Petroleum Plays of the Bowen and Surat basins

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SUMMARY

The plays of the Bowen and Surat basins consist of conventional structural plays along major regional structures and depositional platforms, most of which have some stratigraphic component. These can be subdivided into three main regions: the eastern and western flanks of the Taroom Trough, and the Denison Trough. Coal seam gas is found in fairway zones within the Permian coals of the Bowen Basin, which can be subdivided into two main fairways: structurally associated plays in the southern Bowen Basin, and a tighter play in the northern Bowen Basin. Coal seam gas is also found along a broad fairway in the Walloon Coal Measures of the Surat Basin. Recent exploration for new targets has highlighted potential for tight gas in the deeper sections of the Bowen Basin, though further evaluation is required. More speculative plays within the region include tight gas within potential, but untested targets in the deeper sections of the Denison Trough.

Key words: petroleum, petroleum exploration, Queensland, Bowen Basin, Surat Basin

INTRODUCTION

A petroleum play is an exploration concept that groups fields together based on similar characteristics, generally lithological or structural, that can be applied at regional or local scales. Conventional plays can be grouped by style of trap and geological region, or by target formation. Unconventional exploration uses a play based approach extensively, as prospective areas can generally be defined by mappable characteristics. Examination of play characteristics and their spatial distributions can highlight areas that may contain new exploration prospects.

Since the early 1960s, the Bowen and Surat basins have been the target of extensive exploration for petroleum. Prior to the 1990s, discoveries were primarily found in structural traps, with a variable contribution from stratigraphic trapping. Since the 1990s, there has been a shift from conventional discoveries to accumulations needing some application of additional technology for their extraction, for example, coal seam gas in the Permian and Jurassic coal measures, or reduction of formation damage in Permian sandstone reservoirs.

GEOLOGICAL SETTING

The Bowen Basin is an elongate, back-arc to foreland, Late Carboniferous to Middle Triassic, NNQ-SSE trending basin which spans across 160,000 km^2 of eastern Queensland and northern New South Wales (Green, 1997). There are two main deopocentres in the Bowen Basin: the Denison Trough in the west and the Taroom Trough in the east. These are separated by the Comet Ridge. There are several other troughs of similar age in southern Queensland (e.g. the Arbroath and Esk troughs), though these are generally considered to be separate depositional systems.

The Bowen Basin first opened as a series of half grabens and grabens related to Early Permian back-arc extension, into which up to 10,000m of fluvial to lacustrine sediments were deposited (Green, 1997). Extensive volcanic activity from an active subduction arc along the eastern margin of the basin accompanied this deposition. A passive, thermal sag phase followed, marked by a basin-wide marine transgression and temporary cessation of volcanic activity. Deposition was dominated by deltaic sediments which prograded into the basin from the west. In the late Permian, foreland loading along the eastern margin led to a compressional phase which cut the basin off from marine influence. During the Early to middle Triassic, the basin filled in with alluvial to coastal plain sediments. A compressional pulse in the Triassic terminated deposition in the Bowen Basin and caused deformation and uplift of deposited formations (Fielding *et al*., 1997).

The Surat Basin a large intracratonic basin deposited from the late Triassic to Cretaceous. It extends across 300,000 km^2 of central southern Queensland and northern New South Wales. It unconformably overlies the southern Bowen Basin, and is contiguous across the Nebine Ridge with the Eromanga Basin in the west, and over the Kumbarilla Ridge with the Clarence-Moreton Basin in the East. It has

one main depocentre in the Mimosa Sycline, which overlies the axis of the Taroom Trough of the Bowen Basin. It contains up to 2,500m of primarily sedimentary rocks deposited in primarily fluvial to lacustrine environments from the latest Triassic to early Cretaceous. Five cycles of deposition have been noted in the Surat Basin, and have been linked to global changes in sea level. Each cycle has higher-energy sand deposition at its base, which gradually fines upwards into finer-grained units dominated by siltstone, mudstone and coal (Exon and Burger, 1981).

