13

GEOLOGY

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13 Geology

This chapter provides a summary of the geology within the proposed Project area (tenements), and an assessment of the potential direct and/or indirect impacts associated with the construction, operations, and decommissioning phases of the Project. For additional detailed information regarding the Project's geology, refer to the Groundwater and Geology Technical Report (Appendix L) of this EIS. Appendix L contains bore and geological model data, compiled during the construction and calibration of a predictive groundwater model, used to simulate the geology and hydrogeology of the Project area. Additional information regarding an assessment of geological structures (faults) has been included in the Groundwater Model Technical Report (Appendix M) of this EIS. A cross reference to the locations where each of the requirements of the ToR has been addressed is given in Appendix B which references both the study chapters (Sections 1 through 34) and/or Appendices (A through EE).

Consideration of potential environmental impacts in regards to geology has been undertaken in this chapter to allow for the development of optimum mitigation and management measures.

13.1 Legislative Context

Compiled in Table 13-1 is a summary of the relevant policies, guidelines, and legislation, with regards to the geology assessment within the Project area.

Table 13-1 Summary of Relevant Policies, Guidelines and Legislation to the Project Area

Policy, Guidelines, or Legislation	Description	Relevance to the Project – Geology Assessment
Environmental Protection Act 1994 (EP Act) (reprinted as in force 14 August 2012)	The EP Act is intended to protect the environment of Queensland, and sets out the relevant approval and regulation framework. The objective of this act is to protect Queensland's environment while allowing for development that improves total quality of life, both now and in the future.	All persons must not carry out any activity that causes, or is likely to cause, environmental harm unless the person takes all reasonable and practical measures to prevent or minimise the harm (Section 319 of the Act). This general duty to the environment requires the implementation of proactive measures to prevent environmental degradation and act in accordance with the precautionary principle. This requirement is underpinned by the impact assessment and mitigation process in this study.
Water Act 2000 (Water Act) (Qld) (reprinted as in force 30 June 2012)	The purpose of the Act is to provide for the sustainable management and efficient use of water and other resources, a regulatory framework for providing water services and the establishment and operation of water authorities.	The potential alteration of geology, through hydraulic stimulation, can alter associated groundwater resources. These indirect impacts are considered to ensure responsible activities.
Petroleum and Gas (Production and Safety) Act 2004 (P&G Act) (reprinted as in force 1 July 2011)	The purpose of the P&G Act is to facilitate and regulate the carrying out of responsible petroleum activities and the development of a safe, efficient and viable petroleum and fuel gas industry.	The potential alteration of geology, through hydraulic stimulation, can alter (quality and quantity) associated groundwater resources. These indirect impacts are considered to ensure responsible activities.

Policy, Guidelines, or Legislation	Description	Relevance to the Project – Geology Assessment
Water Supply (Safety and Reliability) Act 2008	The purpose of the Act is to provide for the safety and reliability of water supply in Queensland. The Act sets out requirements for E Plans and obligations in relation to the potential to impact on drinking water supplies.	The Project is automatically captured by this process for injection, direct supply or discharge of water, however; an exemption can be applied for. In regards to geology, possible associated water management options (i.e. deep aquifer injection) have a potential to alter and affect the aquifer geology (pressures, storage, properties). These indirect impacts are considered to ensure responsible activities.
Sustainable Planning Act 2009	This Act seeks to achieve ecological sustainability through managing development processes and associated environmental effects, and to streamline the coordination of planning and local, regional and state planning instruments.	The potential alteration of geology, indirectly, as a result of CSG-related activities (depressurisation) is considered to achieve ecological sustainability as a result of management of associated environmental effects.

13.2 Assessment Methodology

For the purpose of the geology assessment, the following tasks were conducted:

- Desktop review of available geological information for the Bowen Basin and associated CSG literature;
- Compilation of a description of the geology within the Project area;
- Compilation and generation of geological data and GIS maps to support the development of a numerical model, which is provided in the Groundwater Model Technical Report (Appendix M of this EIS);
- The identification and assessment of likely impacts of the proposed CSG activities on the geological resources;
- A review and identification of optimum measures for management and mitigation of geological impacts; and
- The provision of monitoring and/or commitment recommendations.

13.3 Study Area

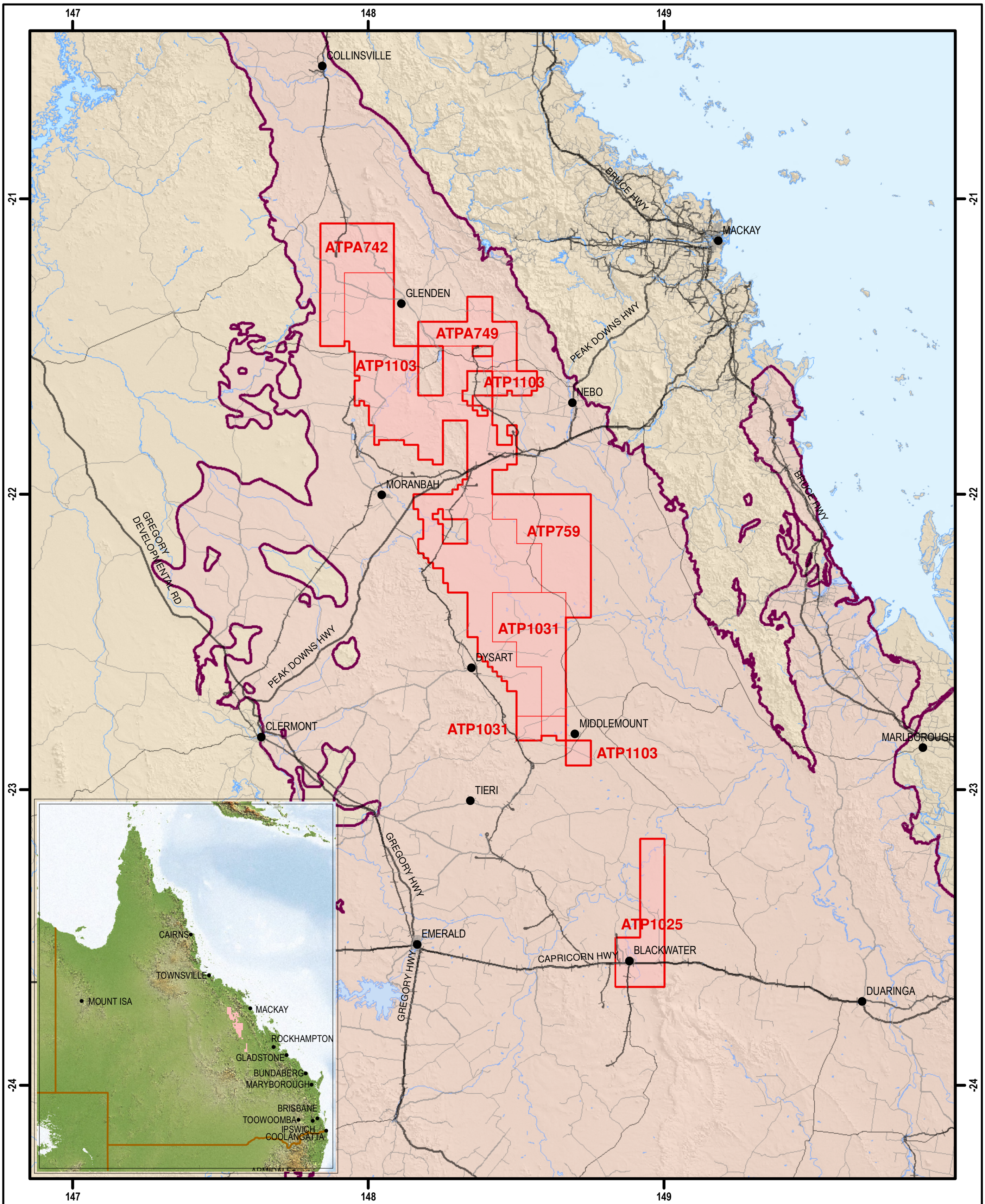
13.3.1 Project Area

The Project area considered during the geology assessment, is a contiguous parcel of tenements, approximately 8,000 km^2, and includes:

- Authority to Prospect (ATP) 1103 and 1031; and
- Authority to Prospect Applications (ATPA) 742, 749, and 759.

These tenements extend approximately 100 km north, 70 km east and 120 km south of the town of Moranbah in central Queensland.

A separate tenement, ATP 1025, located around the town of Blackwater is also included in the Project area (Figure 13-1).



N
W E
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0 10 20 40 60 km

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Projection: Geographic (GDA94)

Bowen Gas Project Tenements	Primary Road
Bowen Basin	Other Road
	Railway
	Watercourse

