The Geology of NSW

The geological characteristics and history of NSW with a focus on coal seam gas (CSG) resources

A report commissioned for the NSW Chief Scientist's Office, May, 2013.

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Contents

A brief Glossary of Terms

The following constitutes a brief, but by no means comprehensive, compilation of some of the terms used in this review that may not be clear to a non-geologist reader. Many others are explained within the text.

- **Tectono-thermal**: The involvement of either (or both) tectonics (the large-scale movement of the Earth's crust and lithosphere), and geothermal activity (heating or cooling the crust).
- **Orogenic**: pertaining to an orogen, ie. a mountain belt. Associated with a collisional or mountain-building event.
- **Ma**: Mega-annum, or one million years. Conventionally associated with an age in geochronology (ie. million years before present).
- **Epicratonic**: "on the craton", pertaining to being on a large, stable landmass (eg. Tasman Epicratonic Province – the long-lived, "stable" province of the Tasmanides (the 5 aggregated fold-belts that form most of Eastern Australia).
- **Porosities**: the ratio of the volume of a rock that consists of pores (or space, as opposed to solid grains), to the volume of the rock as a whole.
- **Permeabilities**: – a measure of the capability of a rock or sediment to permit flow of fluids through its pore spaces (measure in Darcies).
- **Graben**: (from the German for ditch or trench), a block of rock , bounded by faults on at least two sides, that has depressed relative to the surrounding land, in response to slip (normal faulting) along the bounding faults.
- **Downdip**: in the general direction (or parallel to) the dip of a rock unit or fault.
- **Epeirogenic**: very large-scale uplift or depression of large portions of a continent.
- **Infrabasins**: specifically, "below-basin" – a smaller basin or trough which exists within - and at a lower stratigraphic level than - a larger basin structure.
- **Syn-rift**: Occurring at the same time as rifting.
- **Two-way travel time**: the time taken for a seismic signal to travel down to a subsurface reflector, and then back to the surface. For a known velocity structure, two-way time can be converted to depth.
- **Thermal subsidence:** surface subsidence related to the slow cooling (and thus thermal contraction and density increase) of the lithosphere following an extensional episode.
- **Vitrinite reflectance**: A measure of the thermal maturity, or peak temperatures, in a sedimentary rock, using a measure of the reflectance of incoming light off the organic maceral (coal mineral) vitrinite. Vitrinite reflectance increases with increasing thermal maturity.
- **Structural trough**: An elongate, small trough-like structure in the underlying basement, formed due to tectonic (generally extensional) processes.
- **Province:** An area or geological domain with a similar geological history.

- **Plutonic suites:** A collection of "plutons" - or large, roughly rounded intrusive igneous bodies, of a similar providence.
- **Regressive-transgressive**: The retreat or advance of the local sea level, generally recorded in sedimentary rocks, due to either global or local sea-level changes.
- **Overmature**: Having experienced temperatures above those conducive to hydrocarbon formation.
- **Oil window**: The temperature range conducive to the formation of oil (about 60-150^{o}C), below which organics are stable as kerogen, and above which hydrocarbons degrade to natural gas.
- **Drape**: to lay over, as in a sedimentary unit being deposited over an existing, undulating surface or unit.
- **Anthracite**: high-grade lustrous coal with a high carbon content and low impurities levels. Forms at the highest temperatures of all forms of coal.
- **Gravity map**: a map of variations in the gravitational acceleration of the Earth, generally relative to the surface. Variations in gravity are sensitive to subsurface density structure, in particular, variations between deeper basement and infilling sediments, and are a crucial dataset for constraining basin geometry.
- **Magnetic map**: a map of variations in total intensity of the Earth's magnetic field, relative to a constant level, generally the surface. Magnetic variations are sensitive to differences in magnetic susceptibility between different rock-types (due to different concentrations of magnetic minerals such as magnetite, hematite, etc). This facilitates a mapping of basement lithologies beneath a non-magnetic sedimentary cover, and is one of the most widely used geophysical datasets for mapping subsurface geology.
- **Potentiometric head**: A hypothetical surface representing the level to which groundwater would rise if not trapped in a confined aquifer.

1. Introduction

This report was commissioned by the NSW Chief Scientist's Office in May, 2013. It was requested as part of an investigation into the responsible extraction of coal seam gas within NSW, and in particular balancing the existing utilisation of these basins for groundwater and agriculture, and the needs of local communities, with the development of the CSG industry.

This report was tasked with providing a coverage of the broad geological history of NSW, from the detailed geological evolution of different geological terranes, to a coverage of the regional geophysics, hydrogeology, and local petrophysical constraints.

The potential scope of such a work is great, and we have focussed this work on a discussion of the geological context of both coal-seam gas and the hydrogeology of NSW. In particular, this involves an understanding of the geology of the major coal-bearing basins of NSW, and this forms the major focus of this work.

2. Scope

A complete, detailed geological history of NSW is beyond what could be achieved within the timescale of this commissioned report. Instead we have opted to focus on coal-bearing sedimentary basins of NSW. However, the formation of these sedimentary basins is contingent on the regional geodynamics of NSW, and their present structure is a product of the basement structure and topography generated by these deformational episodes. As such we have included a brief discussion of the background history of NSW as a prelude to a discussion of basin evolution.

We have focussed the bulk of this report on sedimentary basins with demonstrated coal resources, as these are of the most immediate relevance to this synthesis. These include the major coal fields of the Sydney-Gunnedah-Bowen Basin system, as well as the Surat Basin, the Clarence Moreton Basin, the Murray Basin (containing lignite only), the Oaklands Basin (a deep, older graben within the Murray Basin containing coal), and the smaller Gloucester Basin. We present a discussion on the structure, evolution, geology/sedimentary history, and geophysics of each basin. We have not considered smaller coal resources outside these major sedimentary basins (eg. Ashford coalfield, or Cranky Corner Basin).

Regional hydrogeology information on a basin-scale is rarely available for the majority of NSW. While significant data exists for regional aquifers, much of this data is not public domain, or alternatively is at smaller, local scales. Rather than separate out the discussion into of hydrogeology in each basin discussion, we synthesis the hydrogeology of NSW into one section, with some discussion of the physical properties of aquifers proximal to coal seams, and of coal seam aquifers, where such information exists in the public domain.

This report is, primarily, a literature review and synthesis, primarily of public domain data, with emphasis on peer-reviewed published literature where possible. We have included all relevant references at the end of each chapter. We have utilised public domain government resources (from Geoscience Australia (GA) and DTIRIS/NSW Geological Survey) if available. We have processed some geophysics (magnetics and gravity) for the purposes of this report (sourced from the Geophysical data delivery system of GA).

This report will be structured into the following sections:

- Brief history of NSW Geology
- Sydney-Gunnedah-Bowen Basin System
- Surat Basin
- Clarence Moreton Basin
- Gloucester Basin
- Murray Basin
- Oaklands Basin
- NSW Hydrogeology
- NSW seismicity and stress state
- A synthesis and summary

3. A brief history of NSW Geology

The focus of this report is on the geology and evolution of the coal-bearing sedimentary basins of NSW. However, it is necessary to understand the nature, structure, and – briefly – the evolution of basement structure of these basins, in order to address their current state, and tectono-thermal evolution. This section will outline a brief geological history of NSW, and the basement structure of NSW's primary sedimentary basins.

The major sedimentary basins of NSW; the Sydney-Gunnedah-Bowen, Clarence Moreton, Surat, Murray and Gloucester basins (Figure 3.1) overlie Ordovician to Early Cretaceous basement comprised of the Delamerian Orogen, Lachlan Fold Belt (LFB), New England Fold Belt (NEFB) and Thomson Fold Belt (TFB) collectively known as the 'Tasmanides'.

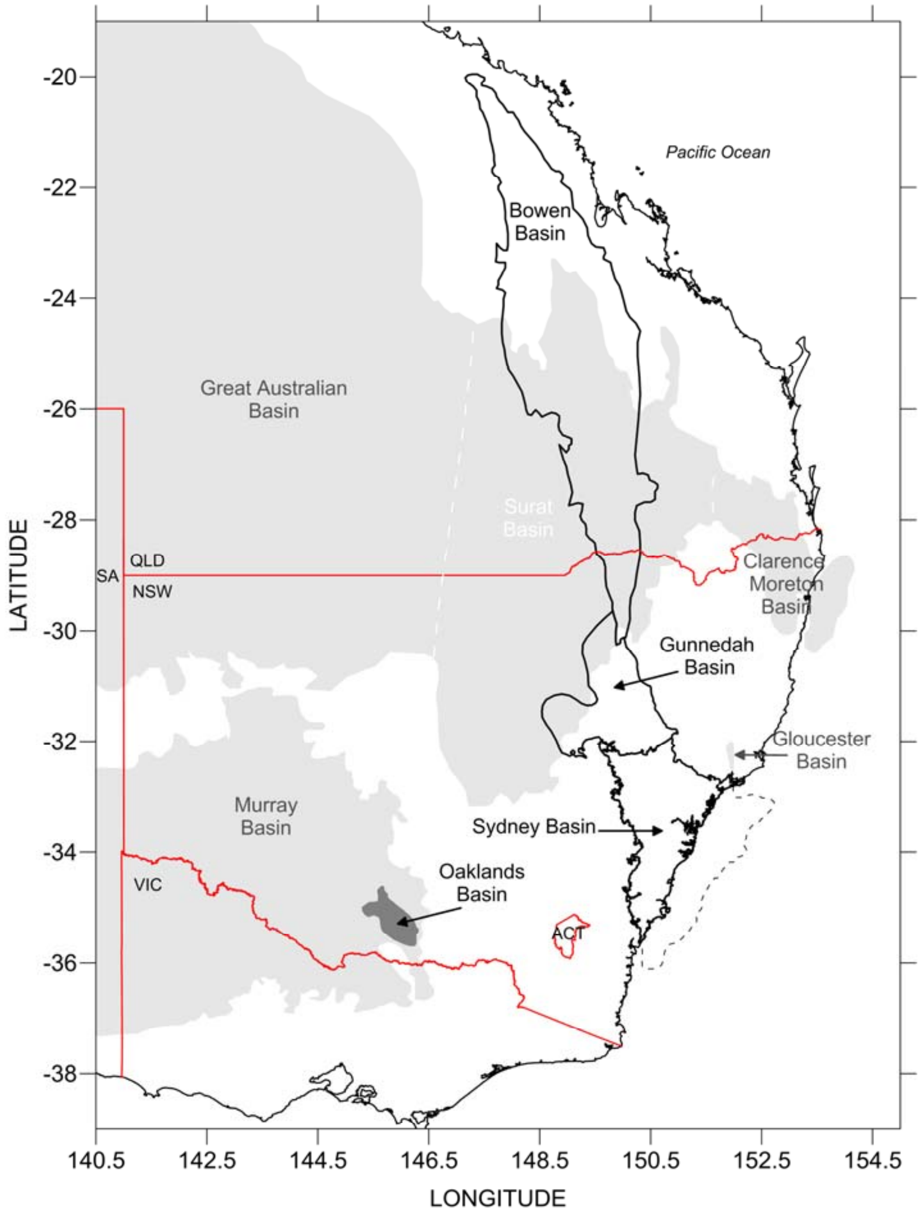

Figure 3.1. Sedimentary basins of New South Wales. Adapted from Danis (2012) and Krassay *et al*. (2009).

The Tasmanides are a collection of orogenic / fold belts along the eastern part of Australia (Figure 3.2) record: the break-up of the Meso-proterozoic supercontinent, the formation of a passive margin, the establishment of convergent margin orogenic belts (from the Middle Cambrian), the collision of Gondwana with Laurussia to form Pangaea (320 to 330 Ma) (Veevers 2000) and the beginning of the Gondwana Pangaea break-up (227 Ma) (Glen 2005). The Tasmanides of eastern Australia represent one sector of the Pacific margin of Gondwana that stretched 20,000 km through New Zealand, Antarctica and into South America whose history reflects extension or rifting, separated by short interval deformation events, in a convergent margin setting along the proto-Pacific plate (Glen 2005).

The Lachlan, New England and Thomson orogenic / fold belts have been identified as the substrate and sediment source to major sedimentary basin systems of NSW, including the extensive Sydney-Gunnedah-Bowen Basin. Their development and tectonic evolution, from the Ordovician to Early Permian, provides valuable background information on lithologic composition and geological structure. The key deformation events; the Delamerian Cycle, Lachlan Super Cycle and Hunter-Bowen Super Cycle, which are comprehensively described in the work of Scheibner & Veevers (2000), Veevers (2000) and Glen (2005), are summarized in Table 1 for the three orogenic belts.

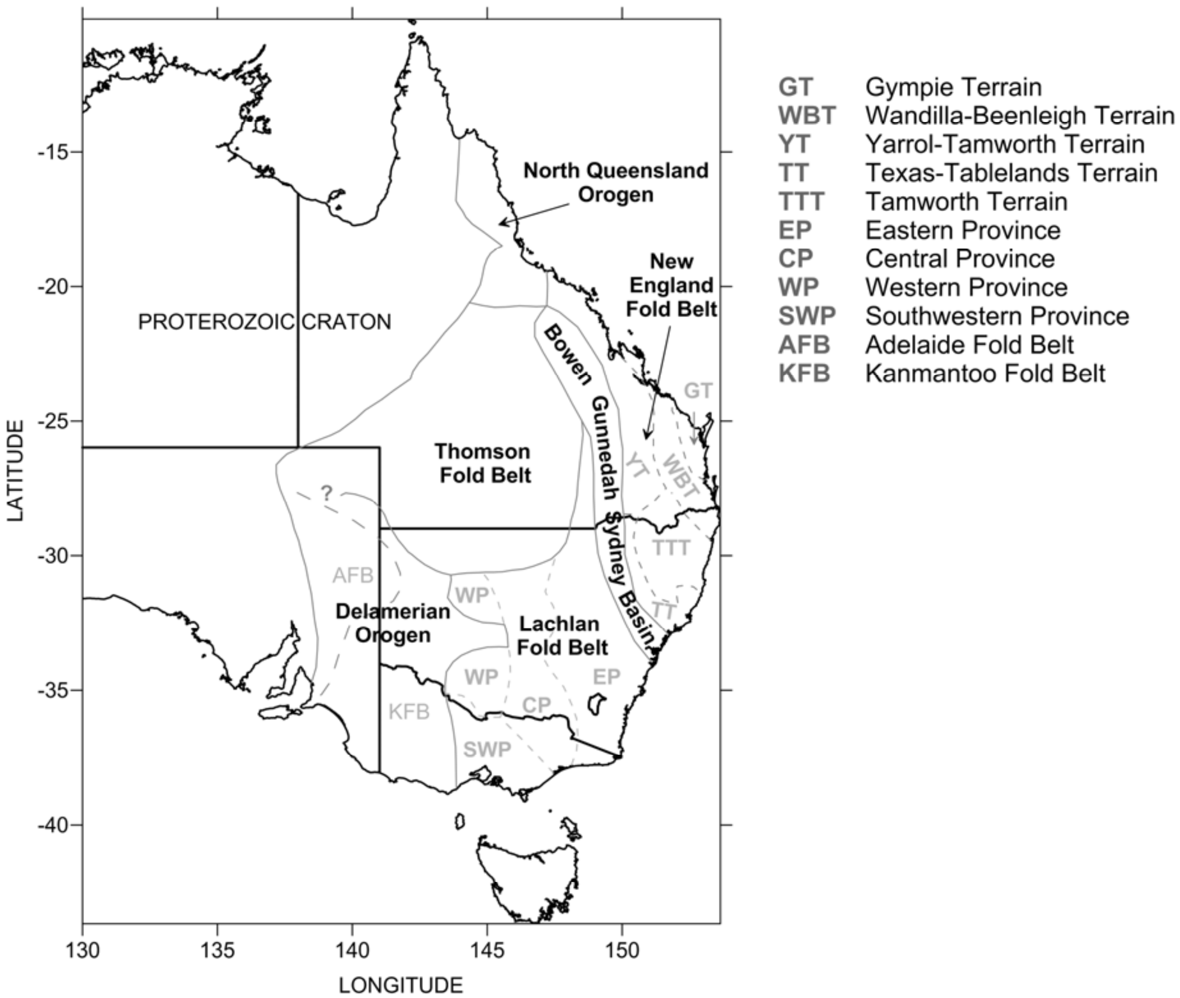

Figure 3.2. Subdivision of the Tasmanides. Adapted from Danis (2012), Leitch (1974), Scheibner & Veevers (2000) and Glen (2005).

Table 3.1. Major geological events in the history of NSW (adapted from Danis 2012).

Age	Timing Ma	Location	Orogenic Stage	Tectonic Environment	Comments / Details
CANIZOIC	0 to 1	Tasman Epicratonic Province		Episodes of upwarp, erosion and deposition	Alluvial, eluvial, lacustrine, Aeolian, coastal and shelfal sediments. Deep weathering.
	1 to 11	Tasman Epicratonic Province		Faulting (reactivation of old faults)	Sediments post-dating the Late Tertiary hiatus, minor intraplate volcanics
	11 to 33	Tasman Epicratonic Province		Passive margin development, extension and contraction isostatic uplift, erosion	Tasman passive margin, intraplate igneous rocks are widespread, forming lava fields and central volcanoes forming a belt ~150 km wide that follows an arc that is almost parallel to the east coast with southward younging consistent with the northward drift of the Australian plate over a mantle plume. Sediments post dating the Mid Tertiary hiatus.
	28 to 65	Tasman Epicratonic Province		Passive margin development, extension and contraction uplift, erosion	Sediments are transgressively over eroded surfaces, subsidence in the Murray Basin, continuous rise of the East Highlands, and termination of spreading in the Tasman Sea
JURASSIC - CRETACEOUS	65 to 200	Tasman Epicratonic Province		Uplift and erosion	Breakup and dispersal of Pangea and east Gondwanaland, development of passive continental margins around Australia bordered by oceanic lithosphere. Development of the Great Dividing Range. Formation of epicontinental basins with potential fluid hydrocarbon sources.
TRIASSIC	200 to 227	New England Fold Belt (NEFB) and Sydney Gunnedah Bowen Basin (SGBB)	Mesozoic Rifting	Right lateral transtensional rifting, subsidence	Deposition confined to the intramontane half grabens of the Clarence-Moreton Basin. Initiation of the Great Australian Basin in the sump of the lowlands between the western-central craton and the NEFB. By 200 Ma quartzose sediment encroached and crossed in places the eroded foreland basin and orogen. Maar volcanic diatremes (200 to 190 Ma) in Sydney Basin. The Garrawilla Volcanics (basalt) (221 to ~160 Ma) and other Jurassic igneous rocks in the Surat Basin.

Table 3.1. continued

Age	Timing Ma	Location	Orogenic Stage	Tectonic Environment	Comments / Details
TRIASSIC	227 to 235	NEFB	Hunter-Bowen Super Cycle 4	Collision	Minor plutonic activity confined to Demon Fault, regarded as the transpressional conduit of the magma. Right lateral movement (~6 km) on Demon Fault – Venus Fault.
	227 to 235	SGBB	Hunter-Bowen Super Cycle 4	Collision, uplift	Basins converted into fold-thrust belts as deformation fronts migrate westwards. Thrusting (233 Ma) of Tamworth Belt westward over Middle Triassic and unconformably overlying Early Jurassic rocks of the Surat Basin. High angle reverse faults terminate at the unconformity between the Gunnedah and Surat Basins. Vitrinite reflectance data confirm the removal of up to 2 km of Triassic and Permian sediments during the Late Triassic Period of erosion in Gunnedah Basin. Compression and left lateral strike slip movement on the Hunter-Mooki Fault have result in a number of high relief anticlines in front of the main thrust. Movement on Lapstone Monocline-Nepean Fault system (en echelon high angle reverse faults, some wrenching and sinistral transpressive motion) may be during Late Triassic.
	242	NEFB	Hunter-Bowen Super Cycle 4	Collision	Cycle 4 was terminated by the collision of Gympie Terrane / Province with Gondwana in the Early to Middle Triassic. This deformation is inferred to have caused the Bowen phase of the Hunter-Bowen Super Cycle, a major crustal loading event.
	235 to 250	SGBB	Hunter-Bowen Super Cycle 4	Convergence, relative uplift from 244 to 235 Ma	Environmental change above the Permian Triassic boundary coincided with the end of tuff and coal deposition and the onset fluvial sedimentation. In the Sydney Basin this was especially derived from the NEFB and synchronous with major periods of volcanism and granite emplacement. Uplift led to shedding of large amounts of craton derived detritus in to the Bowen, Gunnedah and Sydney Basins forming the Clematis and Lower Napperby formations and Hawkesbury sandstone respectively. Final filling (235 to 230 Ma) of the basins dominated by detritus shed from the NEFB but finer grained suggesting lesser topographic expression and reduced thrusting.

Table 1. continued

Age	Timing Ma	Location	Orogenic Stage	Tectonic Environment	Comments / Details
PERMIAN	250 to 258	NEFB	Hunter-Bowen Super Cycle 4	thrusting	Intense folding/faulting and metamorphism in southern NEFB (255 Ma), moderate folding in adjacent basins.
	250 to 258	SGBB	Hunter-Bowen Super Cycle 4	Convergence, crustal loading	All basins converted to coal bearing foreland basins, fed in pulses from volcanic detritus and uplifted detritus (~253 Ma) from NEFB. Crustal loading synchronous with active volcanism and granite formation. Marine regression ~253 Ma. Broad folding after coal deposition associated with sinistral transcurrent faults.
	258 to 264	SGBB	Hunter-Bowen Super Cycle 4	Compression	Conversion of rift basins in the Sydney-Gunnedah-Bowen Basin system to foreland basins
	264	NEFB	Hunter-Bowen Super Cycle 4	Convergent magmatic arc	Extrusion of widespread ignimbrite sheets and emplacement of major I-type granites of the New England Batholith
	265	NEFB	Hunter-Bowen Super Cycle 3		Un-roofing of Barrington Tops Granodiorite. Deposition of Greta Coal Measures in Sydney Basin, Maules Creek Coal Measures in the Gunnedah Basin and Reid Dome Beds in the Bowen Basin.
	267 to 268	NEFB	Hunter-Bowen Super Cycle 3	Compression, large scale folding	N-S deformation into the Permian Basins. Formation of oroclines. Intense folding / faulting in north NEFB and Bowen Basin (265 Ma).
	268 to 300	SGBB	Hunter-Bowen Super Cycle 3	Extension, detachment faulting	Extensional or transtensional rifts that are floored by volcanics or underlain by intrusive rocks. Rift voclanics at the base of the Sydney Basin include the 292 Ma Rylstone Volcanics and 270 Ma Werrie Basalt. Interpretation of the Early Permian extension include subduction of a spreading ridge, slab break-off and changes in the plate boundary configuration form retreating to advancing.

Table 3.1. continued

Age	Timing Ma	Location	Orogenic Stage	Tectonic Environment	Comments / Details
CARBONIFEROUS	268 to 300	NEFB	Hunter-Bowen Super Cycle 3	Extension (rifting 300 to 280), N-S compression, dextral transtension	Emplacements of granites and serpentinites and formation of rift sedimentary basins. Inception of the Bowen-Sydney Basin. From 302 Ma deposition of glacigenic sediments. Dextral transtension produced orocline related pull-apart basins and widespread volcanism. Marine transgression at 288 Ma.
	300 to 310	NEFB	Hunter-Bowen Super Cycle 2	Uplift, strike/slip faulting, crustal block rotation, extension	Erosion during glaciation, development of Sydney-Gunnedah basin by extension (~302 Ma). Thick extensional volcanics (Rylstone Volcanics) and voluminous plutons (Hillgrove, Wongwibinda, Bundarra) erupted in an intra-montane setting
	320	LFB	Lachlan Super Cycle *Kanimblan*	Deformation, uplift	Arc widens by emplacement of high level I type granitoids generated by melting of underlying Ordovician volcanic rocks. Granite emplacement i.e. Bathurst Batholith (330 to 315 Ma), Gulgong Plutonic Suite and other granites along a 600 km long belt to the SSE and in the subsurface to the NNW.
	330 to 350	LFB	Lachlan Super Cycle *Kanimblan*	Shallow subduction, E-W shortening (340 Ma)	Kanimblan upland mountain building. N-S thrusts. Intrusion of S and I type granites and A type volcanics.
DEVONIAN	362	NEFB	Hunter-Bowen Super Cycle 2	Convergence	Subduction and extensional granites
	376	NEFB	Hunter Bowen Super Cycle 1	Convergence	East facing continental or intra-oceanic arc dominated by intermediate volcanism, forearc basin and subduction complexes with accreted terranes.
	382 to 394	LFB	Lachlan Super Cycle *Tabberabberan*	Contraction, strike/slip	Major basin inversion, growth faults undergoing varying degrees of reverse/oblique reactivation and development of basin inversion structures. Brittle conjugate NE and NW trending faults offsetting major plutons and producing small amount of extension.
SILURIAN	415 to 430	LFB	Lachlan Super Cycle *Tabberabberan*	Rifting	Horst and grabens in wide back-arc region. Basin formation and granitoid emplacement. Some granites emplaced into extending upper crust, co-magmatic with and overlain by felsic volcanic rocks erupted in extensional basins. Other foliated granites were emplaced into the middle crust at depths of 10 km then exhumed by thrusting a further 1 km to 2 km.

Table 3.1. continued

Age	Timing Ma	Location	Orogenic Stage	Tectonic Environment	Comments / Details
ORDOVICIAN	435 to 450	LFB	Lachlan Super Cycle *Tabberabberan*	Convergent	Intra-oceanic arc
	443 to 490	LFB	Lachlan Super Cycle *Benambran*	Convergence E-W compression (495 Ma)	Westward subduction beneath fore-arec basin, volcanic arc and marginal sea. Turbidite deposition.
CAMBRIAN	530	NEFB	Delamerian Cycle	NE subduction, convergence	Ecologite blocks exhumed in Peel-Manning Fault system. Closure of basin margin.
	530	LFB	Delamerian Cycle	NE subduction, convergence	Mafic and ultramafic rocks exposed as fault slices in the hanging walls of major thrust faults

The Delamerian Orogen

The Delamerian Orogen is generally defined by the distribution of rocks that have undergone a multi-stage mid-late Cambrian to earliest Ordovician deformation and is divided into two parts, the Adelaide Fold Belt and Kanmantoo Fold Belt. The Delamerian Orogen extends through western NSW, into South Australia and south into Victoria and Tasmania.

The rocks of the Adelaide Fold Belt are divided into two sequences, the Willyama Supergroup and the Adelaidean sequence, separated by an unconformity (Branagan & Packham 2000). The province is largely developed in South Australia, stretching from south of Adelaide to the northern end of the Flinders Ranges and just extending east into NSW. The older sequences of the Willyama Supergroup are composed of regionally metamorphosed sandy and shaly rocks, thought to be Palaeoproterozoic in age. Regional metamorphism, producing a variety of schists and gneisses, is dated at 1600Ma. The granite gneisses that occur in the supergroup are regarded as the products of intense metamorphism and local melting, but as they are affected by at least three periods of strong metamorphism their original nature is obscured. The basal unit of the Adelaidean sequence is of Late Neoproterozoic age and is roughly the same age as the glacial beds which form part of the sequence in the South Australian part of the Adelaide Fold Belt.

The rocks of the Kanmantoo Fold Belt are found in the region of South Australia between the Adelaide Hills and the Murray River and in western Victoria and western New South Wales. The oldest formations may be Palaeozoic and were originally fine grained sediments and volcanics. Granite data of Foden *et al*. (2002) suggests that the Kanmantoo Trough was developed directly on oceanic crust and similarly the presence of Proterozoic E-MORB basalts suggests that Cambrian turbidites there were developed on pre-break-up extensional volcanic rocks (Glen 2005).

The Lachlan Fold Belt

The Lachlan Fold Belt (LFB) extends northwards from eastern Tasmania through Victoria and New South Wales into the central west of Queensland. In north-western NSW the LFB is covered by the extensive Jurassic-Cretaceous Great Artesian Basin (Figure 3.1). The LFB is comprised of predominantly early Ordovician through to Late Carboniferous rocks which record the three major deformation events (Branagan & Packham 2000) of the Lachlan Supercycle (Glen 2005) and parts of the earlier Delamerian Cycle (Table 3.1). The Lachlan Super Cycle is comprised of three events; the Benambran Cycle (Ordovician-Silurian boundary), Tabberabberan Cycle (late Early to Middle Devonian boundary) and Kanimblan Cycle (in the Early Carboniferous) with the events observed also in the New England Orogen (Benambran and Tabberabberan only) (Glen 2005). The LFB is subdivided into four main provinces (Figure 3.2) based on major faults and differences in geology as discussed in the work of Scheibner & Veevers (2000).

The second part of the Lachlan Super Cycle, the Tabberabberan Cycle, is characterised by major sedimentary basin formation and the emplacement of granitoids during rifting, in the late Early-Middle Devonian, and reflects localised strike slip tectonics. There are differing views as to whether these deformations were part of a longer-lived deformation prograding from the west (i.e. Gray & Foster 1997; Gray *et al*. 1997) or related to oblique strike-slip collision (Glen 2005). In summary the LFB is comprised of multiply deformed turbiditic sediments, Silurian-Devonian volcanics, numerous periods of granitic intrusion and large plutonic suites.

The New England Fold Belt

The most easterly component of the Tasmanides is the New England Fold Belt (NEFB) occupies much of coastal QLD and extends south into north-eastern NSW underneath the Mesozoic cover of the Clarence-Moreton and Surat basins (Figure 3.1). The NEFB has an inferred thrust contact with the Eastern subprovince of the LFB (Glen 2005) and is divided into several structural 'subprovinces' by Leitch (1974) or 'terrains' by Scheibner & Veevers (2000) (Figure 3.2). The subdivision reflects the development of a Late Devonian-Carboniferous convergent margin (Hunter Bowen Supercycle 1, Table 3.1) consisting of arc, forearc basin and accreted terranes (Glen 2005). The NEFB forms the basement to the eastern part of the Sydney Basin (Glen 2005) and extends offshore as the Currarong Orogen (Jones & McDonnell 1981; Jones *et al*. 1984) or 'offshore uplift' (Bradley 1993; Alder *et al*. 1998) as represented in seismic data.

The Hunter-Bowen Super Cycle, divided into four cycles, in the NEFB records the Middle Devonian to Triassic (376 to 227 Ma) convergent margin development of East Gondwana which is expressed in the evolution of the NEFB and the Sydney-Gunnedah-Bowen Basin system (SGBB). The elements of this margin have been studied by numerous authors including Leitch (1974), Day *et al*. (1978), Cawood (1982), Cawood & Leitch (1985), Aitchison & Flood (1992) and Cawood *et al.* (2011) and are from west to east, an arc, a forearc basin and subduction complexes together with accreted terrains.

The Hunter-Bowen Super Cycle 3, in the Early Permian, is characterised by crustal extension associated with the inception of the SGBB. The Early Permian SGBB rift basin and other smaller rift basins, developed above the deformed rocks of the forearc basins, the accretionary complexes and on top of the rocks of older basement of the Lachlan, Thomson and North Queensland fold belts (Glen 2005).

Foreland loading of the southern NEFB commenced in the late Early Permian and volcanic detritus and uplifted detritus fed the developing foreland basins (i.e. Sydney-Gunnedah basin). In the Early Triassic uplift between 244 Ma and 235 Ma (Fielding *et al*. 2001) led to the shedding of large amounts of craton-derived detritus into the SGBB (Table1). The Hunter-Bowen Super Cycle 4 ends at the time of the collision of the Gympie Terrane with Gondwana causing a major crustal loading event and widespread thrusting and folding. Glen (2005) suggests that thrusting in the offshore part the NEFB during Hunter-Bowen Super Cycle 4 could be responsible for the formation of major N-S folds and blind faults in the main part of the Sydney Basin. In summary the NEFB is comprised, with multiply deformed accretionary terrain sediments, Devonian-Carboniferous volcanics and numerous granitic intrusions including large plutonic suites.

Thomson Fold Belt

The Thomson Fold Belt (TFB) underlies much of central and western Queensland and a small portion of north-western NSW, where it is concealed by the Mesozoic cover of the Great Artesian Basin. The TFB is more difficult to define due to limited outcrops, but contains deformed sediments, volcanics and granite intrusions. Drill-hole data indicates that rocks range in age from Precambrian through to Late Devonian (Murray 1994; Scheibner & Veevers 2000). The TFB could form part of the substrate of the western portion of the Bowen Basin, as Cambrian or older rocks deformed by the Delamerian Cycle occur along the margin (Glen 2005), and is thought to extend south in the subsurface (Withnall 1995) but its full extent is unclear . Drilling has shown concealed igneous rocks along the southern boundary but the age of these is unknown (Glen 2005). With little outcrop of the TFB exposed the discussion on the development and tectonic history is limited.

NSW Geology

The surface geology of NSW is shown in Figure 3.3. For detailed 1:250,000 geological maps refer to Geoscience Australia (http://www.ga.gov.au/products-services/maps/maps-of-australia.html) for each major sedimentary basin of this report.

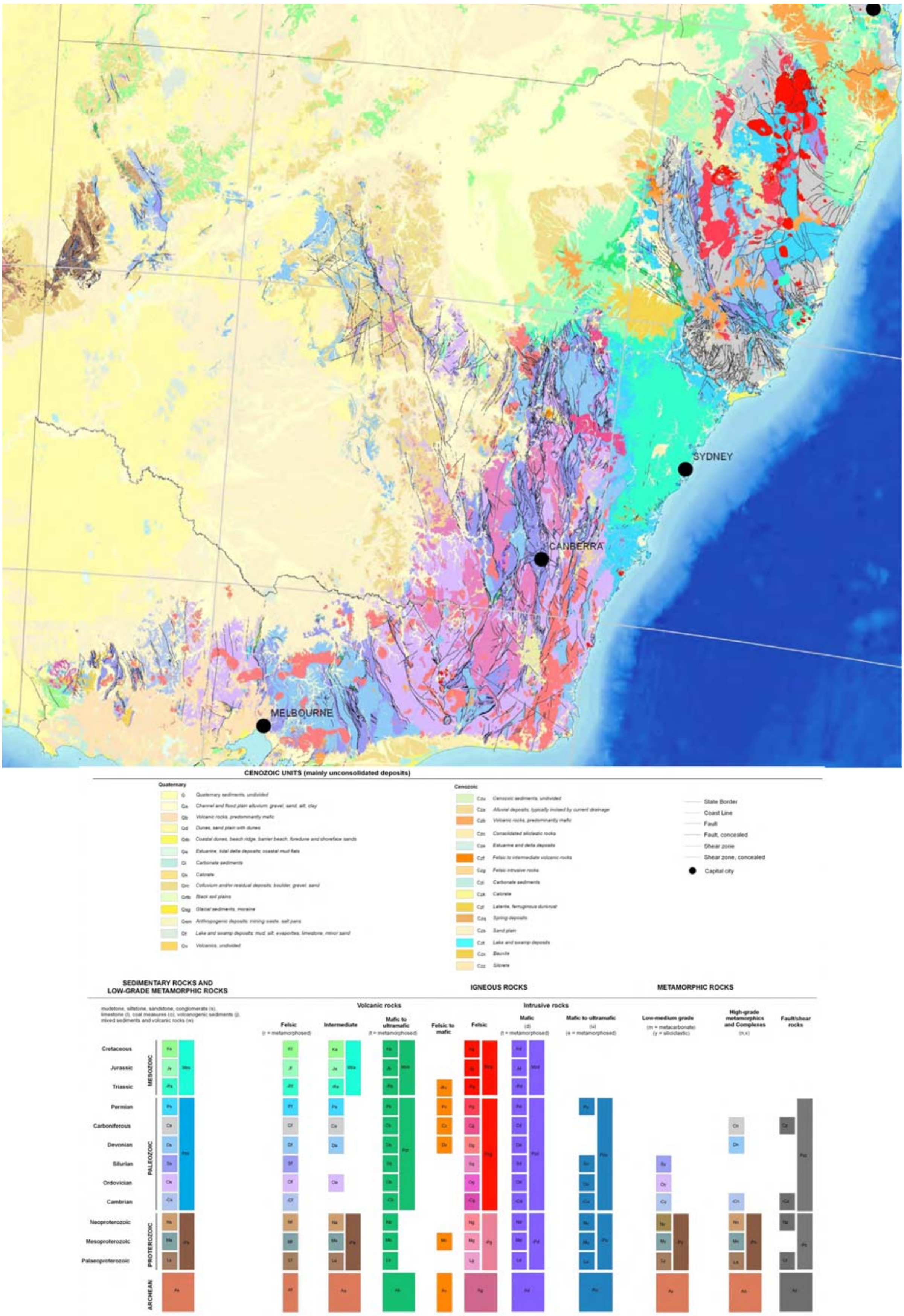

Figure 3.3. 1:1 million Surface Geology of New South Wales (available from Geoscience Australia, Surface Geology of Australia 1:1 million scale map).

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4. Evolution of the Sydney-Gunnedah-Bowen Basin System

The SGBB is a major north-south Permian to Triassic structural basin, approximately 1600 km long (Glen 2005), that extends from the south coast of southern NSW, near Ulladulla, to near Bowen on the coast of northern Queensland (Figure 3.1 and Figure 4.1) and covers an area of over 260,000 km^2 (Cadman & Pain 1998).

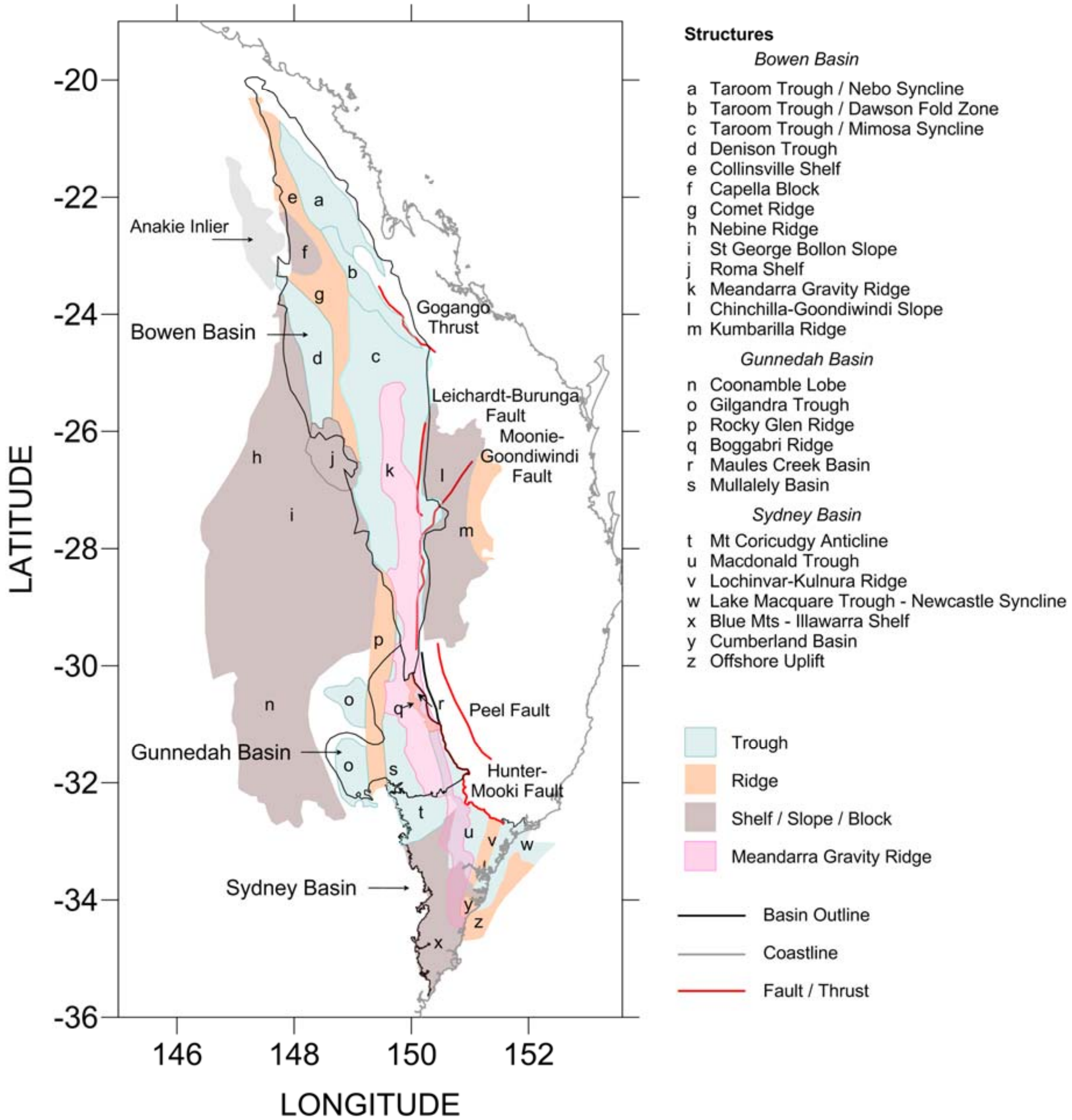

Figure 4.1. Structural element subdivisions of the Sydney-Gunnedah-Bowen Basin system. Structural elements modified from Adler *et al*. (1998) and Krassay *et al*. (2009).

Numerous authors have studied many aspects of the SGBB for its stratigraphy, structure and evolution, several key compilations of information and ideas have been made by Herbert & Helby (1980) for the Sydney Basin, Tadroz (1993) for the Gunnedah Basin and a thematic issue of the Australian Journal of Earth Science (2009, vol 55, issue 3) on the evolution of the Bowen Basin. These works, along with the work of Fielding *et al*. (1995, 2000), Murray (1994), Cadman & Pain (1998), Branagan & Packham (2000) and Langford & Patchett (2005) and Danis *et al*. (2010, 2011, 2012) and Danis (2012) form the basis of this review.

Tectonic Overview

The SGBB originated in the Early Permian, during Cycle 3 of the Hunter-Bowen Super Cycle (Table 3.1), as extensional (or transtensional) rifts floored by volcanics or underlain by intrusive rocks. The substrate of the SGBB system is considered by Glen (2005), for the Bowen Basin, to be the TFB in the west and the NEFB in the east. Korsch *et al*. (2002) notes the Gunnedah Basin is built over crust of the LFB, whilst the substrate of the Sydney Basin is inferred to be LFB in the west (O'Reilly 1990) and NEFB in the east (Roberts & Engel 1987). A combination of post-rift subsidence and the cessation of loading in the late Early Permian created marine conditions in Cycle 4 of the Hunter-Bowen Super Cycle where foreland loading of the southern NEFB is recorded in the deposition of the first major coal measures; Greta Coal Measures in Sydney Basin, Maules Creek Coal Measures in Gunnedah Basin and Reid Dome Beds (Denison Trough) in the Bowen Basin, mixed with volcanic detritus and coal interbedded with volcanics. By the end of the Late Permian (250 Ma) the SGBB system had been converted to a coal bearing foreland basin, fed with pulses of volcanic detritus and uplifted detritus from the NEFB (Table 3.1), where crustal loading was synchronous with active volcanism and granite formation (Glen 2005). At the Permian-Triassic boundary a major environmental change coincided with the end of tuff and coal deposition and the onset of fluvial sedimentation, derived from the NEFB, and synchronous with major periods of volcanism and granite emplacement. By the Middle to Late Triassic the SGBB converted into fold-thrust belts in response to westward migrating thrust fronts (Glen 2005). Crustal shortening is observed in the SGBB system, with Glen (2005) suggesting greater amounts in the Bowen Basin than the Gunnedah and Sydney basins. Tadroz (1993) observes that the western part of the Gunnedah Basin still retains elements of its early rift geometry by being divided into north-south blocks by major cross-faults.

