: Growth Mechanisms and Geometry, *Carbonate Cementation in Sandstones*. Blackwell Publishing Ltd., pp. 179-192.

- Wall, V.J., 1987. Hydrocarbon reservoir quality in the Cooper/Eromanga Basins. Final report, NERDDC Project No. 808 (ref 84/4067). Department of Earth Sciences, Monash University (unpublished).
- Warren, L.A., Maurice, P.A., Parmar, N., Ferris, F.G., 2001. Microbially mediated calcium carbonate precipitation: Implications for interpreting calcite precipitation and for solid-phase capture of inorganic contaminants. *Geomicrobiology Journal* 18, 93-115.
- Wigley, T.M.L., Plummer, L.N., 1976. Mixing of carbonate waters. *Geochimica et Cosmochimica Acta* 40, 989-995.
- Wilke, F.D.H., Vásquez, M., Wiersberg, T., Naumann, R., Erzinger, J., 2012. On the interaction of pure and impure supercritical CO₂ with rock forming minerals in saline aquifers: An experimental geochemical approach. *Applied Geochemistry* 27, 1615-1622.
- Wright, D.T., 1999. The role of sulphate-reducing bacteria and cyanobacteria in dolomite formation in distal ephemeral lakes of the Coorong region, South Australia. *Sedimentary Geology* 126, 147-157.
- Wright, D.T., Wacey, D., 2005. Precipitation of dolomite using sulphate-reducing bacteria from the Coorong Region, South Australia: Significance and implications. *Sedimentology* 52, 987-1008.
- Xu, T., Apps, J.A., Pruess, K., 2005. Mineral sequestration of carbon dioxide in a sandstone–shale system. *Chemical Geology* 217, 295-318.
- Xu, T., Apps, J.A., Pruess, K., Yamamoto, H., 2007. Numerical modeling of injection and mineral trapping of CO₂ with H₂S and SO₂ in a sandstone formation. *Chemical Geology* 242, 319-346.
- Zhang, C., Vali, H., Romanek, C., Roh, Y., Sears, S., Phelps, T., 1999. Chemical and morphological characterization of siderite formed by iron-reducing bacteria, Lunar and Planetary Institute Science Conference Abstracts, p. 1855.
- Zhang, C.L., Horita, J., Cole, D.R., Zhou, J., Lovley, D.R., Phelps, T.J., 2001. Temperature-dependent oxygen and carbon isotope fractionations of biogenic siderite. *Geochimica et Cosmochimica Acta* 65, 2257-2271.
- Zuddas, P., Mucci, A., 1998. Kinetics of calcite precipitation from seawater: II. The influence of the ionic strength. *Geochimica et Cosmochimica Acta* 62, 757-766.
- Zuddas, P., Pachana, K., Faivre, D., 2003. The influence of dissolved humic acids on the kinetics of calcite precipitation from seawater solutions. *Chemical Geology* 201, 91-101.