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PROJECT AREA

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Figure: **13-1**

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13.4 Geology

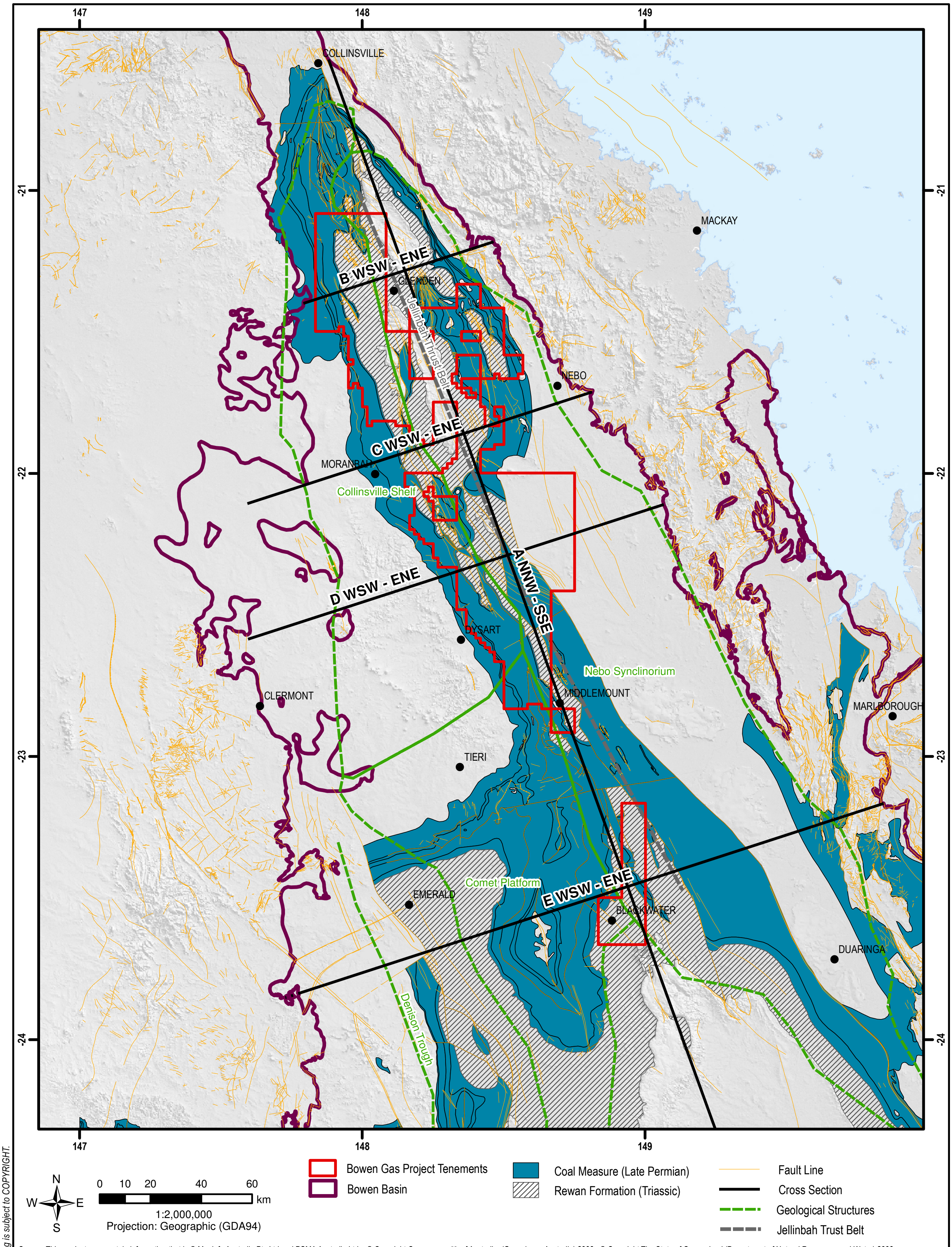
The Project area covers a large portion of the north-south trending, Early Permian to Middle Triassic, geological Bowen Basin. The Bowen Basin covers an area of approximately 200,000 km^2, and is exposed over 600 km from Collinsville in the north to Rolleston in the south. The Bowen Basin contains a sedimentary sequence of Permo-Triassic clastics, which attain a maximum thickness of 9,000 m in the depocentre of the Taroom Trough (Figure 13-2).

The Bowen Basin is divided into a number of tectonic units comprising north north-west to south south-east trending platforms or shelves, separated by sedimentary troughs. The major structural unit surrounding the Project area is the Collinsville Shelf, underlain at shallow depths (one or two kilometres) by the Clermont Stable Block, which bounds the northern Bowen Basin to the west. The Collinsville Shelf was a stable tectonic environment and is characterised by a monoclinal accumulation of sediments, which dip gently (two to eight degrees) and thicken to the east. The Project is located within the northern Bowen Basin.

Folding within the basin is gentle and mostly related to drag on thrust faults at the eastern margin of the basin limb. The boundary between the Collinsville Shelf and the adjoining major axis of deposition, the Nebo Synclinorium, a northerly extension of the Taroom Trough, is marked by a major thrust fault system termed the Jellinbah Thrust Fault Zone. Scarcity of regional significant structures distinguishes the Collinsville Shelf sediments from the more disturbed formations of the Nebo Synclinorium (Elliot, 1989). The important structural elements of the Bowen Basin are illustrated as Figure 13-2.

Regionally, the stratigraphic sequence is presented in Section 13.4.4 and can be summarised as follows: the Permo-Triassic sediments of the Bowen Basin are overlain by a thin covering of unconsolidated Quaternary alluvium and colluvium, poorly consolidated Tertiary sediments of the Tertiary Suttor and Duaringa formations and, in places, remnants of Tertiary basalt flows (URS, 2012). The Triassic Rewan Formation underlies the Tertiary units across most of the Project area, and few outcrops of the Moolayember Formation and Clematis Sandstone can be found in outcrops in the northern Project area. The Permian Blackwater Group coal measures and associated over- and interburden are located below the Triassic strata and overly the Back Creek Group, the basement of the Project area. The surface geology of the sedimentary succession is shown in Figure 13-3.

Additional regional geology and references are provided in the Groundwater and Geology Technical Report (Appendix L) of this EIS.



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BOWEN GAS PROJECT EIS

IMPORTANT STRUCTURAL ELEMENTS OF THE PROJECT AREA

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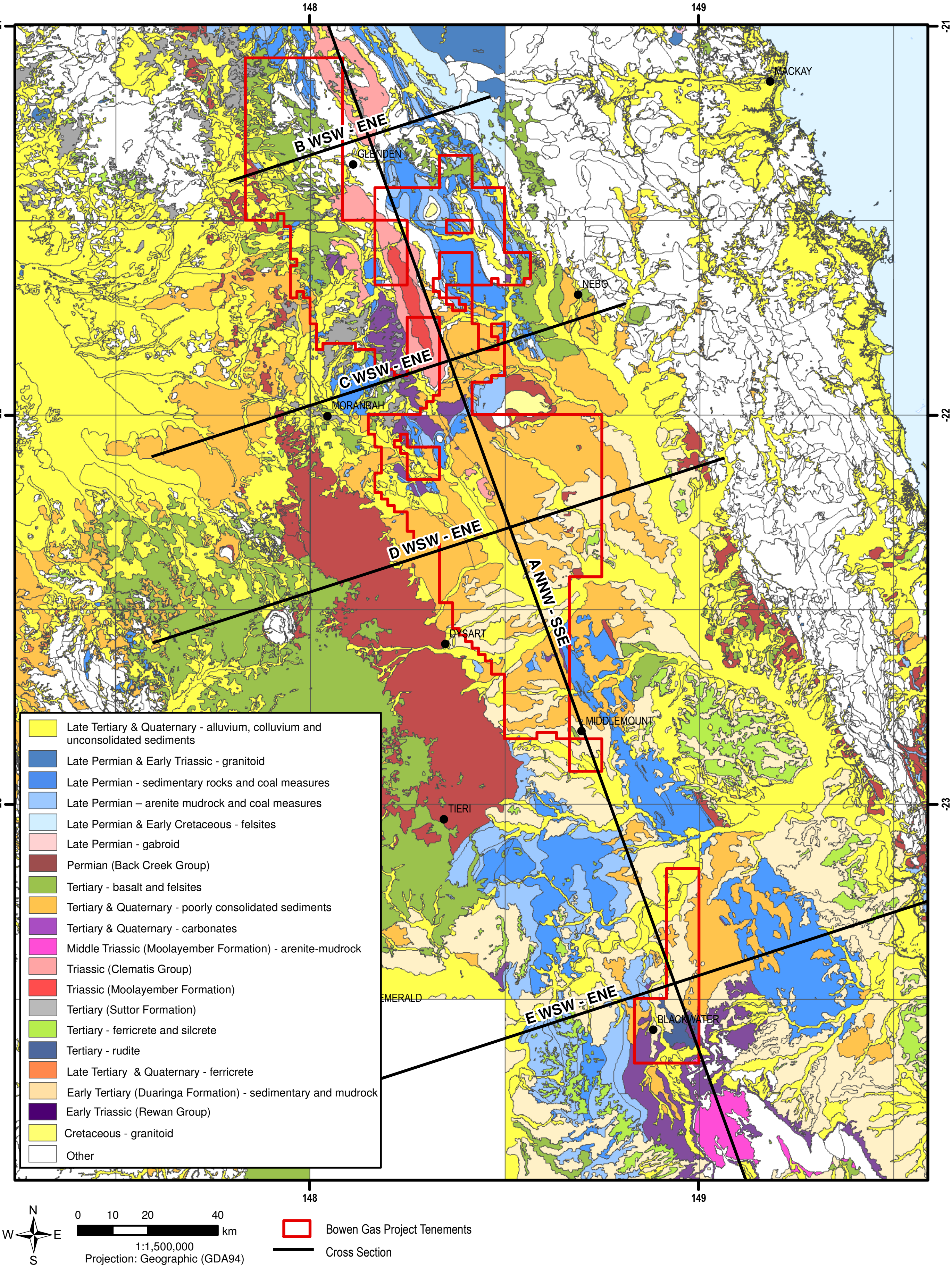

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BOWEN GAS PROJECT EIS

SURFICIAL GEOLOGY OF THE PROJECT AREA

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Figure: **13-3**

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13.4.1 Geological Evolution

Bowen Basin Formation

Deposition in the Bowen Basin commenced during an Early Permian extensional phase, with fluvial and lacustrine sediments and volcanics being deposited in a series of half-grabens in the east, while in the west a thick succession of coals and non-marine clastics were deposited. Following rifting there was a thermal subsidence (sag) phase extending from the Early to Late Permian, during which a basin-wide transgression allowed deposition of deltaic and shallow marine, predominantly clastic sediments as well as extensive coal measures. Foreland loading of the basin spread from east to west during the Late Permian, resulting in accelerated subsidence, which allowed the deposition of very thick successions of Late Permian marine and fluvial clastics, again with coal and Early to Middle Triassic fluvial and lacustrine clastics. Sedimentation in the basin was terminated by the Middle to Late Triassic (Geoscience Australia, 2008).

Permian

The extensional phase of basin development resulted in an Early Permian marine sequence. The Back Creek Group is lithologically variable, regionally developed, and comprises four formations: the Tiverton, Gebbie, Blenheim, and Exmoor, in ascending stratigraphic order. The northern Collinsville Coal Measures are considered to be a non-marine facies equivalent of the Gebbie Formation.

The sag phase (post-extension thermal subsidence) during the mid-Permian resulted in basin-wide marine transgression and regression cycles for the remainder of the Middle Permian and for much of the Late Permian (Geoscience Australia, 2006).

The Late Permian resulted in reactivation of the volcanic arc (uplift of the New England Orogen) and westward thrusting in the New England Orogen, which transformed the Bowen Basin into a foreland basin. The resultant infill gave rise to widespread, coal-forming alluvial and delta plain conditions, preserved as the equivalents of the Blackwater Group (Fielding *et al*. 1993). In the northern half of the basin, eastward prograding deltas combined with major axial fluvial systems to deposit the upper delta plain Moranbah Coal Measures (MCM) and equivalents (lower delta plain German Creek Formation and the coal barren, shallow marine MacMillan Formation) (Boreham, 1994).

Non-marine deposition of the Fort Cooper Coal Measures (FCCM) and equivalents (Burngrove and Fairhill Formation) were conformably overlain. Subsequent subdued volcanic activity in the east which occurred contemporaneous to the prograding deltas allowing for the deposition of peat that subsequently formed the Rangal Coal Measures (RCM).

Triassic

Intensifying uplift and thrusting in the east, coupled with an inferred climatic change involving hot, humid conditions with pronounced wet and dry periods, saw the Permian swamps replaced by a fluvial environment during the Triassic. The first of which was the red-bed sediments of the Early Triassic Rewan Formation. These volcanic lithic sediments, which are devoid of coal, conformably overlie the

Permian Blackwater Group in the centre of the basin and unconformable at the basin edges (Boreham, 1994).