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5. Sydney Basin

Structure

The Sydney Basin is a north-south trending basin, containing generally flat lying Permian-Triassic sequences, approximately 250 km long, averages 100 km in width, ranges from 2km to 4km in depth (Veevers 1984; Danis *et al*. (2011) and covers an area of approximately 37,000 km^2 onshore and 15,000 km^2 offshore (Bembrick & Lonergan 1976; Adler *et al*. 1998).

The structural framework (Figure 5.1) is described by Herbert & Helby (1980) and comprises eleven onshore structural elements; the Hunter Valley Dome Belt, Hornsby Plateau, Blue Mountains Plateau, the Cumberland Basin with Fairfield, Penrith and Botany sub-basins, Woronora Plateau, Illawarra Plateau, Sassafras Plateau and Boyne Mount Plateau and four offshore principle elements; the Offshore Syncline, the offshore extension of the Newcastle Syncline, an offshore extension of the New England Fold Belt and the Offshore Uplift of the Currarong Orogen. The Hunter-Mooki thrust system is generally considered the north-eastern boundary and the north-western boundary is the Mt Coricudgy Anticline. The Sydney Basin extends offshore to the margin of the continental shelf (Mayne *et al*. 1974) and is difficult to define. Branagan & Packham (2000) note that the basin basement is marked by a number of faults which were active during sedimentation, and produced broad folds, monoclines and faults in the sedimentary succession.

Sedimentation in the Sydney Basin can be divided into many distinct depositional episodes, related to marine transgression and regression and terrestrial sedimentation. In the Sydney Basin the total thickness of the sedimentary package ranges on average from 2 to 3 km over much of the basin, based primarily on drill-hole records and deep seismic profiles (e.g. Herbert 1989; Maung et al 1997; Adler *et al*. 1998; Arditto 2003; Blevin *et al*. 2007) and gravity modelling (e.g. Qureshi 1984; Qureshi 1989; Leaman 1990; Danis et al. 2011; Danis 2012). Danis et al. (2011) notes sediment thickness is greatest in the Cumberland Basin, the central part of the Sydney Basin, ranges from 3 to 3.5km in the Newcastle and Hunter Coalfields and thins to around 1.5 km over the Mt Coricudgy Anticline and Western Coalfields, near the boundary with the Gunnedah Basin and is less than 1 km thick south of the Southern Coalfields.

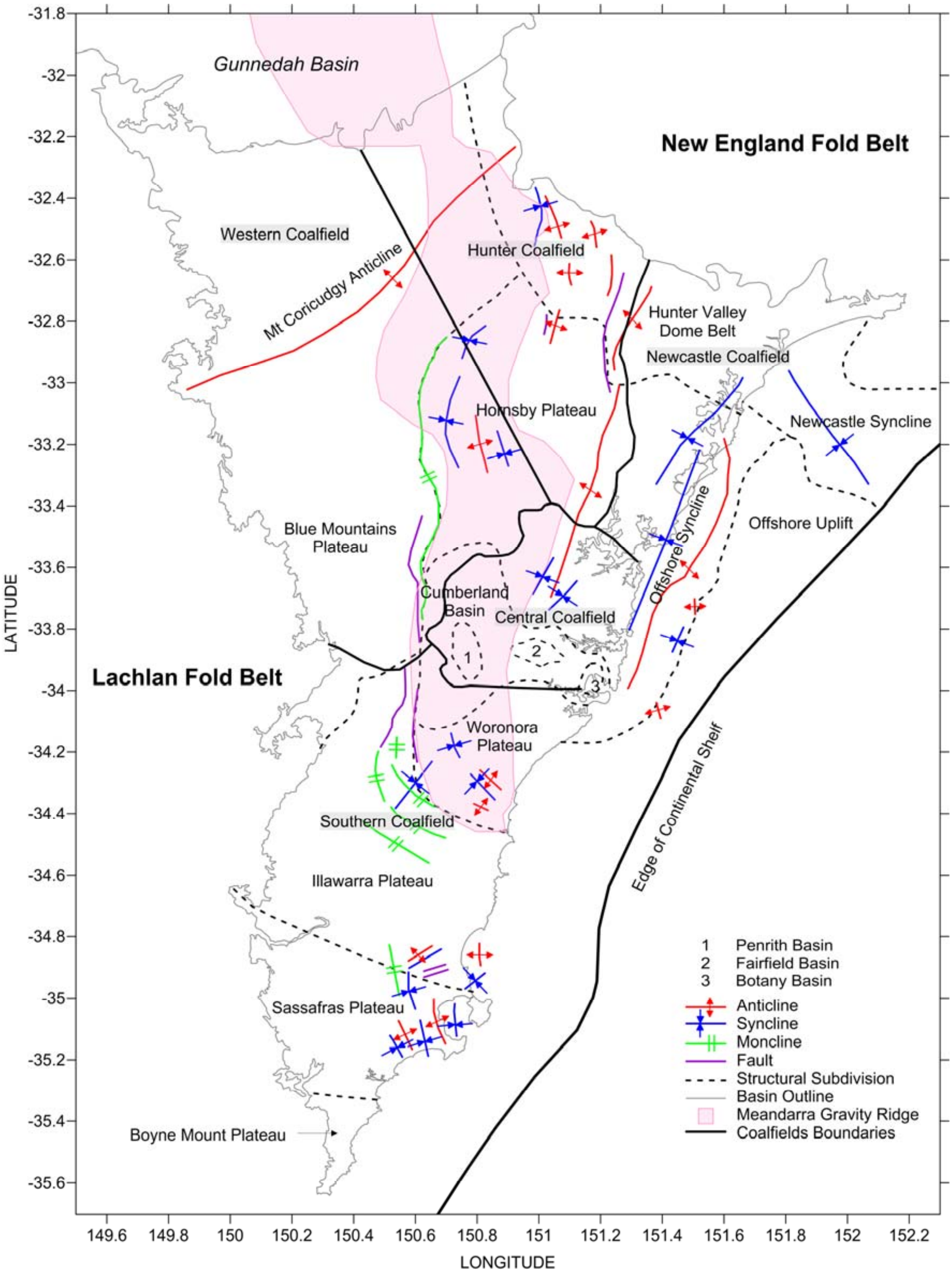

Figure 5.1. Structure and tectonic map of the Sydney Basin. Compiled from Danis (2012), Herbert & Helby (1980), Shepherd & Huntington (1981), and NSW 1:250 000 scanned geological maps Sydney SI56-5, Wollongong SI56-9, Newcastle SI56-2, Ulladulla SI56-13 and Singleton SI56-1.

Geology

Table 5.1 presents a simplified stratigraphy, comparing each of the major coalfields of the Sydney Basin, and Figure 5.2 presents a schematic NE-SW cross-section of the Permian to Triassic stratigraphy in the Sydney Basin.

Table 5.1. A simplified stratigraphy of the Sydney Basin. Modified from Herbert & Helby (1980).