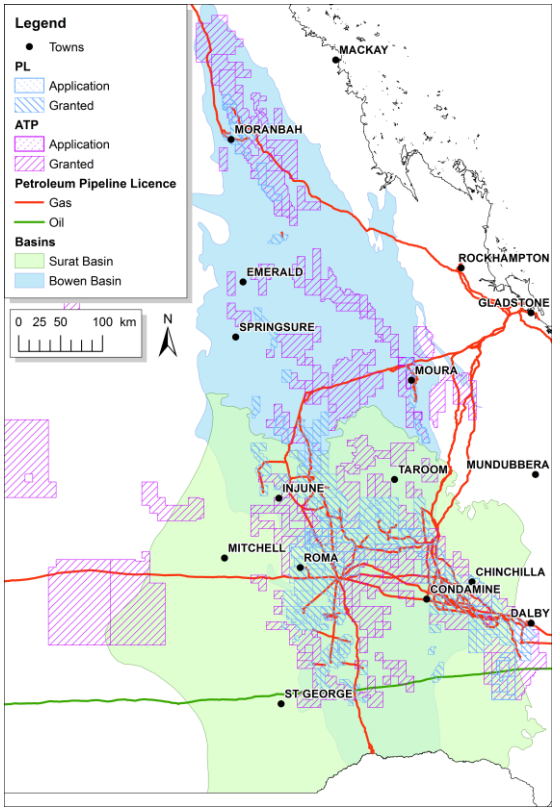

Figure 1 Bowen and Surat basins in Queensland, showing tenure, towns and pipelines

PLAY ELEMENTS

The petroleum plays of the Bowen and Surat basins are inexorably linked, as the main source rocks are found in the Bowen Basin, while the oil and gas has migrated up the sequence, including being reservoired in the Surat Basin. A general sequence of source, reservoir and seal formations for the western and eastern Taroom Trough, and the Denison Trough is shown in Table 1.

Source rocks quality and maturity

The source rocks in the Taroom Trough are dominantly found in the Permian Back Creek and Blackwater groups, though some contribution is thought to have come from the Triassic Snake Creek Mudstone (Al-Arouri *et al.*, 1998).

The Back Creek Group comprises Lopingian-aged shallow marine formations. In the eastern Taroom Trough, it includes the Oxtrack, Barfield, Banana, Flat Top, Wiseman and Burunga formations. Units in the western Taroom Trough include the Muggleton and Tinowon formations and Black Alley Shale. Potential source rocks in this sequence have fair to good organic richness (0.7-4% TOC), though a low HI and a poor hydrocarbon yield (Al-Arouri *et al.*, 1998). It contains gas-prone Type III/IV organic material, and is generally mature for oil in the south of the Taroom Trough and mature for gas in the northern Taroom Trough.

The Blackwater Group comprises Lopingian deltaic coal bearing formations of the Bandanna Formation and its lateral equivalents. It has fair to good oil source rock characteristics, with good generative potential and Type II/III kerogen. The Blackwater Group is in the low oil window in the south, and like the Back Creek Group, increases in maturity towards the north.

Al-Arouri (1996) highlighted the potential of the Triassic aged Snake Creek Mudstone as a potential source rock within the Bowen Basin based on molecular and isotopic data. The Snake Creek mudstone is a fair to good oil source rock, with good generative potential (Al-Arouri, 1998).

Recent source rock analysis of 32 samples from the Bowen Basin examined potential source rocks from 18 formations in the Taroom and Denison troughs (Mahlstedt and Horsfield, 2016; Troup and Gorton, 2017). The results from these analysis showed that carbonaceous mudstones generally had TOC between 0.69-12.3 %, though with low HI values (< 100mgHC/gTOC), while coals had higher TOC and generally higher HI values. This implies that coals present in these formations have better generative characteristics than carbonaceous mudstones.

Carbonaceous mudstones from the Precipice Sandstone, Evergreen Formation and Walloon Coal Measures and coals from the Walloon Coal Measures have good potential to be source rocks, though they appear to be immature throughout the Surat Basin. The Walloon Coal Measures (the youngest of the three units) has Rv,max of between 0.35-0.65 % (Ryan et al, 2012), putting it at best into the very early oil window. The Lower Evergreen has potential to be marginally mature, though there has been no accumulation traced to an Evergreen Formation source.

Within the Denison Trough, most shales and coals in the Reids Dome beds and Cattle Creek Formation have source rock potential (Thomas *et al*, 1982). Like the source rocks of the Taroom Trough, those found in the Denison Trough are dominated by Type III organic matter, and are gas prone (Anthony, 2004). The source rocks of the basal Reids Dome beds are within the dry gas window, those of the middle Reids Dome beds are in the late oil to wet gas window, and the Cattle Creek Formation is in the oil window.