Uplift in the west resulted in the alluvial quartzose deposits of the Clematis Sandstone around the Early-Middle Triassic boundary. A return to dominantly alluvial systems in the Middle Triassic saw the deposition of the youngest Bowen Basin sequence, the Moolayember Formation. The Moolayember Formation consists mainly of mudstone and lithic sandstone deposited under less stable conditions than the Clematis Sandstone. Uplift, folding, and erosion took place in the Upper Triassic, and in the Lower Jurassic the Surat Basin was deposited unconformably overlying the Bowen Basin (Dickins *et al.*, 1973).

Cainozoic

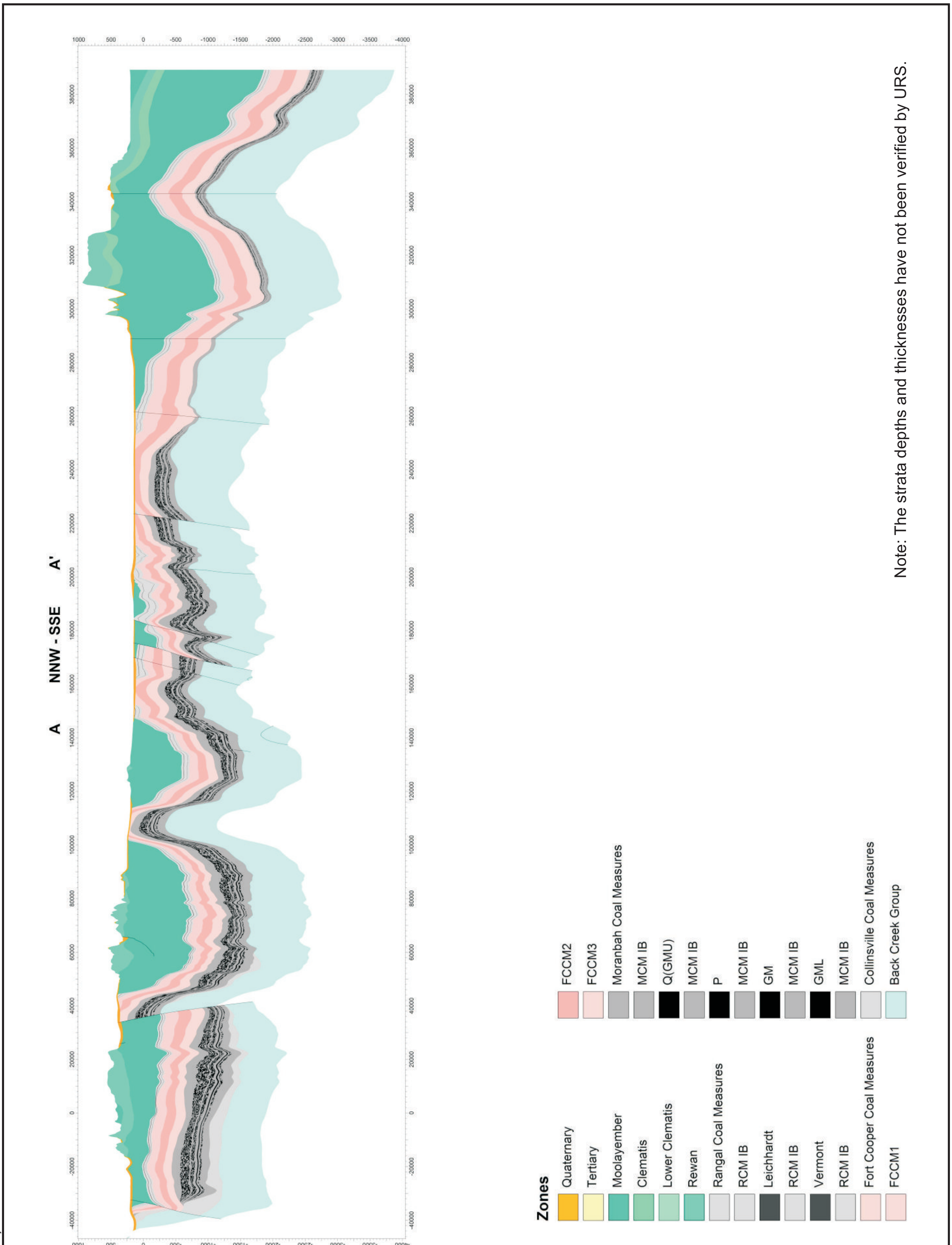
Post-basin faulting and a Cretaceous volcanic event led to emplacement of intrusive structures and subsequent Tertiary basin development (i.e. the Duaringa Basin) happened concordantly with the emplacement of Tertiary intrusions as the entire basin was subjected to a long period of deep weathering where lateritic profiles were strongly developed. Terrestrial Tertiary deposits mantle much of the basin with surface basalt and associated intermediate and acid rocks are found over large areas of the northern Bowen Basin.

13.4.2 Structural Controls

The structural geology of the Bowen Basin in reference to the Project area is dominated by the Comet Platform in the west and the Jellinbah Thrust Belt (Figure 13-2). The Jellinbah Thrust Belt is a northwest trending zone of thrust faults with throws in the order of 100 to 500 m, illustrated in cross sections derived from Arrow's geological model, on Figure 13-4 through Figure 13-8. Individual faults are typically 10 to 80 km long.

The regional tectonic setting is generally a compressive tectonic environment, in which thrust faulting and folding are dominant, especially along the eastern margin (SRK, 2008). The majority of thrust faults dip at shallow angles to the east and propagate up into the Permian sediments. The thrust belt follows the northwest trending synclinal axis of the Basin as most of the fault segments trend north-west suggesting inheritance from earlier basement structures. The north-south faults line up with north-south structures in the Denison Trough, suggesting the presence of Early Permian rift structures at depth. Figure 13-2 illustrates the main structural features within the Project area.

Figure 13-4 depicts cross section A-A’ and shows general faulting across the Project area in a north-south orientation. Figure 13-4 to Figure 13-8 illustrate cross sections and depict localised thrust faults and resultant throws and compartmentalisation of geological blocks. Figure 13-8, cross section C-C’, shows the largest throw as a result of a thrust fault, approximately 500 m. Compartmentalisation of geological blocks appear to have limited separation and no repetition of geological units as a result of faulting.



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BOWEN GAS PROJECT EIS

GEOLOGICAL CROSS SECTION A - A'

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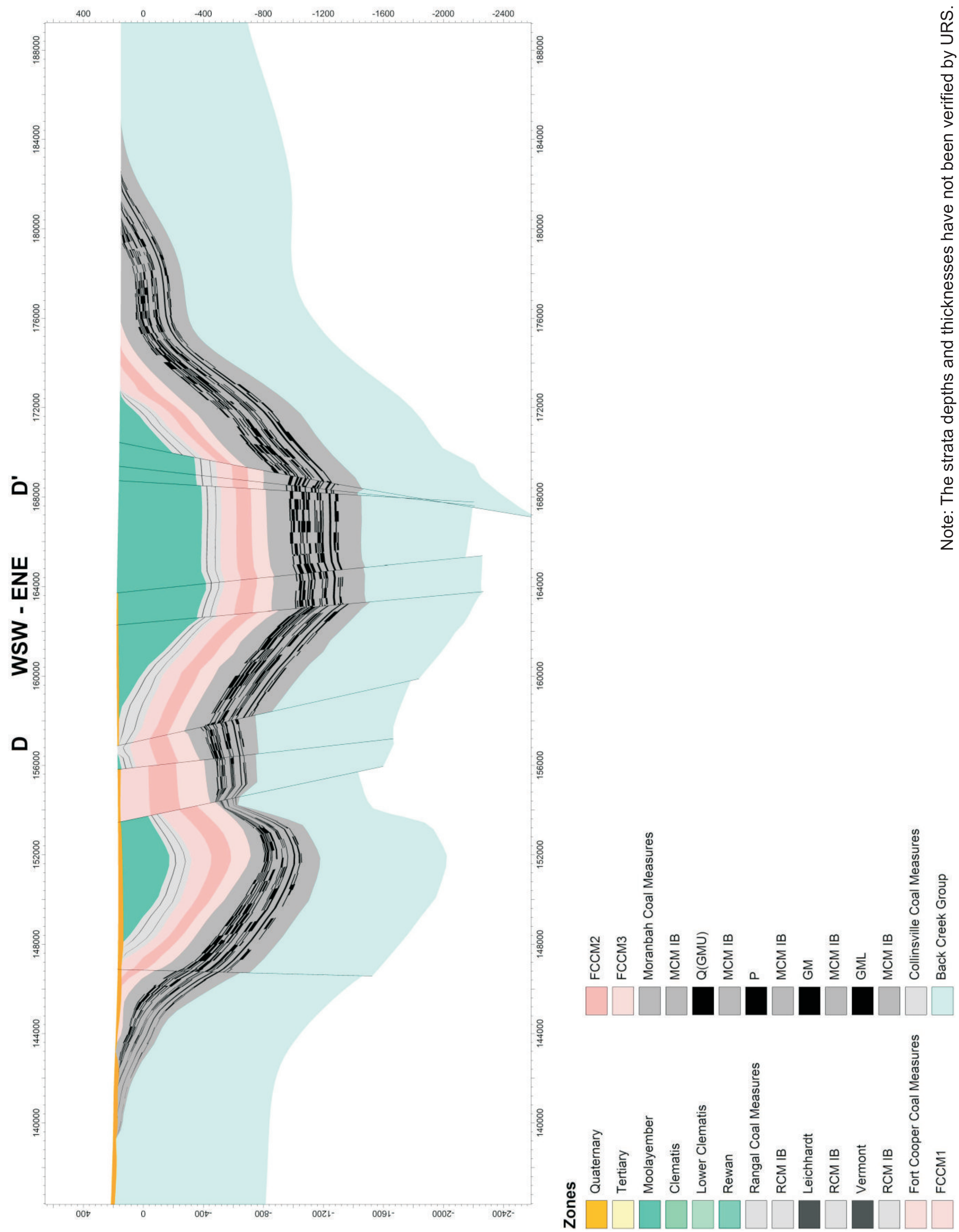

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BOWEN GAS PROJECT EIS

GEOLOGICAL CROSS SECTION D - D'