		HUNTER COALFIELD	NEWCASTLE COALFIELD	WESTERN COALFIELD	CENTRAL & SOUTHERN COALFIELD
Triassic	EARLY TO MIDDLE				Wianamatta Group
			Hawkesbury Sandstone		Hawkesbury Sandstone
			Terrigal & Newport Formations		
		Narrabeen Group	Narrabeen Group	Narrabeen Group	Narrabeen Group
Permian	LATE	Singleton Supergroup: Wollombi Coal Measures	Newcastle Coal Measures	Illawarra Coal Measures: Wallerawang Subgroup	Illawarra Coal Measures
		Watts Sandstone	Waratah Sandstone		
		Wittingham Coal Measures: Denman Formation	Dempsey Formation	Baal Bone Coal Measures	Bargo Claystone
		Jerrys Plains Subgroup		Charbon Subgroup	Sydney Subgroup
				Cullen Bullen Subgroup	
		Archerfield Sandstone	Kulnura Marine Tongue	Marrangaroo Conglomerate	Erins Vale Formation
		Bulga Formation		Nile Subgroup	Cumberland Subgroup
		Vane Subgroup	Tomago Coal Measures	Shoalhaven Group: Budgong Sandstone	Budgong Sandstone / Gerringong Volcanics
				Berry Siltstone	Shoalhaven Group: Berry Siltstone
		Maitland Group: Mulbring Sandstone	Maitland Group: Mulbring Sandstone		Nowra Sandstone
		Muree Sandstone	Muree Sandstone		Wandrawandian Siltstone
		Branxton Formation	Branxton Formation	Snapper Point Formation	Snapper Point Formation
	EARLY	Greta Coal Measures: Rowan Formation	Greta Coal Measures	Metasediments & Granite	Yarrunga Coal Measures
		Skeletar Formation			Yadboro & Tallong Conglomerates / Pebbly Beach Formation
		Gyarran Volcanics / Dalwood Group: Farley Formation	Dalwood Group: Farley Formation		
		Ruthorford Formation	Ruthorford Formation		
		Allendale Formation	Allendale Formation		
		Lochinvar Formation	Lochinvar Formation		Clyde Coal Measures / Wasp Head Formation
Late Carboniferous		Seaham Formation Conglomerates	Seaham Formation Conglomerates / Kuttung Series		Talaterang Group Conglomerates

~~~~ Unconformity

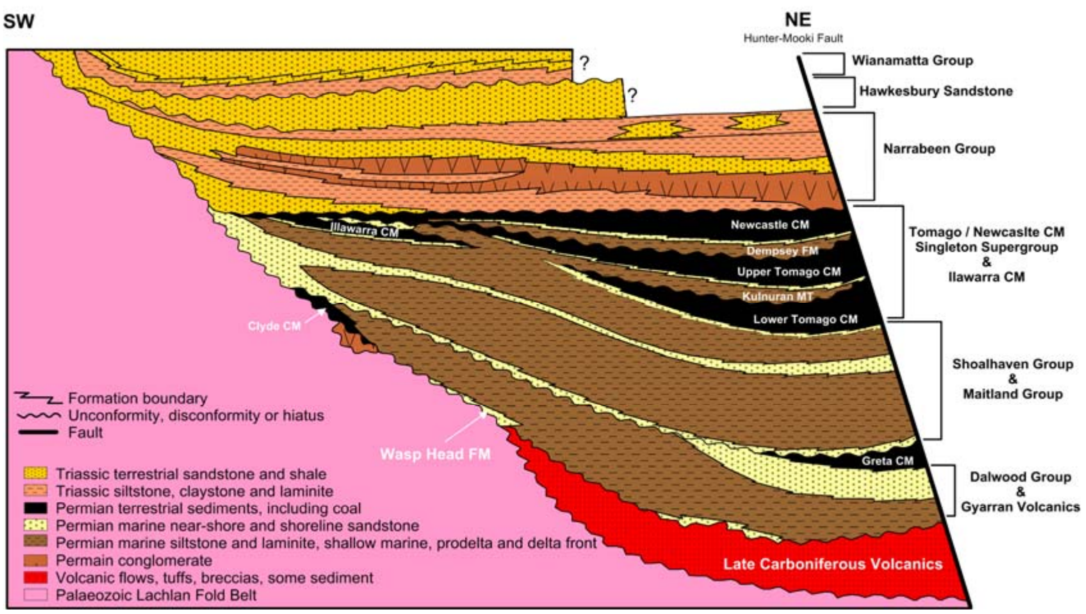

Figure 5.2. A NE-SW schematic cross-section of the Permian to Triassic stratigraphy in the Sydney Basin. Adapted from Danis (2012) and Herbert & Helby (1980).
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During the Late Carboniferous, cratonic rocks of the LFB were emergent and stood elevated at more than 600 m (Herbert 1972). Extensive volcanism during rifting resulted in huge volumes of coarse volcanic debris deposited to the east of the rift (Kuttung Volcanics) and this was followed by alpine and valley glaciers depositing thick fluvioglacial conglomerate, diamictite and varves and the deposition of the Talaterang Group and Seaham Formation conglomerates in eroded valleys of LFB Palaeozoic basement. Volcanism continued into the early Permian with thick basaltic and rhyolitc sequences (i.e. Lochnivar Formation and Dalwood Group). As volcanism subsided subsidence and marine deposition became characteristic with the deposition of the Clyde Coal Measures, Dalwood Group and Greta Coal Measures in extensive marine transgressions. This was followed by basin wide subsidence in the early Late Permian resulting in a transgression which expanded the area of marine deposition with the basal units of the Maitland Group (Branxton Formation) being deposited from reworked fluvio-deltaic sediments in the northern part of the basin and the Shoalhaven Group (Snapper Point Formation) in the southern and wester parts of the basin derived from eroding Late Devonian quartzite headlands. With the movement of the Early Permian sea westwards over the LFB considerable quantities of boulders and pebbles were eroded from coastal cliffs. Another regressive-transgressvie episode occurred prior to the mid Permian finalising the deposition of the Maitland Group and upper parts of the Shoalhaven Group (Berry Siltstone).

After the mid Permian uplift of the NEFB lead to rapid subsidence, erosion and the deposition of as much as 2000m (Herbert & Helby 1908) of terrestrial and marine sediments during three major regressive episodes. These sediments contain the most important coal in the basin; the Tomago Coal Measures, Illawarra Coal Measures and the Singleton Super Group. The source of the sediment in the deltaic environment is from the NEFB with prodelta and delta front environments responsible for the lower Newcastle Coal Measures in the north-eastern part of the basin which can be correlated with the Bargo Claystone in the southern part and with the upper part of the Singleton Super Group (Denman Formation) in the north.

In the Late Permian to Middle Triassic major alluvial systems prograded and sediment was deposited from the NEFB forming the Narrabeen Group, which comprises up to 800 m of lithic conglomerate, quartz lithic sandstone and shale, and Hawkesbury Sandstone. The Narrabeen Group was deposited in three episodic environments; estuarine/ alluvial, fluvial and fluvial-deltaic. Subsidence caused limited transgression and an upward transition to fluvio-deltaic deposits of the upper Narrabeen Group in the Newport and Terrigal Formations of the north-eastern part of the basin. Uplift of the Lachlan Fold Belt to the southwest of the Sydney Basin tilted and led to the erosion of Late Permian and Early to Middle Triassic sediments in the southern part of the basin.

The Middle Triassic Hawkesbury Sandstone is up to 250 m thick and dominantly coarse quartz rich sandstone. The deposition of the Hawkesbury Sandstone occurred in an alluvial environment that has been compared by Conaghan & Jones (1975) with the huge Brahmaputra River system in India. The sand was probably derived from upper Devonian quartzites in the LFB and graphite, commonly found throughout the sandstone, may have been derived from Victorian Ordovician graphitic slates (Herbert & Helby 1980). Overlying this is the Wianamatta Group (comprising the Ashfield Shale, Minchinbury Sandstone and Bringelly Shale), up to 300 m thick and dominantly shale with sporadic thin lithic sandstones. The Wianamatta Group was the last phase of sedimentation directly related to the tectonic development of the Sydney Basin, with sediments deposited in a continuous succession of environments grading upward from subaqueous, to shoreline and ultimately to alluvial during a single major regression

(Herbert & Helby 1980). Deposition in the Sydney Basin was terminated by deformation in the Mid-Triassic. Although Jurassic sedimentation is not evident in the Sydney Basin there are Jurassic volcanic breccia pipes (diatremes). According to Herbert & Helby (1980) it is possible that an unknown, but not great, thickness of early Jurassic sediments may have extended from the Great Artesian Basin unconformably over the Sydney Basin but have since been completely eroded.

CSG Potential

Coal bearing formations in Permian aged sediments are extensive in the Sydney Basin and range in depth from near the surface to over 1 km. The Sydney Basin is divided into five major coalfields; Southern, Central, Newcastle, Hunter and Western, and comprised of black anthracite coal bed of a few centimetres to several meters, interbedded with sandstones, shales, tuffs and claystone. During coal bore drilling in the late 19th Century a number of bores encountered flows of natural gas. The earliest commercial gas was produced from a borehole drilled in Balmain Colliery in 1937 which produced 4300 m^3/week with the hydrocarbons produced used as a motor fuel during WWII. The Sydney Basin has favourable geological attributes for the development of coal seam methane. Gas flows have been observed in the following stratigraphy:

- ❑ Clyde Coal Measures
- ❑ Shoalhaven Group – Conjola subgroup
- ❑ Illawarra Coal Measures – Erins Vale Formation, Bulli Seam and Kembla Sandstone
- ❑ Narrabeen Group – Coalcliff Sandstone, Scarborough Sandstone and Bulgo Sandstone

Gas flows from Australian Oil and Gas Corp Ltd well in the Bulgo Sandstone at Camden-10 well (Well Completion Report [WRC] 050, http://digsopen.minerals.nsw.gov.au/) recorded 14160 m^3/day. Flows of 1020 m^3/day were measured in the Australian Oil and Gas Corp Ltd wells in the Illawarra Coal Measures in Baulkham Hills-1 (WRC 053) and Dural-2 (WRC 035). There are over 60 wells in production near Campbelltown and Camden in the southern coalfield of the Sydney Basin and over 50 wells not in production (Figure 5.3). AGL is currently producing CSG from its Camden Gas Project and Rosalind Park Gas processing plant in the Illawarra Coal Measures.

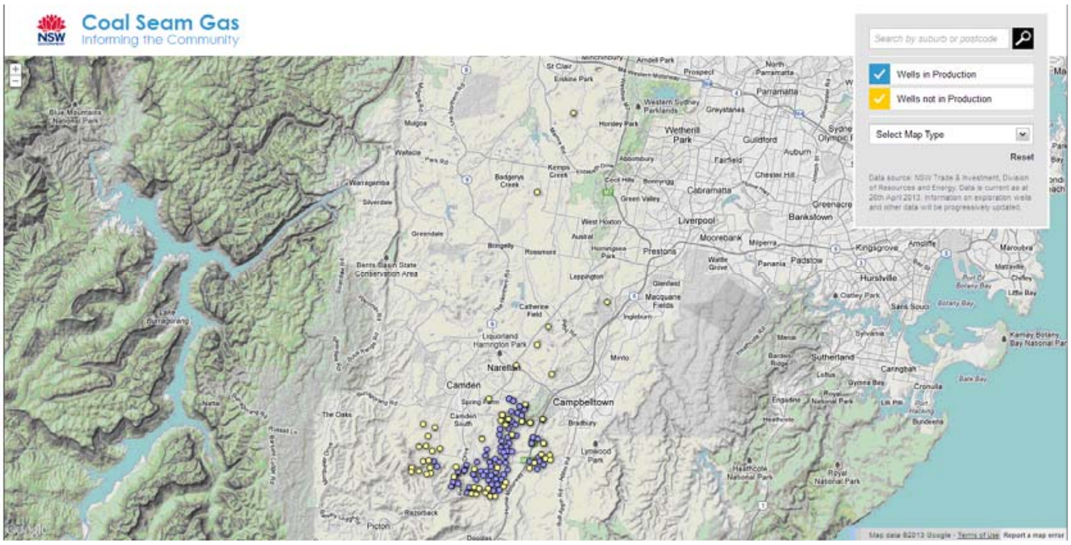

Figure 5.3. Location of CSG wells in production and not in production in the Sydney Basin. From www.csg.nsw.gov.au

1. Permian Coal Measures

Reservoir potential has been identified in the Permian coal sequences which comprise interbedded sandstone, coal, siltstone and claystone with potential reservoirs and seals in many parts. The early Permian marine sandstones of the Shoalhaven Group (Muree, Nowra and Cessnock) show good reservoir character and a sealed by the Mulbring Siltstone, Berry Siltstone and siltstones of the Branxton Formation. However many sandstones contain significant lithic components and exhibit poor permeability. Total organic carbon (TOC) and coal maceral analysis of Late Permian Coal sequences indicate the Tomago, Newcastle, Wollombi, Wittingham and Illawarra Coal measures are good potential gas sources (Cadman & Pain 1998). The Late Permian coal measures show sources of both oil and gas, with the offshore basin possibility more prone to oil. Fine grained sediments deposited during the brief marine incursions that took place during the Late Permian may also have some potential as oil sources.

Vitirinite reflectance data indicates the Permian sequences are overmature and generating dry gas in the central and eastern Sydney Basin, mature for oil generation of the western flank and immature to mature on the northern and southern flanks (Cadman & Pain 1998). Grybowski (1992) suggests that the Early Permian source rocks probably commenced generating hydrocarbons as early as the Triassic but did not attain peak maturity until the Late Jurassic and oil and gas generation in the Late Permian coal measures probably began in the Late Jurassic. Oil shale has also been recorded in the upper parts of the Late Permian Coal Measures around Joadja in the South, Newnes and Glen Davis in the west and in the Greta Coal Measures.

2. Narrabeen Group

Initially the gas recovered from the Narrabeen Group reservoirs was thought to have been sourced from Late Permian coals, as these gases are methane rich, but it appears more likely that these were charged from Triassic shales and claystones (Dooralong Shale, Wombarra Claystone, Stanwell Park Claystone). Sandstone porosity in the Narrabeen Group is variable, with porosities of up to 20 % recorded in some of the cleaner, more quartzose rich units. However in most cases primary porosity has been reduced by the growth of authigenic clays (Cadman and Pain 1998). Permeabilities are generally low (less than 10 millidarcies) and reservoir quality is only moderately good. Attempts to improve the reservoir by stimulation through fracking have so far proved unsuccessful in wells Cecil Park-1 and Badgelly-1.

Triassic source rocks of the Narrabeen Group are considered overmature in the deepest depocentres of the basin but lie within the oil window in the central and eastern portion of the basin and are immature to marginally mature in the far north and southwest (Cadman & Pain 1998). Hydrocarbon generation within the Narrabeen ground was into initiated until the middle of the Cretaceous (Grybowski 1992). Oil has been reported in the basal Narrabeen Group and porosities of 9 % and permeabilities of 0.16-0.28 millidarcies (www.resources.nsw.gov.au/geological/overview/regional/sedimentary-basins/sydbasin).

Geophysics

Seismics

Since the late 1950's reflection surveys have been conducted in the Sydney-Gunnedah-Bowen Basin system, initially by the Bureau of Mineral Resources and private survey companies. Results and interpretation of deep seismic reflection profiles have been undertaken by many authors, including R. Korsch, K. Wake-Dyster, D. Johnstone, D. Finlayson, S. Mayne and P. Arditto. Some seismic reflection profiles are available in the Onshore Deep Seismic Survey dataset (Kilgour 2002) from GA, whilst others can be accessed through State Government department archives such as DIGS. Figure 5.4 shows the location of two selected seismic reflection profiles which have been interpreted.

The east-west profile CD87-115, near Camden, has been interpreted by Blevin *et al*. (2007) for section CD87-115b (Figure 5.5) and shows generally flat lying Permian to Triassic sediments, which appear to thicken towards the east with high-angle, low-to-moderate displacement normal faults offsetting the flat laying sediments. Blevin *et al*. (2007) based on the two-way travel time conversion interpretation of Figure 5.6 suggests basement begins at ~1.75 km on the western end of the profile and deepens to ~2.3 km at the eastern end.

Offshore of the Sydney Basin, profile SY81-24 (Figure 5.7) has been interpreted by Arditto (2003) for economic basement (i.e the depth to the base of petroleum and or coal bearing units as shown by the blue line), the top of the Gerringong Volcanics (green line) and the base of the Narrabeen Group (light blue line). Numerous faults (red lines) are also interpreted. In this profile, near the coast (SP 0) the basement is deepest and then shallows towards SP 800, associated with the structure of the offshore uplift (Figure 5.7). Using the two-way travel time conversion (Figure 5.6), which measures the time taken for the seismic signal to propagate down to a reflector, then back up to the surface (see glossary), basement depth is estimated at ~3 km close to the coast, shallowing to ~2 km over the offshore uplift before deepening to ~3.5 km near the continental shelf.

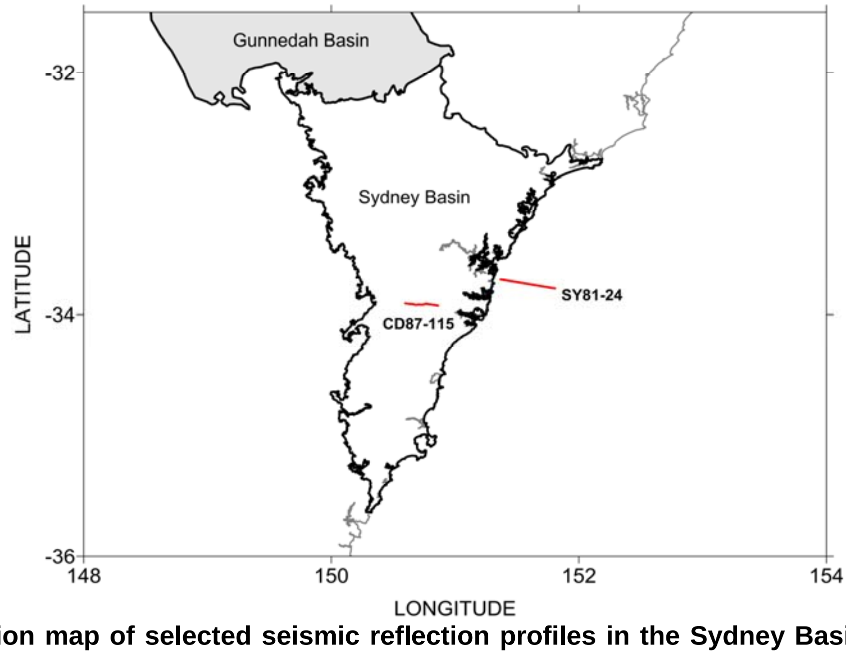

Figure 5.4. Location map of selected seismic reflection profiles in the Sydney Basin. Profiles shown as red lines. Adapted from Danis (2012).

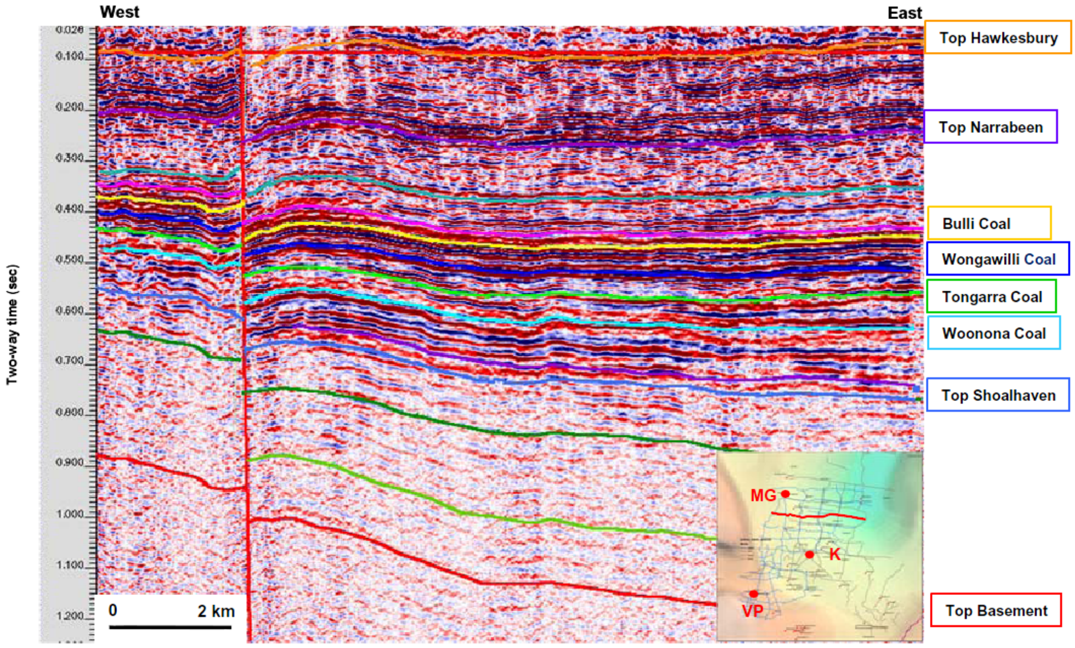

Figure 5.5. Seismic reflection profile line CD87-115b from Blevin *et al*. (2007). Map insert shows nearby boreholes MG = Mulgoa 1, KH = Kirkham 1and VP = Victoria Park 1.

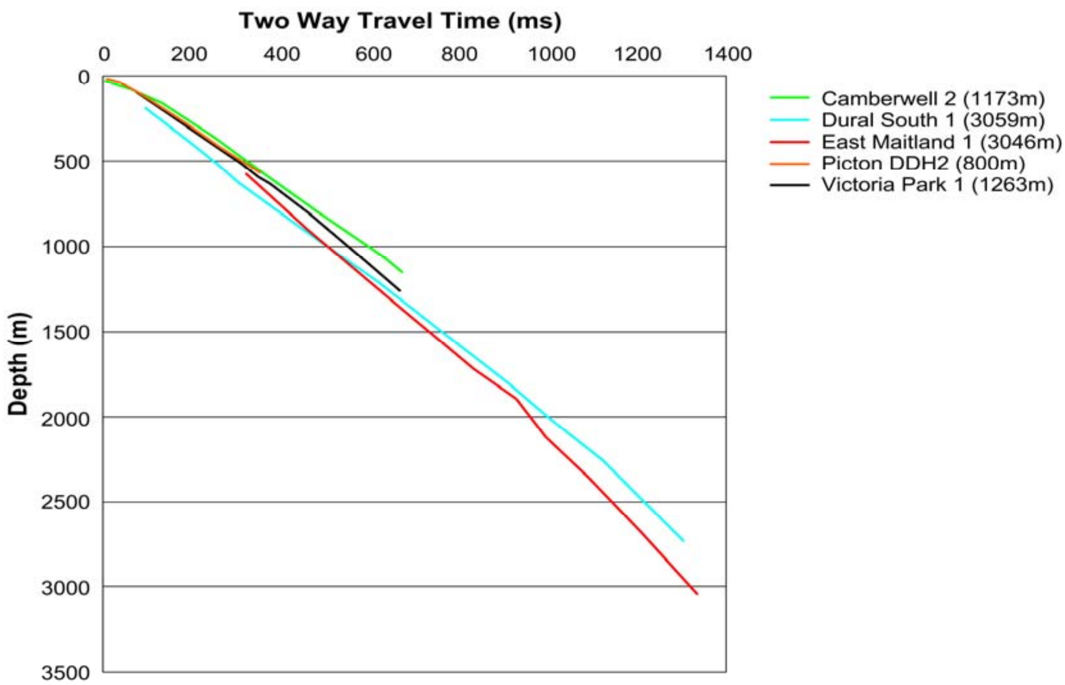

Figure 5.6. Down-hole plot of well velocity data using check shots, measured in milliseconds two way travel time, against well depth in metres to used to convert seismic reflection profile travel times into depth. Modified from Blevin *et al*. (2007).

SY81-24

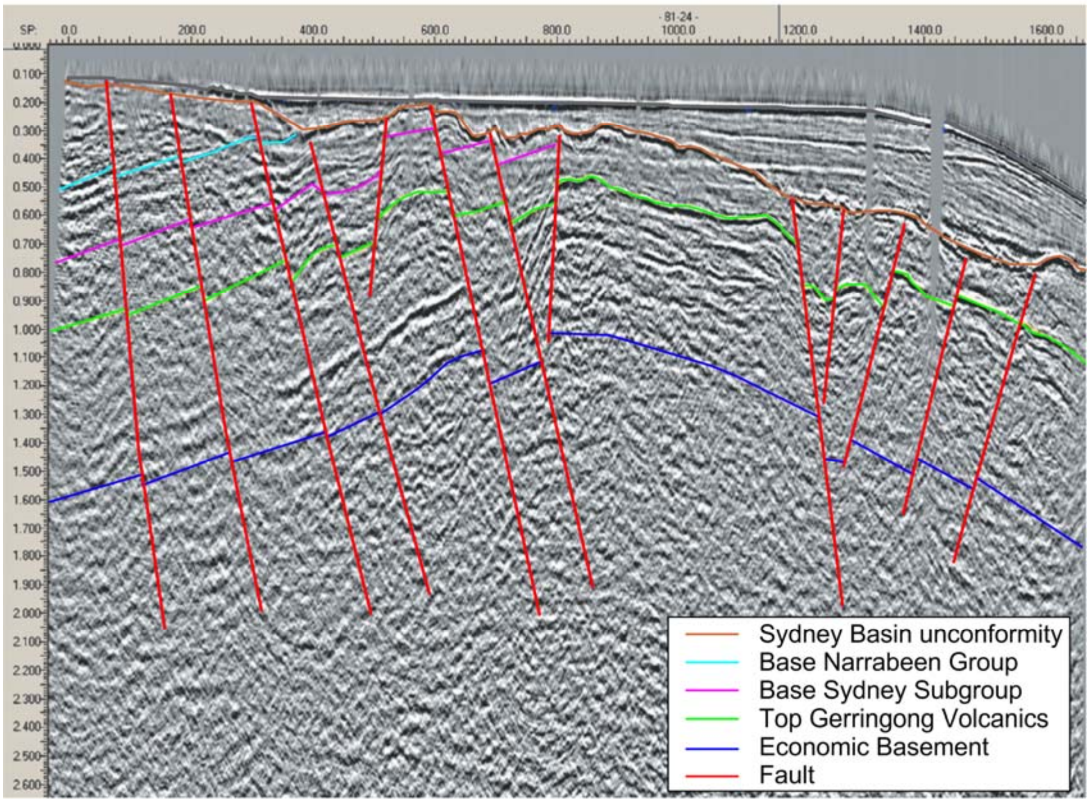

Figure 5.7. Interpreted seismic reflection profile SY81-24. Modified from Arditto (2003).

Potential Field

The gravity anomaly map of the Sydney Basin (Figure 5.8) shows gravity lows as blues to greens and highs as yellow to red. The gravity data, in units of milligals (mgal) is downloaded from the national geophysical archive (Geoscience Australia), and constitutes an amalgam of different surveys over a wide time span. The gravity map is particularly sensitive to buried density anomalies, generally due to major lithological contrasts. Areas of known large granite intrusions such as the Bathurst Batholith, centred around 149.5 ^{o}E -33.5 ^{o}S, show as distinctive purple lows. Gravity lows on the western side of the Sydney Basin generally correspond to exposed mapped granites. Features like the Meandarra Gravity Ridge described by Qureshi (1989) and Krassay *et al.* (2009) appear as a blue to green moderate gravity high extending from the Gunnedah Basin into the Sydney Basin, but is generally not well defined within the Sydney Basin. Within the basin there are several gravity lows (near Mossvale, Muswellbrook and north western Sydney) which may be related to buried granites in the basement.

The total magnetic intensity map (Figure 5.9) for the Sydney Basin shows low intensity in blue to purple and high intensity as red to white. Some magnetic anomalies correspond to surface volcanics, e.g. the Gerringong Volcanics exposed south of Sydney, and the Rylstone Volcanics around Rylstone whilst offshore the high intensity anomalies may relate to volcanic sea mounts. Other anomalies may be related to deeper features including the basal rift volcanics and buried plutons.

Volcanics, intrusions and faults, which may be discernable on either the gravity and or the magnetic maps, have the most potential to affect the permeability of aquifers and aquitards.

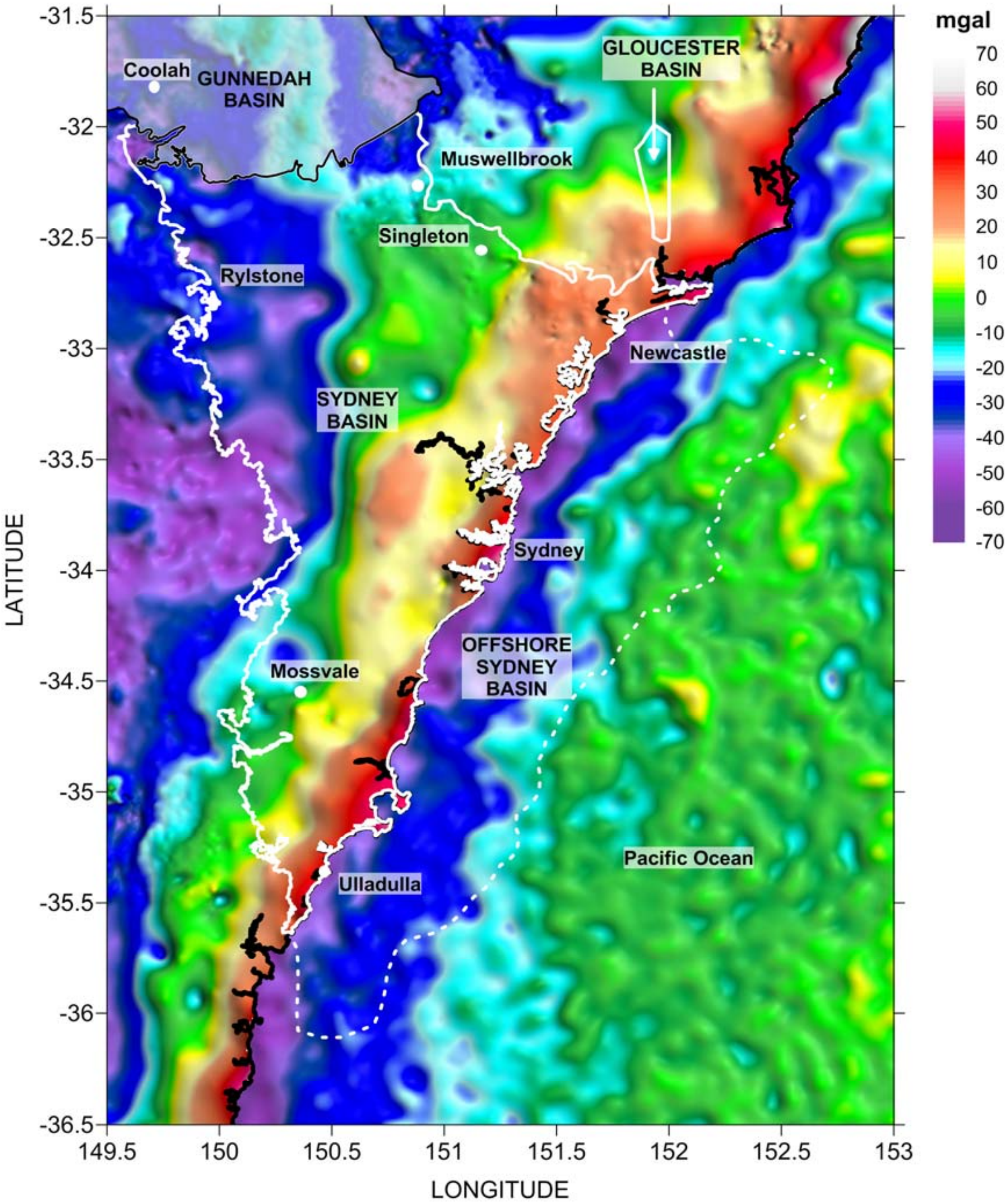

Figure 5.8. Spherical Bouguer gravity map of the Sydney and Gloucester Basins, NSW (data available from Geoscience Australia).

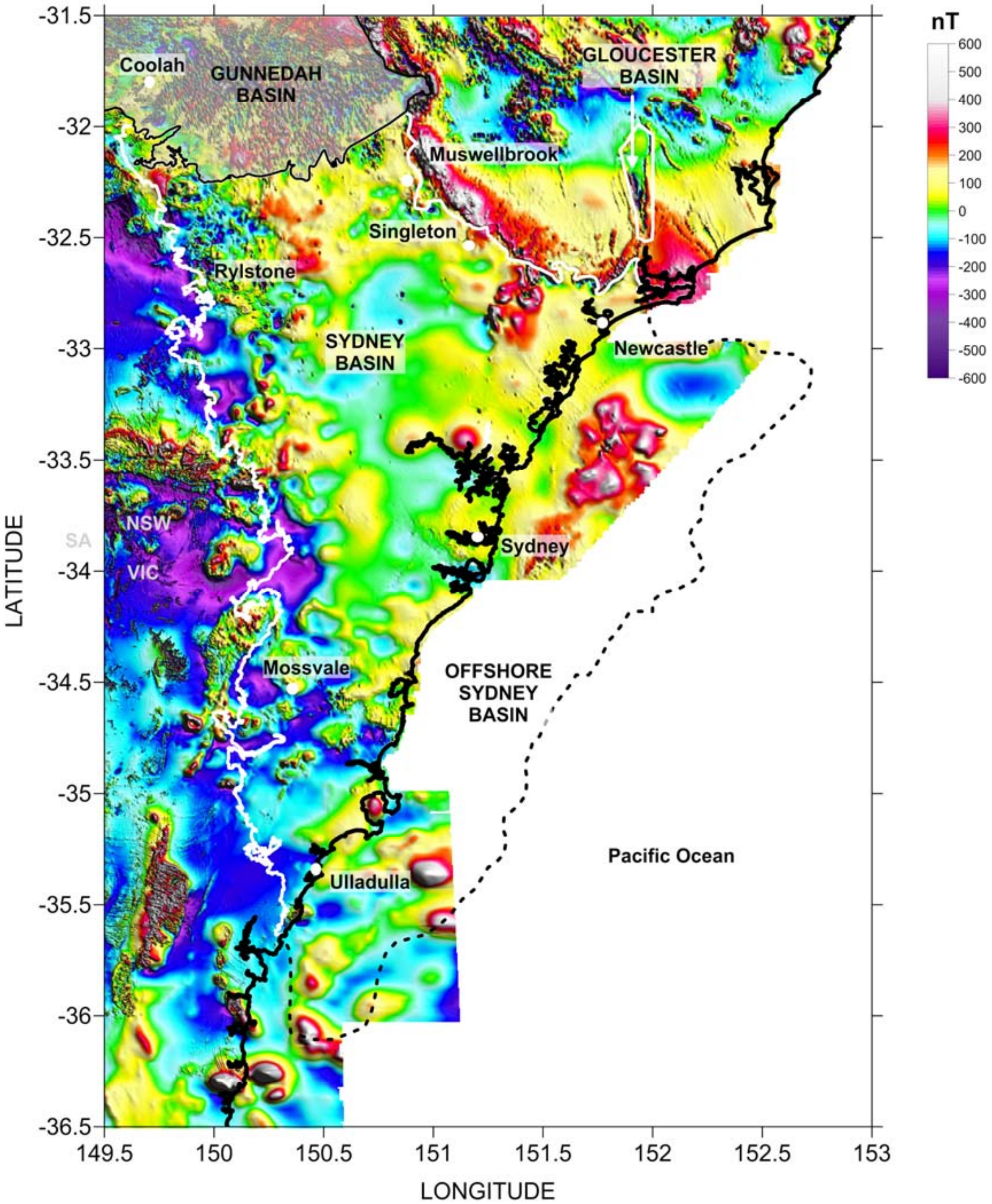

Figure 5.9. Total magnetic intensity map of the Sydney and Gloucester Basins, NSW (data available from Geoscience Australia). The data is from an amalgam of different surveys over time, reduced to a common level, presented in nano-Teslas (nT). The magnetic map is sensitive to changes in the magnetic character of dominant lithologies, and is useful for mapping buried rock units with distinctive magnetic signatures, such as volcanics.

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6. Gunnedah Basin

Structure

The Gunnedah Basin is a structural trough in north-eastern NSW, which forms the middle part of the SGBB system (Figure 3.1 and Figure 6.1). It is bounded by a regional unconformity surface over the LFB in the west and by the NEFB to the east along the Hunter-Mooki Fault. The basin appears continuous with the Bowen Basin in the north and the Sydney Basin in the south, however boundaries are generally drawn between the Bowen and Gunnedah around Moree and between the Gunnedah and Sydney south of Coolah from near Ulan to south of Quirindi (Tadroz 1993). Bembrick *et al*. (1993) defines the northern boundary along a transverse structural high north of Narrabri and the southern boundary along the Mount Coricudgy Anticline. Subsequent modification to these structural subdivisions is based mainly on aspects of stratigraphy and sedimentation within the basins and not on the structures which influence the deposition of the Permian and Triassic sediments (Tadroz 1993).

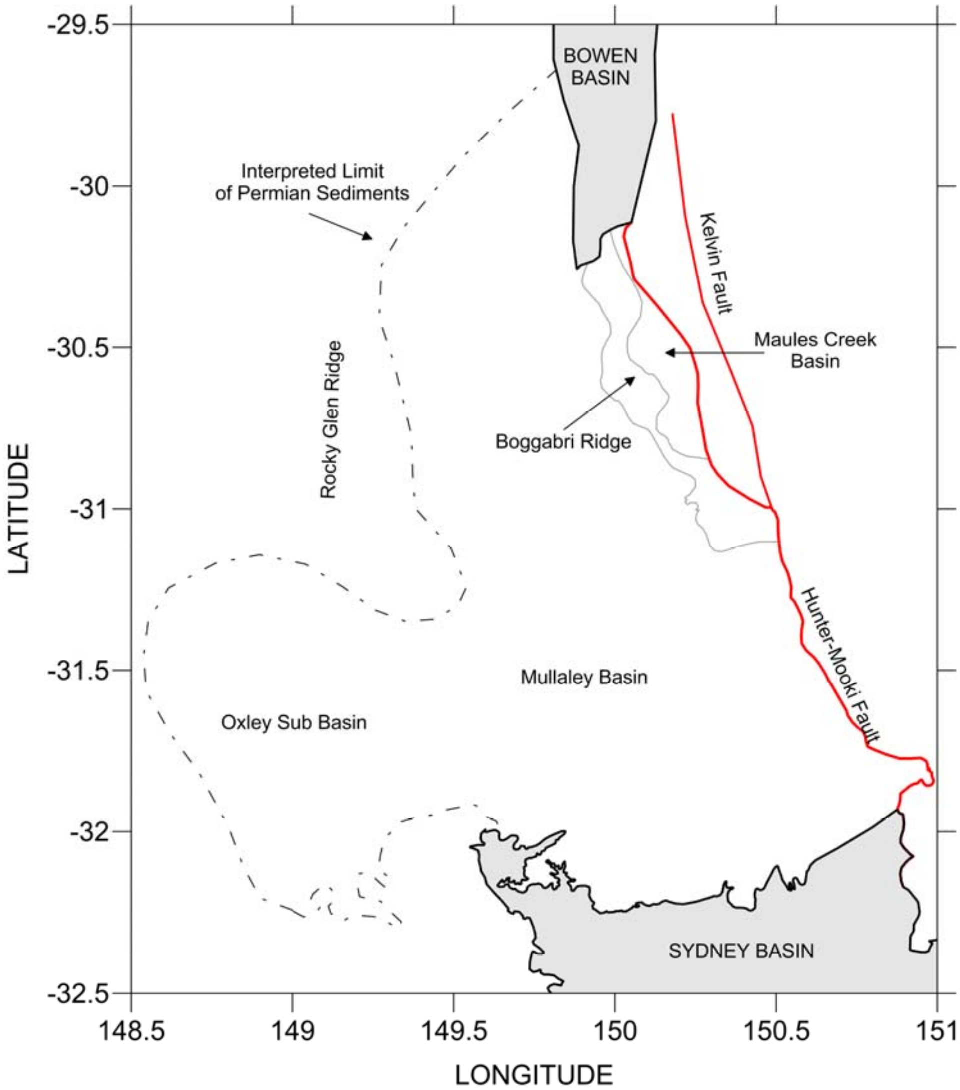


Figure 6.1. Structure and tectonic map of the Gunnedah Basin. Modified from Danis (2012) and Tadroz (1993).

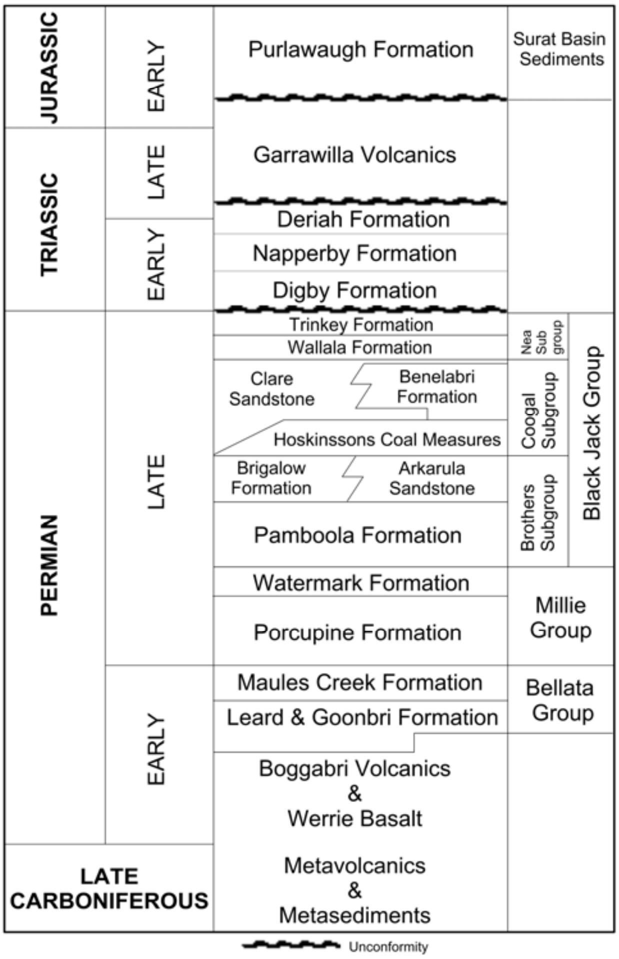
The northerly orientated Boggabri Ridge divides the Gunnedah Basin into two main parts, the Maules Creek Basin and Mullaley Basin (Figure 6.1) and to the west of the Mullaley Basin is the Oxley sub-basin. Sedimentation in the basin follows similar distinct depositional episodes, related to marine transgression and regression and terrestrial sedimentation, as in the Sydney Basin. The Gunnedah Basin is characteristic of a typical intracontinental rift basin and covers an area of approximately 15,000 km^2 (Cadman & Pain 1998) The basin is approximately 150 km long, 100 km wide and up to 3 km deep with to 2 to 3.5 km of volcanics overlain by up to 1 km of sediments (Danis *et al*. 2010).

The extensional tectonic regime in the Late Carboniferous initiated basaltic and rhyolitic rift volcanics (Boggabri Volcanics / Werrie Basalt) which unconformibly overlie the medatsediment and metavolcanic basement rocks of the LFB.

Geology

Table 6.1 presents a simplified stratigraphy of the Gunnedah Basin and Figure 6.2 is an E-W schematic cross-section of the Gunnedah Basin showing Carboniferous to Triassic stratigraphy.

Table 6.1. Simplified stratigraphy of the Gunnedah Basin. Modified from Tadroz (1993).



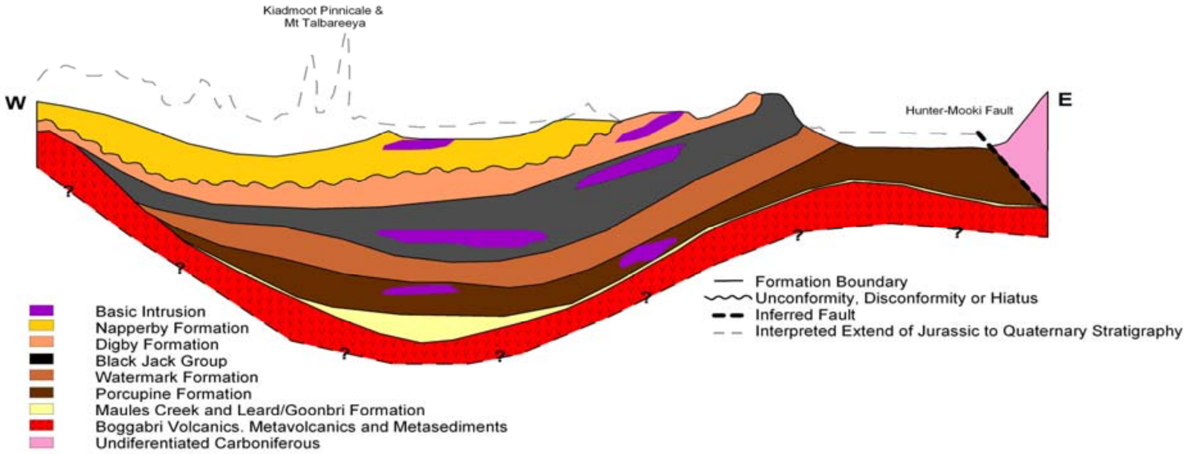


Figure 6.2. An E-W schematic cross-section of the Gunnedah Basin showing Carboniferous to Triassic stratigraphy. The approximate extent of Jurassic to Quaternary stratigraphy shown as dashed line. Modified from Danis (2012) and Tadroz (1993).

In the Gunnedah Basin, marine and non-marine Permian and Triassic sediments rest unconformably upon the Late Carboniferous to Early Permian silicic and mafic volcanics of the Boggabri Volcanics. Rifting in the extensional tectonic regime during the Hunter Bowen Super Cycle 3 produced half-graben like structures that received sediment from neighbouring highlands (Tadroz 1993) with basin fill localised in small, rapidly subsiding, troughs separated by highlands and ridges of silicic and mafic volcanics. Fluvial processes redistributed weathering from the dormant volcanic terrane with the northerly orientated Boggabri Ridge acting as the principal sediment source. The lacustrine sediments of the Leard and Goonbri Formations accumulated in the most rapidly subsiding areas but were soon inundated by the coal bearing alluvial fan deposits of the Maules Creek Formation (Danis *et al*. 2010). The Maules Creek Formation attains a thickness in excess of 800 m in the Maules Creek Basin and possibly thicker adjacent to the Mooki Fault but to the west of the Boggabri Ridge the formation is less than 100 m thick.

Compression during Hunter-Bowen Super Cycle 4 converted the rift basin into a foreland basin. In the early part of the Late Permian deposition the marine shelf sediments of the Porcupine Formation occurred. These sediments are equivalent to the Snapper Point Formation (base of the Shoalhaven Group) and Braxton Formation (base of the Maitland Group) in the Sydney Basin. The Porcupine Formation is up to 10 m along the western margin of the Mullaley basin, 20 to 60 m thick in the north and from 30 to >170 m thick in the south and south-east. The Watermark Formation gradationally overlies the Porcupine Formation and is characterised by siltstone and claystone, ranges in thickness from 175 to 230 m and represents the maximum extent of Late Permian marine regression in the Gunnedah Basin. Deposition of the lower Black Jack Formation in the middle Late Permian is characterised by a south-westerly progradation of deltas, sourced from the NEFB region, followed by regional inundation and shallow marine sedimentation. Deposition of the coal-bearing Black Jack Formation occurred in the middle Late Permian where lowering of the sea level provided appropriate conditions for widespread peat accumulation. Sedimentation was interrupted by a marine incursion, caused by tectonic subsidence, resulting in the deposition of the Arkarula Sandstone and the upper Black Jack Formation which is characterised by conglomeratic sandstone and an abundance of tuff and pyroclastic detritus (Tadros 1993).