Reservoirs, traps and seals

Average properties for the major conventional reservoirs in the Bowen and Surat basins are shown in Table 2**.** They are generally found in a depth window between 1000m and 3000m. They have a variety of depositional environments, though they are dominated by fluvial sandstones.

Most traps across the basins are stratigraphic, with some structural component to them. Most traps in the Showground and Precipice sandstones have formed as a result of drape over or onlap onto pre-existing palaeo highs (Towler *et al.*, 2016). Due to the dominance of fluvio-deltaic environments in the sequence, there should also be good potential for stratigraphic traps. In the Denison Trough, traps are dominated by structural closures (Towler *et al.*, 2016).

Important regional seals for the basins include the Rewan Group, the Snake Creek Mudstone Member and the Evergreen Formation, with some potential contribution from the Black Alley Shale, and the Walloon Coal Measures. These seals have the potential to be leaky, as most also contain reservoir facies. Intraformational seals are also important where stratigraphic traps are targeted, and are found within most formations.

Table 1 Source, reservoir and seal formations in the Taroom and Denison Troughs

Taroom Trough

West	Source	Reservoir	Seal
Griman Creek Formation			
Surat Siltstone			
Wallumbilla Foramtion			
Bungil Formation			
Mooga Sandstone			
Orallo Formation			
Gubberamunda Sandstone			
Westbourne Formation			
Springbok Sandstone			
Walloon Coal Measures	CSG		
Hutton Sandstone			
Evergereen Formation			
Precipice Sandstone			
Moolayember Formation			
Snake Creek Mudstone Member			
Showgrounds Sandstone			
Rewan Group			
Bandanna Formation	CSG		
Black Alley Shale			
Tinowon Formation			
Combarngo Volcanics			
Timbury Hills Formation			

East	Source	Reservoir	Seal
Griman Creek Formation			
Surat Siltstone			
Wallumbilla Formation			
Bungil Formation			
Mooga Sandstone			
Orallo Formation			
Gubberamunda Sandstone			
Westbourne Formation			
Springbok Sandstone			
Walloon Coal Measures	CSG		
Hutton Sandstone			
Evergereen Formation			
Precipice Sandstone			
Moolayember Formation			
Snake Creek Mudstone Member			
Clematis Group			
Baralaba Coal Measures	CSG		
Burunga/Wiseman formations			
Flat Top Formation			
Barfield Formation			
Oxtrack Formation			
Buffel Formation			
Camboon Volcanics			

Denison Trough

	Source	Reservoir	Seal
Moolayember Formation			
Showgrounds Sandstone			
Clematis Group			
Rewan Group			
Bandanna Formation	CSG		
Black Alley Shale			
Peawaddy Formation			
Freitag Formation			
Ingelara Foramtion			
Catherine Sandstone			
Upper Aldebaran Sandstone			
Lower Aldebaran Sandstone			
Cattle Creek Formation			
Reids Dome beds			

Table 2 General reservoir properties for reservoir formations in the Taroom and Denison Troughs