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Figure: **13-5**

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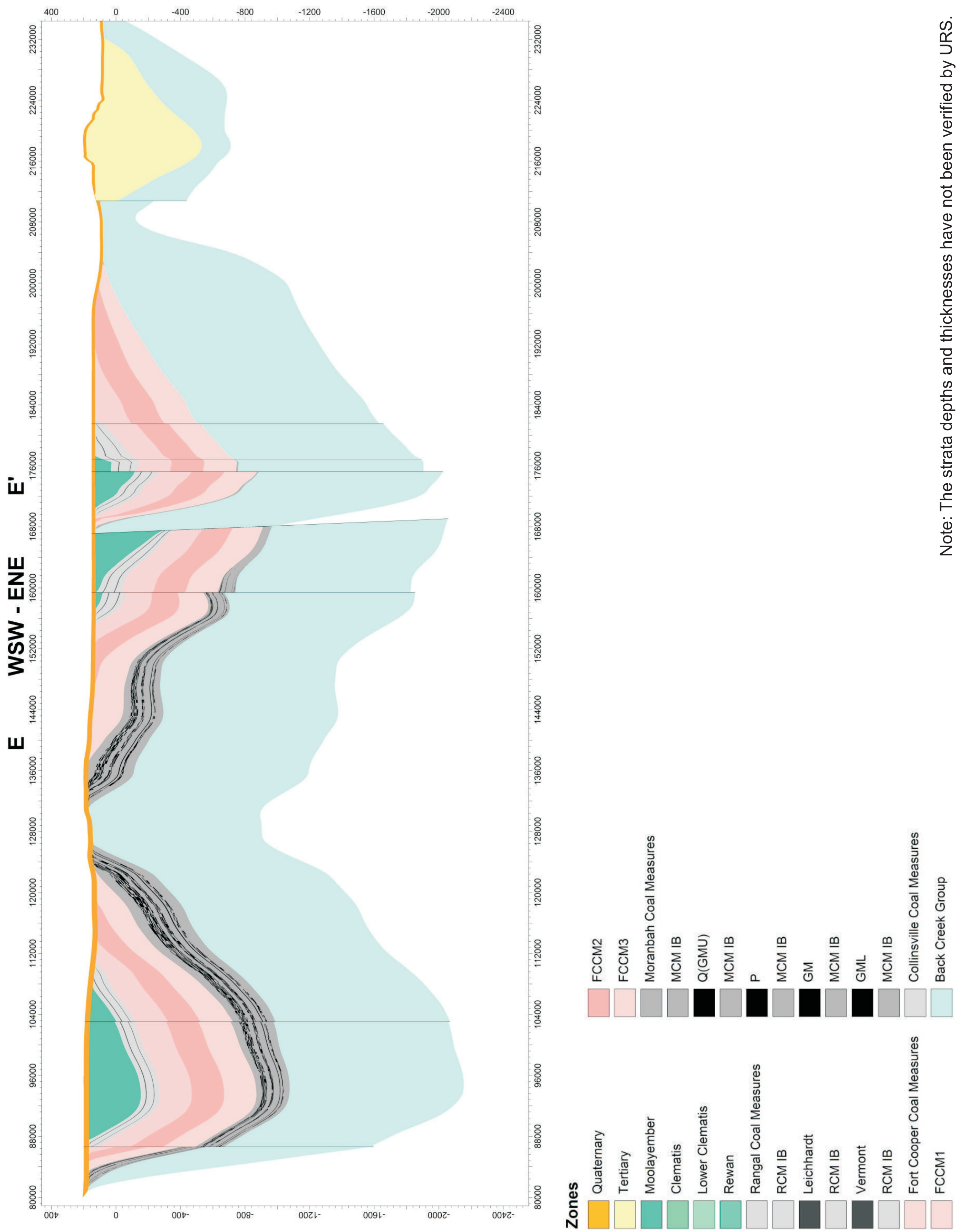

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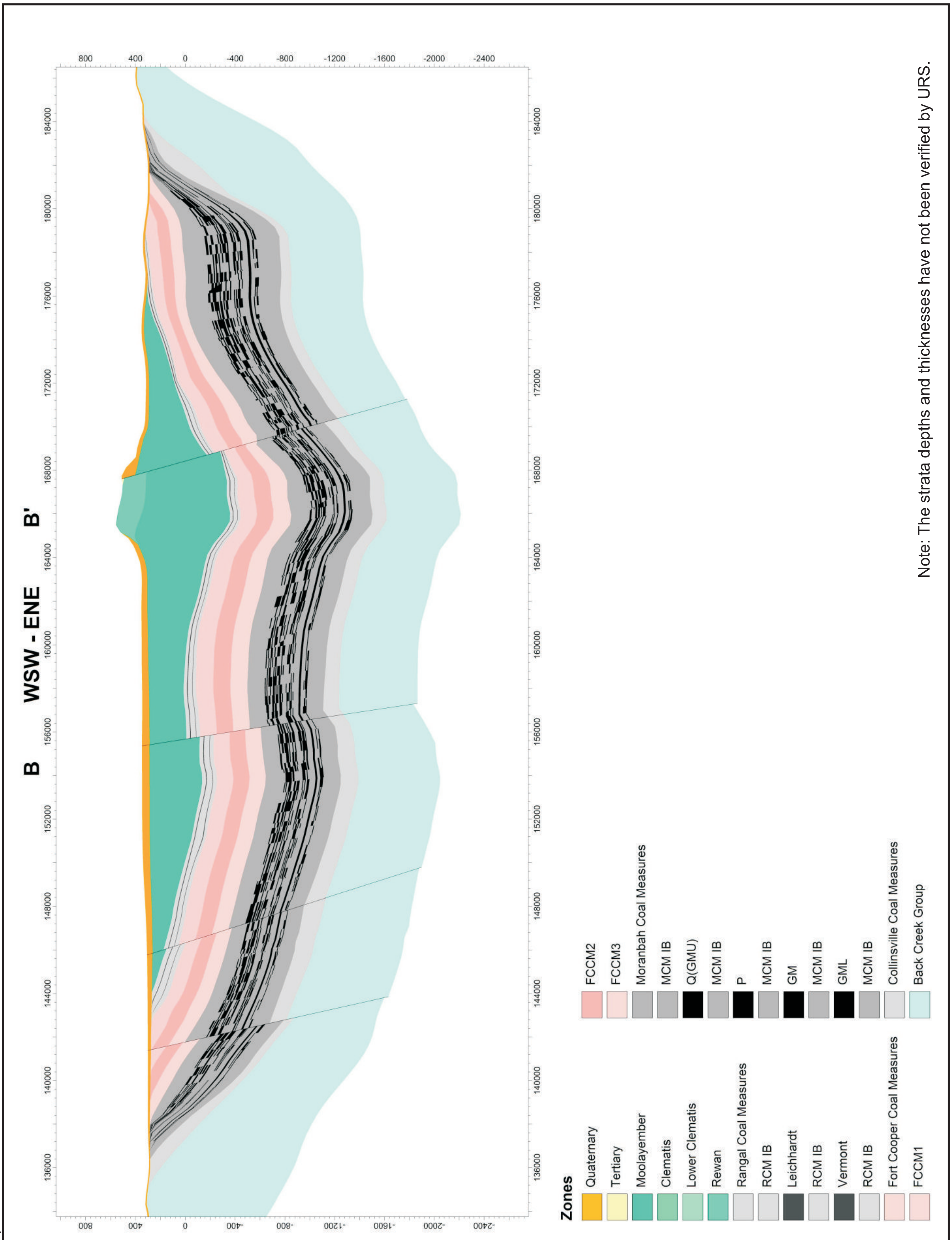

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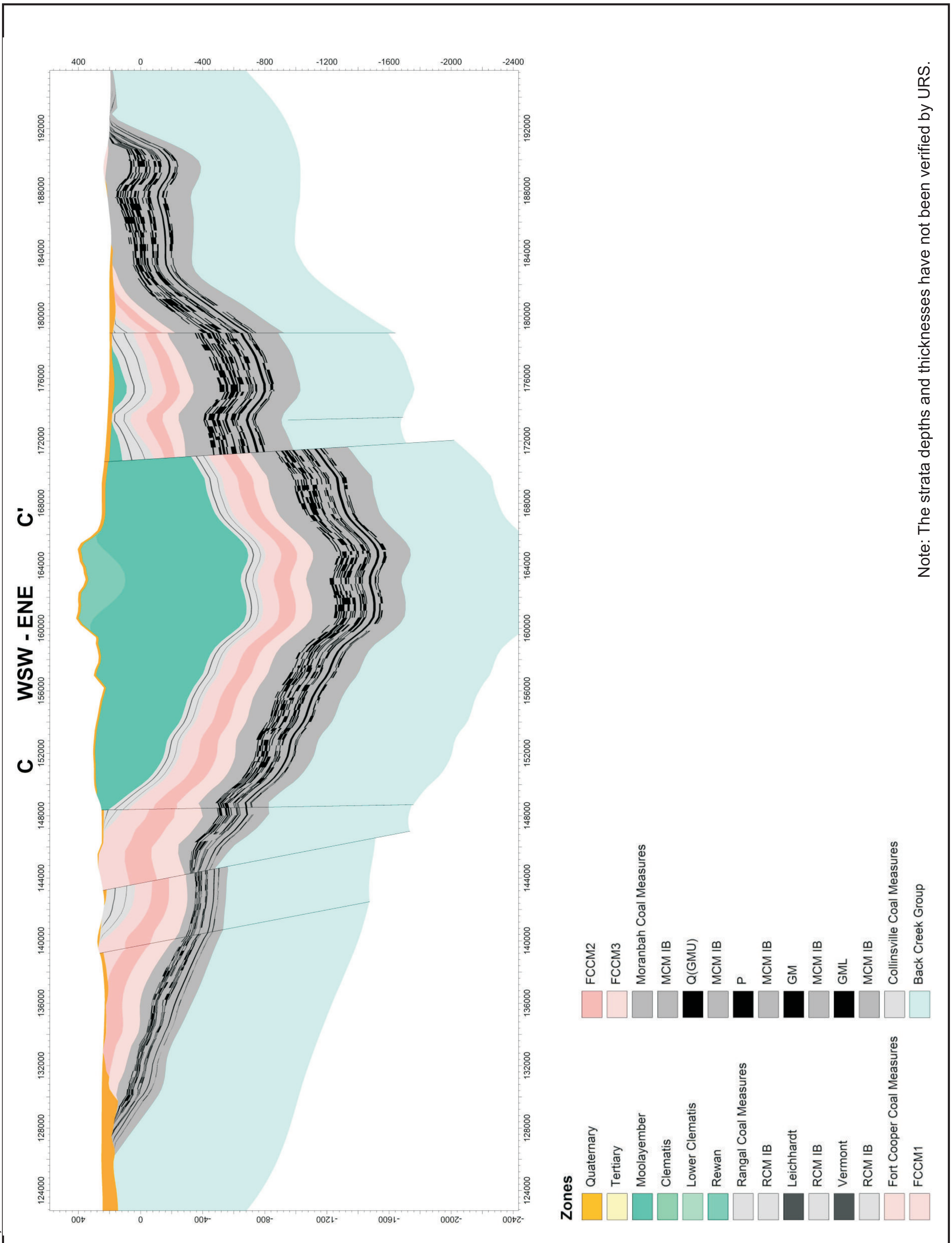
BOWEN GAS PROJECT EIS

GEOLOGICAL CROSS SECTION B - B’



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BOWEN GAS PROJECT EIS

GEOLOGICAL CROSS SECTION C - C'

13.4.3 Mapped Geology

The surface geology mapped across the Project area is diverse (Figure 13-3). Approximately half of the Project area is covered by Late Tertiary and Quaternary unconsolidated sediments. This cover includes the Isaac River alluvial sediments, with thicknesses of 10 to 50 m along the Isaac River. The characteristics of the superficial Quaternary alluvium reflect the nature of the source rocks, weathering, transport, and depositional conditions. Poorly sorted clay, silt, sand and gravel represent floodplain alluvium: locally mottled, poorly consolidated sand, silt, clay and minor gravel, generally dissected by high-level alluvial deposits reflect present stream valleys.