In the Late Permian convergence resulted in major basin tilting and uplift, which is particularly evident in the northern Gunnedah Basin, the termination of coal sedimentation and erosion of a thick section of Permian rocks. A regional angular unconformity exists between the Black Jack Group and the overly Triassic Digby Formation. Deposition resumed in the Early Triassic with a major alluvial systems that prograded southwards and south-westwards over the eroded surfaces of the coal measures or the underlying sediments (Tadroz 1993). Thick conglomerate sequences in the form of large alluvial fans and outwash sediments were introduced from the NEFB region across the Hunter-Mooki Fault system to the south-eastern Gunnedah Basin as the lower part of the Digby Formation. Renewed subsidence resulted in the deposition of the Napperby Formation, a sequence of siltstone/claystone, interbedded sandstone/siltstone to sandstone, derived from the NEFB and represent progradation of lacustrine deltas. The Deriah Formation is a distinctive green sandstone at the top of the Triassic sequence in the Gunnedah Basin is thought to be a response to the contemporaneous volcanic activity in the NEFB or possibly the appearance of the Nandwear Igneous Complex north east of Gunnedah. Equivalent lithologies to the Hawkesbury Sandstone are not present in the Gunnedah Basin, as the NEFB remained the dominate source of sedimentation. Final filling of the Gunnedah Basin was dominated by detrutus shed from the NEFB (Glen 2005). A major mid-Triassic episode of deformation cause reverse faults and uplifted small blocks from which vitrinite reflectance data suggests up to 2km of Triassic and Permian sediments (Tadroz 1993) was removed. Compressional and left lateral strike-slip movement on the Hunter-Mooki Fault resulted in a number of high relief anticlines (Glen 2005). During the Nurassic-Cretaceous and the breakup and dispersal of Pangea and east Gondwanaland, epicontinental basins (e.g. Surat Basin) developed and resulted in sedimentation and volcanism (Garrawilla Volcanics) in the northern and western parts of the basin.

CSG Potential

Discoveries of gas in the Gunnedah Basin have been in the Permian Porcupine Formation and Black Jack Group and Triassic upper Digby Formation. The Porcupine Formation, comprised of lithic sandstones and minor conglomerates and siltstones, showed gas flows of 28 000m^3/day from Wilga Park 1 located 12 km WSW of Narrabri. This reserve is considered to be small and capable of generating only dry gas (Cadman & Pain 1998).

Gas has been recorded in bores and wells whilst drilling the Black Jack Group and is thought to be coalbed methane associated with Late Permian coal sequences. The Arkarula Sandstone is considered a potential reservoir with porosities of 16 % to 18 % and permeabilities of 6 to 31 millidarcies (Cadman and Pain 1998, Hamiton *et al*. 1988). The Brigalow Formation is also considered a primary exploration target though reservoir properties are variable with porosity averaging 15-20% and permeabilities varying between 10 millidarcies and several darcies (Hamilton *et al.* 1988). Both the Arkarula and Brigalow are sourced from fluvial sand pulses which transgressed the basin from west, and derived from the LFB. The Clare Sandstone is also considered a potential reservoir with 11 % to 20 % porosity and permeabilities of up to 277 millidarcies. Seals for the Black Jack Group are considered to be by the intraformation shales, siltstones and claystones.

The upper Digby formation is comprised of medium to coarse grained quartzose sandstone with gas flows of 9600 m^3/day recorded in Coonarah 1/1A, located 23 km west of Narrabri. Porosities of up to 13 % and permeabilities of over 700 millidarcies have been measured (Cadman & Pain 1998).

Vitirinite reflectance data (e.g. Hamilton *et al*. 1988; Russell & Middleton 1981; Etheridge 1981) indicate that Jurassic and Triassic source rocks are immature over most of the northern Gunnedah Basin and only towards south the Triassic becomes marginally mature. The Permian section is marginally mature over much of the basin but to the west of the Boggabri Ridge, in the Maules Creek sub basin and in the south eastern Gunnedah Basin the Permian source rocks are considered marginally mature to mature (Cadman & Pain 1998). In the vicinity of igneous intrusives, which are common throughout the basin, elevated thermal maturities are anticipated.

Southwest of Narrabri there are over 50 coal seam gas wells, which are not in production, shown on the NSW Coal Seam Gas location map (Figure 6.3).

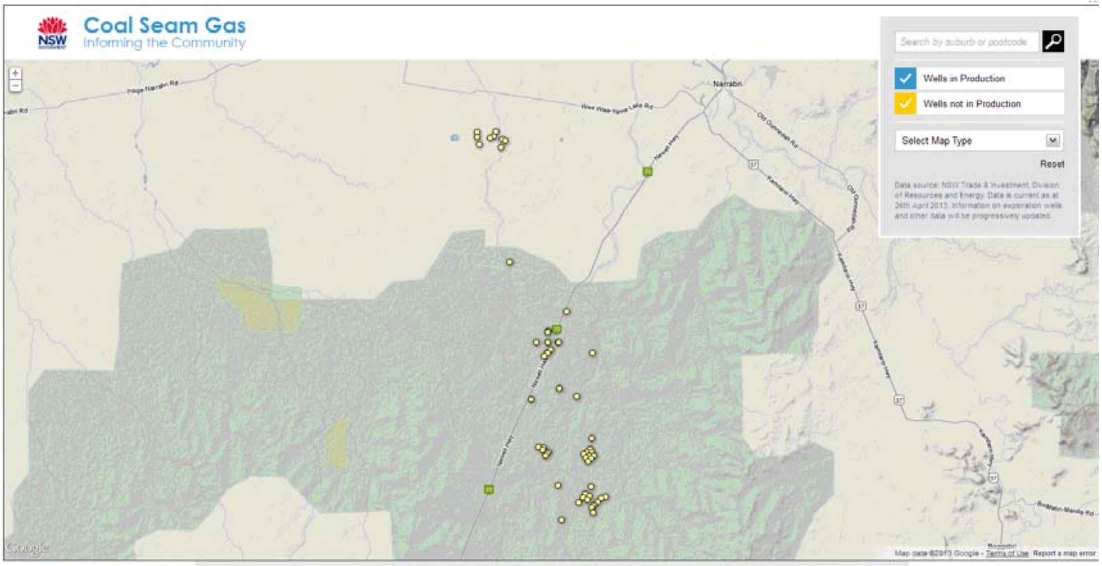


Figure 6.3. Location of CSG wells in production and not in production in the Gunnedah Basin. From www.csg.nsw.gov.au

Geophysics

Seismics

In the Gunnedah Basin, profile BMR91.G01 (Figure 6.4 and Figure 6.5) shows the geometry and structure through the northern part of the basin. Korsch *et al.* (1993) provides an interpretation of the seismic reflection profile and a detailed interpreted geological cross-section through the Gunnedah Basin (Figure 6.5). The profile shows the Lachlan Fold Belt exposed on the surface in the west at the Rocky Glen Ridge and then extending underneath the sediments of the Gunnedah Basin to be truncated by the Tamworth Belt at the Kelvin Fault and the New England Fold Belt at the Peel Fault. A closer look of the profile across the Gunnedah Basin shows the basal Permian Volcanic unit (of the Boggabri Volcanics and Werrie Basalt) is underneath the sediments of the Gunnedah Basin and truncated by the Kelvin Fault. The basal volcanics interpreted at the surface, in the centre of the Gunnedah Basin, are correlated with the exposed Boggabri Ridge. On the edge of the Gunnedah Basin the geometry of the major faults is clearly observable. Sediments from the Gunnedah Basin are interpreted to extend some distance down the Mooki Fault before being truncated at the base of the Kelvin Fault.

Korsch *et al*. (1993) interprets a large amount of volcanics at the base of the Gunnedah Basin at depths of 1 km or less (based on the two-way travel time conversion in Figure 5.6).

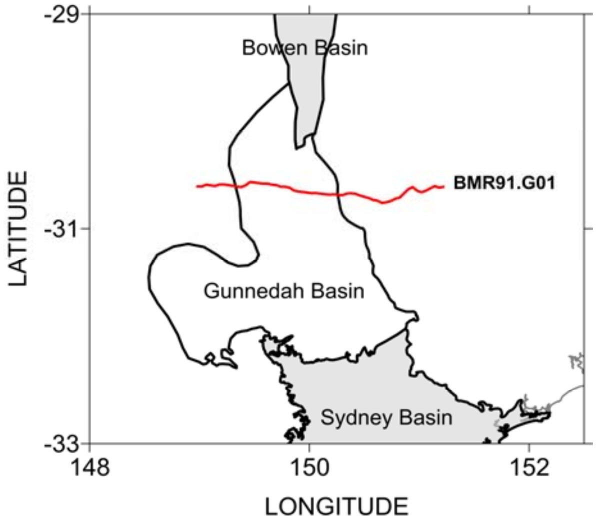


Figure 6.4. Location map of selected seismic reflection profiles in the Sydney-Gunnedah Basin. Profiles shown as red lines.

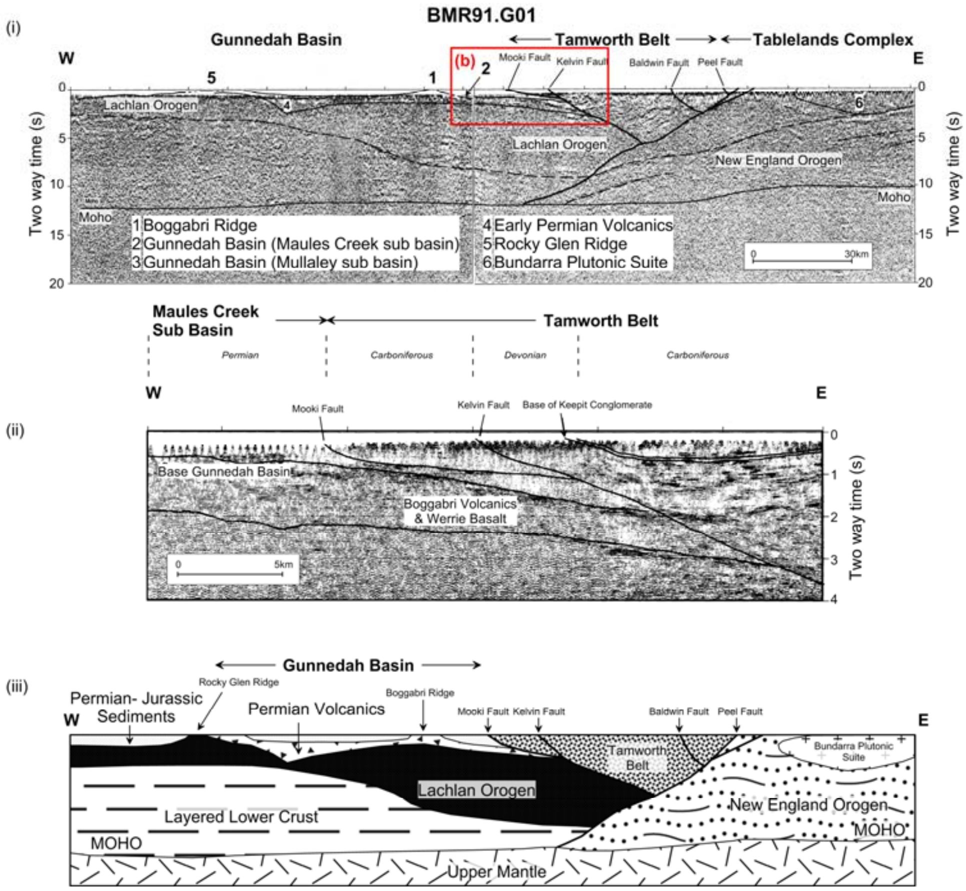


Figure 6.5. (i) Interpreted deep seismic reflection profile BMR91.G01 of the Gunnedah Basin with (ii) close up of the Gunnedah Basin near the Mooki Fault and (iii) an interpreted geological cross-section. Modified from Danis (2012) and Korsch *et al*. (1993).

Potential Field

The gravity anomaly map of the Sydney Basin (Figure 6.6) shows gravity lows as blues to greens and highs as yellow to red. The Meandarra Gravity Ridge described by Qureshi (1989) and Krassay *et al.* (2009) appears as a blue to green moderate gravity high extending from the north of the Gunnedah Basin near Moree to the south and into the Sydney Basin. This ridge is associated with basal rift volcanics which is generally less than 1 km beneath the surface. Gravity lows in the western part of the basin correspond to exposed and buried mapped granites.

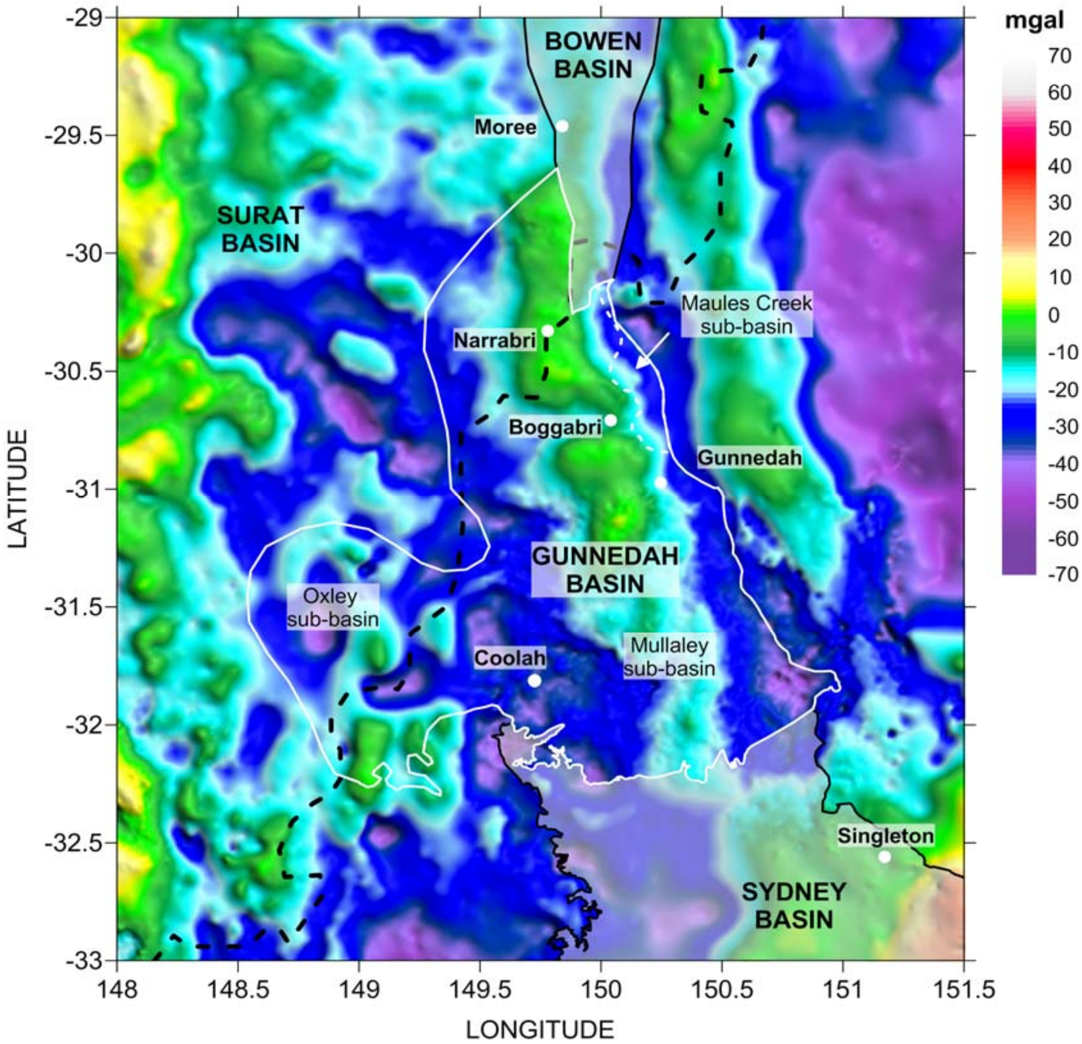


Figure 6.6. Spherical Bouguer gravity map of the Gunnedah Basin, NSW (data available from Geoscience Australia).

The total magnetic intensity map (Figure 6.7) shows low intensity areas as blue to purple and high intensity as red to white. Within the Gunnedah Basin the areas of high intensity correspond to exposed surface volcanics of Tertiary and Jurassic age, such as the Liverpool Ranges and Garrawilla Volcanics, are numerous exposed Jurassic volcanics. Exposed basal volcanics show as high intensity areas along the Boggabri Ridge, however their full subsurface extent is ambiguous. With the exception of around Narrabri the features shown on the western boundary of the basin most likely correspond to deeper structures given the presence of overlying Surat Basin sediments.

Volcanics, intrusions and faults, which may be discernible on either the gravity and or the magnetic maps, have the most potential to affect the permeability of aquifers and aquitards.

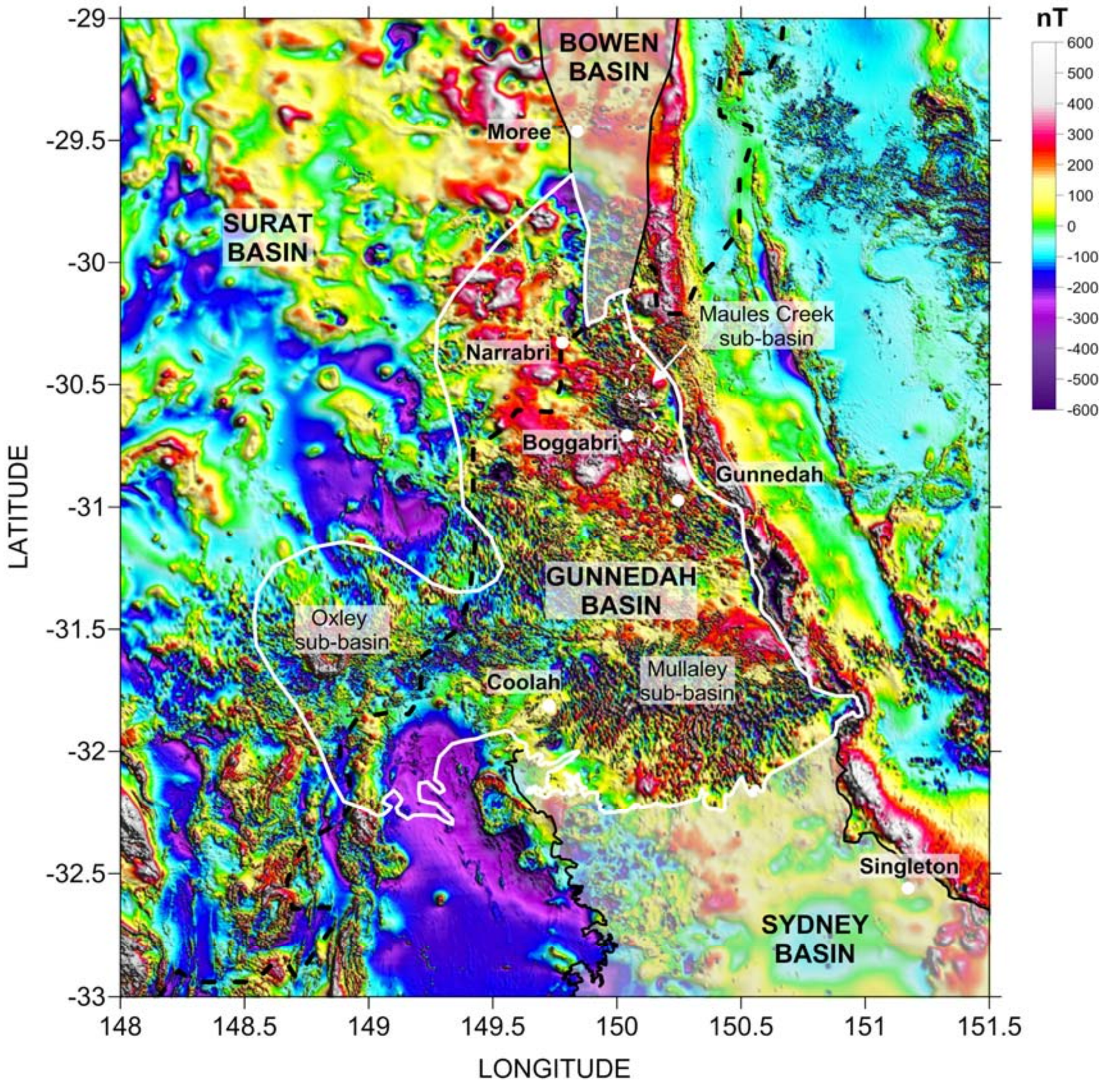


Figure 6.7. Total magnetic intensity map of the Gunnedah Basin, NSW (data available from Geoscience Australia).

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7. Bowen Basin

Structure

The Bowen Basin is an elongate, north-south trending, asymmetrical basin extending from northern NSW through central QLD covering an area of approximately 200,000 km^2. It is the largest part of the SGBB system at approximately1200 km long, 350 km wide and 8km deep. The Bowen is divided into 13 main structural areas with the major structural features shown in Figure 7.1. The eastern boundary of the basin is marked by a series of north-south orientated thrust faults (Moonie-Goondiwindi and Leichardt-Burunga) extending south from the Connors-Auburn Arch.

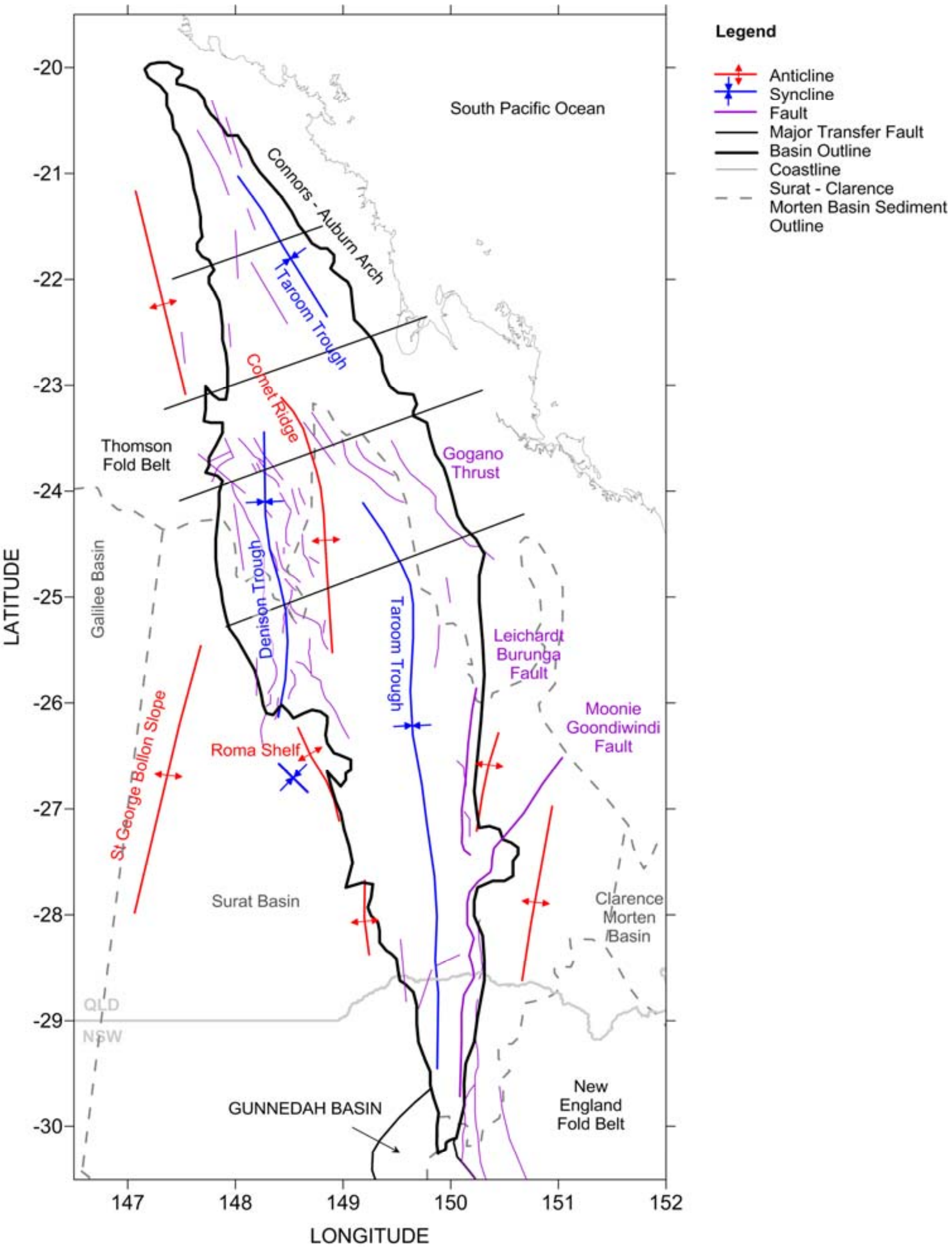

Figure 7.1. Structure and tectonic map of the Bowen Basin. Compiled from Danis (2012), Baker *et al*. (2009), Tadroz (1993), Fielding *et al*. (1995) and Cadman & Pain (1998).

The western margins are less well defined, with sediments deposited on the Saint George-Bollon Slope thinning and inter-fingering with sediments of the Galilee Basin. The Comet platform separates the two major depositional centres of the Denison and Taroom Trough (Cadman & Pain 1998). The Bowen Basin appears continuous with the Gunnedah Basin the south however the southern boundary is generally drawn around the basement high near Moree (Tadros 1993). Deep crustal seismic reflection surveys (e.g. Finlayson *et al.* 1990; Korsch *et al*. 1992) and gravity modelling (Danis *et al*. 2012) show the basins asymmetrical nature, the generally north-south orientation of major faults, thrust zones and deep sedimentation in the central part of the basin. The asymmetric basin shape and elongate depocentre (Waschbusch *et al.* 2009) formed between the early Late Permian and the late Early Triassic in association with contraction, compression and thrusting events (Fielding *et al*. 1995).

Sedimentation is estimated to range between 8 km (Danis et al 2012) to up to 10 km thick (Korsch & Totterdell 2009) and is a repeated sequence of marine and terrestrial deposition resulting in the formation of sandstones, shales, claystones and coal intermingled with extrusive volcanics and the intrusion of plutons. A simplified stratigraphy is presented in Table 7.1 and Figure 7.2 is schematic cross-section through the central part of the Bowen Basin.

Table 7.1. Simplified stratigraphy of the Bowen Basin. Modified from Day *et al*. (1983), Cadman & Pain (1998) and Fielding *et al*. (1995).

AGE		GROUP	WEST SIDE	Denison Trough	Comet Ridge	Collinsville Shelf	Roma Shelf	Taroom Trough	EAST SIDE
CRETACEOUS	Early	Rolling Downs Gp	Wallumbilla FM				Wallumbilla FM		
CRETACEOUS / JURASSIC	Early / Late	Blythesdale Gp	Bungil FM Mooga SS Orallo FM Gubberamunda SST				Bungil FM Mooga SS Orallo FM Gubberamunda SST		
JURASSIC	Middle	Injune Creek Gp / Walloon FM	Westbourn FM Springbok SS Wallon CM				Westbourn FM Springbok SS Wallon CM		
JURASSIC	Early	Bundamba Gp	Hutton SS Evergreen FM Precipice SS				Hutton SS Evergreen FM Precipice SS		
TRIASSIC	Late								
TRIASSIC	Middle	Mimosa Gp	Moolayember FM			Moolayember FM		Moolayember FM / Wandoan SS	Wandoan SS
			Clematis FM			Clematis FM			Cabawin FM
TRIASSIC	Early	Rewan Gp	Rewan FM						Cabawin FM
PERMIAN	Late	Black Water Gp		Bandanna FM Black Alley Shale / Winnathoola CM Peawaddy FM Catherine SS / Ingelara FM	Rangal CM Fort Copper CM Moranbah CM German Creek FM		Bandanna FM Black Alley Shale / Winnathoola CM Tinowon FM / Wallabella CM Muggleton FM	Baralaba CM Gyranda FM Flat Top FM	Kianga FM
		Back Creek Gp		Freitag FM	Aldebaran SS	Blenheim FM		Barfield FM	Back Creek FM
	Early			Aldebaran SS		Collinsville CM		Oxtrack FM	
				Cattle Creek FM		Tiverton FM		Buffel FM	
				Reid Dome Beds			Combarngo Volcanics	Camboon Volcanics	
CARBONIFEROUS	Late					Lizzie Creek / Bulgonnuna Volcanics	Roma Granite	Camboon Volcanics	Camboon / Connors Volcanics
			Timbury Hills FM				Timbury Hills / Kuttung FM	Kuttung FM	

Gp= Group, CM= Coal Measures, FM= Formation, SS= Sandstone, SST= Siltstone

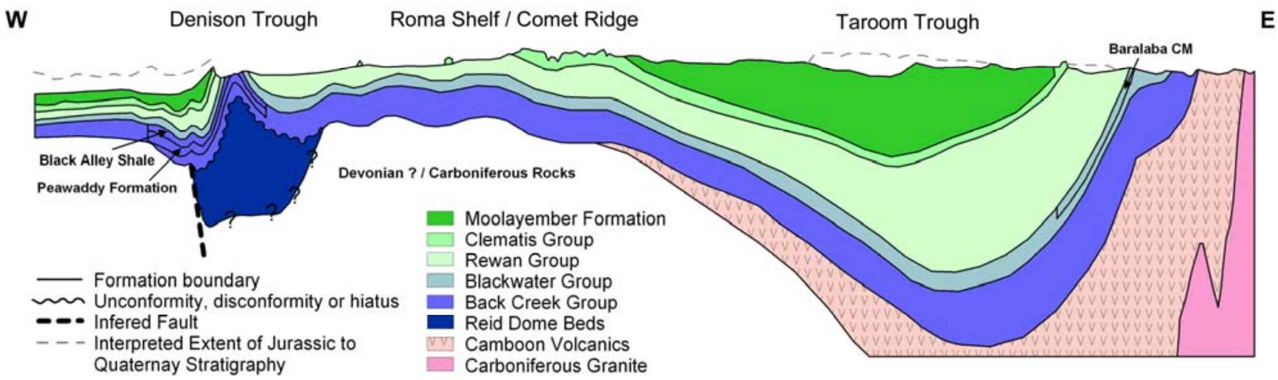

Figure 7.2. E-W schematic cross-section of the central Bowen Basin showing Carboniferous to Triassic stratigraphy. Approximate extent of Jurassic to Quaternary stratigraphy shown as dashed line. Adapted from Danis (2012) and Malone *et al*. (1967).

Whilst only a fraction of the Bowen Basin is present within NSW the depositional history, structure and geology of the basin as a whole is given here for a more complete understanding.

The first period of extensional activity in the latest Carboniferous to earliest Permian (Fielding *et al*. 1995, 2000) produced the lower Lizzie Creek, Bulgonunna and Connors volcanics around the northern part of the basin prior to the formation of the Denison Trough. In the Early Permian a series of extensional basins formed with a series of grabens and half grabens from crustal extension (Cadman & Pain 1998; Elliott 1989) producing the Denison and Taroom Troughs. The earliest deposits in the Denison comprising fluvial and lacustrine facies with locally thick coal bodies were the sequences of the Reid Dome beds interbedded with a bimodal suite of basaltic and felsic rocks (Fielding *et al*. 1995, 2000). Volcanics (Combarngo Voclanics) were laid in the west on the flank of the Roma Shelf and in the east of the Taroom Trough (Camboon volcanics/andesite) (Murray 1994; Cadman & Pain 1998).

Rift development in the Denison Trough and volcanism in the Taroom Trough was succeeded by a period of thermal subsidence, driven by foreland loading (Brakel *et al*. 2009), depositing sediments from marine transgressive-regressive cycles through the late Permian. Quartz rich sediment continued to be shed eastwards from uplifted basement into the western part of the Denison Trough. In the Denison Trough subsidence produced four marine to marginal-marine transgressive-regressive cycles which deposited the Cattle Creek Formation, Aldebaran Sandstone, Freitag Formation and Peawaddy Formation. In the Taroom Trough subsidence produced the marine volcaniclastic sediments at the top of the Camboon Volcanics (Brakel *et al*. 2009) and the lower Back Creek Group.

Towards the end of the Permian tuffacous silts and shales were deposited followed by coal sequences. The effects of thrust loading on the eastern margin of the basin in the Late Permian limited the volumes of volcanic detritus entering the basin and lead to the deposition of the upper part of the Back Creek Group. The residual marine basin, now isolated from the palaeo-Pacific ocean, was infilled by three southward progradational pulses of the Blackwater Group such that by the end of the Permian alluvial plain conditions were established across the entire basin. At the end of the Permian granites intruded to the east of the basin and there was movement on the Moonie-Goondivind Fault and Leichardt Fault which continued into the Triassic (Cadman & Pain 1998).

As thrust loading proceeded the basin became overfilled and coal-bearing facies gave way to the reddened alluvial strata of the Rewan group, consisting of interbedded red, gray-green and dark grey shales, siltstones and lithic sandstone with minor amounts of conglomerate (Cadman & Pain 1998) approximately <300 m thick, shortly before the Permian-Triassic boundary (Fielding *et al*. 1995). Sediments were derived from elevated source areas to the south, east and north and were distributed by meandering streams (Day *et al*. 1983). Arc derived sediment continued to accumulate in the Bowen Basin at least until latest Middle Triassic, interrupted by a massive influx of quartzose, craton-derived sediment of the Clematis Group (Fielding *et al*. 1995). Renewed subsidence of the Taroom Trough was marked by the accumulation of sediments from the Middle Triassic Moolayember Formation (lithic sandstone, mudstone, shale and conglomerate <1650 m thick) in a fluvio-lacustrine environment (Day *et al*. 1983) with sediment sourced from areas in the north and east.

Extensive erosion occurred in the Middle to Late Triassic (Waschbusch *et al*. 2009) and movement on the faults on the eastern margin ceased (Cadman & Pain 1998). It has been estimated that up to 3000 m of strata may have been removed (Beeston 1986). Closure of the Bowen Basin occurred, followed by the deposition of the unconformably overlying Surat Basin in the Early Jurassic to Early Cretaceous (Waschbusch *et al*. 2009).

CSG Potential

The work of Cadman & Pain (1998) has reviewed hydrocarbon discoveries in the Bowen basin and this information is summarised in this section. Hydrocarbon discoveries have been made in the Bowen Basin in the following stratigraphic units:

- Reid Dome Beds
- Cattle Creek Formation – Staircase Sandstone
- Aldebaran Sandstone
- Freitag Formation
- Ingelara Formation
- Catherine Sandstone
- Peawaddy Formation
- Mantuan Formation
- Tinowon Formation
- Back Creek Group
- Bandanna Formation
- Blackwater Group
- Rewan Formation
- Showgrounds Sandstone
- Clematis Sandstone
- Moolayember Formation

Of these units, the following are present in the southern most part of the Bowen Basin in NSW at the boundary with the Gunnedah Basin.

1. Blackwater Group

The Blackwater Group contains Permian coal measures in the NSW portion of the Bowen Basin. It is the lateral equivalent of the Bandanna Formation which is used to describe the Late

Permian coal measures deposited on the Roma Shelf and Denison Trough. Just north of the NSW/QLD border, approximately 80-100km away, discoveries have been made at the Bellbird accumulation, though non commercial, which flowed oil at 32 bbls/day in a drill stem test and at Cabawin. The Cabawin discovery flowed both oil and gas with porosities on average 14 % and a typical permeability of 1millidarcy. In the NSW portion of the Bowen Basin this unit could be considered potential for CSG, though commercial quantities are likely to be low, and currently no significant finds have been reported.

2. Rewan Formation

The majority of discoveries in this formation have been restricted to the Desnison Trough, Roma Shelf or western Flank of the Taroom Trough (Saint George-Bollon Slope). Porosity and permeability within the Rewan Formation is variable, ranging from 5 % to 20 % porosity and 0.1 to 1 millidarcies for permeability, as silicification and clay alteration has in part reduced primary porosity and permeability. It has been observed in the Roma Shelf where the Rewan Formation onlaps Permian sediments that the formation becomes increasingly fine grained and this is thought to act as a vertical hydraulic barrier to hydrocarbons generated from downdip Permian source rocks (Butcher 1984). This hydraulic barrier may also be present in the southern part of the Bowen Basin at the boundary with the Gunnedah Basin as no significant finds have been reported and the potential for CSG is likely to be low.

3. Moolayember Formation

Discoveries in the Moolayember Formation have been for both oil and gas in commercial and non-commercial quantities. Significant discoveries of oil and gas have been made near Kincora, 130 km north of the NSW/QLD border. The reservoir consists of light grey, poorly sorted, sublabile, angular and quarztose fluvial sandstones with porosities ranging from 13 % to 20 % and permeabilities of less than 20 millidarcies (Cadman & Pain 1998). The seal for the Moolayember reservoir is provided by intraformation shales and mudstones as the Jurassic sandstones of the Surat basin which overly the Moolayember Formation do not provide a competent seal. No significant finds have been reported in NSW and the potential for CSG is likely to be low.

Geophysics

Seismics

In the central Bowen Basin, the east-west deep crustal profile of BMR84.14 (Figure 7.3 and Figure 7.4) highlights the complete geometry of the basin with a typical extensional rift basin, Early Permian volcanics and deep thick sediments bounded on each side by shallower basement. A separate Bureau of Mineral Resources (BMR) survey was conducted across the Taroom Trough (Figure 7.4) and has been interpreted by Kilgour (2002).

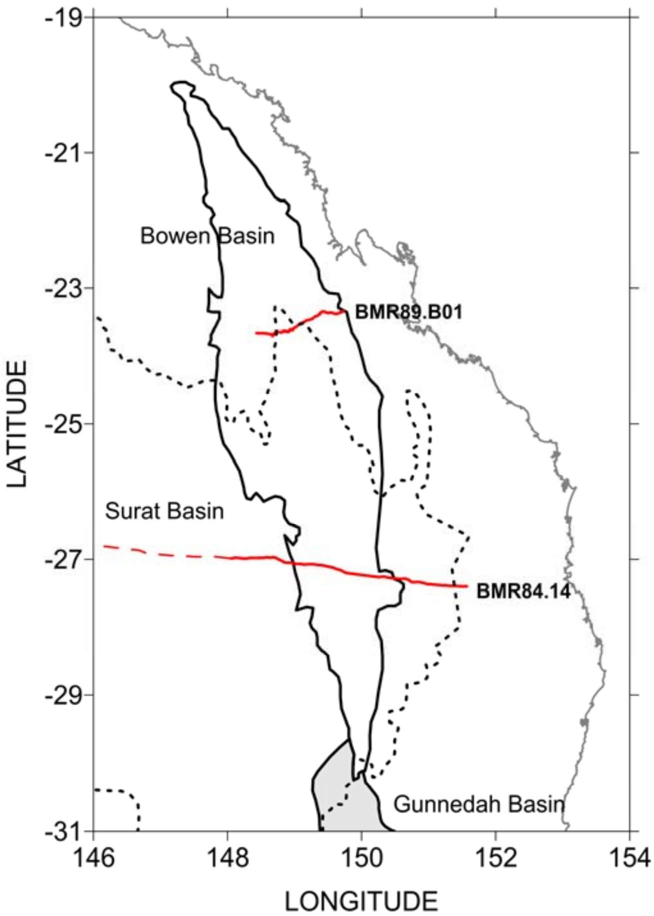

Figure 7.3. Location map of selected seismic reflection profiles in the Bowen Basin. Profiles shown as red lines. Dashed red line shows the full profile length of BMR84.