Taroom Trough	Porosity	Permeability	Reservoir lithology	Depositional Environment
Hutton Sandstone	15-25%	<100mD	Quartzose to sublabile sandstone with minor siltstone and mudstone	Fluvial
Boxvale Sandstone Member	15-25%	20-240mD	Coarse sandstone at the base to well sorted fine grained quartzose sandstones	Fluvial to possible shoreface or delta
Basal Evergreen Formation	15-25%	20-240mD	Fine to medium grained sublabile to labile sandstone	Fluvial
Precipice Sandstone	20-25%	110-700mD	Thickly bedded pebbly quartzose sandstone, minor lithic sublabile sandstone, siltstone and mudstone	Fluvial; braided to meandering stream
Moolayember Formation	13-27%	0-74mD	Light grey, poorly sorted, sublabile, angular and quartzose sandstones	Fluvial to fluvio-lacustrine
Showgrounds Sandstone	<17%	<700mD	Moderately well sorted quartzose sandstone interbedded with siltsone and shales	Prodelta, distal or distributory mouth bar sequence
Showgrounds Sandstone	<17%	<700mD	Poorly sorted, very coarse to very fine sandstone and siltstone	Moderate flow fluvial environment
Showgrounds Sandstone	12-20%	500mD-10D	Poorly sorted, coarse to very coarse sandstone and conglomerate	High flow fluvial environment
Clematis Group	-	-	Poorly sorted, sheetlike fluvial sandstone with thin interbeds of red-brown mudstone	Fluvial
Rewan Group	15-20%	0.1-1.0mD	Poorly sorted, sub angular to subrounded sub-lith arenite to lithic and quartz arenite	Fluvial; terrestrial red beds
Tinowon Formation	9-21%	1-360mD	Coarse to very coarse, fairly well sorted subangular to subrounded sandstone	Deltaic
Denison Trough				
Mantuan Formation	20-30%	20mD	Fossiliferous coquinitic silstone and sandstone to fine to medium grained micaceous quartzose sandstone	Marginal marine to restricted marine
Catherine Sandstone	8-28%	0.02-800mD	Quarztose to sublabile sandstone, siltstone and mudstone	Coastal to nearshore marine
Freitag Formation	23-28%	<4000mD	Quartzose sandstone, rarely conglomeratic and micaceous with thin interbeds of fissile siltstone	Marginal marine
Aldebaran Sadnstone	7-14%	low	Quartzose sandstones, conglomeratic or feldspathic in part, with thin interbeds of carbonaceous mudstone and rare, thin coal laminae	Deltaic
Cattle Creek Formation	5-18%	5-19mD	Quartzose to sublabile sanstone	Marine to marginal marine
Reids Dome beds	<10%		Carbonaceous sandstone, grey siltstone, shale and coal with minor anhydrite and dolomite	Alluvial fan to coal swamp to fluvial to marine

CONVENTIONAL PLAY FAIRWAYS

There are several regions of conventional petroleum production within the Bowen and Surat basins. They can be broadly subdivided into the eastern flank and western flank of the Taroom Trough and the Denison Trough. These regions are shown on Figure 2.

Only three discoveries have been made on the Eastern Flank: Moonie, Cabawin and Bennett. Of these, the discovery at Moonie is the most significant. The Moonie Oil Field is the largest accumulation of oil in the Surat Basin, containing over 75% of the discovered oil resource (Cadman and Pain, 1998). It was discovered in a structural trap where the Precipice Sandstone has draped over a Bowen Basin structural high, and is bounded by the Moonie-Goondiwindi Fault in the north and west, and a north striking thrust fault complex in the east (Mack, 1964). The Moonie Field is sourced from Permian source rocks down dip of the accumulation with migration likely happening during Walloon Coal Measures deposition time. Despite best efforts to explore along the Moonie-Cabawin Trend for another field of a similar scale, no other large accumulation has been discovered, and it is possible that the Moonie Field itself is unique (Cadman and Pain, 1998).

On the western flank of the Taroom Trough, there are approximately 100 conventional petroleum fields. These are found associated with two main structural regions: the Roma Shelf and the Wunger Ridge. The strata on the western side of the basin are gently dipping and largely undistubed and thus migration pathways along this side of the Taroom Trough are probably long (Thomas et al., 1982). The Rewan Group, the main seal formation over the Permian sequence thins to the west, and pools in the overlying Triassic Showgrounds sandstone are found beyond the edge of the pinch out. Breaching, faulting or pinchout of the overlying Snake Creek Mudstone Member further to the west has enabled migration further up the sequence.

The Roma Shelf is a broad subsurface platform on the western edge of the Taroom Trough. Most of the fields in this region are producing from the Precipice Sandstone, with secondary reservoirs in the Tinowon Formation on the eastern flank of the shelf, the Moolayember Formation in the central region and Timbury Hills Formation in the west near the Arbroath Trough. In the southwest of the Roma Shelf, pools are found within the Evergreen Formation and Boxvale Sandstone Member and the Moolayember Formation.

The Wunger Ridge is a subsurface structural high to the south of the Roma Shelf. It is interpreted to have been a basement palaeo-high during Permian and Triassic time, as the Permian and Triassic units onlap the structure. The fields in this area are typically reservoired in the Showgrounds Sandstone, with a significant stratigraphic component to the trapping mechanism. The Wunger Ridge area includes the Silver Springs field, which is the largest conventional gas accumulation found so far in the Bowen Basin. This field is now depleted, and is being used for gas storage. The oil and gas accumulations on the Wunger Ridge occur updip from Permian sediments, which are close to the oil and gas window (Thomas et al., 1982).