The Tertiary sediment cover includes thick, clay-rich laterite, a result of the laterisation of Permian units during the Tertiary period. In addition, Tertiary aged infill includes palaeochannel deposits and basalt flows provide surficial cover across the Project area. The major Tertiary formations mapped in the Project area include the Duaringa and Suttor formations.

Outcrop of consolidated formations are confined mainly to the northern portion of the Project area. The consolidated formations represented in surface outcrop include: the Late Permian Blackwater Group (FCCM, MCM and RCM) in the northernmost and north-eastern portion of the Project area; the mid-Triassic Moolayember Formation and Clematis Sandstone in the north-central portion of the Project area; and the Early Triassic Rewan Formation can be found in the northern portion of the Project area.

13.4.4 Stratigraphy

The stratigraphy of the Bowen Basin within the Project area is summarised in Table 13-2. The Late Permian Blackwater Group comprises (from oldest to youngest) the MCM, the FCCM, and the RCM.

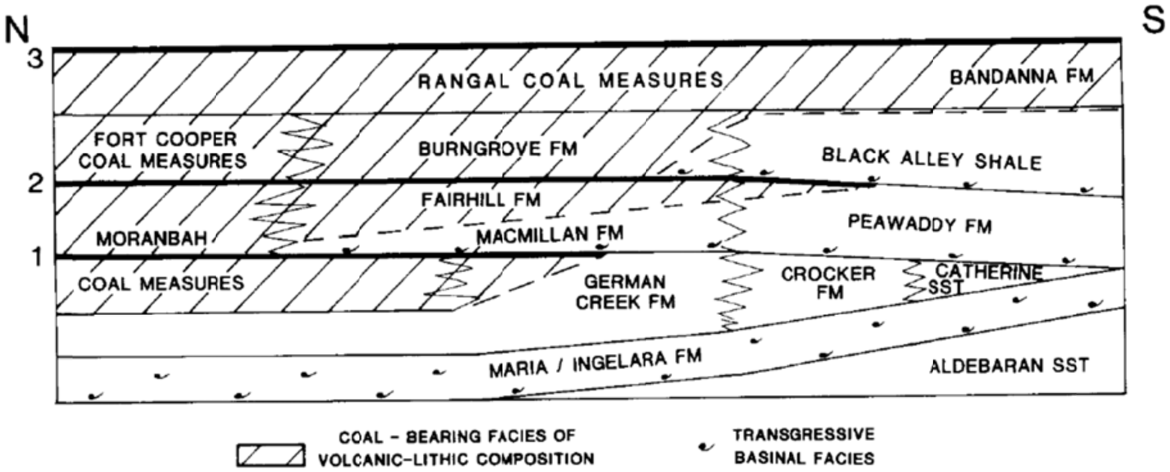
Table 13-2 Regional Stratigraphy

Age	Stratigraphic Unit		Lithology	Typical Thickness (m)	Occurrence
Quaternary	Alluvium		Clay, silts, sand, gravel and floodplain alluvium	15-35	Confined to present day stream alignments, floodplains, alluvial fans, high terraces and palaeochannels
Tertiary	Suttor Formation		Clay, silt, sand, gravel, colluvium, fluvial and lacustrine deposits including cross-bedded quartz sandstone, conglomerate, claystone	0-120	Most extensive in the mine areas and to the east
	Basalt		Olivine-rich weathered basalt remnants, moderately weathered and fresh basalts	0-80	Isolated outcrop, inferred dykes, and flow remnants in the northern tenements
	Duaringa Formation		Mudstone, sandstone, conglomerate, siltstone, some oil shale, lignite and basalt	0-50	Most extensive in the mine areas and to south and east

Age	Stratigraphic Unit		Lithology	Typical Thickness (m)	Occurrence
Triassic	Moolayember Formation		Mudstone, lithic sandstone, interbedded siltstone, mudstone, sandstone and thin coal seams	0-200	Isolated outcrop in the north and subcrop / outcrop in the south
	Clematis Sandstone		Quartz sandstone, some quartz conglomerate, minor reddish brown mudstone	0-300	Isolated outcrop in the north and subcrop / outcrop in the south
	Rewan Formation		Green lithic sandstone, pebble conglomerate, red and green mudstone	200-800	Underlies majority of Project area, thin in the centre, increasing in thickness as progrades east and west; Outcrop in the north, small, isolated outcrop in the centre of the Project area north of Middlemount
Late Permian	Rangal Coal Measures		Coal seams, carbonaceous shale and mudstone, tuff, siltstone and mudstone	25-200	Underlies Project area; Outcrop or subcrop in the majority of the Project area
	Fort Cooper Coal Measures and equivalents		Coal, brown and green sandstone, labile sandstone, quartzose sublabile sandstone, calcareous and tuffaceous sandstone, mudstone, carbonaceous mudstone siltstone, conglomerate, carbonaceous shale, tuff, volcanic conglomerate	100-600	Underlies Project area; Outcrop or subcrop in the majority of the Project area
	Moranbah Coal Measures and equivalents		Coal, quartzose to sublabile, locally argillacoues sandstone, siltstone, mudstone, carbonaceous mudstone	100-700	Underlies Project area; Outcrop or subcrop in the majority of the Project area
Middle Permian	Back Creek Group		Quartzose to lithic sandstone, siltstone, carbonaceous shale, minor coal and sandy coquinite	400-1,200	Underlies Project area; outcrop west of mines and extends under mined areas to the east, basement of Project area

The coal measures within the Blackwater Group are recognised to have different nomenclature across the Bowen Basin, as detailed in Section 13.4.1. Table 13-2 provides the various coal measure names (equivalents) for the coal measures in the north and the southern part of the Bowen Basin. These equivalents are further discussed and illustrated in Chart 13-1 below.

Chart 13-1 Schematic North-South Cross-Section of Permian Sediments across Bowen Basin



Source: Fielding *et al.* (1993)

The coal measure nomenclature equivalents of the Blackwater Group represent three pulses of recognisable southward-directed drainage during foreland basinal deposition.

The MCM are the oldest of the Blackwater Group, are found in the northern Bowen Basin, and represent the first of the three recognisable pulses of deposition during the late Permian. The southern Bowen Basin equivalents of the MCM are the German Creek Formation and the overlying MacMillan Formation.

The second pulse of drainage during infill of the Bowen Basin, advancing further south than the first and is classified in the north as the FCCM. Equivalents of the FCCM found in the southern Bowen Basin are the Fairhill Formation and overlying Burngrove Formation.

The third pulse involved the southward propagation of the RCM, which are found across the entire Project area.

13.4.4.1 Quaternary

Alluvial Deposits

The Quaternary alluvial deposits unconformably overlie the Tertiary Basalts, Rewan Formation, Clematis Sandstone and Moolayember Formation (where present) within the Project area. Quaternary alluvium is comprised of irregular (fining up and down) sequences of unconsolidated clay, silt, sand and gravel that have been unconformably deposited in an eroded, valley-fill environment. These deposits are a reflection of the meandering and braided nature of their depositional environment that includes cross-cutting and the reworking of older alluvial deposits. Alluvium exists predominantly around creeks, rivers and associated flood plains within the Project area. The alluvial deposits are generally thin, linear, irregular and lensoidal in nature with a typical thickness between 15 and 35 m (SKM, 2009) but have been reported up to 50 m thick along the Isaac River.

Distribution

Quaternary alluvial deposits are extensive throughout the Isaac and Mackenzie River sub-catchments (Pearce and Hansen, 2006). Data obtained from bore logs regarding alluvial deposits are uneven with the greatest concentration of bores occurring in the alluvium of Fennel Creek, Nebo Creek, Denison Creek and Connors River.

The total alluvial area in the Isaac Connors sub-catchment is 294,437 ha, of which 144,490 ha is associated with the Isaac River, including its tributaries and downstream of the junction with Connors River (SKM, 2009). River alluvium occurs in the Project area, mainly along the Upper Isaac River and Stephens Creek, Devlin Creek and Twelve Mile Creek near Blackwater, throughout the central and southern portions of the Project area. Available data indicates that the saturated alluvium thicknesses range from 15 to 25 m.

The Upper Isaac River has well-defined alluvial channels, whereas the Lower Isaac River (outside the Project area) has anabranches. Along Funnel Creek, east of the Project area, the alluvium is heavily braided.

Figure 13-3 depicts the distribution of Quaternary sediment distribution across the Project area.

13.4.4.2 Tertiary

Suttor Formation and Undifferentiated Tertiary Sediments

The undifferentiated Tertiary sediments and the Suttor Formation are the dominant Tertiary sediment units in the Project area. The Tertiary Suttor Formation comprises quartz-rich sandstone, conglomerate, sandy claystone and silicified claystone.

In the central part of the Mackenzie River sub-catchment a thick succession of Tertiary sediments were deposited in the Duaringa Basin. Similar successions of Tertiary sediments were also deposited in the Suttor Basin northwest of the Isaac River sub-catchment and in isolated basins southeast of the Mackenzie River sub-catchment (Pearce and Hansen, 2006).

The Tertiary sediments in the Project area are made up of the mud, sands, gravels, residual soils and colluviums of the undifferentiated Tertiary strata, as well as the Suttor Formation. These Tertiary sediments generally consist of lenses of palaeochannel gravels and sands separated by sandy silts, sandy clays and clays. The thickness and extent of these Tertiary sediments are variable; a review of available borehole logs within the western boundary of the Bowen Basin (near Moranbah) showed the Tertiary sediments vary in thickness up to approximately 120 m with a typical thickness of up to 15 m.