This profile, although it does not entirely match BMR84.14, because the location of overlap is approximate only, it shows a similar basement structure with the boreholes used to pick stratigraphic horizons marked. Using the two-way travel time conversion (Figure 5.6) depth to basement in the Taroom Trough is estimated at approximately 6 km. In the north-eastern part of the Bowen Basin seismic reflection profile BMR89.B01 (Figure 7.5) shows the geometry over the eastern edge of the basin is a highly faulted area. In the interpreted geological cross-section (Figure 7.5) Korsch *et al*. (1993) suggest the basement is the Thomson Fold Belt, which extends under the Jellinbah Thrust before truncating on the New England Fold Belt. Basement in the Blackwater Zone is estimated by Korsch *et al*. (1993) to be approximately 3 km deep and almost 6 km deep under the Yarrabee Thrust.

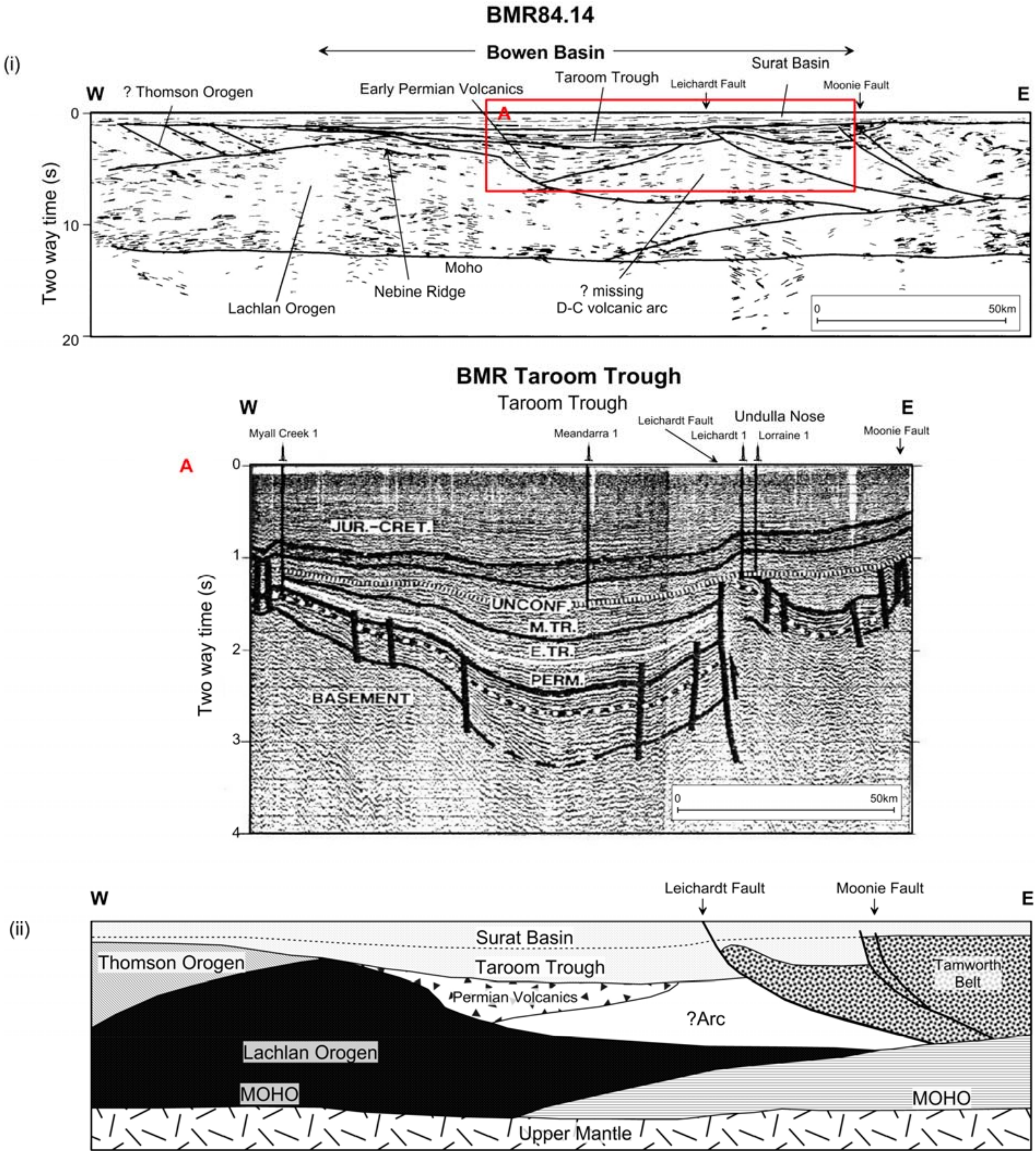

Figure 7.4. (i) Interpreted deep seismic reflection profile BMR81.14 of the Bowen Basin with the red box the approximate location of BMR profile across the Taroom Trough with boreholes (modified from Kilgour 2002) and (ii) the interpreted geological cross-section of BMR81.14 (modified from Danis 2012 and Korsch *et al*. 1993).

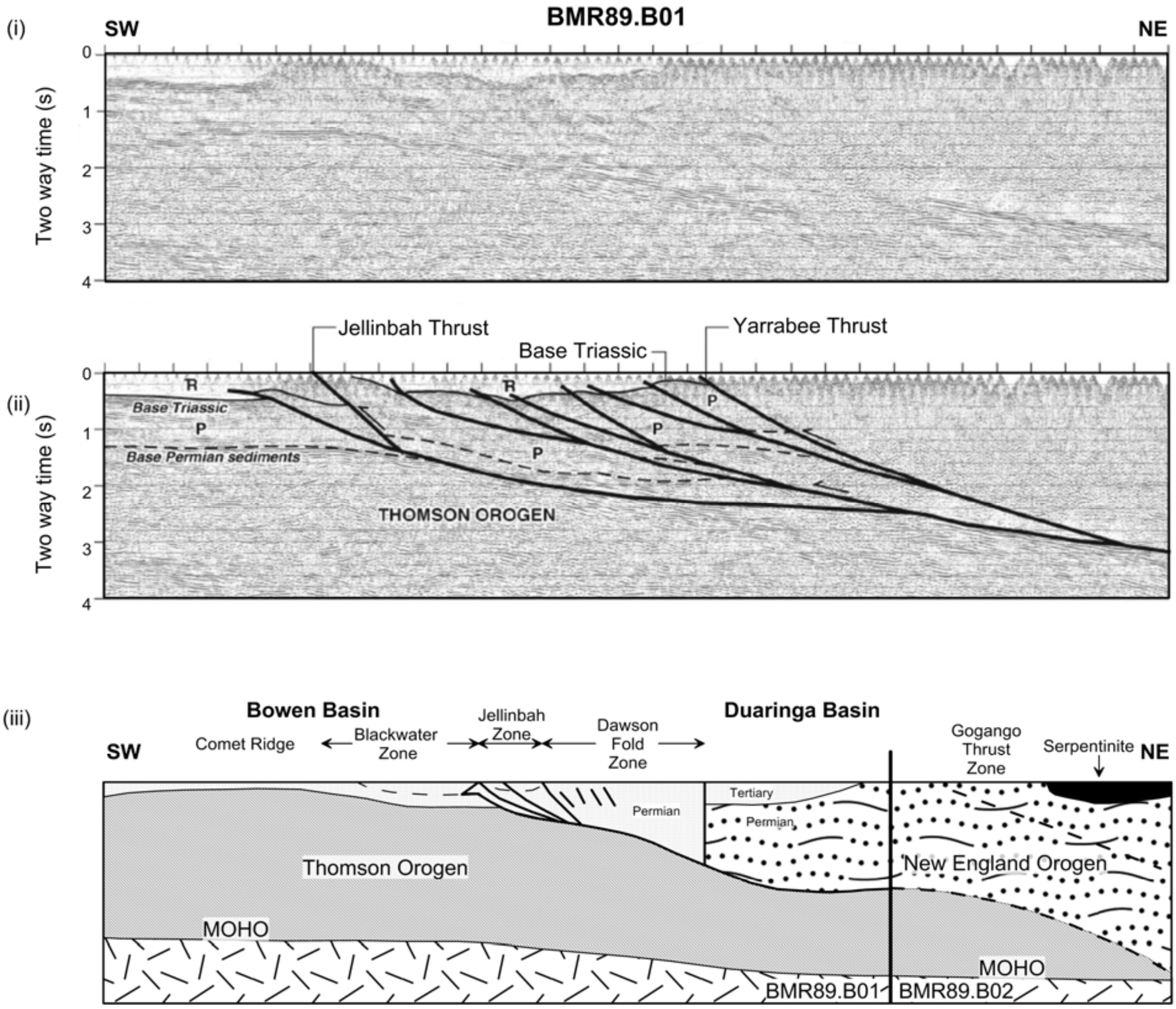

Figure 7.5. Deep seismic reflection profile BMR89.B01 north-eastern Bowen Basin (i) unmigrated profile, (ii) interpreted structure (Korsch et al. 2009b) and (iii) interpreted geological cross-section of BMR89.B01 and extension BMR89.B02 (modified from Danis 2012 and Korsch *et al*. 1993).

Potential Field

The gravity anomaly map of the Bowen Basin (Figure 7.6) shows gravity lows as blues to greens and highs as yellow to red. The known areas of large granite intrusions, such as the New England Batholith (centred around 152 ⁰E -30 ⁰S) and Roma Granites (centred around 149 ⁰E -27.5⁰S) show as distinctive purple lows. The extension of the Meandarra Gravity Ridge as described by Krassey *et al.* (2009) is apparent as a blue green moderate high extending up to Meandarra in the southern part of the basin. The total magnetic intensity map (Figure 7.7) shows low intensity areas as blue to purple and high intensity as red to white. Within the Bowen Basin exposed volcanics in the northern most part are represented by high intensity anomalies. The Meandarra Gravity Ridge shows as a high intensity anomaly extending as far north as Nebo. Danis (2012) showed the deep basal rift volcanics extend almost the entire length of the Bowen Basin. Faults, particulary the Leichardt Burunga and Moonie Goondawindi and some buried plutons are also more clearly defined in the magnetic map than the gravity map. Volcanics, intrusions and faults, which may be discernable on either the gravity and or the magnetic maps, have the most potential to affect the permeability of aquifers and aquitards.

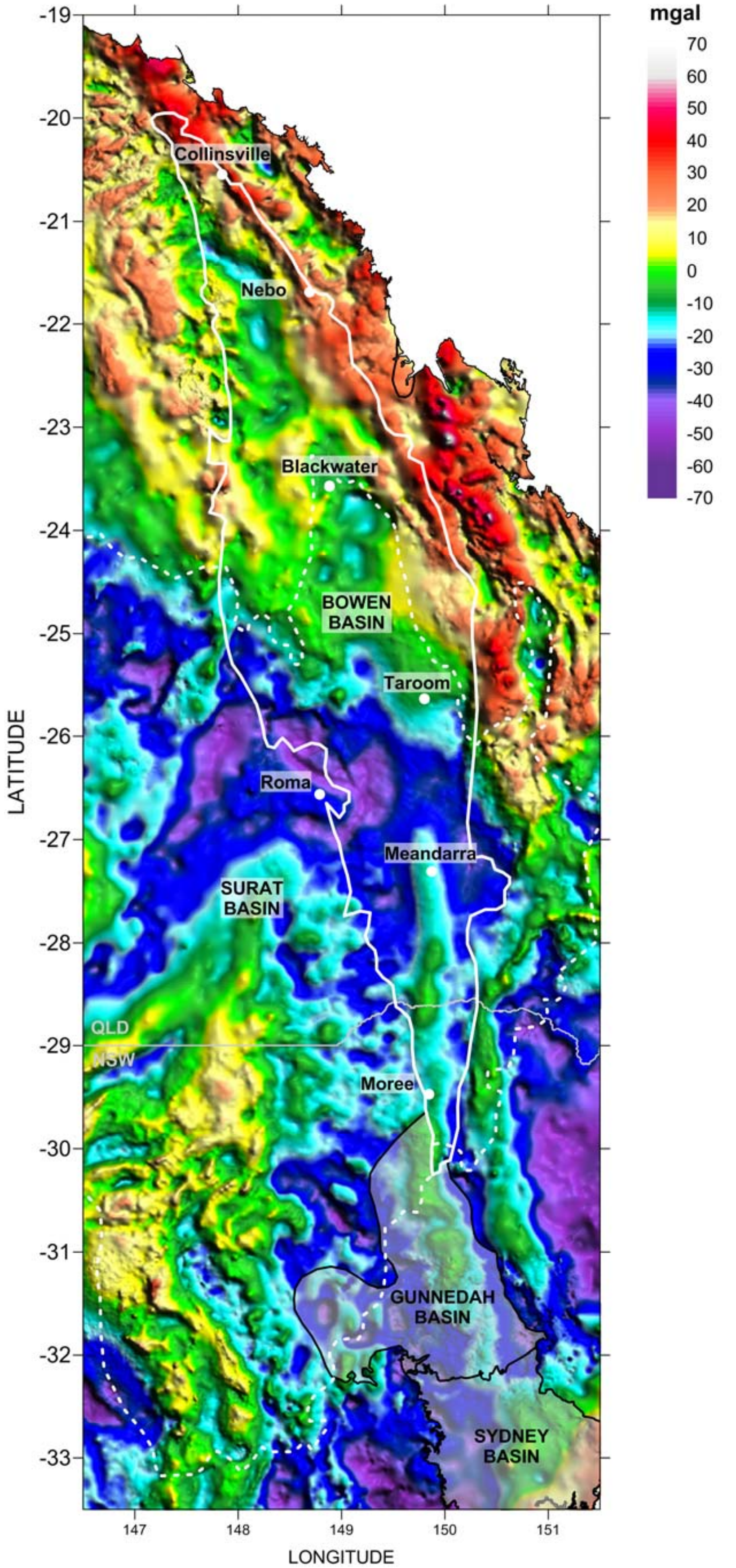

Figure 7.6. Spherical Bouguer anomaly map of the Bowen and Surat Basin systems, NSW and Queensland (data available from Geoscience Australia).

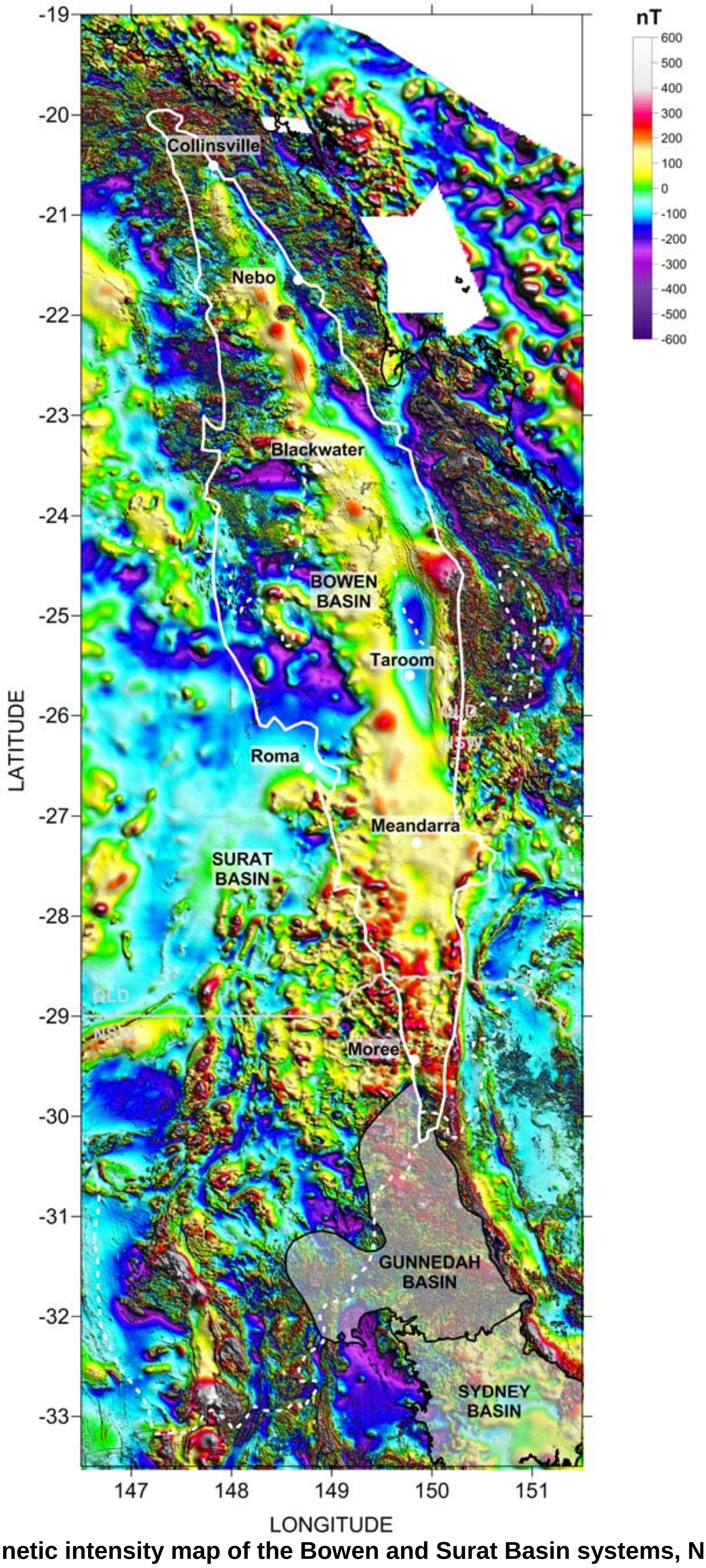

Figure 7.7. Total magnetic intensity map of the Bowen and Surat Basin systems, NSW and Queensland.

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8. Surat Basin

Structure

The Surat Basin is part the large Jurassic-Cretaceous intra-crationic basin, which includes also the Eromanga and Clarence Moreton basins, that covers over 1.7 million km^2 of Eastern Australia. The Surat Basin is a north-south elongate system with an asymmetric with synclinal geometry that unconformably overlies the Gunnedah Basin in the east in NSW and the Bowen Basin in the northeast in QLD. It covers an area of about 270,000 km^2 and contains up to 1800 m of undeformed Jurassic sediments and 900 m of Cretaceous age strata (Goscombe & Coxhead 1995). Structures within the Surat Basin (Figure 8.1) sequence have resulted from either drape over pre-existing basement highs or differential compaction resulting in lower relief than lose found in the underlying Triassic section (Golin & Smyth 1986). A contractional deformation event early in the Late Cretaceous led to limited propagation of thrust faults from the underlying section into the Surat Basin sequence (Cadman & Pain 1998), however more commonly it resulted in folding and uplift of Surat sediments over deeper reactivated thrust faults (Korsch & Totterdell 1996). A simplified stratigraphy is presented in Table 8.1 and Figure 29 is schematic cross-section through the central part of the Surat Basin.

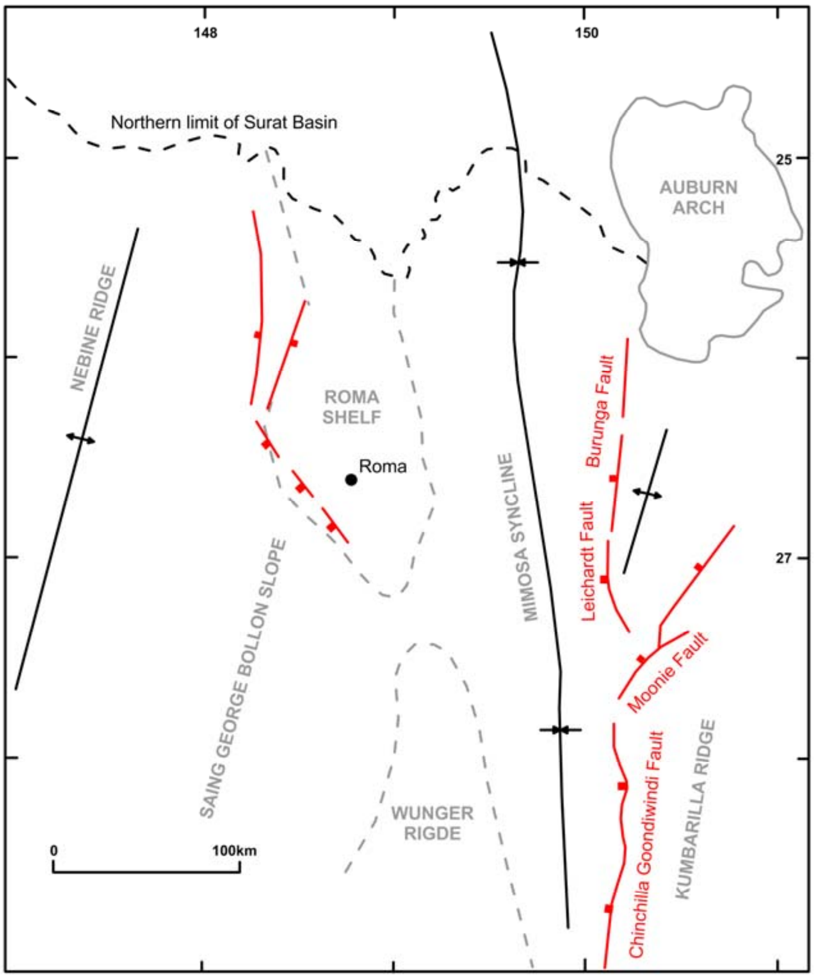

Figure 8.1. Structural elements of the Surat Basin (Adapted from Cadman & Pain 1998).

Table 8.1. Simplified stratigraphy of the Surat Basin (Adapted from Cadman & Pain 1998).

Period	Epoch	Formation	
CRETACEOUS	EARLY	Griman Creek Formation	
		Surat Siltstone	
		Wallumbilla Formation	
		Bungil Formation	
		Mooga Sandstone	
JURASSIC	LATE	Orallo Formation	
		Gubbermamunda Sandstone	Pilliga Formation
		Westbourne Formation	
	LATE / MIDDLE	Springbok Sandstone	
	MIDDLE	Walloon Coal Measures	
		Eurombah Formation	
	EARLY	Hutton Sandstone	Purlawaugh Formation
		Boxvale Sandstone	
		Evergreen Formation	
		Precipice Sandstone	

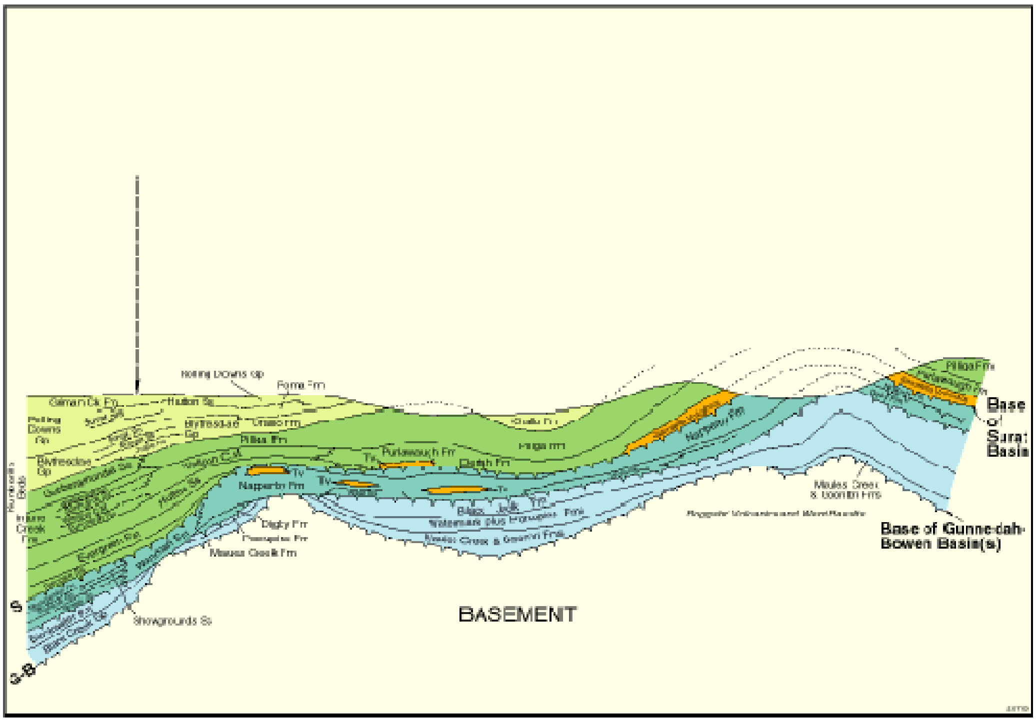

Figure 8.2. Simplified 2D cross section through the centre of the mid-Surat Basin (from NSW resources).

Geology

In the early Jurassic, regional subsidence commenced and the first sediments deposited were the fluvial sandstones of the Precipice Sandstone derived from Precambrian rocks bordering the west and southwest of the Great Artesian Basin (Martin 1981; Cadman & Pain 1998). The unit is thickest in the Mimosa Syncline adjacent to the Chincilla-Goondiwindi and Moonie Faults and thins to less than 40 m over the Roma Shelf in the Bowen Basin. Overlying this is the Jurassic age Evergreen Formation representing a trangressive phase comprising basal fluvial sandstones, superseded by siltstones, shales and minor fine grained sandstones deposited under fluvio-lacustrine to marginal marine environments (Cadman & Pain 1998). The Evergreen Formation is more areally extensive than the Precipice Sandstone and thickens towards the north and east into the Mimosa Syncline.

Towards the end of the Early Jurassic a regressive sequence, the Hutton Sandstone, of fluvial, deltaic and lacustrine sandstones with minor siltstones shales and coals, was deposited over most of the Surat Basin. Deposition of this sequence was widespread and is continuous with the Eromanga Basin to the west. It is fairly uniform and ranges in thickness from 150m to 250 m. By the Middle Jurassic, coal swamp environments began to dominate and the Walloon Coal measures transgressed the Hutton Sandstone. They are interbedded with mudstones and siltstones laid down in fluvial environments (Exon, 1976). The Walloon Coal measures reach a maximum thickness of around 400 m in the north and east of the basin.

At the end of the Middle Jurassic fluvial conditions returned and the Springbok Sandstone, comprising fine grained lithic sandstones with interbedded, carbonaceous and micaceous siltstones and mudstones was deposited. The Springbok Sandstone reaches a maximum thickness of around 200 m (Cadman & Pain 1998) and interfingers with the Adoir Sandstone of the Eromagna Basin in the west. In the Late Jurassic an interbedded fluvial sequence of lithic sandstones, mudstones and siltstone sediments of the Westbourne Formation were deposited. By the end of the Jurassic to the earliest Cretaceous a series of fluvial sandstones (Gubberamunda, Orallo and Mooga) infilled the slowly subsiding Surat Basin. Marine influences returned and the Bungil Formation comprising lithic sandstones, mudstones and siltstones was deposited in a paralic environment. This mairne transgression culminated with the depoisiton of the marine mudstones siltstones and lithic sandstones of the Wallumbilla Formation and Surat Siltstone (Cadman & Pain 1998).

Near the end of the Early Cretaceous a regression led to the deposition of the Griman Creek Formation, which rests conformably on the Surat Siltstone and this unit consists of thinly interbedded siltstone, fine grained sandstone and mudstone with conglomerates and coals becoming more common towards the top of the sequence. In the Late Cretaceous a contraction deformation even resulted in folding and uplift of sediments followed by erosion. Deep weathering profiles and surfical secrete deposits developed during this time. Epeirogenic movements tilted the entire sedimentary section to the southwest in the Oligocene, resulting in extrusion of basalts to the north and east of the Surat Basin and increased erosion in the north.

CGS Potential

Whilst no commercial oil or gas discoveries have been made in the New South Wales part of the Surat Basin a potential gas field has been identified in the underlying Gunnedah Basin in the east. The Surat in NSW has not been considered a CSG exploration target due to its low coal rank which reduces the methane content of the coal reservoirs. The Precipice Sandstone is a primary hydrocarbon exploration target and contains numerous oil and gas accumulations. Reservoir properties are highly variable within the unit with the best porosities and permeabilities found in the coarser braided stream deposits of the Lower Precipice Sandstone. The producing Precipice Sandstone in QLD has porosities averaging around 20 % with permeabilities around 100 millidarcies. Most discoveries have been made within the Roma Shelf in QLD. The Evergreen Formation also constitutes an important hydrocarbon reservoir with most discoveries made near the Mimosa Syncline in QLD. Reservoir properties are variable with porosities ranging between 15 % to 25 % with permeabilities ranging from less than 20 millidarcies to more than 240 millidarcies. The Hutton Sandstone is a prolific producer in the Eromanga basin to the west but relies on intraformational siltstones, mudstones and tight sandstones to provide effective top seal in close proximity to Permo-Triassic faulting. Porosity values generally range between 15 % to 25 % with permeabilities rarely exceeding 100 millidarcies (Cadman & Pain 1998). Both the Walloon Coal measures and Westbourne Formation are not generally regarded as an exploration objective however the Walloon Coal measures are a rich potential source rock.

Geophysics

Seismics

The geometry base of the Surat Basin reflects the underlying structure of the Bowen Basin, as shown in the east-west deep crustal profile of BMR84.014 (Figure 8.3 and Figure 8.4), with generally flat lying sediments. Based on the conversion of two-way travel time (Figure 5.6) the profiles show sediments in the Surat Basin is several hundred metres thick.

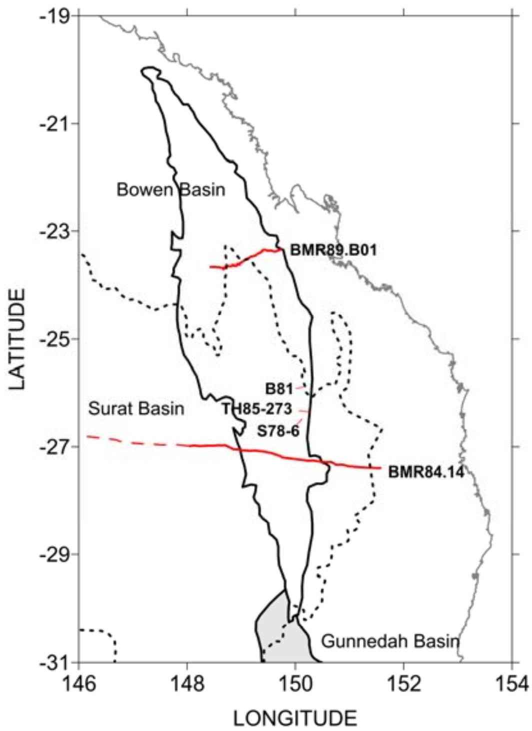

Figure 8.3. Location map of selected seismic reflection profiles in the Surat Basin. Profiles shown as red lines. Dashed red line shows the full profile length of BMR84.

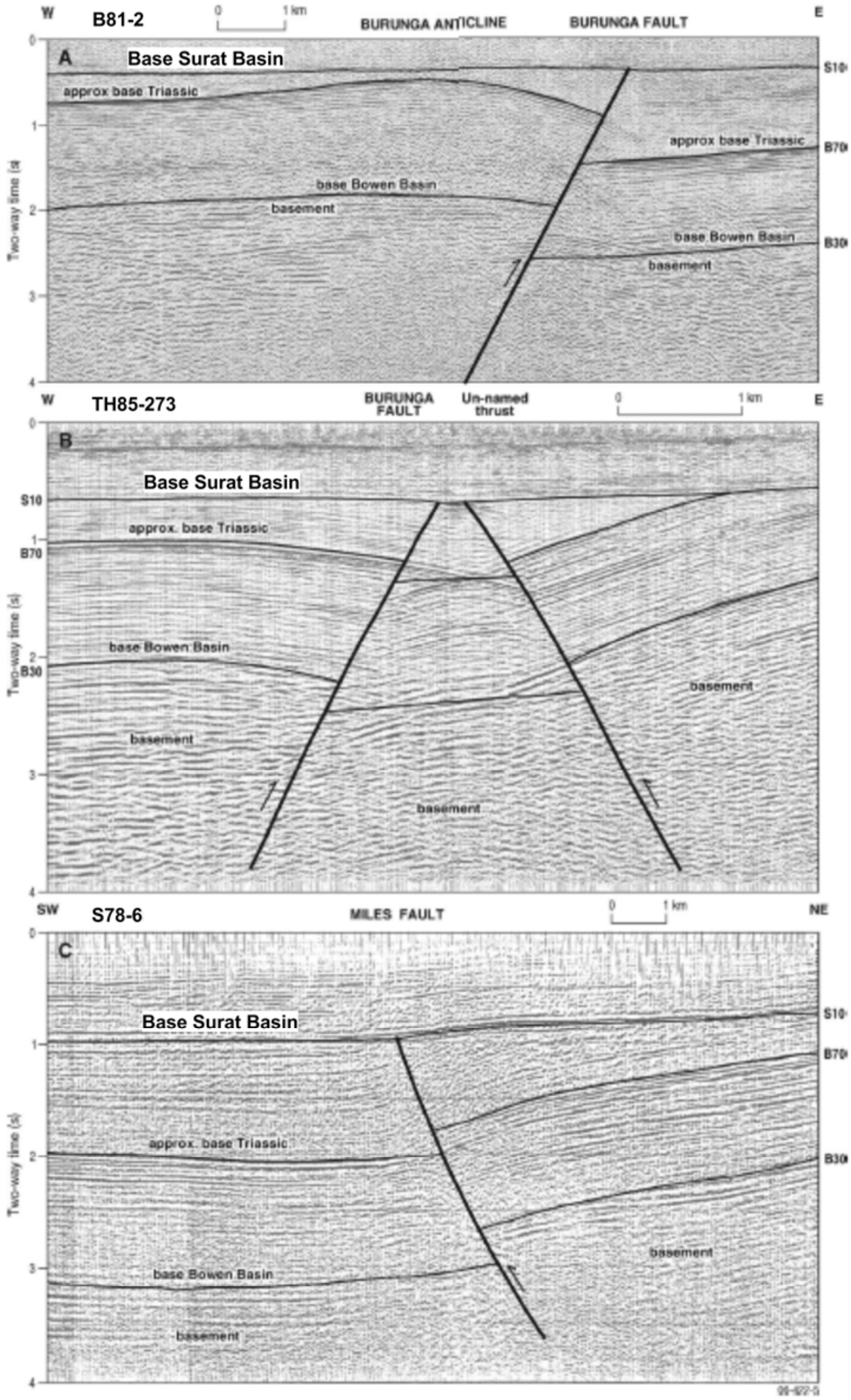

Figure 8.4. Seismic reflection profiles of the Surat Basin across the Leichardt Burunga Fault. Adapted from Korsch *et al*. (2009)

Potential Field

The gravity anomaly map of the Surat Basin (Figure 8.5) shows gravity lows as blues to greens and highs as yellow to red. Gravity lows generally correspond to granites in the basement (i.e. Roma Granite).

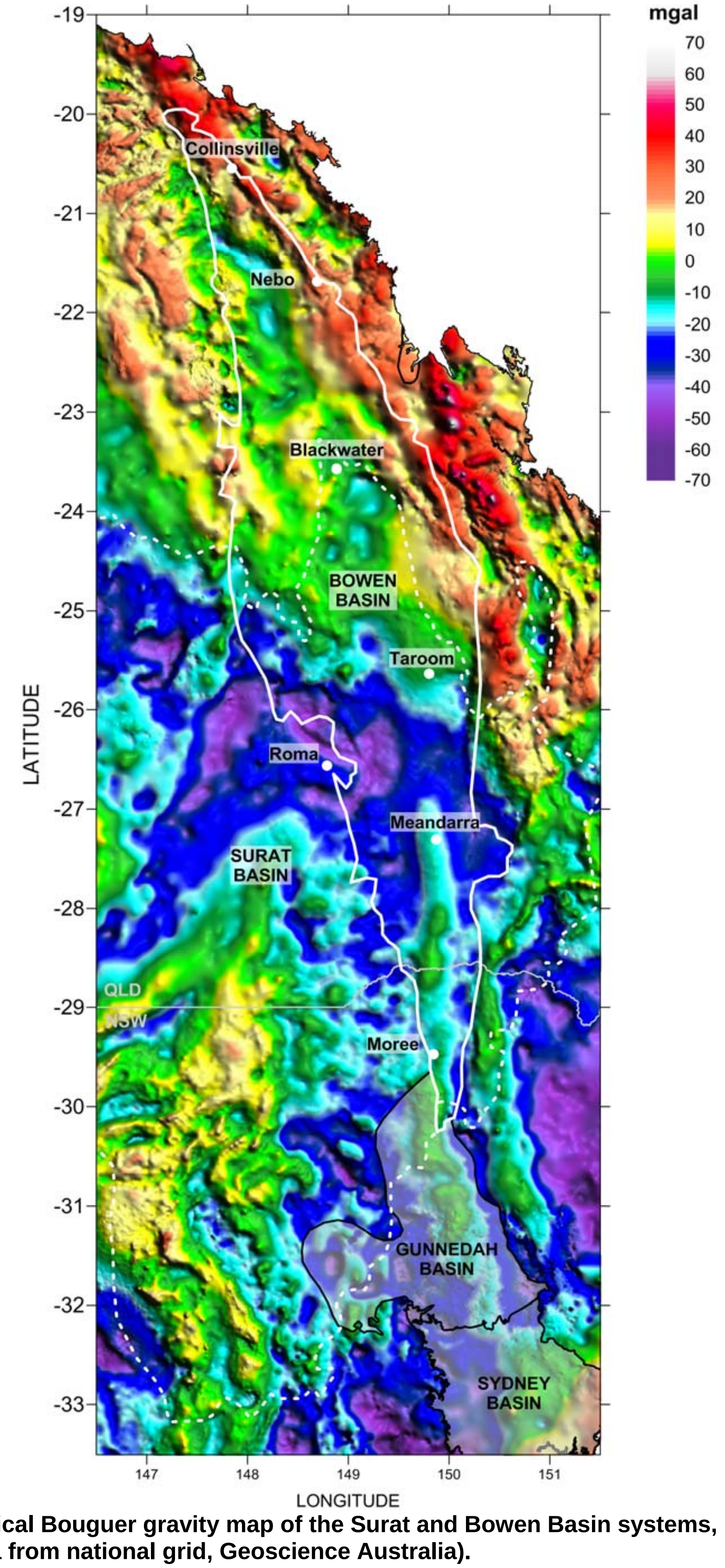

Figure 8.5. Spherical Bouguer gravity map of the Surat and Bowen Basin systems, NSW and Queensland (data from national grid, Geoscience Australia).

The total magnetic intensity map (Figure 8.6) shows low intensity in blue to purple and high intensity as red to white. High intensity anomalies in the Surat relate to deeper structural features, such as faults, and may also be related to volcanic intrusions, particularly in the southern part of the Surat Basin near the Gunnedah Basin.

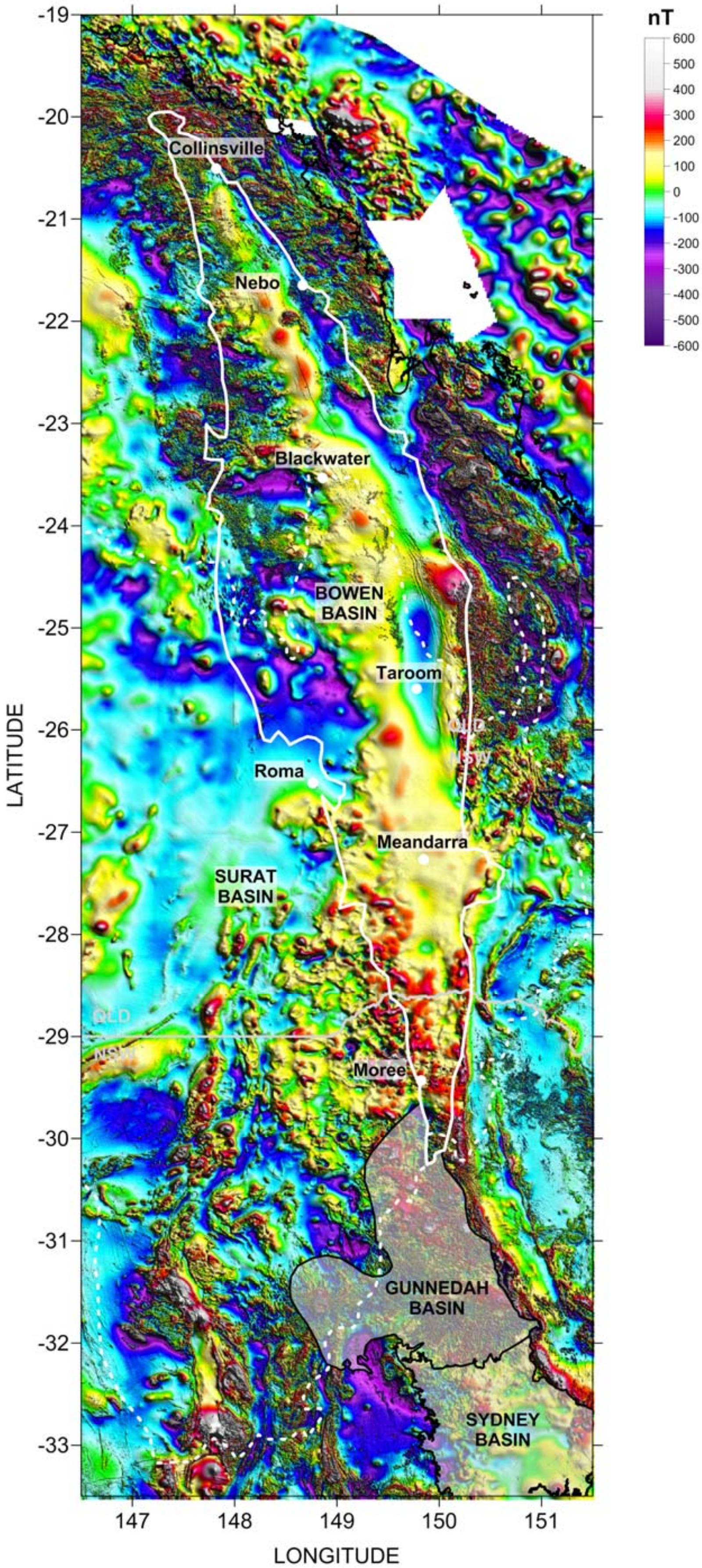

Figure 8.6. Total magnetic intensity map of the Surat and Bowen Basins, NSW and Queensland (data from National grid, Geoscience Australia).

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9. Clarence-Moreton Basin

Basin Structure and evolution

The Clarence-Moreton Basin is located in Northern NSW/Southern Queensland, and is primarily onshore, with some offshore extension onto the adjoining shelf (Figure 9.1). The basin opened during a period of oblique extension in the early Mesozoic (Korsch *et al*. 1989), and consists of continental sediment sequences ranging between 2.5-4k m thick of Triassic-Jurassic age, unconformably overlying a basement of Ordovician to Triassic metasediments, sediments, and igneous rocks.

The Clarence-Moreton Basin can be divided into three sub-basins; the Cecil Plains sub-basin to the west, the Laidley sub-basin in the centre, and the Logan sub-basin in the east. The NSW extension of the Clarence Moreton Basin consists primarily of the Logan sub-Basin. The Basin also extends offshore. The Cecil Plains sub-basin is separated from the Surat Basin by the Kumbarilla Ridge, and from the Laidley sub-basin by the Gatton Arch. The complex South Moreton Anticline divides the Laidley and Logan sub-basins.

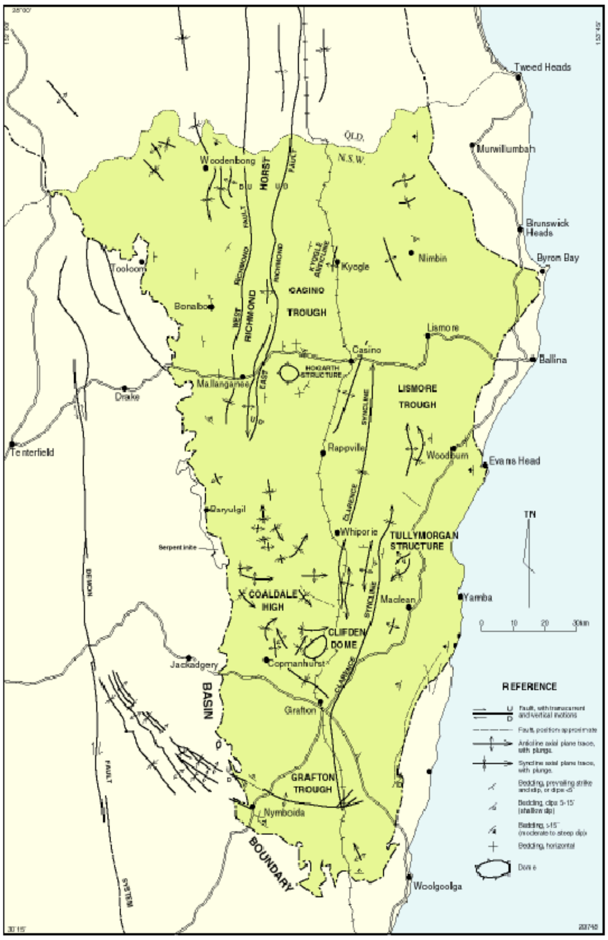


Figure 9.1. Major structural elements of the Clarence Moreton Basin (from resources.nsw.gov.au).

In the late Permian, oblique extension/transtension on the Ipswich Fault formed a basin beneath the Laidley sub-basin. This deformation front stepped to the Logan sub-basin and Esk Trough in the early Triassic. Thermal subsidence created space for deposition along the centres.

Minor strike slip faulting continued within the Ipswich Basin, and the Horrane Trough, which together with ongoing thermal subsidence resulted in ongoing local deposition.

From the late Triassic, through to the Cretaceous, regional thermal subsidence created a topographic depression, and formed the greater Clarence-Moreton Basin. Deposition occurred over much of the basin, with minor dextral strike-slip faulting causing small amounts of local uplift/subsidence.

The Late Cretaceous saw an episode of compression, or transpression, which formed or reactivated minor thrusts within the basin, creating flower structures, hanging wall anticlines, and some fault inversion. Rifting of the east Australian margin in the Palaeogene resulted in the end of this compressional episode, and resulted in heating and uplift with the Clarence-Moreton basin, particularly towards the eastern margin. Later volcanism in the Miocene (basic-intermediate) has thermally perturbed parts of the basin. A simplified stratigraphy is presented in Table 9.1 and Figure 9.2 is schematic cross-section through the central part of the Surat Basin.

Geology

The Basin basement consists of older Triassic infrabasins, and onlap New England Fold Belt Late Palaeozoic sequences (to the south and west), as well as the Yarraman and D'Aguilar Blocks (to the north) and the Beenleigh Block (to the east). The oldest exposed rocks within the basin are the Chillingham volcanics, of Triassic age. Outcropping near Chillingham, they consist of basal conglomerates, rhyolites, rhyolitic tuffs and ignimbrites, and interbedded shales. Korsch *et al*. (1989) identifies a volcano-sedimentary sequence beneath the Chillingham volcanics, to the east of the South Moreton Anticline, within the Logan sub-Basin.

Overlying these volcanics are the mid-Triassic Nymboida coal measures, comprising of lithic sandstones, siltstones, conglomerates, rhyolitic tuffs, basalts, and coals. The late Triassic Red Cliff coal measures overlie the Nymboida measures, and are equivalents of the Evan's Head coal measures, and Ipswich coal measures, further north. This sequence probably represents the last syn-rift deposition.

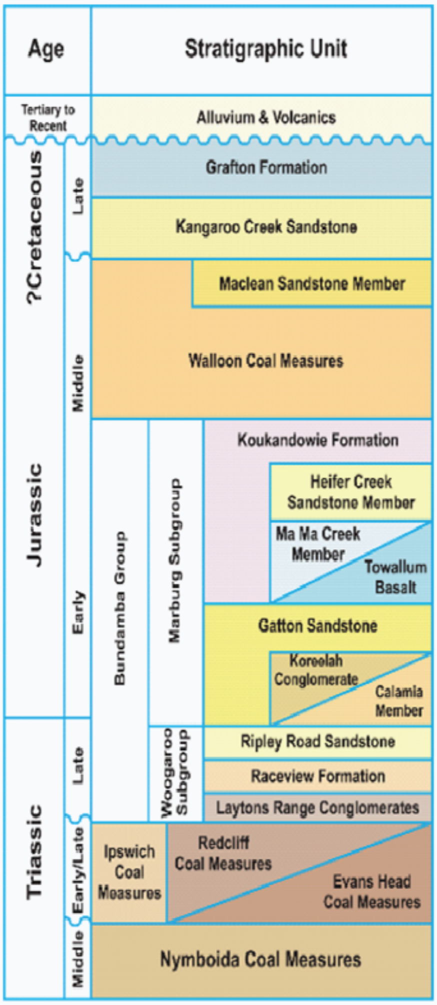
Uplift in the late Triassic led to the development of an unconformity between the underlying units, and the subsequent early Jurassic Bundamba Group. The Bundamba Group consist mostly of conglomerates and sandstones. It is truncated by an unconformity near the top, which separates out an upper unit, the Marburg Subgroup – an interbedded mostly sandstone unit, with siltstone and claystone.

The Marburg Subgroup is transitions with the Walloon Coal Measures, also of Jurassic age. The Walloon Coal measures record a period of lacustrine/paludal deposition also recorded in the Surat and Eromanga Basins. The Measures consist of claystone, shale, siltstone, arenites and coal. Overlying the Walloon formation are the Kangaroo Creek Sandstones, and the fluvial/lacustrine claystones and sandstones of the Grafton formation.

Approximately 1.5-2.5 km of sediment has been removed from the Basin, based on vitrinite reflectance (Ties *et al*. 1985; Russell 1994). Minimum fission track ages between 60-52 Ma along the eastern part of the Basin suggest that the sediments cooled below 70 ^{o}C at that time – indicating that the post-depositional uplift that removed the sediment cover had ceased by that time (Gleadow & O'Brien 1993).

Significant Tertiary volcanic activity occurred around the Queensland-NSW border, and resulted in significant local heating of the sediments (Powell *et al*. 1993).

Table 9.1. Simplified Clarence-Moreton lithological section (from metgasco.com.au).



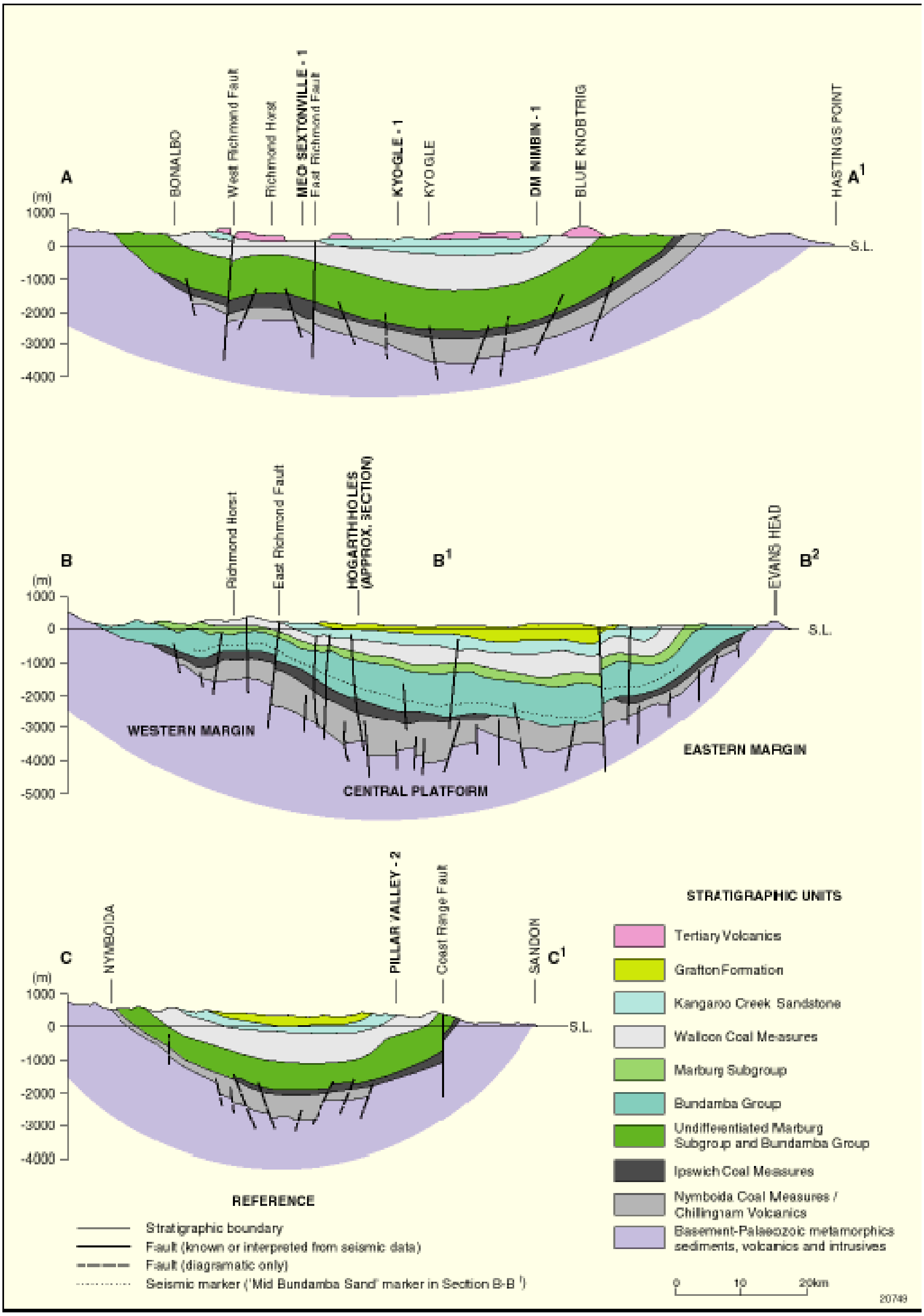


Figure 9.2. Simplified geological cross sections of the Clarence Moreton Basin (from resources.nsw.gov.au)

CSG in the Clarence-Moreton

The Walloon Coal Measures, in particular their extension into the Surat Basin in Queensland, are extensively used for CSG extraction, supplying some 60 % of the state's gas. They are also highly favourable within the NSW of the Clarence-Moreton.

Metgasco are currently exploring the measures, and note they occur between about 200-800 m. They are generally oversaturated, with high has contents (approximately 98% methane), with thick individual seams between 2-9 m.

The Nymboida, and Ipswich equivalent Coal Measures are also probably productive. They are overlain by thick sediments in many areas of the Basin, but near where these units outcrop (e.g. The SW of the basin, for the Nymboida, SE for the Ipswich-equivalent Red-Head Coal Measures) there is evidence of abundant gas. Detailed information for these units is however lacking.

Geophysics

Seismics

Detailed seismic reflection profiles have been collected over the Clarence Moreton Basin (Figure 9.3), the Esk Trough, and the Ipswich Basin in Queensland, and the data was collated and interpreted by Korsch *et al*. (1989). The following figures and analysis have been adapted from that work. While the data and, strictly, the interpretation, including depths of sediments, is relevant primarily to the Queensland portion of the Clarence-Moreton Basin, the general interpretation extrapolated structure is relevant to the Logan and Laidley sub-Basin structure within NSW also.

Korsch *et al*. (1989) note that the Walloon Coal Measures, near the top of the section in Figure 9.4, produce reflections too shallow for the CDP coverage of the survey, and so are not visible at the scale of Figure 9.5. A facies change within the Jurassic Marburg Formation produces a prominent reflector about mid-way through the Clarence-Moreton sequence, which is extensive and correlated not just through the Clarence Moreton Basin, but into the Surat Basin as well (where it lies within the Evergreen Formation).

The synchronous deposition and faulting/subsidence is evident by the on-lap of the sediments to the west of West Ipswich Fault.

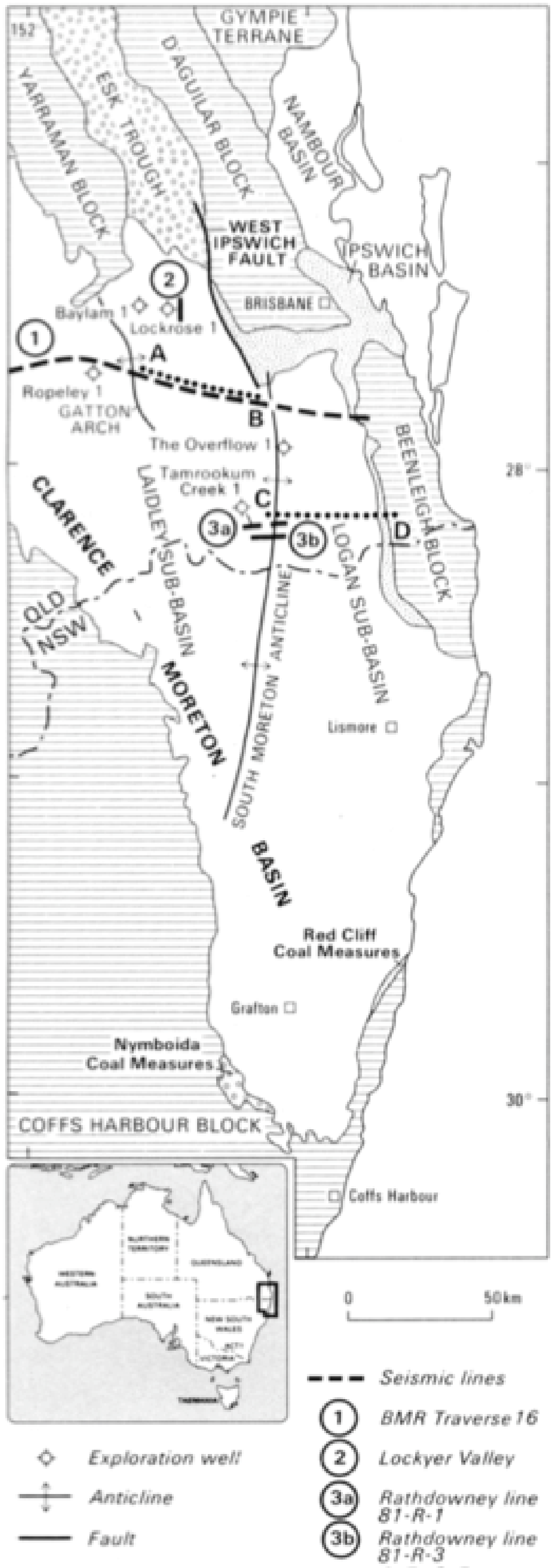


Figure 9.3. Location of seismic profiles discussed by Korsch *et al*. (1989).

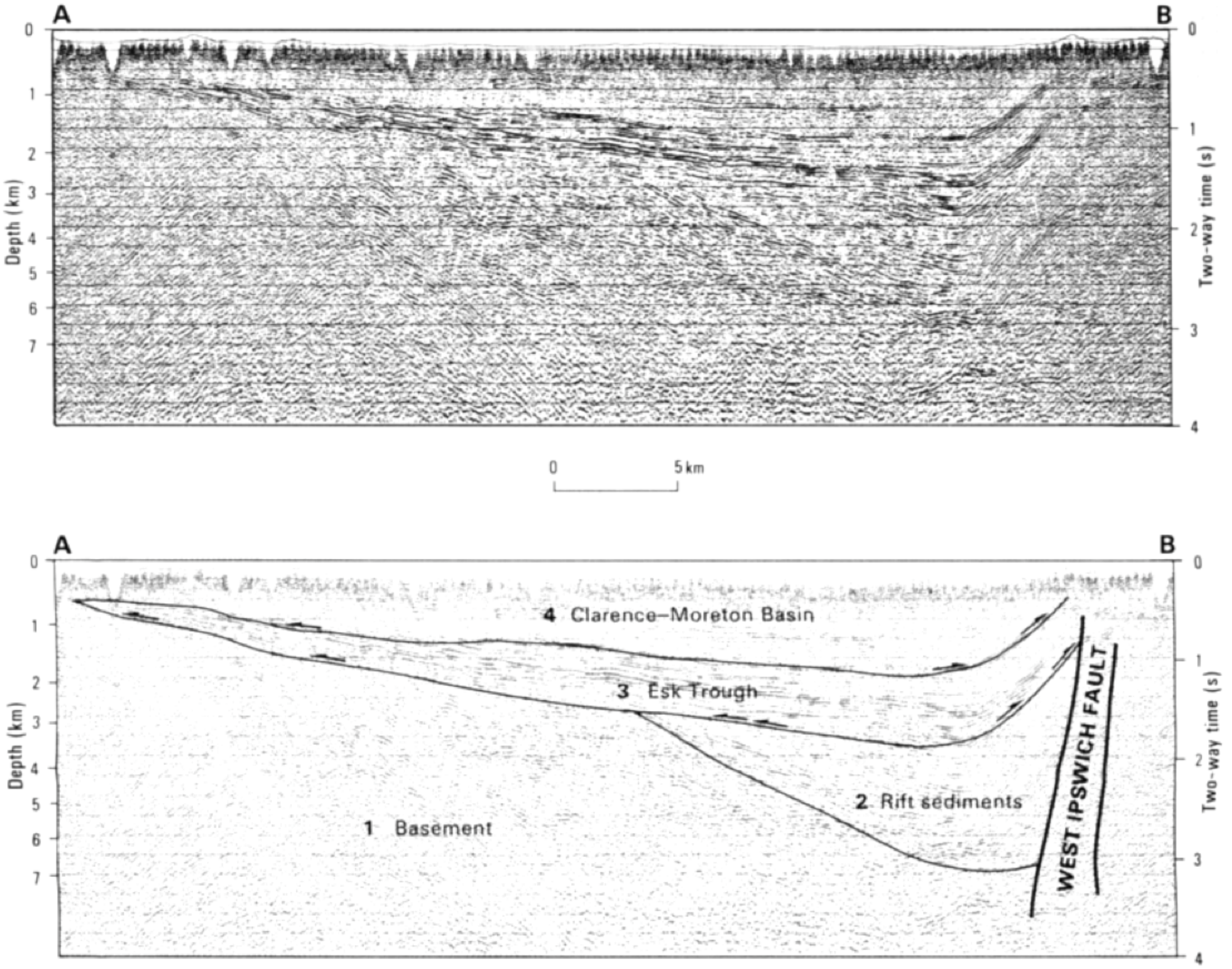


Figure 9.4. Seismic profile AB in Figure 36, across the Esk Trough. The line is unmigrated, and major formations are shown. The Esk Trough sequence includes the Toogoolawah Group, and the Clarence-Moreton sequence incorporates the Bundamba Group and the Walloon Coal Measures. Details of the seismic acquisition are provided in Korsch *et al*. (1989), and depth is from seismic datum.

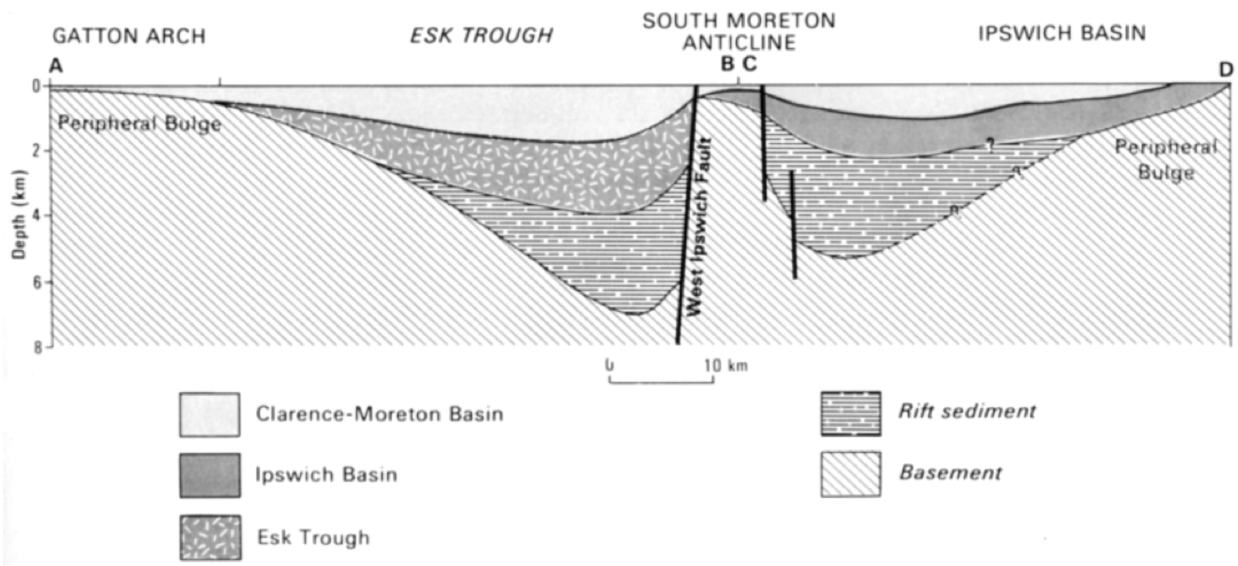


Figure 9.5. Composite cross section by Korsch *et al*. (1989) of the deep structure across the Clarence Moreton Basin (from the Queensland seismic sections). The overlying Clarence Moreton sequence corresponding to the depressions labelled the Esk Trough, and the Ipswich Basin, are the Laidley and Logan sub-Basins within the NSW extension, respectively.

Potential Field

Potential field data (gravity and magnetic) are shown in Figure 9.6 and Figure 9.7 for the NSW portion of the Clarence Moreton Basin. Potential field data in this context is most sensitive to basement structure and geology. Gravity is dominated by large-scale density variations, and tends to be useful in delineating basement/sediment contacts, where sufficient contrast exists. The broad-scale gravity shown in Figure 9.6 tends to show relative lows in regions of significant sediment accumulation (e.g. central Logal sub-Basin within NSW), and highs either correspond to extension of basement blocks (e.g. the Beenleigh Block in far NE NSW, adjacent to the Basin's edge), or to structural highs where the basement is near the surface. The deep troughs are not imaged as well as in the seismics, probably due to an insufficient contrast between the compressed, buried deep sediments, and the surrounding basement. At this scale, crustal thinning, which elevates the mantle contact, is also significant, and probably contributes to part of the eastern seaboard gravity high.

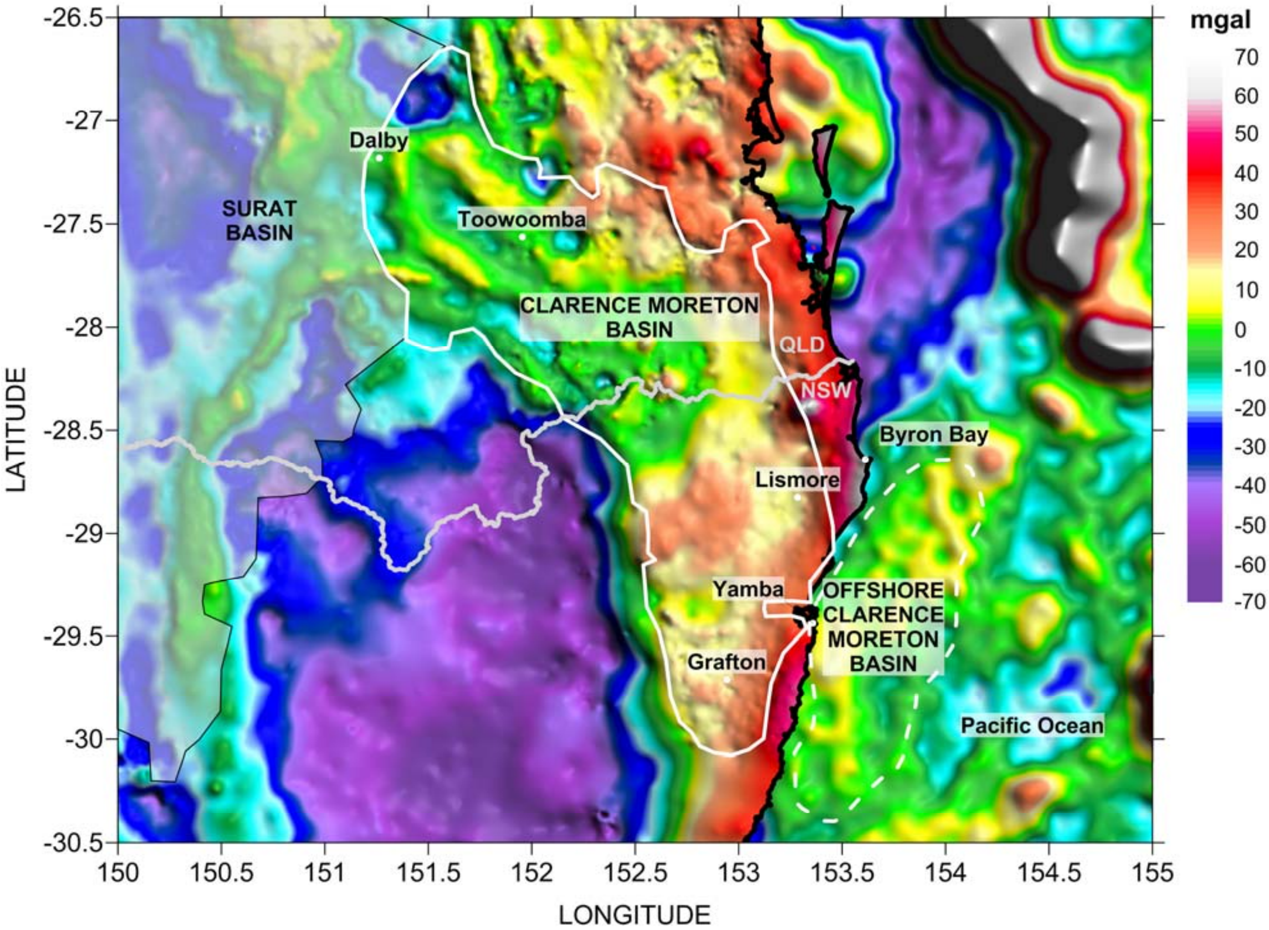


Figure 9.6. Spherical Bouguer gravity map of the Clarence-Moreton Basin (data available from Geoscience Australia).

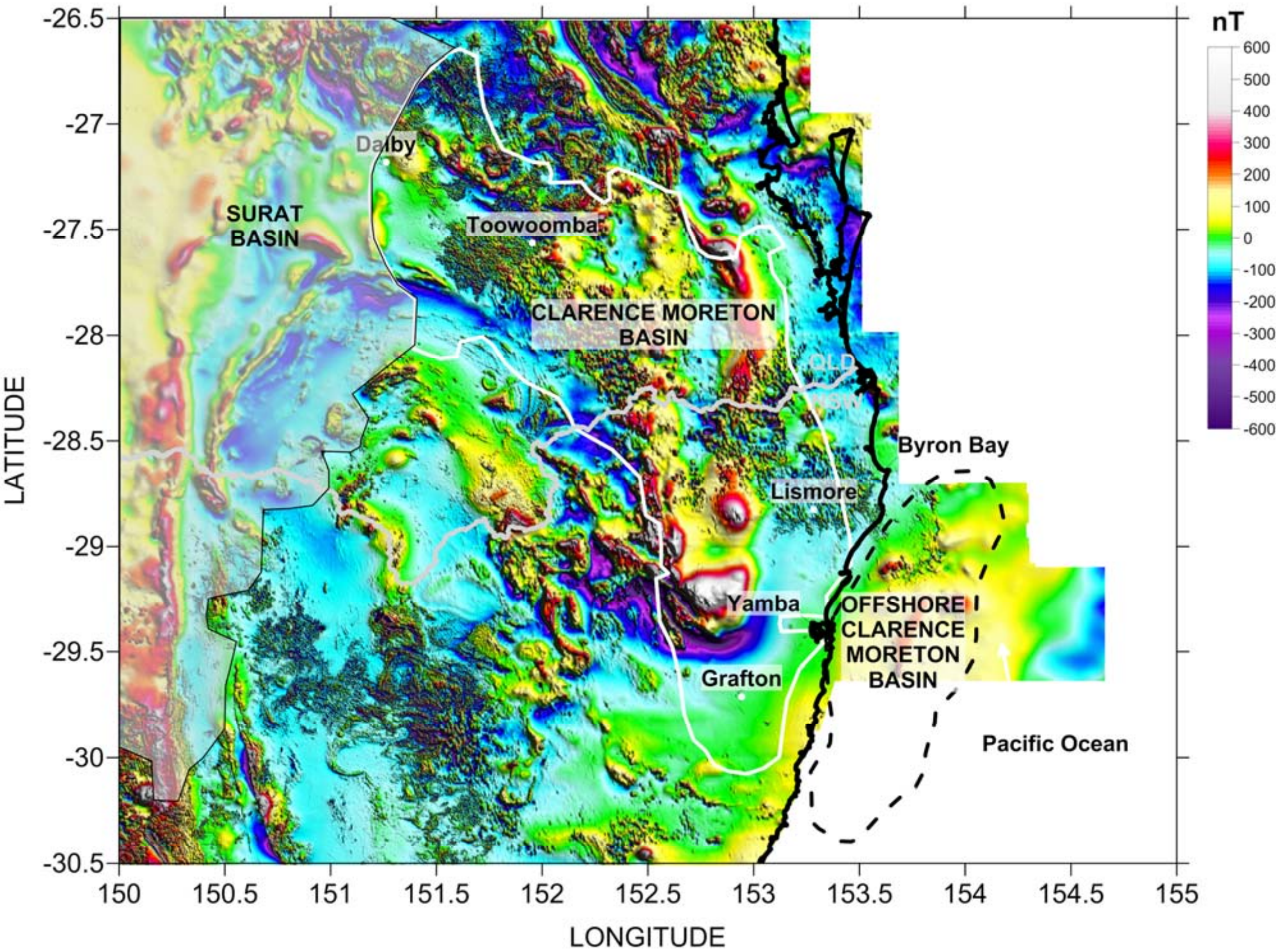


Figure 9.7. Total magnetic intensity map of the Clarence-Moreton Basin (data available from Geoscience Australia).