To the east of the Roma Shelf and the Wunger Ridge, several fields have been discovered in the Tinowon Formation along the flanks of the Taroom Trough. The fields in the Tinowon Formation include Myall Creek, Churchie, Overston and Waggamba. Initial discoveries in the Tinwon Formation were small, and formation damage impeded proper evaluation of the formation. These fields also have a strong stratigraphic component to their trapping mechanism, with gas discovered outside of structural closure in OCA Churchie 3 (Willink et al., 2004). Exploration continues to target the Tinowon Formation along the western flank of the Taroom Trough.

The Denison Trough is the northernmost of the conventional petroleum domains within the Bowen Basin. There are two main regions of production within the Denison Trough, one in the north and one in the south. The northern fields have pools within the Frietag and Peawaddy formations, the Aldebaran Sandstone and the Cattle Creek Formation, while the southern fields also include four fields with pools within the Reids Dome beds. Most of the traps within the Denison Trough region are inverted Triassic half-graben anticline structures, with some structural/stratigraphic traps recognised, but not yet tested (Anthony, 2004).

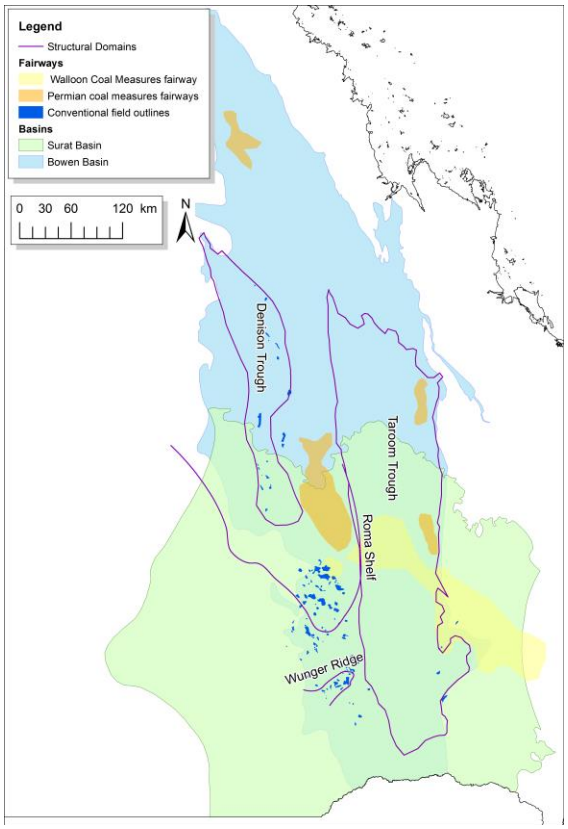

Figure 2 Fairways, conventional fields and structural regions of the Bowen and Surat basins

UNCONVENTIONAL PLAY FAIRWAYS

Shaw et al (2000) showed that the volume of thermogenically generated hydrocarbons exceeds known reserves values by approximately 3 orders of magnitude. They also speculate that the missing hydrocarbons fall into one of four categories: hydrocarbons retained by source rocks, hydrocarbons reservoired in undiscovered conventional reservoirs, gas dissolved into the Great Artesian Basin aquifers, and hydrocarbons lost to the surface over time.

This presents potential for there to be unconventional style plays within the Bowen and Surat basins. There are several unconventional plays present within the Bowen and Surat basins. By far, the most developed of these is the coal seam gas plays within Permian coals in the Bowen Basin and the Jurassic Walloon Coal Measures in the Surat Basin. Other potential (but largely untested) plays include tight, shale and basin centred gas plays. The main CSG fairway regions and the Taroom Trough are shown in Figure 2.

Coal Seam Gas

Exploration for coal seam gas in the Permian coals of the Bowen Basin began in the late 1970s, although it didn't achieve success until the 1990s. The coal seams targetted in the Bowen Basin are generally thick and laterally continuous, with individual seams able to be traced for kilometres. There are two main regions of coal seam gas exploration and development in the Bowen Basin: higher permeability anticline targets in the southern-central Bowen Basin and lower permeability targets in the north.