Volcanics

Cretaceous volcanism was widespread to the east of the sub-catchments and isolated remnants of this activity are preserved in the eastern ranges of the Isaac River sub-catchment. Tertiary volcanic deposits composed mostly of basaltic lava flows overlie the Bowen Basin successions. These Tertiary volcanics occur as isolated exposures throughout the Isaac River sub-catchment. The Peak Range

Volcanics, a series of rhyolite and trachyte plugs and domes have intruded the Tertiary volcanics in the southwest corner of the Isaac River sub-catchment (Pearce and Hansen, 2006).

Tertiary olivine-rich basalts unconformably overly the Rewan Formation and, where present, the Clematis Sandstone and Moolayember Formation. The extrusive Tertiary basalt appears to have flowed into palaeochannels, overlying and cross-cutting the Tertiary sediments. These basalts have shown to be deeply weathered in most places; however, thicker layers appear to be less weathered at the base. Previous studies have reported the basalt units range in thickness up to 50 m and tend to be the thickest, up to 80 m, within palaeochannels (Davies, 1983; Pearce and Hansen, 2006).

The Tertiary deposits lie adjacent to and beneath the Quaternary alluvial deposits. These deposits are found west of Dysart, near Moranbah, west of Nebo, and northeast of Middlemount (Pearce and Hansen, 2006). The Tertiary basalt near Moranbah is reported to be comprised flat lying flows that contain a high number of vesicular layers.

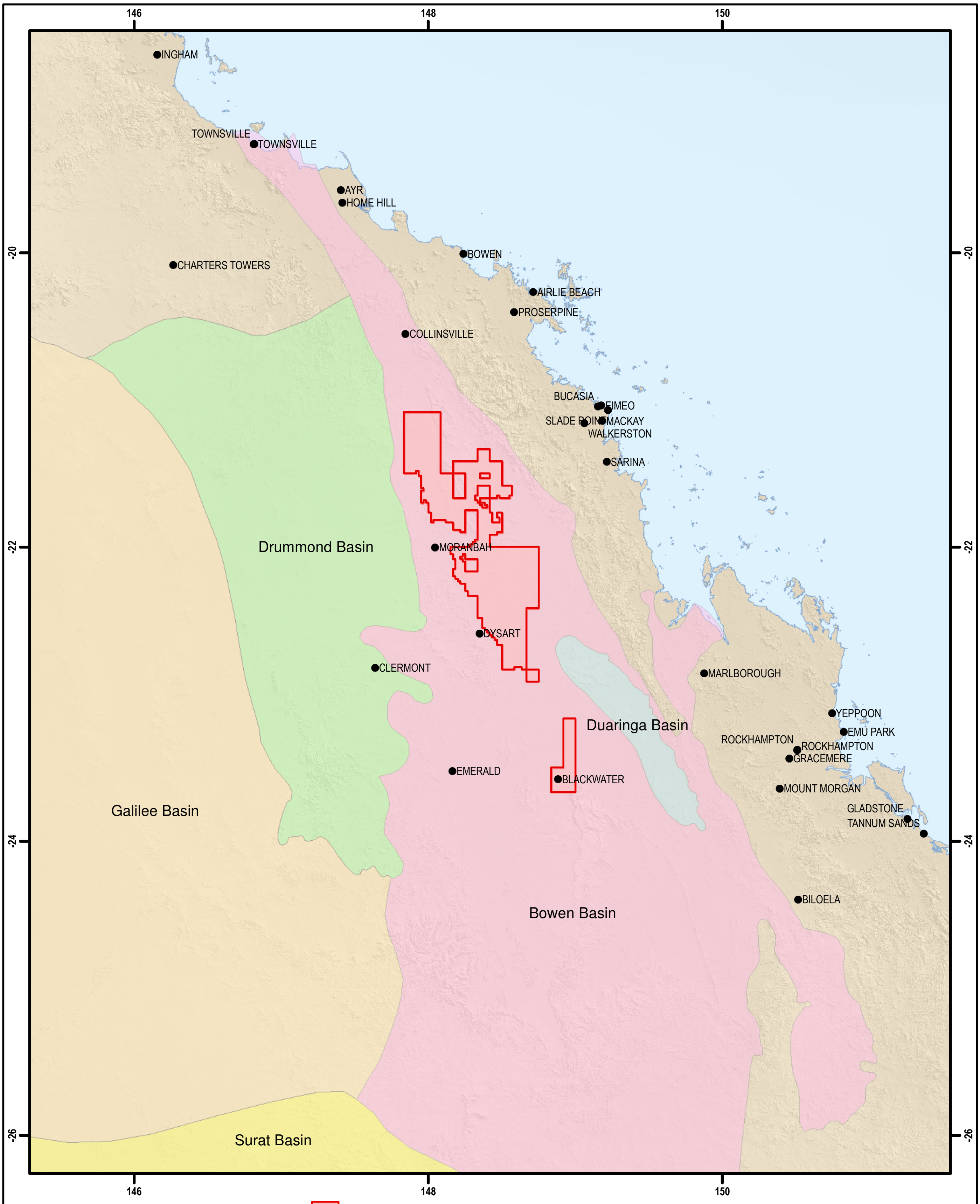
Duaringa Formation

Tertiary Duaringa Formation filled the Duaringa Basin, which formed as a result of post Bowen Basin faulting (Figure 13-9). This Tertiary basin formed concordantly with the Tertiary volcanics, and consists of mudstone, siltstone, sandstone, conglomerate, oil shale, lignite, and basalt. The thickness of Tertiary sediments within the Duaringa Basin can reach several hundreds of metres (NTEC, 2011), while typical thickness in the Project area is less than 50 m.

Distribution

The distribution of Tertiary sediments across the Project area is shown in Figure 13-3. The undifferentiated Tertiary sediments and Suttor Formation occurs extensively throughout the northern portion of the Bowen Basin, although outcrops are not continuous. The Duaringa Formation is mapped as outcrops in the central and southern tenements within the Project area, as shown in Figure 13-3. Considerable amounts of the Tertiary sequence are concealed by younger, overlying alluvium and colluvium in the Project area.

An aeromagnetic geophysical survey has been undertaken over the Bowen Basin (GSQ, 2004). The resultant magnetic data indicates that Tertiary basalt exists as small discontinuous remnants and thicker remnant flows have filled in former drainage systems / palaeochannels. These basalt deposits are found west of Dysart, near Moranbah, west of Nebo, and northeast of Middlemount (Pearce and Hansen, 2006). The Tertiary basalt near Moranbah is reported to be comprised flat lying flows that contain a high number of vesicular layers. For the majority of exploration boreholes that intersected basalt in the Project area the basalt is logged as highly to extremely weathered, clayey, dry.



Bowen Gas Project Tenements

N S W E

0 10 20 40 60 80 100 120 km

1:4,000,000

Projection: Geographic (GDA94)

arrow energy go further

BOWEN GAS PROJECT EIS

SEDIMENTARY BASINAL RELATIONSHIPS

URS

GEOLOGY

Figure: **13-9**

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13.4.4.3 Triassic

Moolayember Formation

The Moolayember Formation outcrops in the northern portion of the Project area, within the northern half of ATP 1103. The Moolayember Formation consists of mudstone, micaceous lithic sandstone, and micaceous siltstone and can be found up to approximately 200 m thick in the Project area.

Distribution

The Moolayember Formation has mostly eroded from the Bowen Basin, but few remnants occur as outcrops along the north-east corner of ATPA 742, and within the northern half of ATP 1103. These outcrops occur along a north-northwest trending ridge overlying outcrops of the Clematis Sandstone in the northern Bowen Basin. As major features of the terrain, these outcrops can rise 50 to 200 m above the general topography and up to 60 km long. Figure 13-3 depicts the distribution of the Moolayember Formation across the Project area.

Clematis Sandstone

The Triassic-age Clematis Sandstone has a localised presence to only a few small outcrops in the northern portion of the Project area. The Clematis Sandstone comprises medium to coarse-grained quartzose to sublabile, micaceous sandstone, siltstone, mudstone and granular to pebble conglomerate; subcrops / outcrops can have thicknesses up to 300 m in the Project area.

Distribution

The Clematis Sandstone has mostly eroded from the Bowen Basin but few remnants occur as outcrop / subcrop along the north-east corner of ATP A742, and within the northern half of ATP 1103. These outcrop / subcrop are major features of the terrain, rising 50 to 200 m above the general topography and up to 60 km long. Figure 13-3 depicts the distribution of the Clematis Sandstone across the Project area.

Rewan Formation

The Rewan Formation (Late Permian to Early Triassic) underlies the Clematis Sandstone and conformably overlies the RCM, except in the northern portion of the Project area, where the RCM outcrops / subcrops.

The Rewan Formation comprises lithic sandstone, pebbly lithic sandstone, and green to reddish brown mudstone, siltstone, quartz sandstone, shale and some volcanilithic pebble conglomerate at the base. Thickness of the Rewan Formation ranges across the Bowen Basin up to 800 m thick (in the depocentre of the basin) but has a typical thickness of 300 m within the Project area (Figure 13-2).

Distribution

The Rewan Formation is a regional-scale confining unit (aquitard) along most of the central axis of the Bowen Basin but is absent from the east and west flanks of the basin (Figure 13-2).

13.4.4.4 Permian

Rangal Coal Measures

The RCM overly the FCCM and comprises both fractured and well-cleated coal seams. The transition between the RCM and the FCCM is generally indicated by the Yarrabee Tuff, a basin-wide marker bed. The Yarrabee Tuff is characterised as a beige / brown tuffaceous claystone.

The RCM are separated by light grey, cross bedded, fine to medium grained sandstone, grey siltstone, carbonaceous shale and mudstone layers. These units have been observed to be competent and restrict vertical seepage between coal seams and from the adjacent over- and underlying stratigraphy. The RCM are generally estimated to be between 25 and 200 m thick (approximately 150 m on average) and subcrop in the northern, southern, and eastern portions of the Project area.

Fort Cooper Coal Measures

The FCCM unconformably overly the MCM, and are mapped to be laterally consistent throughout the Project area. The FCCM occur within the northern portion of the Bowen Basin. In the middle of the basin, around Saraji, equivalents are denoted as the Fairhill Formation and the Burngrove Formation (Table 13-2), because of slight differences in stratigraphy. For the purposes of this chapter, and as the units do not differ too markedly from a geological perspective, these units are referred to as FCCM equivalents.

The FCCM and equivalents consist of up to seven inter-bedded coal seams. These generally consist of thin vitrinite rich coal seams banded with carbonaceous shale, and are interbedded with grey tuffaceous sandstone, lithic sandstone, mudstone and cherty mudstone. The FCCM and equivalents range in thickness from approximately 100 m in the north to approximately 600 m in the south. The coal seams contained within the FCCM and equivalents are typically banded with claystone, mudstone, and siltstone.