The magnetics map shows a strong response from both recent Tertiary volcanics, and basement features. The Tertiary volcanics, which cover the NE portion of the NSW part of the basin, have a characteristically speckled pattern, and their short wavelength variations consistent with the shallow near surface origin of this signal. The main basement features, such as the South Moreton Anticline, is evident as a strong magnetic high, extending to the mid-western edge of the Clarence Moreton Basin. The thick sedimentary packages tend to magnetically low, and preserve few detailed features.

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10. The Gloucester Basin

Structure and Evolution

The Gloucester Basin is a small Permian basin within the southern New England Fold Belt (Figure 3.1 and Figure 10.1), which probably opened in response to the transtensional regime also causing extension in the Sydney-Gunnedah-Bowen Basin systems. It is a small (60 x 12 km), highly deformed Permian depression, containing economic coal and active coal-seam gas prospects (Ward *et al*. 2001).

The Basin itself represents are broadly synclinal structure from east to west (Ward *et al*. 2001), and is heavily faulted, particularly in the southeast portion of the Basin, by a complex series of normal and reverse faults (Ward *et al*. 2001). This activity, and the steep dip of the beds, has made correlation of individual seams difficult.

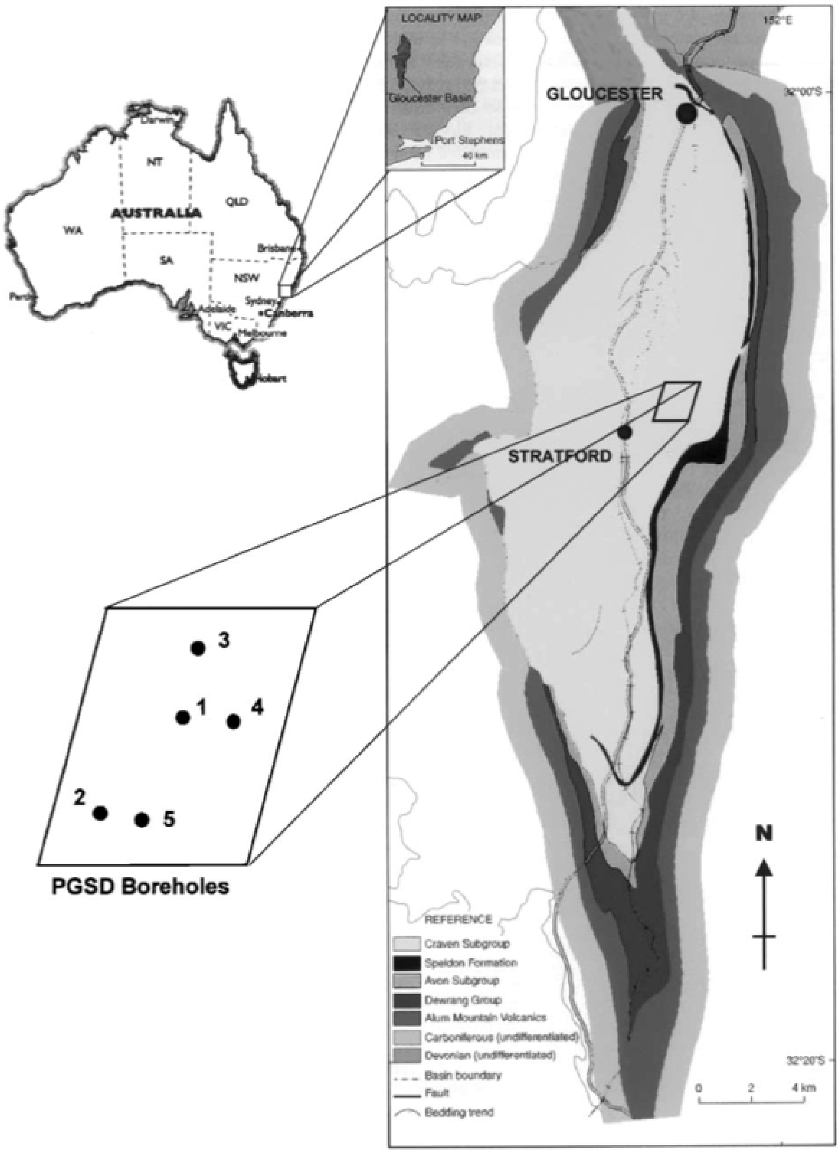

Figure 10.1. Surface Geology and location of the Gloucester Basin (from Ward *et al*. 2001).

Geology

The lowermost units in the basin are the Alum mountain volcanics; a basaltic to rhyolitic volcanic sequence up to 2000 m thick (Ward *et al*. 2001), and are around ca. 280 Ma (Caprarelli & Leitch 2008). These volcanics are probably coeval with the Werrie Basalts which constitute the floor of the Gunnedah Basin (Caprarelli & Leitch 2008).

Overlying the Alum Mountain Volcanics is the Dewrang Group, a late Permian alluvial fan/fluvial/delta plain sequence, which is divided into the older Durrallie Formation, the Wesimantels Formation – which contains a significant coal seam (Weismantels Seam), and overlying Mammy Johnsons Formation (Ward *et al*. 2001).

The Gloucester Coal Measures overlies the Dewrang Group, and is also late Permian (Ward *et al*. 2001). These Measures are split into two coal bearing subgroups; the basal Avon subgroup, and the upper Craven Subgroup, and are separated by the Speldon Formation, a non-coal bearing interval consisting of pebbly sandstones and conglomerates, coarse lithic sandstones, and bioturbated mudstones (Helby *et al*. 1986). Reaching about 80 m thickness, the Speldon Formation probably records an episode of marine transgression onto the Basin.

The ~400 m thick Avon subgroup further consists of the (lower) Waukivory Creek Formation (consisting of fine to coarse sandstones, mudstones, claystones, tuffs, and 6 main coal seams identified by Ward *et al.* 2001), and the overlying Dog Trap Creek Formation (interbedded shales, siltstones, sandstones, and the Glenview coal measure).

The Craven subgroup is up to ~980 m thick, and consists (lowest to highest) of the Wenham Formation, Ward's River Conglomerate, Jilleon and Leloma Formation, and the Crowther's Road Conglomerate. These formations host numerous coal seams (8 named seams in Ward *et al*. 2001; more in the Australian stratigraphic names database, though different seams are allocated to different units between these sources). A simplified stratigraphy is presented in Table 10.1.

Table 10.1. Stratigraphy of the Gloucester Basin (from Ward *et al*. 2001).

GLOUCESTER COAL MEASURES	Craven Subgroup	Leloma Formation	Linden seam
			Bindaboo seam
			Deards seam
		Jilleon Formation	Cloverdale seam
			Roseville seam
		Wards River Conglomerate	Fairbaims Lane seam
			Bowens Road seam
		Wenham Formation	Bucketts Way seam
	Speldon Formation		
	Avon Subgroup	Dog Trap Creek Formation	Glenview seam
		Waukivory Creek Formation	Avon seam
			Triple seam
			Rombo seam
			Glen Road seam
			Valley View seam
			Parkers Road seam
DEWRANG GROUP		Mammy Johnsons Formation	
		Weismantels Formation	Weismantels seam
		Durrallie Formation	
ALUM MOUNTAIN VOLCANICS			

Coal Seam Gas Potential

The Gloucester Basin is an active CSG prospect, with AGL actively exploring within PEL 285. The average total coal thickness within the basin package is ~30 m, at depths between 200-700 m. Active coal mining is occurring at both Duralie and Stratford. CSG target seams within the Gloucester Basin are generally > 200m, beyond the depth of shallow fractured rock aquifers.

The Waukivory pilot project, in the north of the basin, extends earlier deep drilling by Lucas Energy, which demonstrated gas contents of 12-25 m^3/t, permeabilities of 300 milidarcies to 1millidarcies between 100m – 500m. The nearby LMG03 well also achieved production flow rates (>1050 mcfd (thousand cubic feet per day), Lucas Energy 2008).

Many of the coal seams within the Basin are minor aquifers, with AGL's observations (see SRK AGL002 2010, for details) noting wells that intersect seams ~150m below ground level tend to have low water production (~3.9 m^3/day), while seams above 150m depth are wet, and gas wells tend to have higher water production (~28-96 m^3/day). The hydraulic conductivity of these seams varies with depth, from ~8.6×10^{-2} m/day for depths of around 100m, decreasing to 6.1×10^{-3} - 2.36×10^{-2} m/day at 300m, and ~4.86×10^{-4} m/day at 500 m (useful extractable aquifers have hydraulic conductivities > ~10^{-2} m/day, for comparison).

The Gloucester Basin is reasonably complex, and highly faulted at depth, and the continuity of coal seams at depth, and laterally, is poor. This deep faulting may interconnect deeper coal seam aquifers with near-surface fractured-rock aquifers, and this is a course of ongoing investigations (eg. SRK AGL002 2010).

Geophysics

Seismics

The seismic characterization of the shallow coal seams in the Gloucester Basin has been discussed by King (1979) – however, no geographic information for the profiles presented (see Figure 10.1) was provided, making detailed analysis difficult. From 2009-2012 AGL conducted seismic surveys over its petroleum lease (for example, see:
http://agk.com.au/gloucester/index.php/the-project/
http://www.resources.nsw.gov.au/__data/assets/pdf_file/0015/304215/200091013-PEL-285-REF-AGL-Gloucester-Seismic-Surveys.pdf however, to date, this data has not been made public).

The published shallow seismics (King 1979, Figure 10.2) demonstrate the near horizontality of the shallow (~100m) coal measures within the central portion of the basin, in contrast with the steeply dipping nature of units seen at the Basin's edges. The contiguity of units is suggested by the survey, but the resolution is insufficient to determine the fine structure of seams (King 1979).

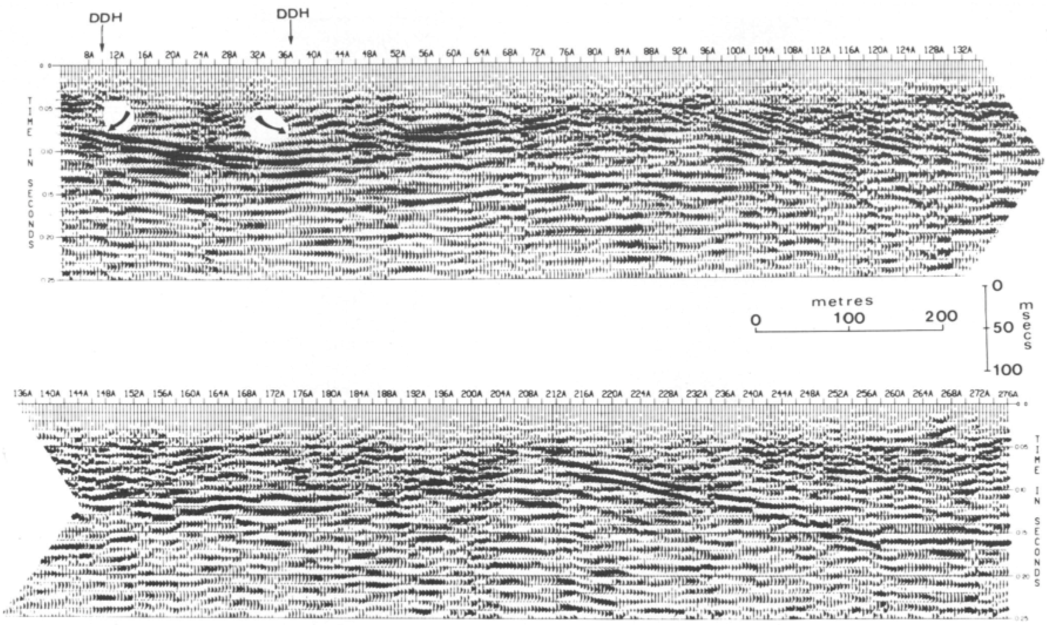

Figure 10.2. Two representative sections of mini-SOSIE seismics from the Gloucester Basin, NSW, from King (1979). No geographic information was provided for the sections. King (1979) notes that the depth to known coal seams (arrows in top figure) are rather consistent across lines, and that the steep dip of units seen in the geology at the edges of the Basin are not seen in the shallow seismics within the centre.

Potential Field

The spherical Bouguer gravity anomaly map of the Gloucester Basin (Figure 10.3) illustrates little detail on this small trough. The regional gravity is dominated at the basin scale by a seaward increase, generally due to extensive crustal thinning during margin rifting. The gravity low toward the northern end of the Basin probably represents enhanced sediment thickness in this area.

The total magnetic intensity map (Figure 10.4) illustrates the basement fabric peripheral to the Gloucester Basin clearly. The roughly "V" shaped spreading of the New England fold-belt basement is evident, narrowing toward the south. Minor anomalies towards the northern extent of the basin possibly reflect buried volcanics in this region.

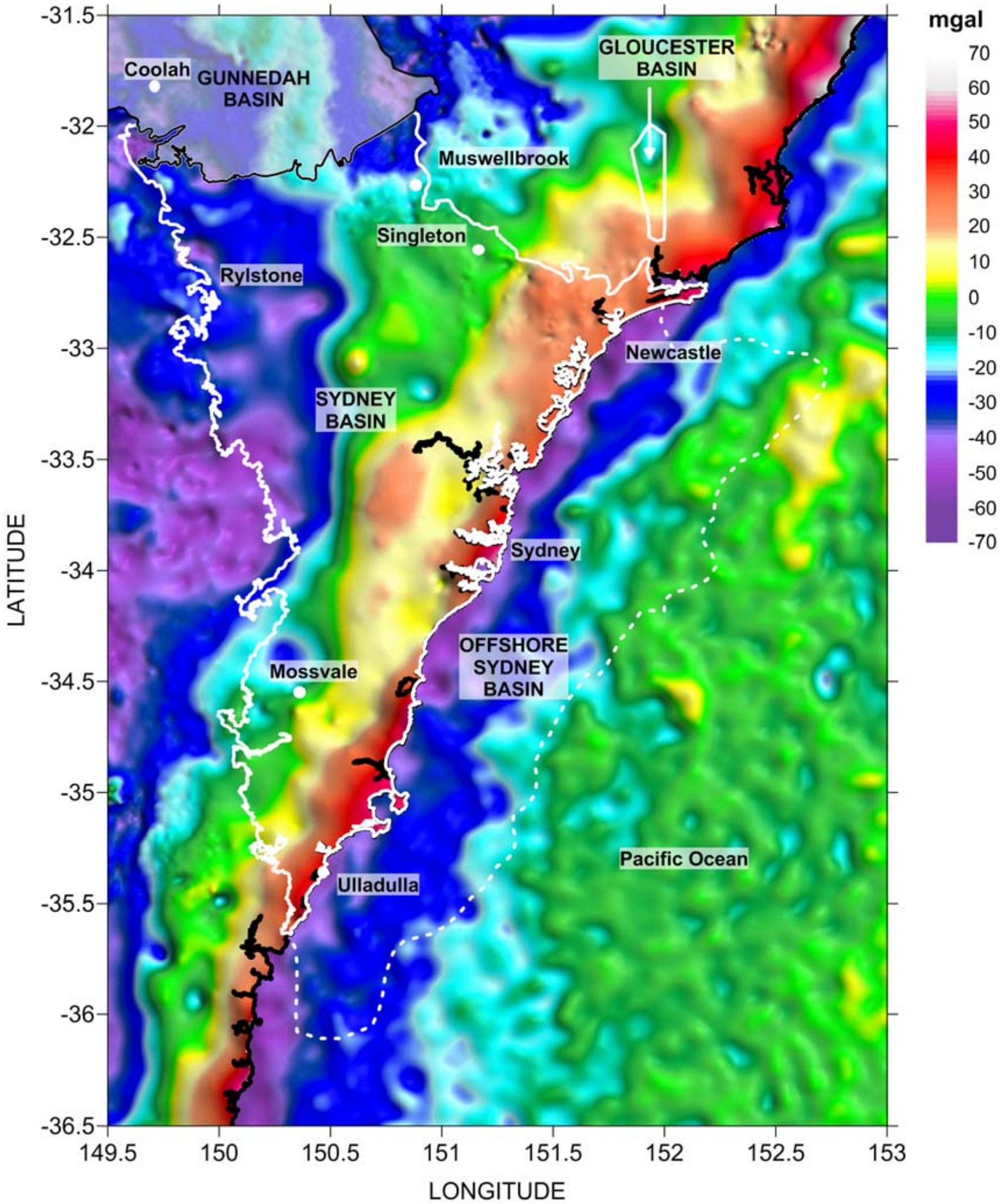

Figure 10.3. Spherical Bouguer gravity anomaly map of the Sydney and Gloucester Basins, NSW (data available from Geoscience Australia).

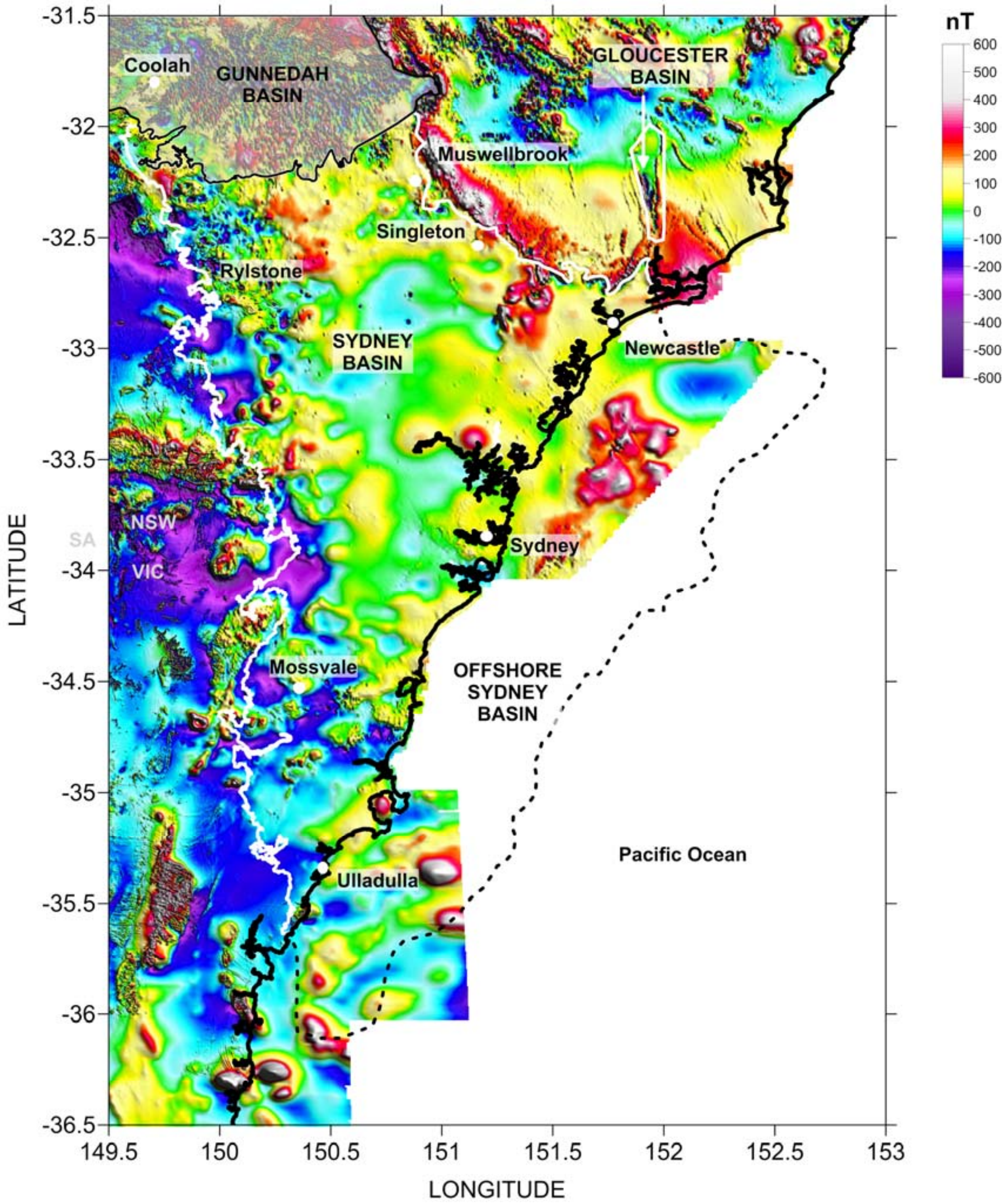

Figure 10.4. Total magnetic intensity map of the Sydney and Gloucester Basins, NSW (data available from Geoscience Australia).

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11. The Murray Basin

Structure and Evolution

The Murray Basin is an extensive, thin sequence of Cainozoic cover that extends of the SW portion of New South Wales (Figure 3.1). These sequences cover a number of basement depressions, however, that host older Paleozoic-Mesozoic sediments.

The Cainozoic sequences of the Murray Basin on-lap Lachlan Fold Belt basement to the east and south, Palaeozoic Darling Basin sediments to the north, the Kanmantoo Fold Belt in the west, and the Willyama and Broken Hill blocks to the northwest. The main Cainozoic depocentre is in the western part of the Basin, possibly a result of a dynamic topography effect due underlying mantle convection (Heine *et al*. 2010).

One of the deeper basement depressions, the Ovens Graben, contains the extensive Coorabin Coal Measures, which resulted in this portion of the Murray Basin being renamed the Oaklands Basin.

Lignite (brown coal) has also been discovered within the sediments of the Murray Basin, near Griffith, at depths of ~90 m (Pels 1969).

Geology

Geophysical evidence, in particular Bouguer gravity, has delineated a number of deep troughs within the Murray Basin, and limited drilling of these features indicate they represent older infrabasin structures beneath the Cainozoic Murray Basin cover. These features include the Ovens Graben, Menindee, Tarrara, Renmark and Wentworth Troughs (Figure 11.1). These features contain sediments of Upper Silurian to Lower Carboniferous age (mostly Devonian), with discontinuous remnants of Permian, Triassic and Cretaceous sediments recorded (Brown *et al*. 1988).

Topographic depression due to mantle flow beneath has been suggested by Heine *et al*. (2010). This led to widespread innundation between 52-37 Ma, and again at 30-5 Ma, and the deposition of an extensive, up to 600 m thick, platform cover sequence of consolidated and unconsolidated sediments.

Inundation in the Cainozoic was from the south, and resulted in the sedimentation of paralic sands and silts, and also outwash sands from the uplifted basin margins (Pels 1969). These are evidenced as Eocene sandstones, predominantly within structural lows within the basin. Subsequent to initial phase, sedimentation continued throughout the Eocene and consisted of carbonaceous and grey, coarse sands, clays, and also brown coal (Pels 1969).

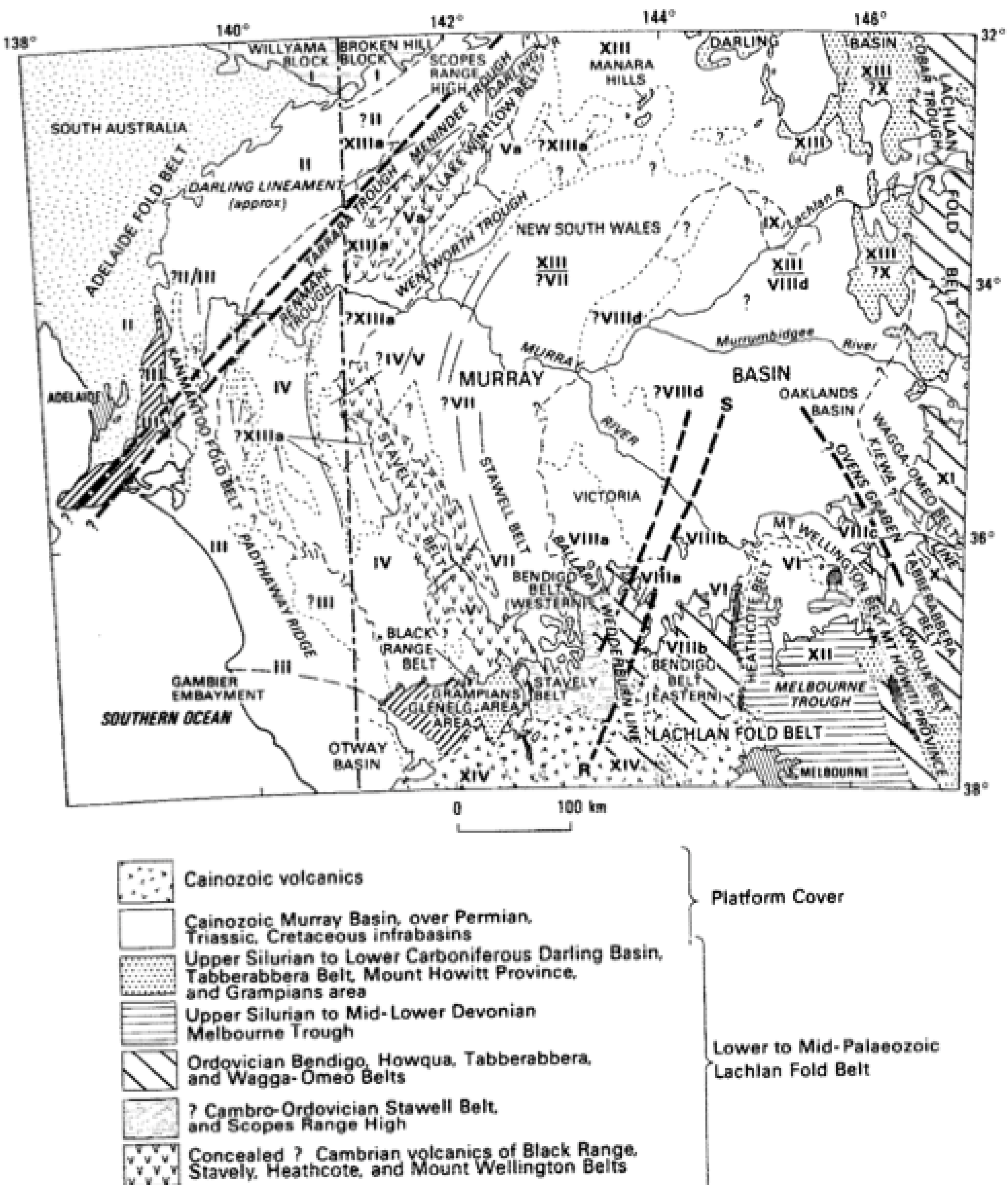

Figure 11.1. Structural elements of the Murray Basin, including the infrabasin depressions the Renmark, Tarrara, Menindee and Wentworth Troughs (NW), and the Ovens Graben (locally renamed the Oaklands Basin, in the SE). From Brown *et al.* (1988).

Bores near Widgelli (east of Griffith), and Warburn (northeast of Griffith) have documented substantial brown coal at depths of 90m. A correlation of the stratigraphy is shown in Figure 11.2. This is considered of low thermal maturity and not generally of interest for thermogenic coal seam gas, though they may host biogenic gas, as they are in contact with groundwater. Anthracite has however been commercially mined within the Ovens Graben – this part of the Basin has been renamed the Oaklands Basin, and is considered separately in the next section.

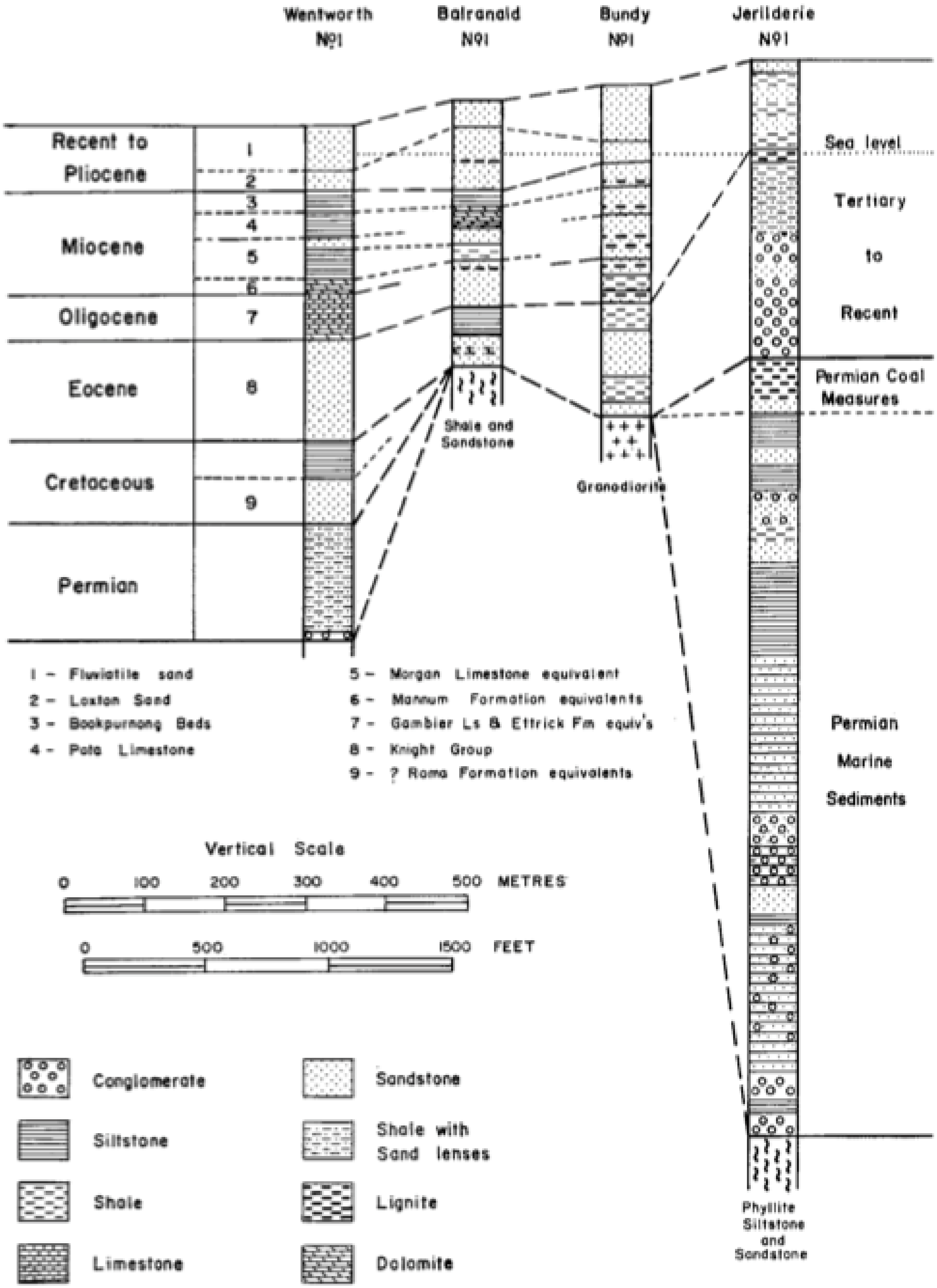

Figure 11.2. Correlation of stratigraphic columns across the Murray Basin (west to east). From Pels (1969).

CSG potential

The Murray Basin contains no significant (anthracitic) coal seams, and the shallow sediments have not generally reached the maturity needed for significant gas production. It has been included here solely because of report of lignite within the sedimentary package near Griffith (Figure 11.2, Pels 1969). Though this is not of significant enough grade for thermal gas production, it is in contact with nearby aquifers, and there is the possibility that biogenic gas (methane) production is occurring locally within these sediments.

Geophysics

The Murray Basin sediments are primarily Tertiary, and fairly flat lying, and have not been subject to deep reflection seismics over much of their extent. Extensive refraction experiments have been undertaken (see summary of Odin *et al*. 1991). Most of these refraction results targeted deeper (Mesozoic and older) depressions and deeper basement structures. Odin *et al*. (1991) reprocessed much of this data, and in conjunction with electrical sounding and borehole data, developed a map of the pre-Tertiary basement topography (Figure 11.3) under the Murray Basin.

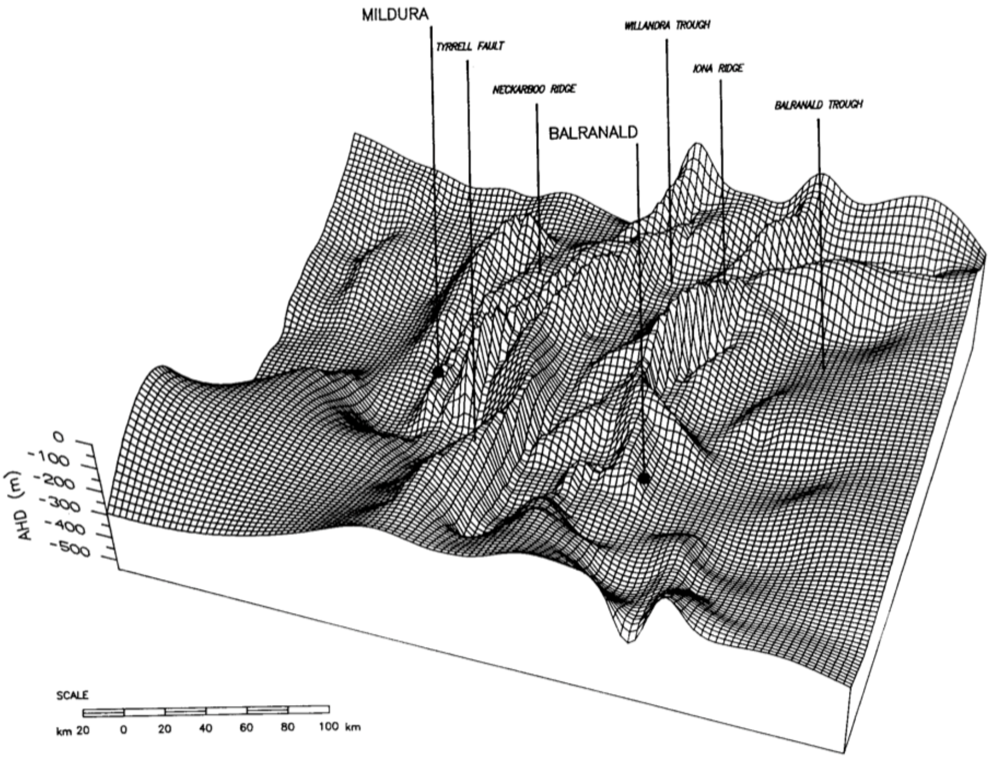

Figure 11.3. Topography of the pre-Tertiary basement of the Murray Basement, based on re-analysis of older seismic refraction data, vertical electrical soundings, and borehole logs (from Odin *et al*. 1991).

The Tertiary Murray Basin sediments are important aquifers, containing up to 4600 million litres of water, and the flow of this groundwater reserve is strongly constrained by the topography of the pre-Tertiary basement (Figure 11.3), which tends to behave as an aquitard, and thus the relevant hydrogeological basement in this area (Odin *et al*. 1991).

A series of ridges are evident in the basement topography, with up to 300 m relief in some areas, trending in NNE direction. Some of the ridges are evidently terminated at the Murray River, and they form important conduits for regional groundwater flow.

Potential Field

The gravity response of the Murray Basin (Figure 11.4) is dominated by the density contrasts within the Paleozoic fold belt underlying much of the Cainozoic sediment. To some extent these same lithological variations control the basement topography too, and there is probably an association with the topographic variations seen within the basement of Murray Basin in the seismics in Figure 11.3, and the gravity in Figure 11.4.

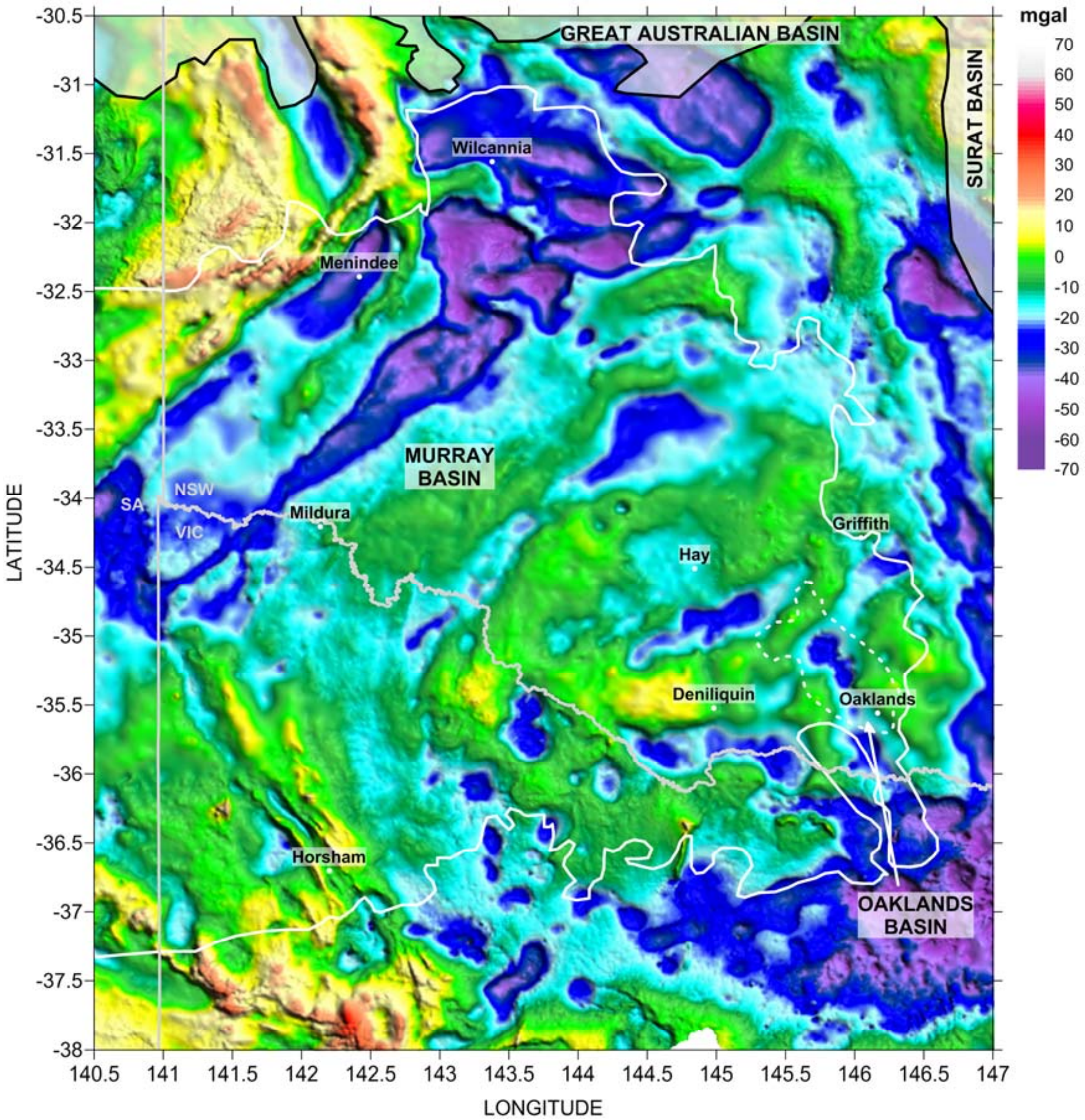

Figure 11.4. Spherical Bouguer gravity anomaly map of the Murray Basin. The anomalies within the Murray Basin itself primarily reflect variations in the basement topography and composition, mapping out the basal Tasmanides units, and to a lesser extent the sediment/bedrock interface (data available from Geoscience Australia).

The magnetic intensity map of the Murray Basin (Figure 11.5) illustrates clearly the lithological variations in the basement units to the basin itself. The fabric follows similar trends to that seen in the gravity, though the magnitude in variation is subdued compared to more highly magnetic (volcanic) units elsewhere.

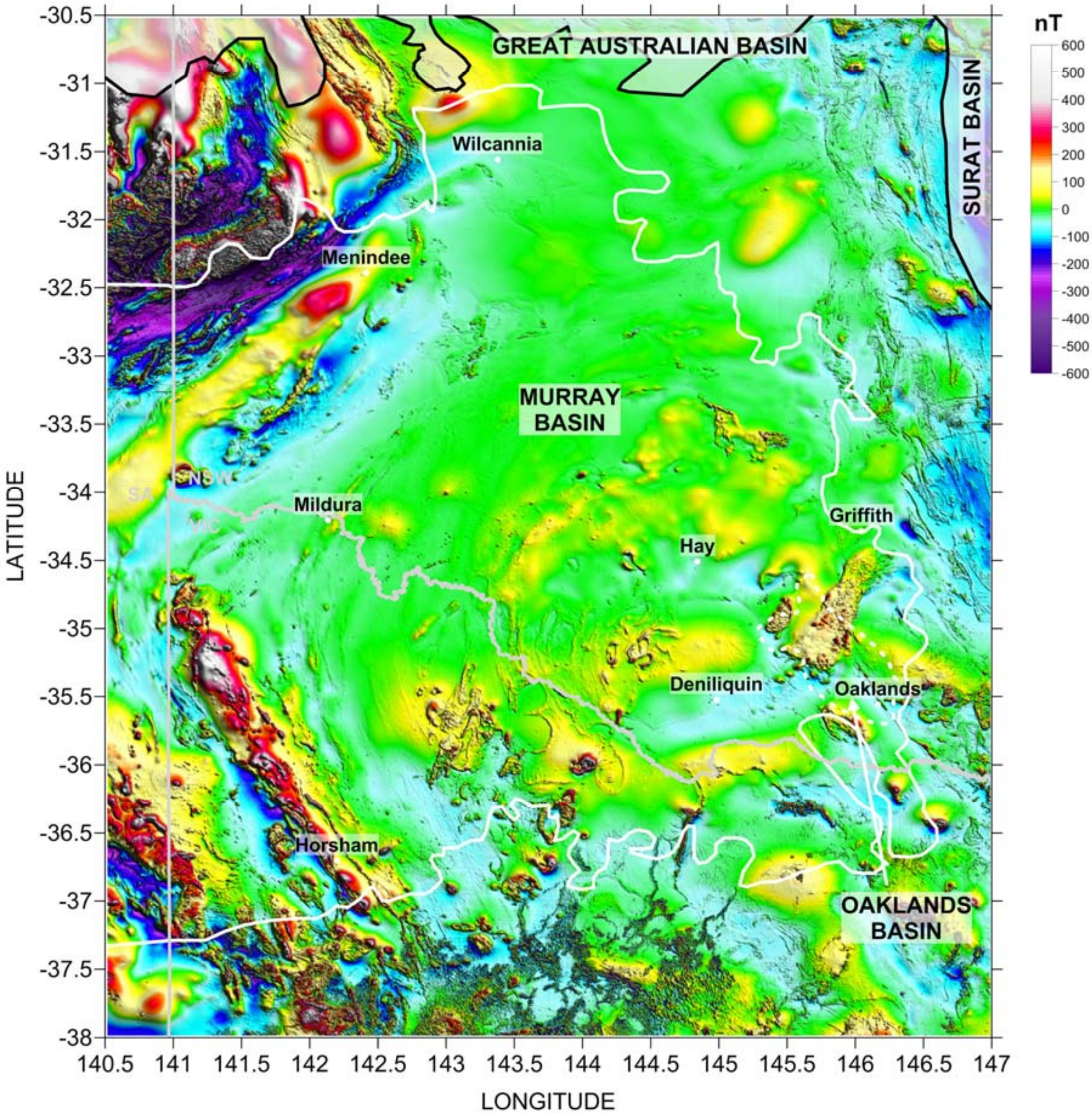

Figure 11.5. Total magnetic intensity map of the Murray Basin, NSW (data available from Geoscience Australia).

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12. The Oaklands Basin

Structure and Evolution

The Oaklands Basin is a small structure (~3,800 km^2) in the vicinity of Oaklands- Griffith – Albury – Jerilderie in south central NSW (Figure 3.1 and Figure 12.1). It contains sediments of predominantly Permo-Triassic age, and lie almost entirely under Cainozoic Murray Basin sediments. It is hosted within the Ovens Graben, which extends into Victoria, and is between 15-25 km wide, and contains over 1km of sediment.

The Basins hosts the late Permian Coorabin coal measures, which are about 15-18 m thick, and is an upward-fining sequence consisting of three main seams separated by shale, sandstones, and some conglomerates (Pels 1969; Stewart & Adler 1995). The coal measures underlie at least 1,000 km^2 of the Oaklands Basin.

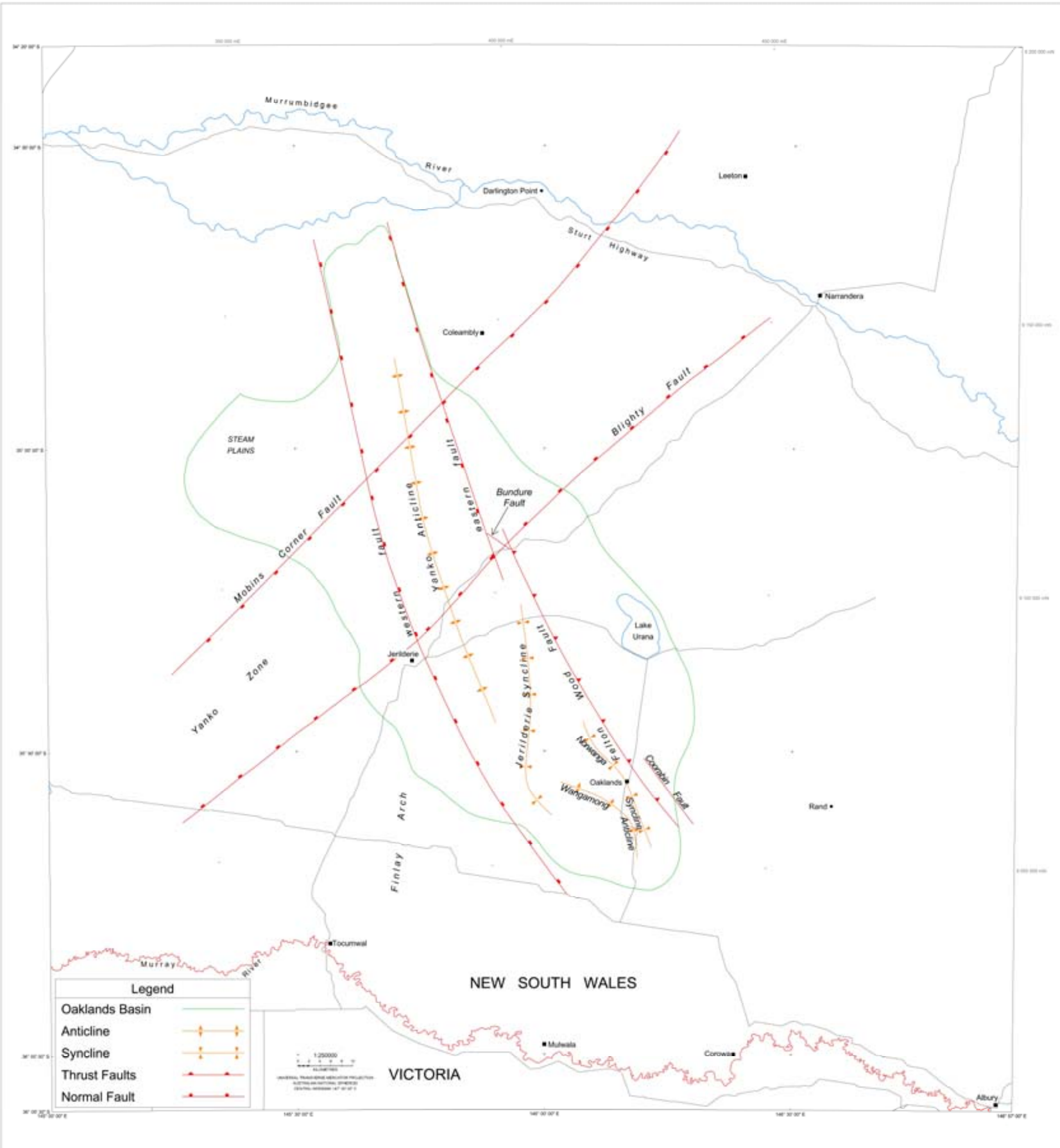

Figure 12.1. Structural elements of the Oaklands Basin (from www.resources.nsw.gov.au).

Geology

As the Oaklands Basin is not exposed at the surface, knowledge of its stratigraphy comes exclusively from exploration drill holes and water bores. The deepest portions of the basin are largely unconstrained.

The oldest sedimentary units encountered (at Jerilderie 1, 25 km west of Urana) are part of early Permian Urana formation (Resources: nsw.gov.au). Outside the Oaklands Basin, the Urana Formation comprises of earlier units, from Early Carboniferous to early Permian – presumably these underlie the observed sedimentary package within the Oaklands Basin too. The Urana Formation mostly represent marine sediments, with a gradation to deltaic sediments towards the upper portions of the Formation. They preserve evidence of glaciogene environment. The top of the formation is heavily weathered.

Overlying the Urana Formation within the Ovens Graben, and to the southeast, are the Narrow Plain Formation, and the Coorabin Coal Measures. To the west, the mid-Triassic Jerilderie Formation unconformably overlies the Urana Formation. The Jerilderie Formation also overlies the Coorabin Coal Measures where the two coincide.

The late Permian Coorabin Coal Measures have been suggested to be primarily fluvial, representing a meandering stream deposit (Morgan 1977). The Jerilderie Formation is a fluvial channel/floodplain deposit, and is poorly consolidated (Yoo 1997).

The Jerilderie formation has been described as lithologically similar to the oldest Murray Basin desposits (the Tertiary Olney Formation; O'Brien 1991), which unconformably overlies it. A simplified stratigraphy is shown in Table 12.1 and a schematic east-west cross section in Figure 12.2.

Table 12.1. Stratigraphy of the Oaklands Basin, and overlying Murray Basin sediments (from www.resources.nsw.gov.au).

Era	Palynological Zones	Stratigraphic Unit			Hydrocarbon Shows
Tertiary	T. bellus - N. asperus	Wunghnu Group	Shepparton Formation		
			Calivil Formation		
		Renmark Group	Olney Formation		
Triassic	A. parvispinosus	Jerilderie Formation			
Late Permian	P. reticulatus	Coorabin Coal Measures	Nowranie Creek Formation		
	Upper Stage 5		Loughmore Formation	Coreen Creek Coal Member	
	Lower Stage 5		Narrow Plain Formation	Lanes Shaft Coal Member	
Early Permian	Stage 3	Urana Formation "Jerilderie sandstone"			Jerilderie 1 (518m) bitumen droplets in thin section Jerilderie 1 (563m) gas flowed at < 500 cubic feet/day Urana 1 (299m) minor gas show and H2S smell Jerilderie 1 (915m) slight gas bleed from core Jerilderie 1 (1005m) S1 value suggests possibly migrated oil
	Stage 2				
Late Carboniferous	Stage 1	Boorhaman Conglomerate			Untested
Early Carboniferous		Mansfield Group			
Ordovician - Devonian		Basement			

(grey band) = unconformity

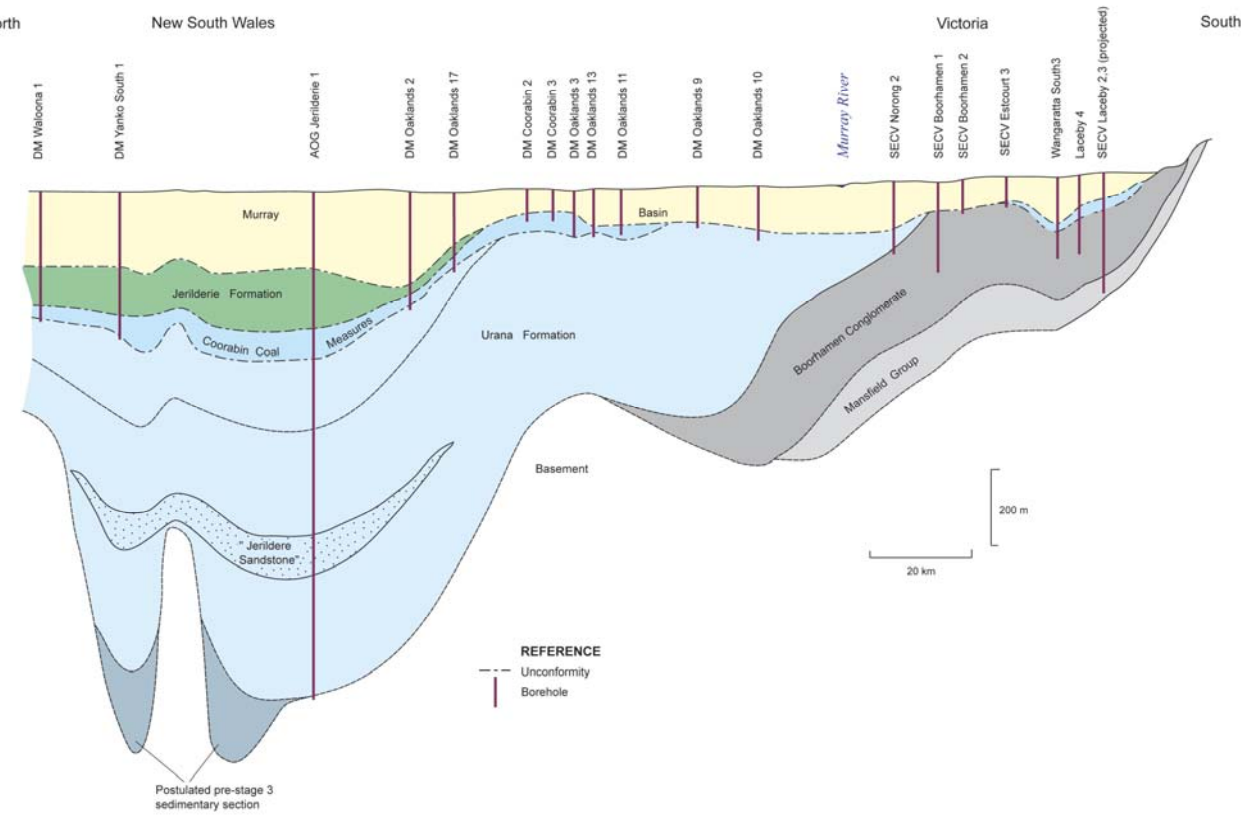

Figure 12.2. Structural East-West Cross Section of the Oaklands Basin (from resources.nsw.gov.au).

CSG potential

Tertiary coals within the Murray Basin sediments overlying the Oaklands Basin have been discussed within the Murray Basin chapter.

Within the Oaklands Basin sequence, the late Permian Coorabin coal measures have been of interest to CSG exploration. They are around 15-18 m thick on average (sometimes <1.5 m thick), consist of three main seams (interbedded with shale, sandstones, and conglomerate), and are at depths of around 113 m-377 m in the south (Yoo 1995). The sediments deepen towards the north, and Jerilderie-1 intersects Permian sediments at ~1328 m depth (Yoo 1995). The coal measures are associated with several regionally significant aquifers, making them a target for biogenic gas production, but also potentially sensitive to groundwater interaction.

Geophysics

Seismics

Four detailed seismic profiles were conducted over the Oaklands Basin in 2009 (Figure 12.3 to Figure 12.7), as part of the NSW Geological Survey's New Frontiers initiative. Four lines were obtained, totalling about 250km of seismics. Most of the lines were acquired with acquisition parameters suitable to sedimentary basins (6 second two-way travel time, and 30m VP), though a small section on the most northerly line (marked in red) was configured for deep crustal imaging. Interpreted lines are available (at cost) from resources.nsw.gov.au.

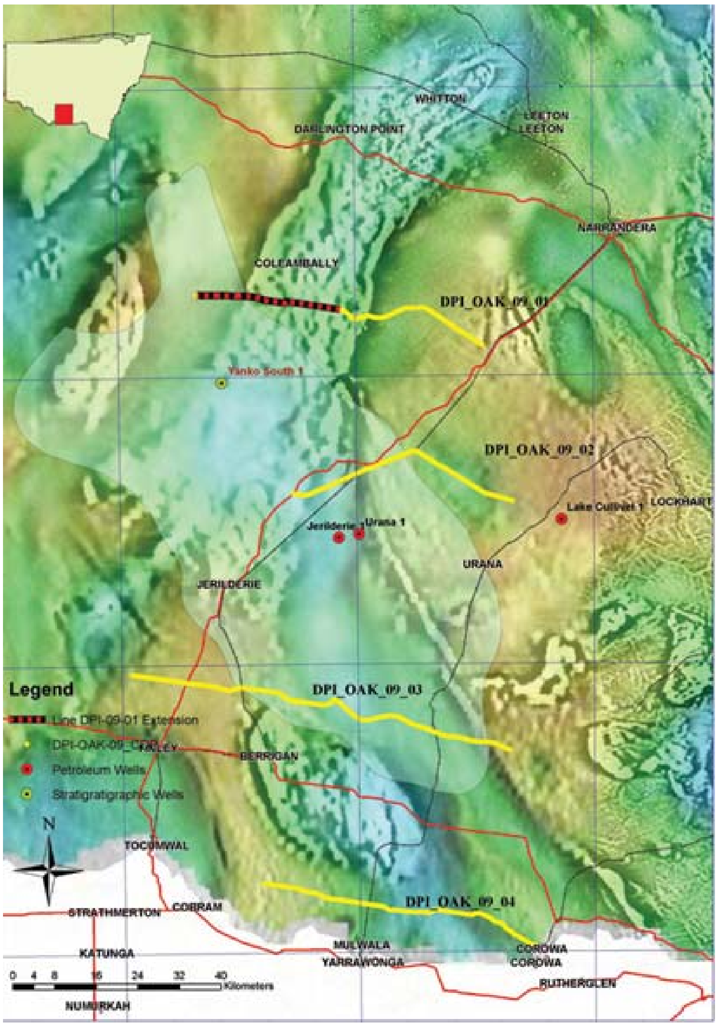

Figure 12.3. Location of 2009 Oaklands Basin seismic profiles. Transparent shape delineates the recognized outline of the basin (from: http://www.resources.nsw.gov.au/geological/about/geophysical-surveys/oaklands-basin-2d-2009-seismic-survey).

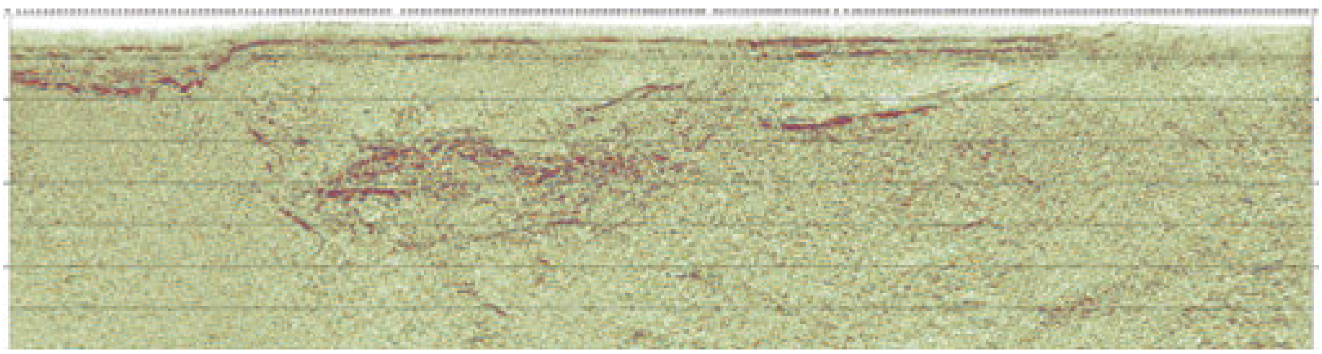

Figure 12.4. Line DPI-OAK-09-01. The most northerly line shown in Figure 12.3 above; shown is the yellow segment (the part of the line configured for sedimentary basin imaging). The seismics show the veneer of the Murray Basin sediments – the Oaklands Basin proper is to the left of the image. The complex basement structure is well defined.

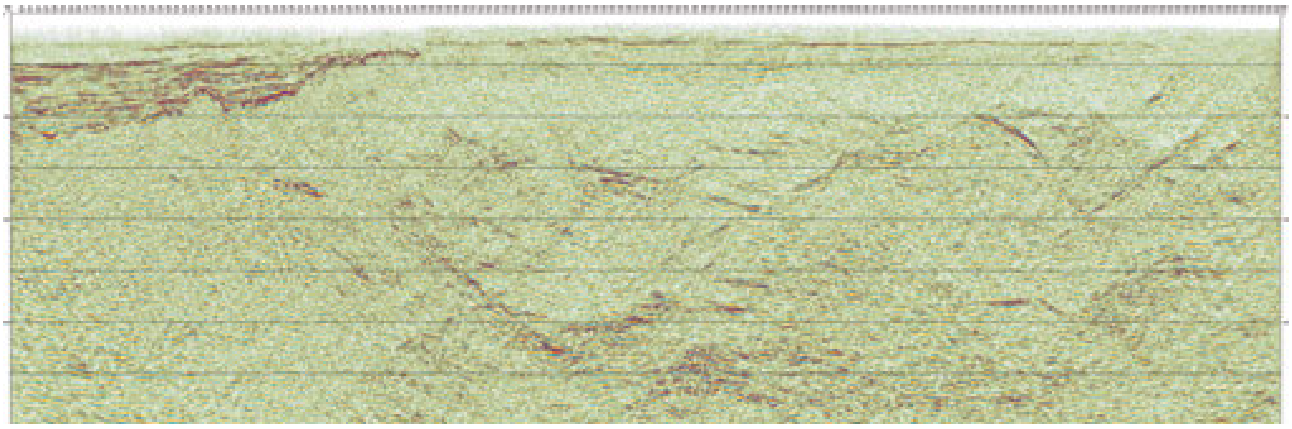

Figure 12.5. Line DPI-OAK-09-02. The 46.83 km line transitions from thick buried Oaklands Basin on the left, to the structural high east of the basin. The near horizontality of the younger (<~mid Triassic) units is demonstrated, and the thick Urana formation again evident. Older unexposed sequences are imaged at depth in the west.

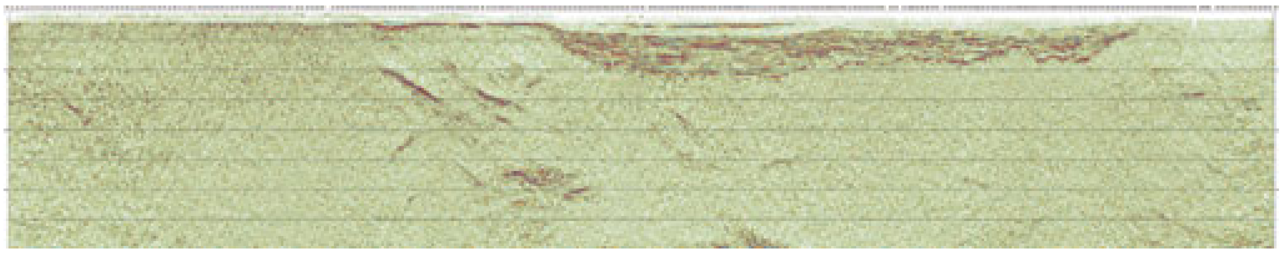

Figure 12.6. Line DPI-OAK-09-03. This 85.53 km line transects the southern part of the Oaklands Basin. The increased thickness of sediments is apparent within the above section, as is the abundant normal basement faulting which led to the formation of the graben structure.

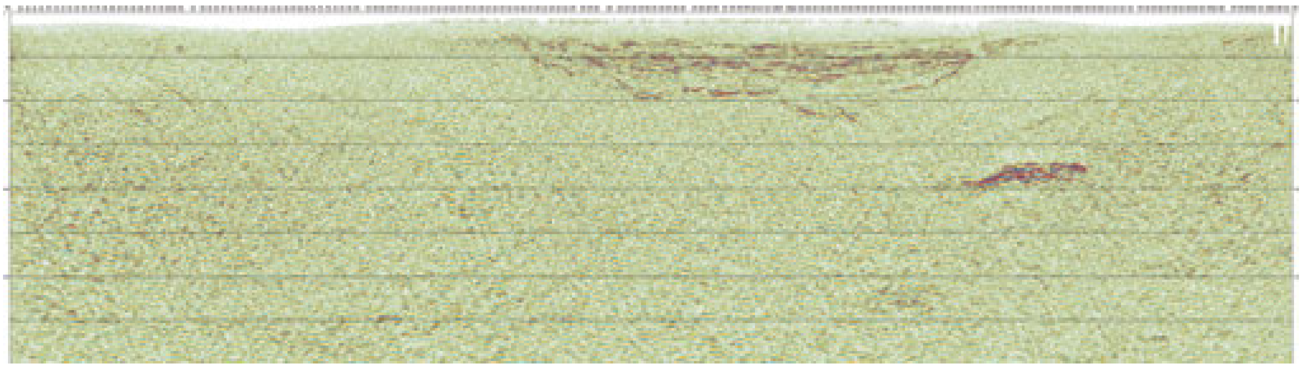

Figure 12.7. Line DPI-OAK-09-04. This 58.38 km line is outside the formal boundary, but still images the more localised sedimentary package within the extended graben structure, which extends into Victoria.