The anticline plays are found at the southern end of the Dension Trough (Fairview) and the eastern margin of the Taroom Trough (Peat and Scotia). These regions have a structural component to the coal seam gas accumulations which serves to enhance the permeability and production from these areas. Lower permeability plays (e.g. Dawson River, Moranbah), are found in the northern Bowen Basin, and are generally targeted by using surface to inseam drilling techniquies (Towler *et al*., 2016).

In the early 2000s, the Jurassic Walloon Coal Measures in the Surat Basin began to be targeted by coal seam gas exploration. In contrast to the Bowen Basin coal seams, seams in the Walloon Coal Measures are generally thin and laterally discontinuous. The gas found in these coal seams is interpreted to be predominantly biogenic, based on vitrinte reflectance measurements and isotopic compositions (Faiz and Hendry, 2006) From the exploration and development of this target, a play fairway has been defined in the northern and eastern areas of the Surat Basin (Ryan *et al*., 2012). The coals have an average gas content of 0.5 to 11.56 m3/t, with a generally increasing gas content with depth. However, there is also a noted relationship of decreasing permeability with depth, which gives a depth cutoff for permeability at approximately 800m (Ryan et al., 2012). There are regions, such as the Undulla Nose and the Kogan Anticline, where structure enhances the permeability of the coal seams.

As coal seams are present throughout most of the basin, it is likely that there are other, albeit deeper, targets for coal seam gas within the Bowen Basin, including the Reids Dome beds, the Wallabella Coal Member of the Tinowon Formation and the Winnathoola Coal Member of the Black Alley Shale.

Basin Centered Gas/Tight gas play

QGC conducted exploration for a deeper tight gas play in the central to southern Taroom Trough, targeting tight sandstones in the lower Rewan Group and Kianga Formation (a Tinowon Formation equivalent on the eastern side of the Taroom Trough (Willink *et al*., 2004), or a Bandanna Formation equivalent (Nicholls *et al*., 2015). This exploration highlighted the potetnial for the deeper formations within the Bowen Basin to contain a tight gas resource, though no resource numbers have been reported. Nicolls *et al*. (2015) delineated a potential basin centred gas play within the Permian to Triassic units in the deeper section (below 2500m) of the southern Taroom Trough. Based on mudlog responses and maturity data for this region of the Bowen Basin, it is likely that this play would contain wet gas. Where the target formations shallow onto the flanks of the basin, there is likely a transition through to tight gas reservoirs, which could be what is observed in the Tinowon Formation play along the western flank of the Taroom Trough.

Speculative plays

The Black Alley Shale is found within the Denison Trough, and has been noted in company stratigraphic wells along the western margin of the Taroom Trough. It was deposited in a shallow marine environment during the late Permian, with the presence of coals in the Winnathoola Coal Member in the south on the Roma Shelf indicating the presence of deltas prograding into the shallow sea. There has been no exploration targeting the Black Alley Shale. The TOC content of the formation is fair to good (up to 8.3%) and based on existing analysis results the kerogen type is interpreted to be Type III/IV, and its maturity is generally low. However the formation has also only been intersected at shallow depths, mostly around the edge of the Denison Trough, and there may be potential for it to be more mature in the central Denison Trough, or if it is present in the deeper parts of the Taroom Trough.

Other potential shale plays exist within the Reids Dome beds and Cattle Creek Formation, where targeting and better characterisation of source rocks within the region could highlight self sourcing reservoir plays where these source rocks are mature.

Due to the relative immaturity of the Surat Basin, it is unlikely to have significant shale or tight gas targets within its sequence. However, in several wells (eg. UOD Flinton 1, SDA Milgarra 1, SOC Kinkabilla Creek 1, MON Grail North 1) particularly in the south of the Surat Basin, the composition of mudgas recorded over the Walloon Coal Measures suggests a reasonably wet hydrocarbon is being held within the coals. As no tests have been conducted over this interval, it is impossible to determine whether this has been generated in-situ, or whether it has migrated into the formation.

CONCLUSIONS

The plays across the Bowen and Surat basins consist of conventional accumulations on structural shelves and flanks of the major troughs in the region, as well as well-established and emerging unconventional plays in the coal seam gas developments of the Bowen Basin and Walloon Coal Measures. Emerging unconventional plays include tight gas within the deeper sections of the Taroom Trough and more speculative plays, such as shale gas in the Reids Dome beds, Cattle Creek Formation or the Black Alley Shale.

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