Moranbah Coal Measures

The MCM overly the Back Creek Group and are interbedded with lithic sandstone, siltstone, mudstone, and conglomerate in the east. Lateral equivalents of the MCM are found towards the southern portion of the Project area. Referred to as MCM equivalents, the German Creek and MacMillan formations reflect a marine influenced depositional environment.

The MCM and equivalents consist of at least four well defined laterally continuous coal packages. These packages encompass the target coal seams for the proposed CSG operations. The MCM and equivalents range in thickness from 100 to 700 m and outcrop in the northernmost portion of the Project area.

Back Creek Group

The Back Creek Group consists of quartzose to lithic sandstone, siltstone, carbonaceous shale, minor coal and sandy coquinite (NTEC, 2011). The Back Creek Group underlies the Blackwater Group across the Project area.

13.4.5 Coal Seam Geology

The Bowen Basin is the most important Permian coal basin in Australia, and exhibits major variations in rank and quality, reflecting both the depositional and tectonic history of the basin (NTEC, 2011). A broad trend of increasing rank from west to east has long been recognised. Coal-bearing horizons have been preserved at many stratigraphic levels throughout the Bowen Basin, but deposits of economic importance are restricted to the Permian age category.

Coal seams with potential for gas generation under development in the basin are contained within the seams of the Late Permian Blackwater Group comprising stratigraphically from youngest to oldest:

- The RCM;
- The FCCM; and
- The MCM.

Figure 13-3 illustrates surface geology of the Project area and locations of five geologic cross sections throughout the Project area. Figure 13-4 through Figure 13-8 present the five geologic cross sections developed within the Project area. The cross sections were used to assist with site conceptualisation and potential impact assessment. These figures were provided by Arrow and were generated as a result of a geological model of the Bowen Basin.

Table 13-3 presents the target coal seams of the current development plan as illustrated in the cross sections presented on Figure 13-4 through Figure 13-8. Coal seam nomenclature used in Table 13-3 is Project specific as developed by Arrow for their regional Bowen Basin geological model.

Table 13-3 Permian Coal Seams within the Project Area

Permian Coal Measures	Coal Seams
Rangal Coal Measures	Leichhardt
	Vermont
Fort Cooper Coal Measures	FCM3
	FCM2
	FCM1
Moranbah Coal Measures	Q (GMU)
	P
	GM
	GML

Note: GM – Goonyella Middle; GML – Goonyella Middle Lower;

13.4.6 Economic Geology

The Bowen Basin is of significant economic importance, due primarily to its extensive deposits of coal and substantial volumes of CSG occurring within the coal deposits, approximately 23% of Australia's 2P (proven and probable) CSG reserves (DEEDI, 2012). Commercial production occurs in the central and southern parts of the basin near Moranbah, Injune, Moura and Wandoan. The Permian coal measures are the main CSG targets.

Arrow's Bowen Basin petroleum tenures are located in and around Moranbah, a close proximity to Queensland's three key energy markets: Townsville, Gladstone, and Brisbane where operations account for approximately 20% of Queensland's overall domestic gas supply. Coal permeability in the Moranbah area is relatively low with production enhanced by in-seam drilling. Development has concentrated on seams at around the 300 m level to avoid the loss of permeability that generally comes with increasing depth.

The Project involves development of the tenements by CSG well installation and construction of infrastructure to treat and transport the CSG and associated water to the Arrow LNG Plant. Currently, for the first phase of development, gas supply from the Bowen Basin is expected to be approximately 520 TJ/d which may equate up to approximately 35% of the total daily demand (plateau) flow rate required by the Arrow liquefied natural gas plant. The Project economic value is discussed further in the Project Description and Economics chapters (Sections 4 and 23) of this EIS.

13.4.7 Seismicity and Ground Stability

Queensland is seismically active, with the highest hazard region lying along the populated eastern coast and near offshore regions. Most Australian earthquakes occur in the crustal layers of the region where, in the north-east of Australia, the average earthquake focal depth has been determined to be 10 km (± 0.5 km). The largest earthquakes recorded in Queensland occurred offshore of Gladstone in 1918 (Richter Magnitude (ML) 6.3) and near Gayndah in 1935 (ML 6.1). Structural damage to buildings was reported in the Rockhampton region during the Gladstone earthquake. In the Rockhampton area, the earthquake was determined to have a Modified Mercalli Intensity (MMI) of VI (denotes how strongly an earthquake affects a specific place and ranges between I and XII). MMI of VII and VIII, which are capable of causing serious damage, were also noted on Quaternary floodplain alluvium in the Rockhampton area. Note: On this scale, minor damage to building contents begins at MMI V, with total destruction to unreinforced masonry buildings at MMI XII.

The most recent, moderate sized earthquake within the broader region of the Project area occurred in 2011, approximately 50 km from Bowen, to the north of the Bowen Basin. It recorded an ML of 5.3. A maximum intensity of MMI V was experienced in Bowen, with some reports of slight damage in Bowen (AEES, 2011).

In Queensland, earthquakes with the potential to cause serious damage or fatalities (ML >5) have occurred on average approximately every five years over the last century, with several near misses to the State's large population centres. A high level of seismic activity runs through a belt just inland of Bundaberg, spanning downwards from Gladstone through Gaydah and beyond.

Although the Project area extends over a considerable distance, the majority of the Project tenements fall within a MMI III zone of expected earthquake intensities.

Structural Features and Faults

Structural features occurring within the Bowen Basin consist predominantly of south to north or south-southeast to north-northwest trending gentle folds and faults. These have resulted from regional compression towards the west-southwest occurring from the end of the Permian to the Middle Triassic.

As mapped by the Geological Survey of Queensland (GSQ, 2004) on the regional Bowen Basin map sheets; major anticlines, synclines and fault lines and other geological structural features that occur within the CSG fields are shown in Figure 13-2. The faults in particular potentially comprise a zone of weakness in the earth's crust that may be subject to differential movement during a significant seismic event in the general area.

13.5 Potential Impacts

Based on the compilation and review of available geology data and CSG activities, an impact assessment has been conducted. The evaluation of available geological information indicates the potential for environmental impacts associated with the Project include:

- Induced seismicity (ground stability);
- Land subsidence due to coal seam depressurisation and dewatering;
- Coal formation subsidence from dewatering, and
- CSG migration.

Coal seam structure can potentially alter the coal through hydraulic stimulation (additional permeability through fractures) and depressurisation (coal matrix shrinkage); however, these potential impacts will not reduce the potential for mining (i.e. CSG production does not lead to sterilisation of coal resources), and may be beneficial to coal mining projects on completion due to incidental mine gas removal. All of these identified potential impacts are recognised to be indirect environmental impacts of CSG-production activities. Mitigation and management of these indirect environmental impacts are discussed in Section 13.7 of this chapter.

13.5.1 Induced Seismicity

A review of regional seismicity data and consideration of the location of potential geological hazards (primarily major geological structures), indicates that there is the likelihood for damage to in-field gas / water gathering pipelines and associated facilities due to potential ground instability.

Induced seismicity refers to typically low magnitude seismic activity (earthquakes and tremors) caused by human activities that alter stresses on the earth's crust. Induced seismicity could result from the following proposed Project activities:

- Drilling;

- Geophysical (seismic) surveys;
- Hydraulic stimulation; and
- CSG depressurisation.

Hydraulic stimulation is the primary Project activity considered to potentially result in induced seismicity. Hydraulic stimulation increases the coal seam permeability by introducing fluid and sand under pressure into the target coal seam to propagate and widen fractures. When fractures are generated or deformed the rock stress state (equilibrium) changes and induced seismic activity can occur.

Induced seismicity as a result of hydraulic stimulation can potentially result in the creation of fractures in the coal seam geology (with potential to interconnect aquifers to generate inter-aquifer flow paths and/or facilitate gas migration pathways), surficial disturbances and/or building damage.

Hydraulic stimulation induced seismicity records indicate minor seismic events that generally register less than 2.0 on the Richter Magnitude Scale. Events of this magnitude are not felt at ground surface, and are only detectable with sensitive equipment. Records of production induced ground motions in the Roswinkel gas field in the Netherlands (Dowding *et al.*, 2011) as a result of hydraulic fracturing and field operations, between 1992 and 2003, indicate moment magnitude 2.25 events. Measurements of motions produced by hydraulic fracturing in a geothermal field in Japan indicated ground motions of such small amplitude that they were inconsequential for consideration of structural response (Dowding *et al.*, 2011). These ground motions (and associated impact on structures) were compared to ground motions generated by typical large-scale open cut (surface) mining blasting. A typical blasting event can produce ground motions with a peak particle velocity of 0.35 centimetres per second (cm/s) to 0.19 cm/s compared to 0.8 cm/s (Roswinkel gas field) or 0.000075 cm/s (Japan geothermal field).

Induced seismicity as a result of hydraulic stimulation is considered to result in minor seismic events, which are likely to be less than the historically recorded magnitudes or those generated by mining activities.

13.5.2 Coal Seam Subsidence

Coal seam subsidence can occur from the production of CSG via volumetric changes in the coal formation and adjacent overburden (referred to as matrix volumetric strain). In some circumstances a volumetric decrease can occur due to pore pressure reduction, which increases the stress applied to the rock matrix. Pore pressure reduction can occur during both dewatering and methane production stages (Myer, 2003). Swelling of coal due to sorption of liquids has been reported by Gregg (1961), and Green and West (1985).

Swelling of coal in the presence of an adsorptive gas (i.e. methane) has also been investigated in the past. Moffat *et al.* (1955) reported studying the swelling and shrinkage of coal with adsorption or desorption of methane. Documented literature estimating the magnitude of subsidence occurring as a result of CSG activities is limited. Generally, subsidence effects in coal formations appear to be negligible. Preliminary estimates of subsidence in the Powder River Basin (PRB), Wyoming, USA due to aquifer drawdown are deemed insignificant at approximately 1.3 cm (Case *et al.*, 2001).

Available literature on risks associated with coal seam subsidence focuses on the impact of coal seam shrinkage upon gas production; while limited data was found regarding the occurrence of subsidence from CSG production or the impacts of CSG induced subsidence (Section 13.5.3). These data suggest subsidence as a result of CSG production will be negligible: maximum recorded land subsidence range of 4 to 6 cm (correlated to large clusters of coal bed methane pumping wells) (Grigg, 2012) over a large CSG field (approximately 32,375 km^2); estimates of coal seam subsidence have been approximated at 1.3 cm (Case *et al.*, 2001).

Although the permeability of coal increases with desorption of CSG during production, the increase in effective stress due to a reduction in pressure also tends to cause a reduction in coal permeability. Results from Harpalani *et al.* (1997) suggest that the decrease in permeability due to increased effective stress is balanced by the overall increase in permeability from matrix shrinkage.