Potential Field

The gravity response (Figure 12.8) of the Oaklands Basin/Ovens Graben system is typical of a thick, sediment-filled graben system. The low density of the infilling sediments, compared with the surrounding basement rock, results in a gravity low within the central portions of the basin (in the vincinity of Jerilderie-1). A NNE trending structure within the Oaklands Basin is probably due to a basement heterogeneity. The magnetic response of this unit (Figure 12.9) suggests it is of volcanic origin.

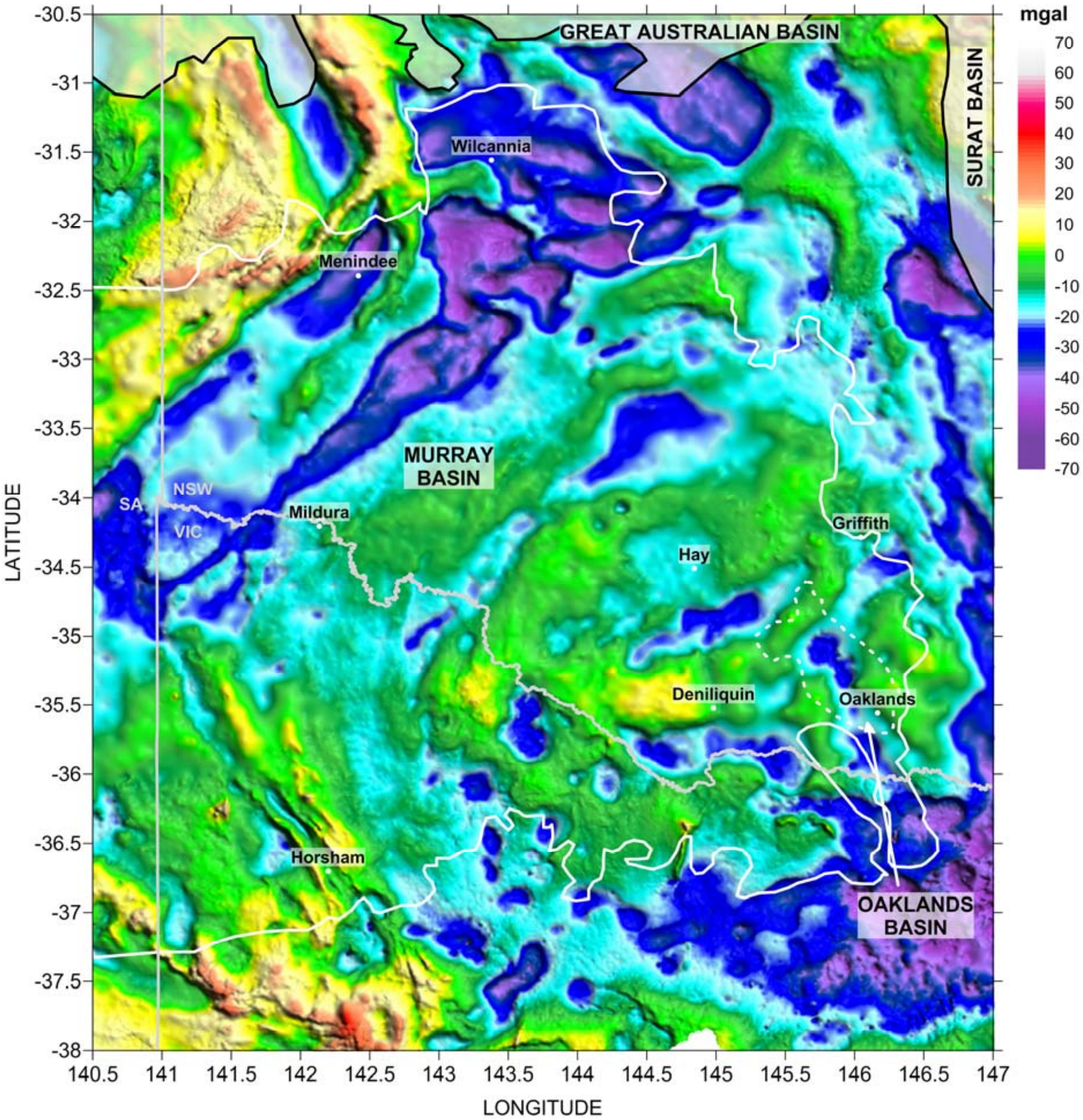

Figure 12.8. Spherical Bouguer Gravity map of the Murray and Oaklands Basin, NSW. The gravity low within the Oaklands Basin is in part due to the thick package of low-density sediments within this graben structure (data available from Geoscience Australia).

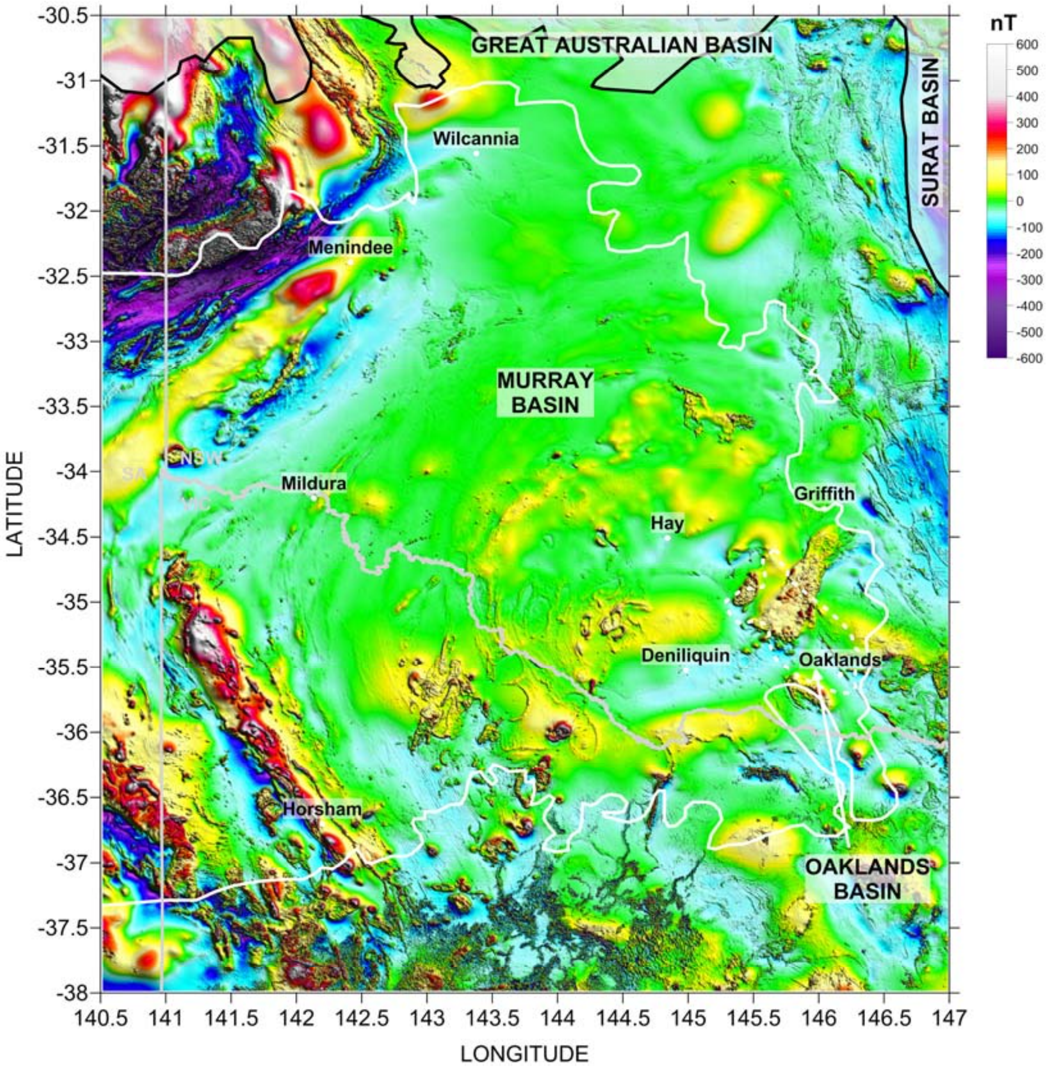

Figure 12.9. Total magnetic intensity map of the Murray Basin and Ovens Graben system. The region of higher-than-average magnetic intensity and fabric probably represents basement heterogeneity – possibly due to volcanic units at depth.

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13. NSW Hydrogeology

Australia is an arid continent, with widespread but unevenly distributed groundwater resources, and more than 60 % of the area of the country is entirely dependent on groundwater and it is a major source for a further another 20 % (Habermehl 1985). The quality and quantity of groundwater varies greatly in different parts of Australia as a result of complex geology and variable topographic, climatic and surface hydrogeological conditions both present day and in past geological time (Jacobson & Lau 1983). Groundwater can come from surficial aquifers (i.e. alluvial) with highly productive yields, deeper sedimentary rock aquifers (i.e. in large sedimentary basins) and fractured rock (i.e. in metamorphic terranes) as shown in Figure 13.1 and Figure 13.2. Many of these aquifers are under embargos or part of water sharing plans, such as in NSW the Water Act 1912 (NSW Government Gazette 2000) or Water Management Plan 2000 (NSW Government Gazette 2006), which are designed to control groundwater extraction for the protection of the resource.

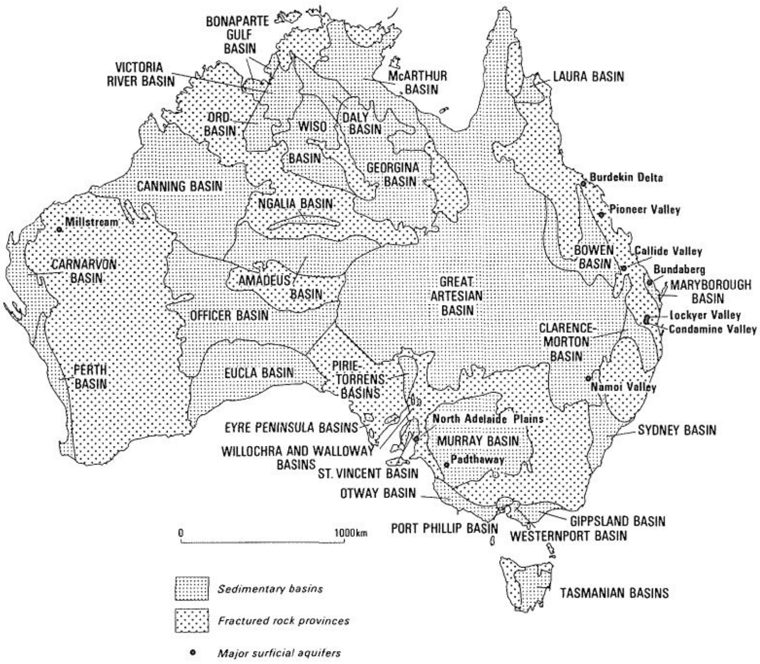

Figure 13.1. Major hydrogeological divisions in Australia. From Habermehl (1985).

All aquifers fall on a continuum between porous media systems and conduit systems (Cook 2003). In a homogeneous porous media groundwater flows through gaps between the sand grains whilst in heterogeneous porous media systematic variations in the size of the sand grains leads to the existence of preferential flow zones. In purely fractured media groundwater flows only in conduits and the aquifer matrix between the conduits is effectively impermeable and has no porosity (Cook 2003). Aquifers contain some degree of heterogeneity and when heterogeneity is more pronounced this has important implications for how groundwater properties are determined from investigations (e.g. pumping tests, permeability tests, modelling) are assessed.

The following section is a generalised discussion on major aquifer types and their typical properties with specific reference were possible to aquifers of the sedimentary basins in NSW.

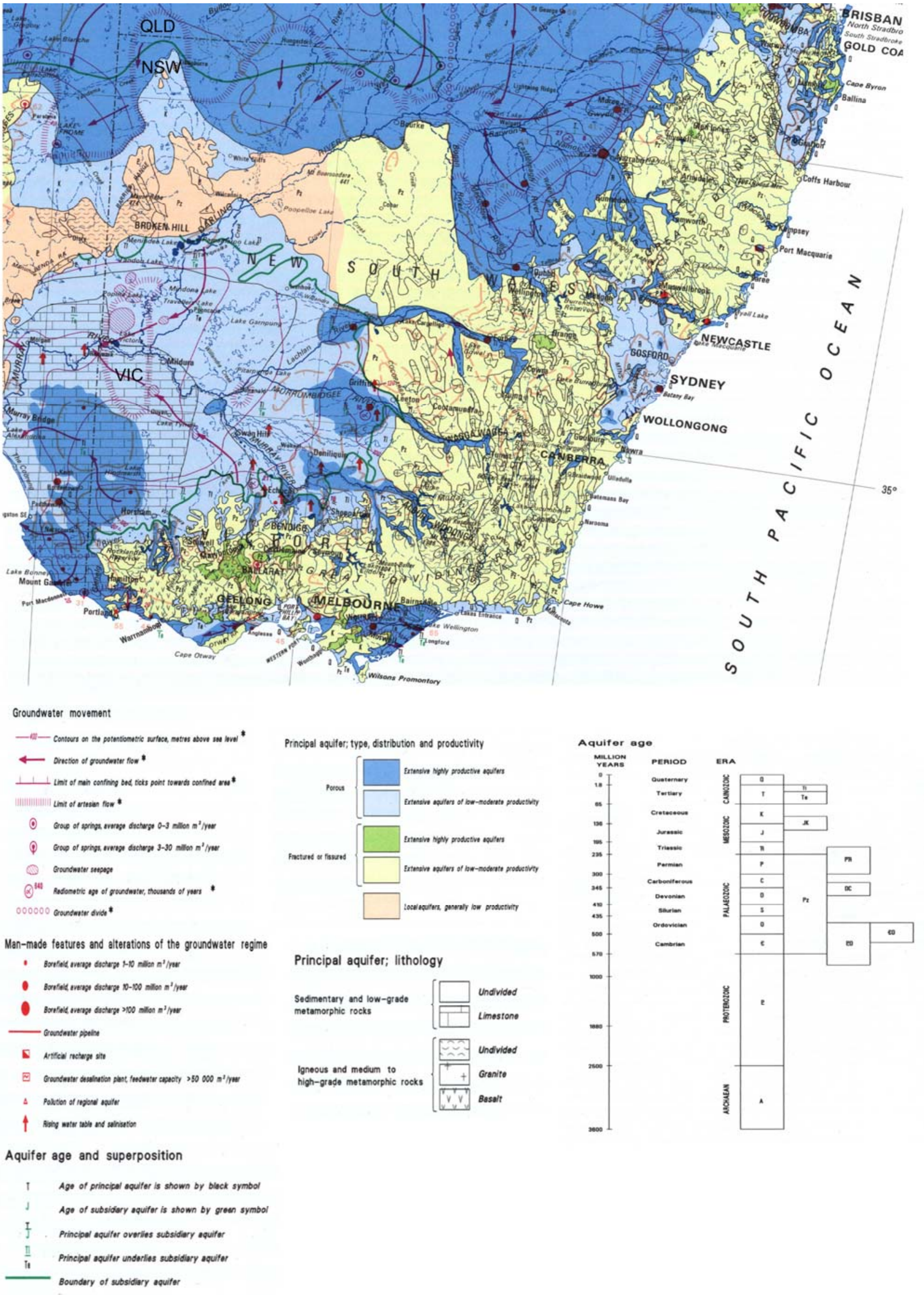

Figure 13.2. Hydrogeology Map of NSW. Adapted from Hydrogeology of Australia 1987 Map (Jacobson & Lau 1987, available from Geoscience Australia).

Generalised Aquifer Characteristics

Aquifer may have:

- Primary permeability
- Secondary permeability

Permeability is the property or capacity of a porous rock, sediment or soil to transmit a fluid and is a measurement of the relative ease with which any fluid moves through a geologic material under unequal pressure. Primary permeability is related to the porosity of the material at the time of deposition. Permeability related to the development of pathways or conduits after deposition or consolidation of the sediment / rock are generally referred to as secondary, such as dissolutions between grains or fracturing. Sedimentary rocks often have better primary permeability over secondary permeability whilst igneous and metamorphic rocks tend to have poor primary permeability and better secondary permeability that is influenced by geological processes.

There are two main types of aquifers:

- Unconsolidated clastic sediments i.e. alluvium / colluvium
- Consolidated rock
    - Primary permeability (sedimentary rocks)
    - Secondary fractured permeability (crystalline basement / sedimentary / igneous / metamorphic)

Unconsolidated Aquifers

Unconsolidated aquifers, often termed surficial, occur in any recent unconsolidated clastic sediments (Habermehl 1985; Cook 2003) i.e. alluvium, colluvium, elluvium and aeolian. Most unconsolidated aquifers are in Cainozoic sediments, are generally less than 150 m below the surface but can be upwards of 800 m deep. In NSW they are generally associated with alluvial / colluvium deposits in the valleys and floodplains of major rivers and coastal aeolian deposits.

These aquifers are generally unconfined, with large variations in yield and quality in vertical and lateral directions with high transmissivities and high yields (most typical in sand and gravel aquifers). Many of these aquifers partly overly sedimentary basins and can be difficult to distinguish as they are part of the continuous sedimentary sequence. Examples of major unconsolidated aquifers in NSW are the Botany Sands (Sydney Basin), Namoi Valley (Gunnedah Basin / Clarence Moreton) and in QLD the Lockyer Valley on the boundary with the Clarence Moreton, the Burdekin Delta and Callide Valley on the boundary of the Bowen Basin.

Consolidated Rock - Sedimentary

Consolidated sedimentary rocks form the largest and most prolific groundwater reservoirs with extensive and thick sandstone forming some of the most productive aquifer systems. The major sedimentary basins in NSW constitute significant groundwater resources, with groundwater extracted from Palaeozoic, Mesozoic and Cainozoic sedimentary rocks. Aquifers generally consist of consolidated clastic sediments which generally have intergranular porosity and may have primary and or secondary permeability.

Sedimentary basin aquifers are generally thick, hydraulically continuous over large areas, confined and form multi-layered aquifer systems separated by semi-pervious layers. Most aquifers produce good yields and exhibit moderate to large storage. Hydraulic characteristics and quality can differ greatly and groundwater movement in many basins is slow (e.g. 0.1 m/day to 1 m/day (eg. Cook 2003; Figure 13.4)).

The hydraulic properties of sandstones, which are the most common aquifers in the major sedimentary basins of NSW, depend on their textural characteristics and are determined by the depositional environment along with post depositional changes due to cementation, consolidation and fracturing. Stratification of sandstones can impart anisotropy, with the hydraulic conductivity parallel with the bedding plane usually higher than perpendicular to it. The horizontal permeability is generally higher (e.g. one order of magnitude) than vertical permeability. Secondary permeability is often defined by cross-bedding, bedding planes, faulting and fractures. The hydraulic conductivity of sandstone is typically one to three orders of magnitude lower than that of unconsolidated sediments (Davis & De Wiest 1966) and this decreased hydraulic conductivity is related to the process of consolidation (i.e. cementing of grains which reduces the interconnection between pore spaces and pore space).

In a heterogeneous sedimentary sequence, thin incompetent beds, such as shales, may be more intensely fractures as compared with thicker units of strong resistant formations, such as mudstones (Cook 2003). The degree of fracturing is related to the rock properties. For example crystalline sandstones may be generally inflexible and therefore fracture more easily than softer tuffaeous or claystone layers which tend to bend / deform. Shales usually have low porosities and the intergranular permeabilities in shales, and siltstones, are also low however fracturing can significantly increase hydraulic conductivity.

Glacial tills are ice transported sediments that are typically unstratified and poorly sorted, containing material from clay to boulder size. Glacial till materials are found in the earliest sedimentary sequences in the Sydney Basin (e.g. Talaterang Group and Seaham Formation Conglomerates). They can be thick and unfractured or wherever fractured glacial tills can provide active hydraulic connections. In clay deposits fracture spacing usually increase with depth, thereby affecting the vertical distribution of permeability (Cook 2003).

Coal seams within the coal basins are generally considered aquifers. They are commonly much less permeable than sand and gravel sediments. The groundwater within coal seams will range from unconfined where seams are exposed at the surface to confined and under pressure. Coal seams are generally deposited in low energy environments and as such, are associated with pelitic (fine grained) sediments such as shale / siltstone / claystone which form confining layers above and or below the seam. Groundwater enters the coal seam either via direct infiltration at exposure or vertically from above or below driven by a pressure gradient. Less likely the groundwater is ancient connate water. Groundwater movement within the coal seam may also be induced by human activities (e.g. mining, pumping, fracking) which results in a change established natural conditions within the seam which may induce vertical leakage.

Tertiary age mafic intrusives consisting of dykes, sills and lacoliths which intrude many of the sedimentary basins and coal measures. These intrusives may either form:

- barriers to lateral groundwater movement;
- conduits for enhanced movement either along or down the intrusion; or

- zone of disturbance around the intrusion resulting in either increased or decreased permeability / porosity.

Intrusion which form barriers (i.e. dykes) may effectively dam groundwater on the up gradient side resulting in a piezometric head difference across the dyke. Preferred groundwater pathways may form along intrusions. These may interconnect vertically or be restricted to particular geological units. The area surrounding intrusions may be metamorphosed, deformed or have multiple small intrusions (e.g. dyke swams) resulting in a change in rock properties, which may seal the rock or make it brittle resulting in more fracturing or opening of preferred pathways for groundwater flow. The increased permeability and fracturing can result in high water expulsion during mining, and stability problems.

Groundwater Flow, Recharge and Discharge

Water entering the ground either; remains temporarily in the soil zone, flows laterally above the groundwater table until it reaches a stream or other low lying body of water or continues to infiltrate downward until it reaches the groundwater table. Groundwater in aquifers exists under two different physical conditions:

- unconfined - when the water table is exposed to the atmosphere at the point of discharge through openings in the overlying rock.
- confined - where it is isolated from the atmosphere at the point of discharge by impermeable geological formations and the confined aquifer is generally subject to pressures higher than atmospheric pressure (Driscoll 1989). By definition an aquifer is considered confined if the potentiometric head (or water level) is above the top of the aquifer unit.

The hydraulic behaviour of confined and unconfined aquifers is different and complicated by the geological environment. Groundwater moves from the point of recharge to the point of discharge at a rate determined by the permeability of the material of which it is flowing through. Unconfined aquifer recharge is via direct rainfall infiltration distributed over the whole spatial extent of the material and may also include leakage from rivers and lakes and or vertical movement from other aquifers. In confined aquifers recharge occurs primarily at the exposed portion of the aquifer, generally at the edges of the sedimentary basin, and vertical movement of groundwater from above or below aquifers may also be considered as recharge though this amount is usually minor.

In the sedimentary basins of NSW groundwater flow direction for unconsolidated aquifers is generally towards the nearest discharge point which is a river, a lake or an ocean or cross boundaries into other aquifers. Groundwater in confined aquifers moves from areas of high pressure towards areas of low pressure as shown in Figure 13.3. Discharge in confined aquifers may be related to basin structure (e.g. the lowest point of the basin) producing down gradient discharge and is extremely slow. In some cases deeply incised valley intersect confined aquifers allowing discharge zones to form in these locations (e.g. Grose Valley, Sydney Basin). The rate at which groundwater moves is controlled by the driving head and the properties of the material through which it flows, and is influenced by activities such as abstraction (e.g. mine dewatering, pumping activities or intersection of groundwater above and below an aquifer), which can produce localised changes in flow and flow direction.

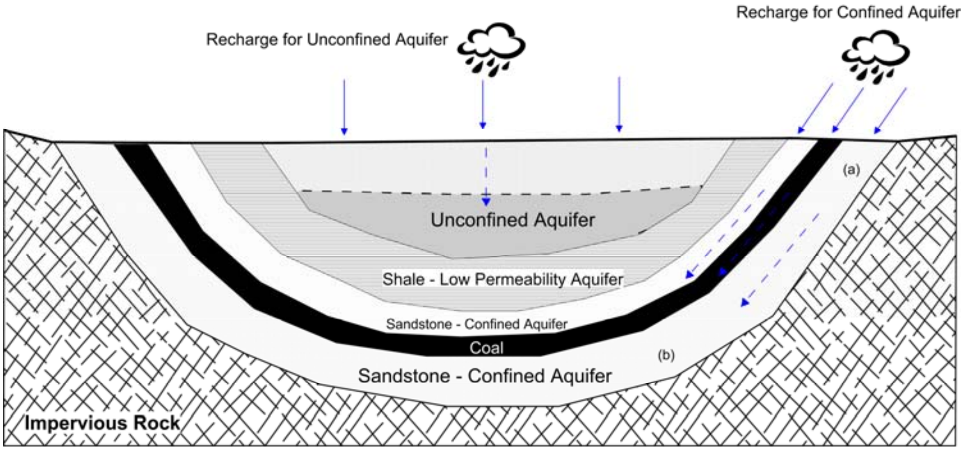

Figure 13.3. Groundwater recharge in unconfined and confined aquifers where (a) is zone of low pressure high potential and (b) is zone of high pressure low potential (adapted from Driscoll 1989).

Aquifer Properties

Porosity

The two important properties of an aquifer that are related to the storage function are porosity (i.e. how much groundwater can be stored in a saturated medium) and specific yield (i.e. the volume of groundwater given up by gravity). Porosity only represents the volume of water an aquifer may hold, not how much water it may yield, as when a saturated material is drained under the force of gravity the material releases only part of the total volume stored in its pores. The porosity for common consolidated and unconsolidated materials is shown in Table 13.1.

The smaller the average grain size the greater the percentage of retention; the coarser the sediment the greater the specific yield when compared to the porosity. For example finer sediments have lower specific yields compared to coarser sediments, even if the porosity is the same. The storage term for an unconfined aquifer is specific yield and for a confined aquifer it is known was storage coefficient. They both relate to the amount of water that can be added or removed per unit surface area per unit head. The storage value is dependent on the water level in the aquifer.

Specific yields for unconfined aquifers range from 0.01 % to 0.30 %, however it should be noted that specific yield cannot be determined for confined aquifers. Typical dimensionless storage coefficients (volume of water released per unit decline in hydraulic head) for confined aquifers range from 0.00001 to 0.001. The higher the value the better the release of water. Table 13.2 presents representative specific yield ranges for selected sediments and sedimentary rocks.

Table 13.1. Porosities for Selected Materials (adapted from Morris & Johnson 1967; Driscoll 1989; Cook 2003 and Sterrett 2007).

Unconsolidated Sediments	Porosity (%)	Sedimentary Rocks	Porosity (%)	Crystalline Rocks	Porosity (%)
Clay	45 to 55	Sandstone	5 to 30	Fractured crystalline rock	<1 to 10
Sand	35 to 50	Siltstone	20 to 40	Vesicular basalt	10 to 50
Coarse Sand	31 to 46	Limestone	1 to 20	Basalt	3 to 35 0 to 75^
Fine Sand	26 to 53	Shale	<1 to 10 1 to 3^	Weathered granite	34 to 57
Gravel	25 to 40			Weathered gabbro	42 to 45
Sand and gavel mix	10 to 35			Dense, solid rock	<1
Glacial till	10 to 25			Coal	<1*
				Unweathered Crystalline rock	0.1 to 1

*From Freeze & Cherry (1979) ^Cook (2003)

Table 13.2. Representative Specific Yield Ranges for Select Materials (from Morris & Johnson 1967; Driscoll 1989 and Sterrett 2007)

Material	Specific Yield (%)
Clay	1 to 10
Sand	10 to 30
Gravel	15 to 30
Sand and gravel	15 to 25
Sandstone	5 to 15
Shale	0.5 to 5
Limestone	0.5 to 5

Hydraulic Conductivity

The hydraulic conductivity is defined as the capacity of a porous medium to transmit water whilst permeability refers to the ease with which any fluid moves through a formation. This is also known as the coefficient of permeability.

Permeability is the property or capacity of a porous rock, sediment or soil for transmitting fluid and is a measurement of the relative ease with which any fluid moves through a geologic material under unequal pressure.

Hydraulic conductivity is governed by the size and shape of the pores and the effectiveness of the interconnection between pores (Driscoll 1989). The rate of movement is related to the fluid and the driving head. Ranges of hydraulic conductivity rocks and unconsolidated sediments are shown in Table 13.3.

Table 13.3. Range of Values of Hydraulic Conductivity of selected sediments and rock types (adapted from Freeze & Cherry 1979; Domenico & Schwartz 1990; Cook 2003).

Unconsolidated Sediments	**Hydraulic Conductivity (m/sec)**	**Sedimentary Rocks**	**Hydraulic Conductivity (m/sec)**	**Crystalline Rocks**	**Hydraulic Conductivity (m/sec)**
Gravel	$3x10^{-4}$ to $3x10^{-2}$	Coal	10^{-6} to 10^{-4}		
Sand	0.1 to 10^{-9}	Sandstone	$3x10^{-10}$ to $6x10^{-6}$ $3x10^{-8}$ to $5x10^{-5}$*	Unfractured metamorphic and igneous rocks	$3x10^{-14}$ to $2x10^{-10}$
Coarse Sand	$9x10^{-7}$ to $6x10^{-3}$	Karst and reef Limestone	$1x10^{-6}$ to $2x10^{-2}$	Fractured metamorphic and igneous rocks	$8x10^{-9}$ to $3x10^{-4}$
Medium Sand	$9x10^{-7}$ to $5x10^{-4}$	Limestone / dolormite	$1x10^{-9}$ to $6x10^{-6}$	Permeable basalt	$4x10^{-7}$ to $2x10^{-2}$
Glacial till	$1x10^{-12}$ to $2x10^{-6}$	Shale	$1x10^{-13}$ to $2x10^{-9}$	Basalt	$2x10^{-11}$ to $4.2x10^{-7}$
Clay	$1x10^{-11}$ to $4.7x10^{-9}$	Fractured siltstone and shale	$1x10^{-7}$ to $1x10^{-4}$^	Weathered Granite	$3.3x10^{-6}$ to $5.2x10^{-5}$
Unweathered marine clay	$8x10^{-13}$ to $2x10^{-9}$			Weathered Gabbro	$5.5x10^{-7}$ to $3.8x10^{-6}$
				Unweathered crystalline rock	$1x10^{-7}$ to $1x10^{-13}$

*Davis 1998, ^ Singhal and Gupta (1999)

In general hydraulic conductivity decreases as depth increases as shown in Figure 13.4.

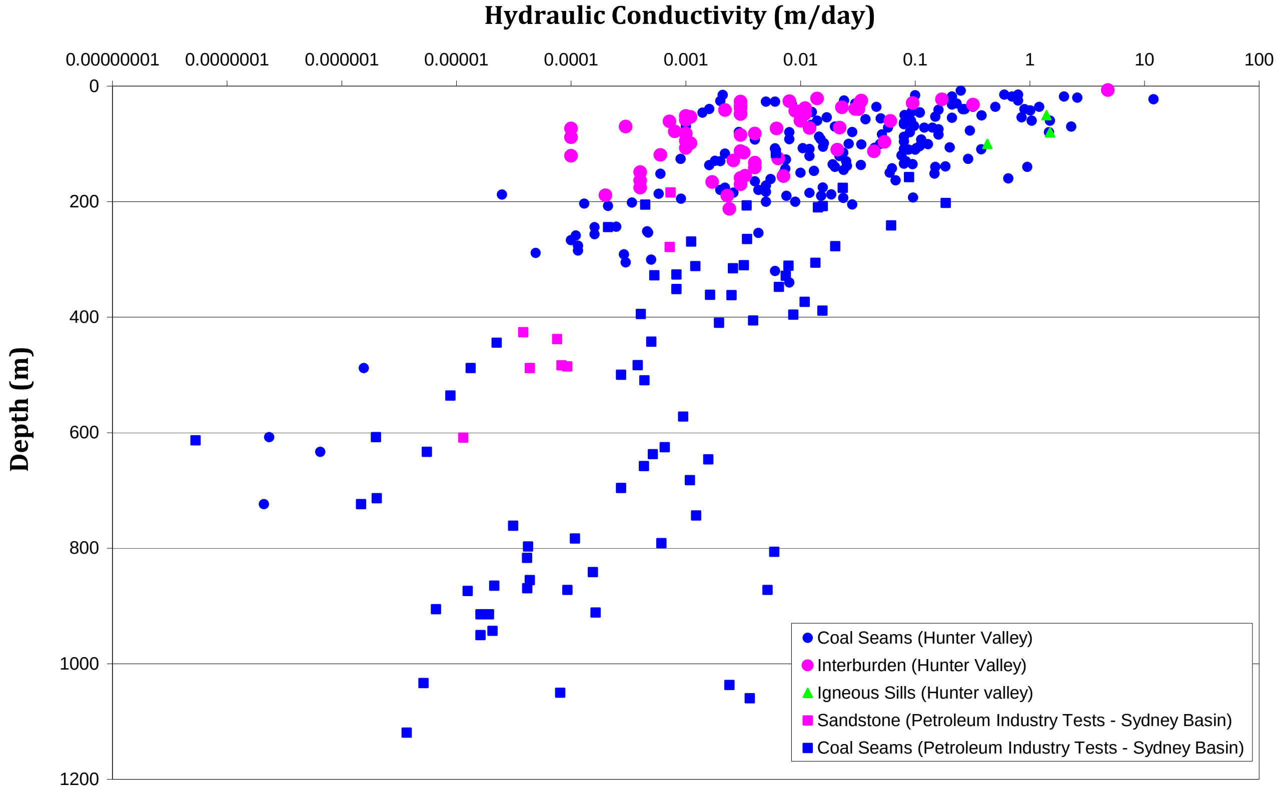

Figure 13.4. Calculated hydraulic conductivity from a range of shallow to deep groundwater aquifers, derived from Packer test, slug tests, pump tests and air lifts of petroleum and coal exploration bores.

Specific examples of permeability of selected sediments in the Sydney Basin are shown in Table 13.4. In the Sydney Basin the permeability of the coal seams ranges from 0.001 to 12 m/day and decreases exponentially with depth. The sedimentary rocks which comprise the interburden strata have permeabilities in the range of 0.0013 to 0.426 m/day (Australian Groundwater Consultants 1984). The groundwater yield in the Permian strata, most of which is encountered in coal seams, in the Upper Hunter Valley in the Sydney Basin generally ranges from 0.5 to 2 L/sec (43 to 172 m^3/day) from depths between 25 to 150 m with some yields as high as 14 L/sec (1210 m^3/day) (Australian Groundwater Consultants 1984).

Table 13.4. Permeability Range of Coal Measures versus Sedimentary and Igneous Rocks in the Upper Hunter Valley (adapted from Australian Groundwater Consultants 1984)

Strata	Permeability (m/day)
Greta Coal Measures	0.001 to 1.99
Singleton Super Group	0.004 to 12
Interburden (sandstone / siltstone)	0.0013 to 0.426
Sill	0.4 to 1.5

Overview of Groundwater in NSW Sedimentary Basins and CSG

In the timeframe required to collate information on groundwater and potential impacts of CSG it was not practical to extensively research properties, models and parameters for aquifers in the sedimentary basins of NSW. Specific information on many individual aquifers and aquitards is commonly not available, though the data may exist, and if it does is generally commercial in confidence. The information presented in this work is generalised aquifer characteristics applicable in a preliminary sense until detailed and specific data is collected. Regional scale and long term monitoring of groundwater in NSW is not commonly undertaken at a detail suitable for comprehensive regional investigations. Resources are available and Government owned centralised databases (eg. ga.gov.au) are being created to collate the current information and provide a mechanism for future data to be submitted and accessed.

This section discusses the geological interactions and implication of CSG activities on groundwater in the coal seams of the sedimentary basins of NSW. The major aquifers of these sedimentary basins can be grouped as follows:

- Recent unconsolidated sediments: these shallow aquifers are most commonly used for potable, recreational, irrigation and industrial water supply with static water levels generally ranging from near surface to around 100 m with reasonable water quality and hydraulic conductivity. A particular example would be the Hunter River alluvial systems in the Sydney Basin.
- Jurassic and Triassic Sandstones: these aquifers are commonly used for potable, recreational, irrigation and industrial water supply. The formation consists of a series of sub groups which may have discrete aquifers of differing quality and permeabilities, which decrease with depth. These aquifers overly the claystone and siltstone dominant early Triassic formations.