13.5.3 Land Subsidence

Subsidence is defined as the movement of the surface strata in response to the loss of underground support (Nagel, 2001). A loss of underground support can potentially result from groundwater extraction from an aquifer / coal seam and associated strata compaction. While hydrocarbon industry-related subsidence is well documented, some of the fundamental phenomena and mechanisms encountered in CSG production from coal have not been studied in detail, and are unable to be explained by the current level of knowledge, such as long term consequence effects (Harpalani *et al.*, 1997; Siriwardane *et al.*, 2009).

The level of CSG-related subsidence data is growing. Land subsidence as a result CSG production has been documented in the PRB, Wyoming, USA. Groundwater has been extracted in the PRB for coal bed methane (CBM), a CSG equivalent term, with production at rates approximately 356 ML per day. As a result of associated aquifer compaction, several centimetres of land subsidence have been measured via interferometric synthetic aperture radar (InSAR). The largest subsidence values measured over the PRB was 4 to 6 cm and, in these areas, subsidence was correlated to large clusters of pumping wells (Grigg, 2012).

InSAR has also been used to quantify the surface response to aquifer depletion in the vicinity of CBM production in the San Juan Basin of Colorado and New Mexico. Results show that there has been enough groundwater production to result in measurable (several centimetres) of subsidence above the CBM fields of the San Juan Basin (Katzenstein, 2012). Given the large areas of these basins, approximately 32,375 km^2 and 12,070 km^2, respectively, land subsidence as a result of CBM (CSG) production is generally viewed as negligible.

Land subsidence is a process that can occur over a wide range of temporal scales, from almost instantaneous settlement to very slow rates of ground level drop over long time-periods. The occurrence of subsidence can cause changes to flood plain morphology (Zekster *et al*., 2005). This could influence surface water runoff and may cause changes to flow regimes, and could precipitate a need to revise flood mapping. The most immediate impact of marked subsidence may involve surface structures (Nagel, 2001). However in cases of regional subsidence, the effects may not be as damaging to structures as localised subsidence.

Structural Considerations

Subsidence and compaction can affect CSG and water production, and well casing deformation can occur due to axial buckling in the reservoir or horizontal shearing in the overburden. Fissuring can be produced through differential settlement of subsiding lands (Zekster *et al.*, 2005). Fissures may be produced at pre-existing faults. Risks of failure or slip of pre-existing faults within the coal formation due to subsidence within the formation are dependent on the depth, in-situ stress state, pressure drawdown, coal strength, and poro-elastic properties (Nagel, 2001). As a formation compacts, system changes which may cause principal stress differences increasing the potential for failure and slippage.

13.5.4 CSG Migration

Gas migration is a potential result of CSG production activities. Gas migration is when natural gas escapes from the coal seam and 'migrates' to undesired areas (i.e. where capture, control or mitigation measures are not located). Gas migration typically occurs along fractures and through permeable soils and groundwater aquifers (Pittsburgh Geological Society Natural Gas Factsheet, 2003).

Gas migration can occur as a result of improper production well installation, improper abandonment or from inappropriate cementing techniques. A well installed near faults or fractures and changes in barometric pressure or temperature contrasts can cause diffuse gas to migrate from areas of high concentration to areas of low concentration.

13.6 Environmental Protection Commitment

The environmental protection commitment with regards to geology is to implement proven techniques and technologies to minimise potential indirect environmental impacts from CSG-related activities. The identified indirect environmental impacts to be minimised include:

- Induced seismicity;
- Coal seam subsidence;
- Land subsidence; and
- Gas migration.

Mitigation and management measures have been recommended to meet the environmental protection commitment of minimising indirect environmental impacts and are discussed in Section 13.7 below.

13.7 Mitigation and Management Measures

CSG operations in the Project area will be conducted in accordance with Arrow's EM Plan, which will provide the minimum baseline standards for operational activities being undertaken. Arrow's EM Plan will present the level of mitigation to be applied to all locations. In areas characterised by higher environmental values, or with higher environmental constraints, schedules will be appended to the EM Plan to detail additional location-specific mitigations identified and recommended in this section.

Management decisions and an adaptive approach to CSG field development will also be informed by the results of potential impact monitoring programs. As CSG field development continues, and these monitoring programs expand, more information regarding the behaviour of the identified potential geological impacts will be used to reduce uncertainty and enable the adaptation of management and mitigation measures to site conditions. Management recommendations are presented in Section 13.8.

Hydraulic stimulation is the primary Project activity considered to potentially result in induced seismicity. Based on the geological and technical information provided by the Arrow with regards to the potential impacts of hydraulic stimulation, it is recognised that:

- Hydraulic stimulation can alter the structural integrity of the targeted coal seams. These represent a relatively small proportion of the total thickness of the target coal packages.
- While the potential for hydraulic stimulation activities to impact on the structural integrity of other geological units can never be completely eliminated, the competent application of proven industry standard technologies, techniques, and monitoring / mitigation measures are considered appropriate for minimising the risk.

On a CSG well field and bore basis, site layout in regards to geological structural features and faults will be considered to minimise the potential for induced seismicity as an indirect result of CSG-related activities (eg fracture stimulation) in [B038].

CSG structures and associated in-field gas / water pipeline facilities will be designed and constructed in accordance with AS 1170.4:2007 [B039], to comply with the minimum criteria considered necessary for the protection of life, by minimising the likelihood of collapse of structures. In terms of engineering design, the stated purposes of designing structures for earthquake loads in accordance with AS 1170.4:2007 are:

- Minimise the risk of loss of life from structure collapse or damage in the event of an earthquake;
- Improve the expected performance of structures; and
- Improve the capability of structures that are essential to post-earthquake recovery to function during and after an earthquake and to minimise the risk of damage to hazardous facilities.

13.7.1 CSG Migration

Risks of gas migration as a result of CSG-related activities are considered low, however, potential impacts can be minimised by constraining CSG activities and field placement to areas not on or immediately adjacent to fault zones that are seismically active and/or have high pressure differentials across them without first assessing the nature of the geological structure(s).

Proper construction, operation and decommissioning of production wells will also minimise the potential for gas migration. The establishment of a gas capture zone (buffer zone) around production well(s) is recommended where geological structures have increased vertical hydraulic conductivity. Within the capture zone, monitoring should be conducted to further develop and refine the buffer between neighbouring bores, faults and structures. The gas capture zone will also act as a barrier that will limit exposure to onsite personnel.

Careful consideration of the placement of CSG production facilities and supporting infrastructure (i.e. water treatment and storage facilities, power generation facilities and workforce accommodation) outside of the (buffer) capture zone will minimise exposure of potential gas migration. Supporting infrastructure and production facilities should be designed with adequate ventilation systems to minimise the potential for exposure and/or gas build up to unsafe / flammable quantities. Regular well integrity testing will also limit potential impacts from gas migration.

13.8 Monitoring

To ensure the identified potential indirect environmental impacts are minimised and the environmental protection commitment with regards to geology is successful, monitoring recommendations are presented in Table 13-4.

Table 13-4 Proposed Monitoring Measures to Minimise Indirect Environmental Impacts

Impact to be Minimised	Proposed Monitoring Measures
Induced seismicity	• Assessment of geological structural features and faults, on a CSG well field and bore layout basis. • Design of all structures (including CSG structures and associated in-field gas / water pipeline facilities) to AS 1170.4:2007 complies with the minimum criteria considered necessary for the protection of life, by minimising the likelihood of collapse of structures.
Coal seam subsidence	• Regular monitoring of surface and subsurface elevations to be conducted to evaluate the potential subsidence impacts associated with CSG depressurisation. • Survey and bore log data can be analysed at periodic intervals over the life of the Project to monitor and measure coal seam subsidence as a potential indirect impact of CSG production on the geology. • An understanding of the baseline coal seam roof and floor elevations for comparison is fundamental.
Land subsidence	• An initial baseline analysis of subsidence within the study area be undertaken to establish pre-CSG development conditions from which potential land subsidence impacts can be measured from during the Project lifecycle. • Regular (not more than five years or until an understanding of subsidence potential is gained) monitoring of surface elevations to understand the potential level of subsidence and subsequent flood predictions associated with CSG depressurisation. Additional monitoring may be required to investigate the potential for environmental harm from land subsidence.
CSG migration	• Consider CSG activities and field placement on or immediately adjacent to fault zones that are seismically active and/or have high pressure differentials across them without first assessing the nature of the geological structure(s). • Proper construction, operation and decommissioning of production wells. • Establishment of a gas capture zone (buffer zone) around production well(s) to monitor fugitive emissions, refine the buffer between neighbouring bores, faults (if faults have enhanced hydraulic conductivity), and structures, and to limit personnel exposure. • Consideration of the placement of CSG production facilities and supporting infrastructure (i.e. water treatment and storage facilities, power generation facilities, workforce accommodation) outside of the (buffer) capture zone. • Supporting infrastructure and production facilities should be designed with adequate ventilation systems to minimise the potential for exposure and/or gas build up to unsafe / flammable quantities.

13.9 Cumulative Impacts

13.9.1 Cumulative Induced Seismicity

A variety of proposed Project activities have the potential to create cumulative induced seismicity impacts:

- Drilling;
- Geophysical (seismic) surveys;
- Hydraulic stimulation; and
- CSG depressurisation.

Adherence to all industry standards as they relate to each of these activities will mitigate potential cumulative impacts. Regular well integrity testing will limit potential impacts.

13.9.2 Cumulative Subsidence

ALOS satellite data are considered by industry to be the most effective tool to monitor subsidence. Arrow and the other CSG proponents are currently outlining a framework to monitor the cumulative impacts associated with subsidence (coal seam and land). Additionally, isostacy associated with other regionally located mining and CSG operations needs to be considered. If cumulative impacts lead to pronounced land subsidence then trigger levels (based on changes to surface water flow patterns and building regulations) will need to be developed. Trigger values will then be compared and a study to assess possible environmental harm should be instigated. Upon completion of the study, management controls can then be identified and implemented.

13.9.3 Cumulative Gas Migration

Faults that are seismically active and/or have high pressure differentials across them will be considered in the placement of well fields, production facilities and supporting infrastructure to minimise potential for fault-related gas migration pathways. Adherence to all industry standards as they relate to well installation, operation and decommissioning will mitigate potential cumulative impacts; while regular well integrity testing and gas monitoring within the gas capture zones will limit potential cumulative impacts.

There is also a potential for CSG migration at the edges of well fields. CSG desorbs from the coal seams as a result of well field depressurisation, and gas can migrate outside of the gas capture (buffer) zone. These fugitive emissions can migrate upwards through structures, old / abandoned bores, low pressure zones, into production wells after shut-off, or can pool in geologic traps. Old and abandoned wells and bores within the CSG well fields should be tested for structural integrity.