- Permian sandstones and coal measures: these aquifers occur interbedded with shales, sandstones and coal and the quality of the groundwater is generally low with brackish to saline water. These aquifers may be used for stock, irrigation and industrial water supply.

In essence the low permeability shales, tuffs and claystones located in the lower Triassic (e.g. Narrabeen Group in Sydney Basin) restrict vertical movement of groundwater and effectively act as barriers between the different formations (eg. Figure 13.4).

The following is a discussion of the characteristics of aquifers proximal to coal measures of interest to CSG exploration within NSW. Insufficient data exists within the scientific literature, or national databases, to assess this wholly independently, and we have utilised commissioned reports where available to constrain the physical properties of these units.

Sydney-Gunnedah Basin

In the Sydney Basin the permeability of the coal seams ranges from 0.001 to 12 m/day and decreases exponentially with depth. The sedimentary rocks which comprise the interburden strata have permeabilities in the range of 0.0013 to 0.426 m/day (Australian Groundwater Consultants 1984). The groundwater yield in the Permian strata, most of which is encountered in coal seams, in the Upper Hunter Valley in the Sydney Basin generally ranges from 0.5 to 2 L/sec (43 to 172 m^3/day) from depths between 25 to 150 m with some yields as high as 14 L/sec (1210 m^3/day). In contrast, one of the most widespread sandstone aquifers, the

Hawkesbury Sandstone, has hydraulic conductivities of 0.1 m/day at the surface and 0.002 m/day at 50 m (Tammetta & Hewitt 2004).

Clarence-Moreton and Surat

Within the Clarence Moreton and the Surat, the permeability or hydraulic conductivity of the strata between the water in the Walloon Coal Measures and the alluvium can only be estimated at this stage. Golders Associates (2009) modelled the likely impact of Coal Seam Gas extraction in the Surat Basin (Walloon coal measures). They quote K (permeability) values for the coal beds in the Walloon Coal Measures at about 1.4 m/day, and for the aquitard layers, 1×10^{-1} m/day. Santos (http://www.santos.com/library/Roma_Shallow_Gas_East_EMP_AppD.pdf) have also calculated their fractured coal aquifers at depth to possess hydraulic conductivities of the order of 5×10^{-10} to 1.2×10^{-5} m/sec, with a most likely value of 1×10^{-6} m/sec, with porosities between 2-11 %.

The Walloon Coal Measures are overlain in the Surat by the Springbok Sandstone, and sandstone aquifer, and underlain by the Hutton Sandstone aquifer (which grades into the Marburg Sandstone in the Clarence Moreton). The upper seams of the Walloon Coal Measures are interbedded with low permeability mudstones, siltstones, and fine grained sandstones, of ~15 m average thickness, partially decoupling the coal-rich lower measures from the overlying Springbok aquifer. This minor aquitard is however absent in some places. Another minor aquitard consisting of about 45 m mudstone, siltstone and fine-medium sandstone underlies the deeper portion of the Walloon Coal Measures, the Taroom Coal Measures, separating it from the underlying Hutton aquifer. The permeability of these aquitards have been estimated at 1.5 m/d to 2.5×10^{-6} m/day, in general averaging 9×10^{-3} m/day.

Bowen

The Bandanna formation within the Bowen Basin (beneath the Surat/Clarence Moreton sequences) is a target for CSG exploration, and is utilised already in Queensland (see Queensland Water Commission, 2009;
http://dnrm.qld.gov.au/__data/assets/pdf_file/0016/31327/underground-water-impact-report.pdf for more information). The Bandanna Formation has variable coal, and is discontinuous from its equivalent in the east by faulting. It is underlain by low-permeability Permian sequences, and generally overlain by thick low-permeability Rewan group mudstones (except where the Rewan group is eroded away, allowing the Precipice Sandstone aquifer to come in contact). Above the Precipice Sandstone, the Evergreen Formation forms an effective hydrocarbon cap in places, separating the Precipice Aquifer from the overlying Hutton Sandstone aquifer. CSG extraction within the Bandanna formation at Fairview (Santos, 25km NE of Injune) and Spring Gully (Origin, north of Roma) have occurred since 1996 and 2005 respectively. The long-term forecasts suggest extraction will depress water levels within the Bandanna group by 200m, but have not discernibly affected the Precipice Sandstone aquifer (Queensland Water Commission 2009).

Gloucester

Parsons Brinkerhoff (2012) presented a model of the hydrogeological structure of the Gloucester Basin CSG project. They considered a dipping, layered structure of the Gloucester Coal Measures, and considered the Bindaboo, Deards, Cloverdale and Roseville Coal seams.

They considered the over-riding aquitard the low permeability Jo Doth tuff, and generalised the interbedded units within the coal seams. On the basis of field permeability data (~20 measurements), they considered the coal seams to have hydraulic conductivities of ~0.002-0.03 m/day, and the interbedded confining units to be in the range 2 x 10^{-6} to 1.5 x 10^{-3} m/day.

The Parsons Brinkerhoff (2012) report concluded that there was distinction, and thus interpreting no connection, between the deeper Permian groundwater aquifer and shallower groundwater aquifers, on the basis of their water chemistry and apparent resident times. This conclusion has subsequently been disputed by others, as the salinity gradients and different timescales could also be explained by confined basal aquifers in basin scale hydrogeological models. The Parsons Brinkerhoff model made extreme lithological simplifications and neglected fracturing and fracture-induced permeability (eg. see reviews http://agk.com.au/gloucester/assets/pdf/Peer_Review_of_Groundwater_Studies.pdf, and http://www.pellsconsulting.com.au/downloads/gloucesterCSGProjectImpactsOnGroundwaterReviewOfAspectsOfThePhase2ReportByParsonsBrinkerhoff.pdf).

Murray and Oaklands

Insufficient hydrogeological data for the Coorabin Coal Measures, or Tertiary lignite/peat in the Murray sediments, exists to develop constraints on the physical properties of the coal seam and surrounding aquifers in these regions.

Induced permeability

CSG activities in the Permian Coal Measures and Triassic/Jurassic sandstones result in an increase in the secondary permeability of the formation in order to release the gas for extraction. To induce a change in the secondary permeability fracking is undertaken and this process imparts stress on the target formation which may propagate to the overlying strata. Fracking also introduces materials (e.g. sand) to hold open the fractures / cleats to improve permeability. These activities result in a zone of increased permeability around the fracking bore (Figure 13.5). Should the imposed changes result in a net change in volume, through introduction of sand or depressurisation, then there is the potential for fracturing of the above confining strata or strata's. In general, the process of fracking and removal of water and subsequent gas results in a net decrease in volume which results in subsidence, which may lead to fracturing.

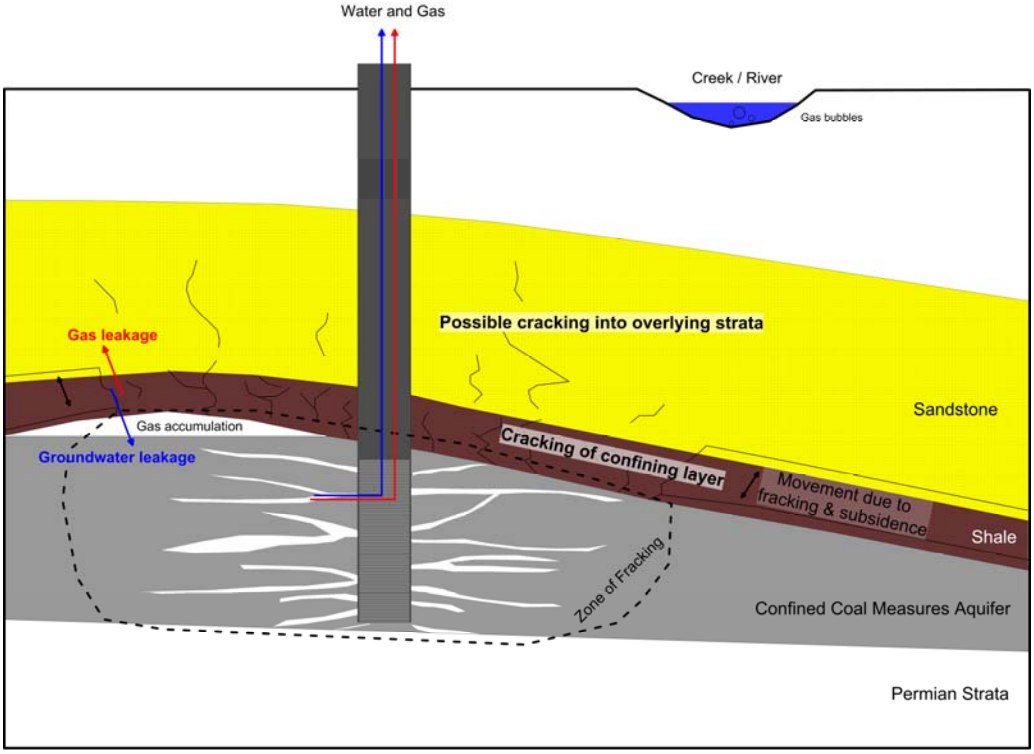

Figure 13.5. Conceptual diagram of interaction of fracking a coal measure in typical Permian/Triassic sedimentary basin sequence.

This produces a change in the pressure gradient with depth (Figure 13.6) and may lead to groundwater movement upwards from the fracked formation into the overlying formation or leakage of groundwater from the overlying formation into the fracked formation. Gas released will migrate upwards until it reaches a barrier. If the overburden barrier of the fracked formation is fractured, gas may migrate out this formation and continue until it reaches another barrier. Movement of groundwater and gas between formations has the ability to transport contamination, either already existing or induced by the fracking process, and reduce water quality through mixing and dissolution. Where movement is upwards into aquifers with potable groundwater resources this would be of serious concern. Where groundwater moves out of a potable aquifer there is a reduction in storage.

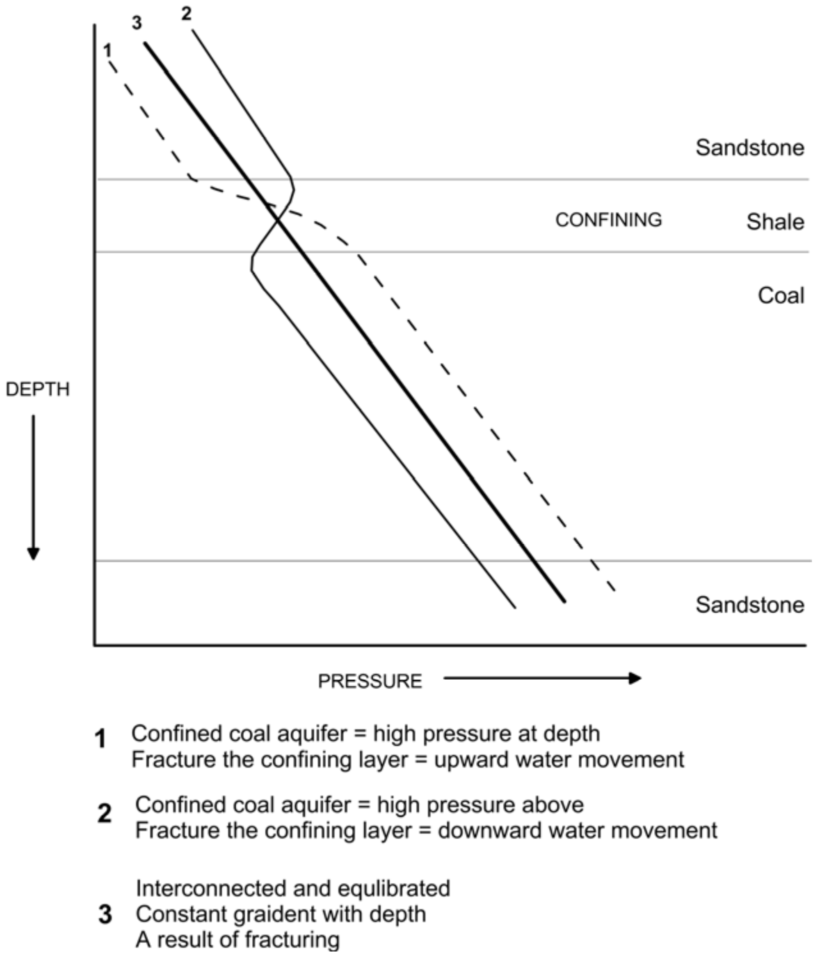

Figure 13.6. Pressure gradient with depth for a confined aquifer that is fractured at the confining layer. Groundwater moves from high to low pressure until equilibrium is achieved.

The process of fracking a formation may be considered similar to brittle deformation in that it is sudden, relatively to the geological time scale (Singhal and Gupta, 1999). Materials which are deformed over a long time can compensate (i.e. through dissolution and grain boundary growth) and effectively heal the stress opened fractures. In brittle deformation this does not happen. Over time the fractures may be infilled with fine grained sediments migrating through them, which may help seal the fractures. Subsidence after the extraction of gas and or groundwater does not necessarily result in the fractured overburden returning to the same level or providing an effective seal. There is some evidence to suggest that fracturing may propagate from longwall panels to surface from as deep as 400 m, resulting in a direct connection between the surface and the mine in isolated areas (Singhal and Gupta, 1999).

The implications of this are:

- Potential connection of surface with fracked seam;
- Interconnection of all groundwater aquifers in between;
- Escape of gas to surface and
- Potential migration of contamination resulting in deterioration of water quality and reduction in aquifer storage.

Gas has explored for and found within the shallower Jurassic / Triassic strata and the shallower fracking the higher the likelihood of fracturing reaching the surface. Shales do not always form a seal and there is suggestion by Cadman & Pain (1998) that the compaction of sediments has produced seals in some places. Of concern is the general higher quality, and use of the Jurassic and Triassic aquifers, and the lower occurrence of reservoir seals above these strata making them more susceptible to deleterious impacts.

Re-injection of extracted groundwater is often done is a different, generally lower, aquifer of poor quality to reduce the cost of treatment. The introduction of fluid with different physical and chemical properties will impact on the quality of the host aquifer and may alter the permeability. Groundwater systems in sedimentary basins are complex, in parts interconnected and local changes may have regional consequences. Understanding the regional and local scale geology and hydrogeology is critical to managing CSG activities in these sedimentary basins. Reducing the zone of disturbance from fracking and or subsidence is important in mitigating the potential for interconnected aquifers. A big unknown remains as to how gas migrates within saturated and unsaturated aquifers with different properties, how this could be modelled and what the impacts of this gas migration and potential contamination could be.

In summary any activity which interacts with an aquifer is likely to result physical changes to the natural conditions within an aquifer. CSG activities by their very nature will result in physical change within the area of influence which has the potential to lead to interconnection of aquifers and subsequent detrimental consequences. The objective should be to minimise the impacts of CSG activities through better assessment of individual leases with bias towards a regional scale and long term assessment criteria and associated interaction with other existing and future activities.

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14. Seismicity and stress in NSW

Stress magnitudes and directions

Stress measurements are commonly undertaken in petroleum exploration in deep boreholes, and a national record of these measurements has been collated in the Australian Stress Map Project (Hillis & Reynolds 2000; Mueller *et al*. 2000). An example of maximum horizontal stress directions is shown in Figure 14.1.

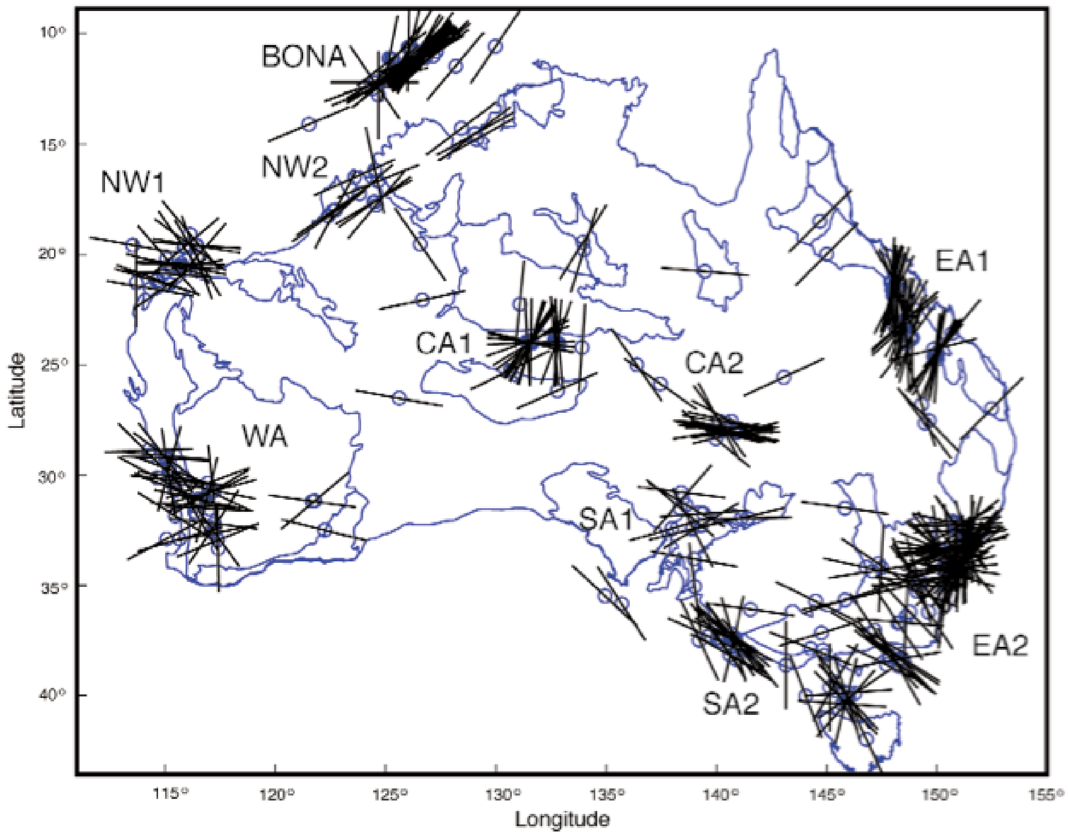

Figure 14.1. Maximum horizontal compressive stress directions, for 386 points in the Australian continent, from the Australian Stress Map Project (Hillis & Reynolds 2000; Mueller *et al*. 2000). Major tectonic blocks are also shown (from Zhao & Mueller 2003).

The stress measurements are concentrated in areas where significant petroleum explorations has occurred (e.g. Sydney Basin in NSW). The stress orientations are strongly sensitive to the continental compressive region (Australia has a convergent margin to the north, and spreading centres to the south and west (e.g. Zhao & Mueller 2003). Stresses are, however, strongly sensitive to lithospheric scale heterogeneities, such as strong tectonically stable blocks. Within-basin sedimentary-package stresses are thus both strongly contingent on both the geometry of these basins, and the tectonic blocks surrounding them, but also depth within the basin package, hydrostatic pressure with depth, and rheology of the lithological units. A state-scale predictive framework for detailed basin stresses does not exist, and due to the impact of small-scale heterogeneities, should really be addressed in local studies.

The regional study of Zhao & Mueller (2000) used a finite element method and iterated on physical properties to minimize deviations from the Australian Stress Map. The found flexural rigidities of 0.04 x 10^{25} Nm for both the Northern and Southern Lachlan fold belts, and 0.037 x 10^{25} Nm for the New England Fold Belt. They included effects such as tomographic structure of the lithosphere to derive a modelled principle stress magnitudes across the Australian continent, shown in Figure 14.2.

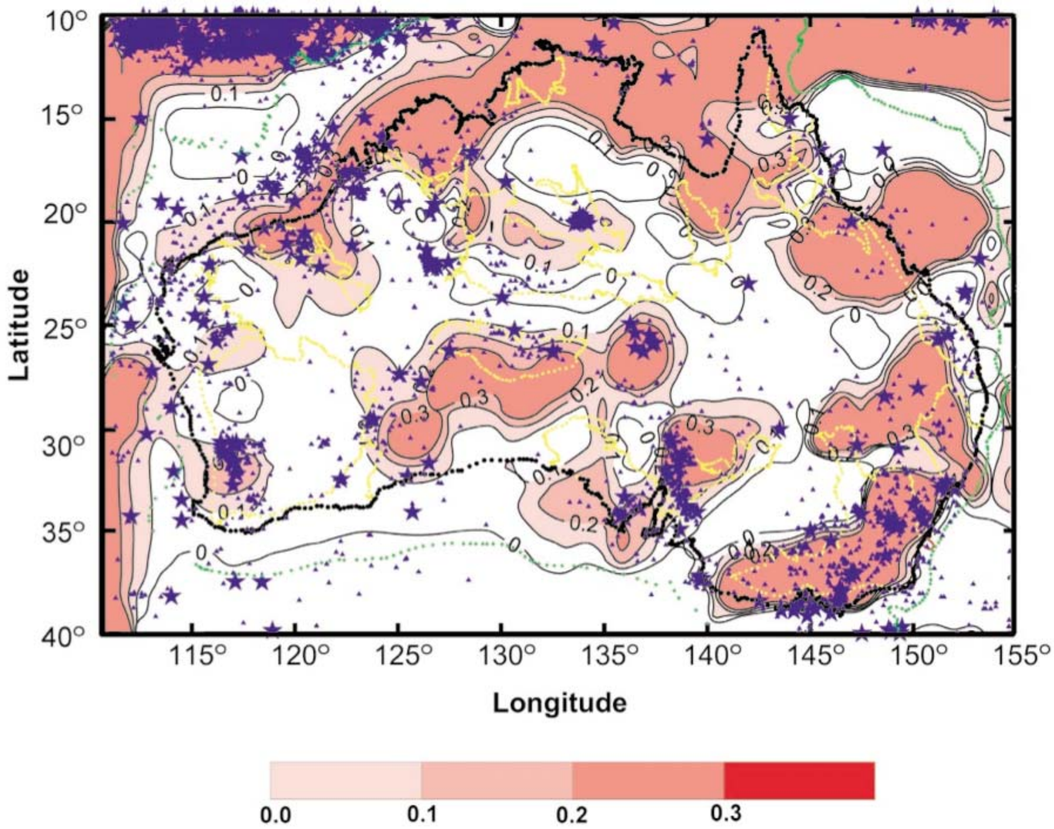

Figure 14.2. Modelled principle stress magnitudes (in units of 100MPa) for Australia, from Zhao & Mueller (2003). Geological blocks are shown as yellow outlines, major earthquakes (M>5.0) shown as stars, dots represent earthquakes with 5 < M < 3. White areas represent areas with compressive stress less than 0.0 (i.e. extensional).

The modelled stresses observed in Figure 14.2 demonstrates large stress gradients across NSW's sedimentary basins. The Sydney-Gunnedah system moves from strongly compressive around the coast in Sydney (a fairly high-seismicity region), to lower compressive in the Gunnedah. The gradient in the Bowen within NSW is primarily compressive, and associated with distributed seismicity. The Clarence-Moreton is large low compressive stress (or extensional), and the Murray-Oaklands is, at this scale, fairly subdued.

Seismicity

Figures 14.3 and Figure 14.4 illustrate two snapshots of seismicity, both from the Sydney Basin historically (Doyle et al. 1968), and from a more recent snapshot (1992-2009) from all of NSW, from the ES&S seismic network, supplemented by GA and other data.

The main observations that can be made from these collations is that much of NSW demonstrates a significant degree of low-level seismicity over long timescales. The regions associated with Lachlan Fold Belt basement in particular show a high density of seismicity, which particular loci of activity around the Sydney Basin in general (particularly the southern Sydney Basin), and around the Gunning Seismic zone.

The density of seismic events lessens towards the more stable, older crust to the west (e.g. the Murray Basin, and to a lesser extent the buried Oaklands Basin, though both are capable of generating significant earthquakes). In addition the seismicity generally decreases towards the north, with the Gunnedah and Bowen (and Surat) generally less active than the Sydney Basin. This trend also holds for the Clarence-Moreton, which occupies a zone of lower compressive stress (Figure 14.2). By corollary, the smaller (and lesser sampled) Gloucester Basin probably has a similar seismic risk as the Sydney Basin.

There is a danger in broad generalisations based on a limited seismic record, in particular there is a risk of events on previously unmapped fault systems whose seismic hazards have not been previously documented. An additional risk these particular seismicity maps do not address, is that of induced seismicity due to either extraction of significant groundwater resources (eg. Holzer et al., 1979), or due to the injection of high-pressure fluids at depth. An assessment of risks associated with these activities require detailed information at a tenement or even basin scale, and local stress measurements, which represent a layer of information beyond that collated in this state-wide summary.

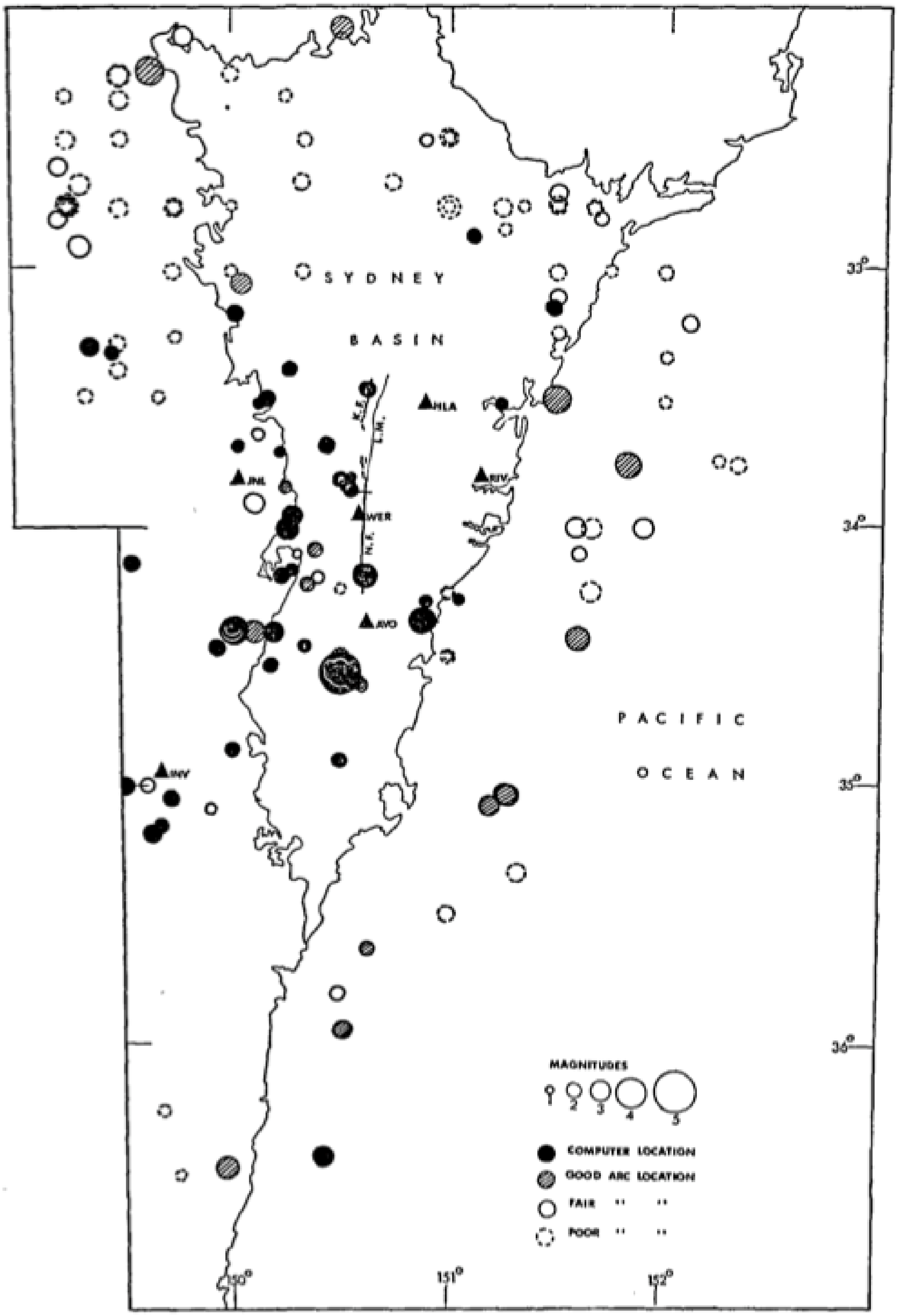

Fig. 1. Seismicity of the Sydney Basin area 1959-67.

Seismic Stations: AVO—Avon; HLA—Halls Lagoon; INV—Inveralochy; JNL—Jenolan; RIV—Riverview; WER—Werombi.

Structures: KF—Kurrajong Fault; LM—Lapstone Monocline; NF—Nepean Fault.

Figure 14.3. Seismicity within the Sydney Basin (from Doyle *et al*. 1968).

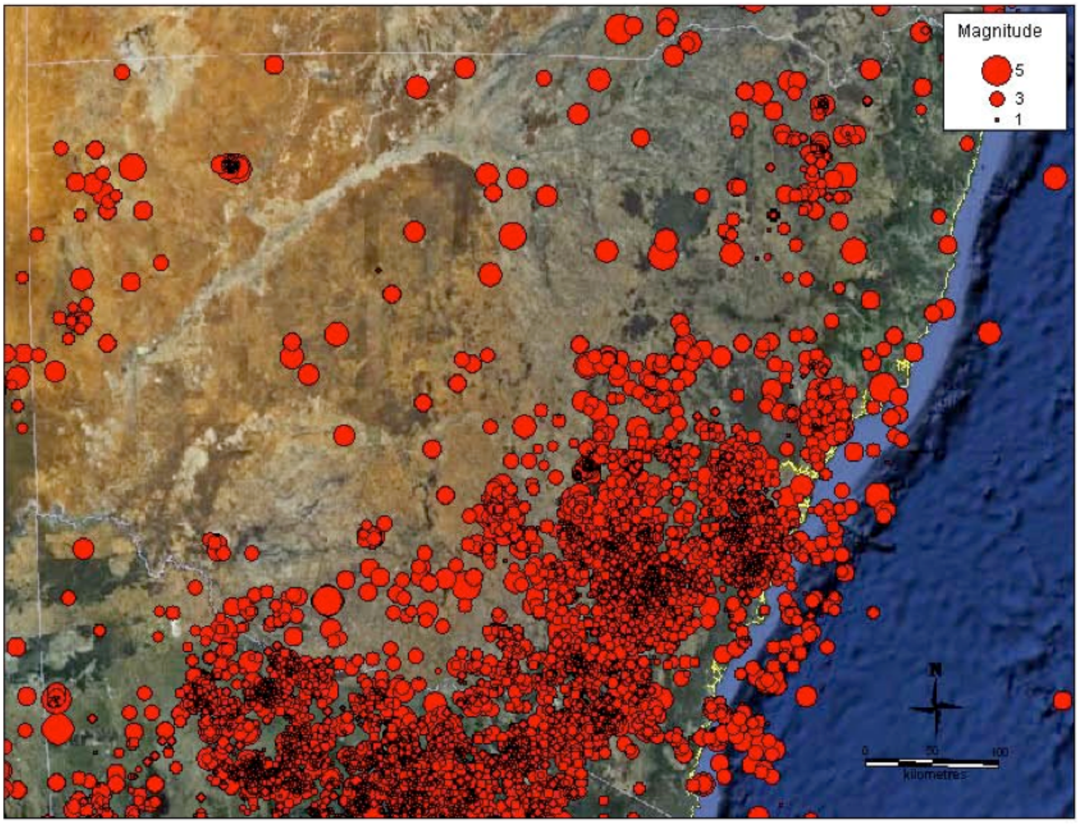

Figure 14.4. Seismic events recorded in NSW from ES&S network form 1992-2009 (from Payne 2009).

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15. Summary and Synthesis

This report has endeavoured to summarize the structure, evolution, and geology of the major coal-bearing basins of NSW, in the context of an investigation into the CSG industry.

Critical to the CSG industry is the interaction of existing groundwater reserves with the dewatering of coal-seam aquifers required for the efficient extraction of gas, and the subsequent disposal of this often saline water. Whilst the distribution of coal within NSW is reasonably well understood, it is clear that the constraints on basin-scale hydrogeological systems are currently insufficient to assess with any level of robustness the physical properties of coal-seam and proximal aquifers (hydraulic conductivity, etc), their lateral extent, the interconnectivity between these aquifer systems, and the effect of faulting on the vertical mobility of these aquifers.

A number of recent commissioned reports have begun bridging the gap in knowledge of these deep aquifer systems, and have been providing important physical constraints (see Chapter 13).

However, independent peer review processes have highlighted a number of limitations of company-procured reports, and this highlights two issues. The first is that the information gathered in these studies needs to be made public; it should minimally be collated and archived in a public server. This includes geophysics (e.g. seismics), physical properties data (hydraulic conductivities/permeabilities, porosities of aquifers/aquitards, etc), as well the reports themselves. The second issue is that independent peer-review is a critical component of this process, it highlights major shortcomings of several reports, and suggests remedies to alleviate such concerns. The process of independent peer review should be integral to any ongoing basin-management programs.

To address the interaction of CSG extraction on existing aquifer systems, further information is required for most of NSW's major basins. The first is representative seismic sections across potential pilot areas. These were, for instance, acquired by AGL for its Gloucester CSG field, and have formed a critical component of developing models for this area. These need to be archived by DTIRIS and made publically available.

The second is collation of physical properties information (porosity/permeability/hydraulic conductivities) for representative lithologies within a basin section. At the moment, these are often measured for industry-sponsored reports, but are not systematically gathered at either a state or federal (e.g. Geoscience Australia) level. This is incredibly important information for this problem, and an important opportunity is being missed in not constructing a state database of this information.

The third is regional, adequately complex models for the hydrogeological dynamics of these sedimentary basins. Local studies often do not adequately represent the dynamics of basin-wide aquifers. Insufficient complexity often leaves out important components, such as fault-generated permeability, lateral variations in aquitard thickness, depth-dependent permeabilities, interconnectivity, discharge etc. These are difficult simulations, particularly with the serial-code industry standards (e.g. the traditional MODFLOW code), but are rather critical to making informed decisions on the sometimes complex dynamics of these groundwater systems.

These suggestions minimally require not only a State-led management strategy for these important multiple-use resources, but also a State investigatory strategy. The form this may take is beyond the scope of this report, but such an approach would give the CSG/groundwater issue a firmer scientific footing.

CSG activities have the potential to cause interconnection between groundwater aquifers, driven by the change in pressure, permeability and stress from the development and extraction process. It is this interconnectivity that provides an avenue for groundwater and gas migration. Whilst the geology and permeability may be favourable to the extraction of CGS in some sedimentary basins and in particular formation they are not necessarily a guaranteed safeguard against the impacts of human induced change on a complex system.

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Dr Cara Danis

12/6/2013