The Waitsia Field, onshore North Perth Basin, Western Australia

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ABSTRACT

The Waitsia Field represents a new commercial play for the onshore north Perth Basin with potential to deliver substantial reserves and production to the domestic gas market. The discovery was made in 2014 by deepening of the Senecio–3 appraisal well to evaluate secondary reservoir targets. The well successfully delineated the extent of the primary target in the Upper Permian Dongara and Wagina sandstones of the Senecio gas field but also encountered a combination of good-quality and tight gas pay in the underlying Lower Permian Kingia and High Cliff sandstones.

The drilling of the Waitsia–1 and Waitsia–2 wells in 2015, and testing of Senecio-3 and Waitsia-1, confirmed the discovery of a large gas field with excellent flow characteristics. Wireline log and pressure data define a gross gas column in excess of 350 m trapped within a low-side fault closure that extends across 50 km^2. The occurrence of good-quality reservoir in the depth interval 3,000–3,800 m is diagenetically controlled with clay rims inhibiting quartz cementation and preserving excellent primary porosity.

Development planning for Waitsia has commenced with the likelihood of an early production start-up utilising existing wells and gas processing facilities before ramp-up to full-field development. The dry gas will require minimal processing, and access to market is facilitated by the Dampier–Bunbury and Parmelia gas pipelines that pass directly above the field.

The Waitsia Field is believed to be the largest conventional Australian onshore discovery for more than 30 years and provides impetus and incentive for continued exploration in mature and frontier basins. The presence of good-quality reservoir and effective fault seal was unexpected and emphasise the need to consider multiple geological scenarios and to test unorthodox ideas with the drill bit.

KEYWORDS

North Perth Basin, Kingia Sandstone, High Cliff Sandstone, Irwin River Coal Measures, Carynginia Formation, Kockatea Shale, Waitsia Field.

INTRODUCTION

The Waitsia gas field is located in production licenses L1 and L2 in the onshore north Perth Basin, WA (Fig. 1). AWE Perth Pty Ltd is the operator with 50% equity and Origin Energy Developments Pty Ltd is the joint venture partner. The field was discovered by deepening of the Senecio–3 well in 2014 and has been appraised by Waitsia–1 and Waitsia–2 in 2015. The results confirm the discovery of a large gas field with excellent flow potential. Proximity to existing gas plants (Dongara and Xyris) and gas export pipelines (Parmelia and Dampier–Bunbury) will facilitate early development with gas to be sold into the domestic WA market.

Waitsia is the biggest discovery in the Perth Basin since the Dongara gas field in 1966 and has successfully defined a new commercial play that warrants further exploration. The field is also the largest conventional discovery to be made onshore Australia in the past 30 years. The purpose of this paper is to describe the key elements of the discovery in anticipation it will stimulate further exploration in the Perth Basin and in other challenging basins of onshore Australia.

GEOLOGICAL SETTING

The onshore north Perth Basin is located 100–350 km north of the city of Perth in WA and covers an area of about 20,000 km^2. It is a narrow elongate trough, approximately 250 km long and up to 90 km wide, developed between Precambrian basement rocks of the Yilgarn Block, Beagle Ridge and Northampton Block (Mory and Iasky, 1996). The sedimentary sequence ranges from the Silurian to the Pleistocene, but the bulk of the section was deposited from the Early Permian to the Early Cretaceous (Fig. 2). Maximum sedimentary thickness is estimated at more than 12 km in the centre of the Dandaragan Trough. Historically, two discrete petroleum systems have been defined in the Permo-Triassic and the Jurassic sequences. The Permo-Triassic system is the focus of this paper because it provides the reservoir, seal and source for the Waitsia Field and is the main oil and gas producing interval for the basin (e.g. the Dongara, Hovea and Beharra Springs fields). This paper further separates the Permo-Triassic system into two discrete plays, one specific to the Early Permian succession and the other to the Late Permian/Early Triassic succession consistent with the definition from Ferdinando and Longley (2015). Large gas resources have also been discovered in the Jurassic system (Gingin, Red Gully and Warro fields), but long-term sustained production has not yet been achieved (Department of Mines and Petroleum, 2015).

The tectonic history of the basin has been described by various authors (Dentith et al, 1993; Mory and Iasky, 1996; Song and Cawood, 1999; Norvick, 2004; Thomas, 2014) and the main structural events are summarised in Figure 2. The basin has a complex geological history comprising multiple phases of extension with intervening periods of subsidence, uplift and erosion. In the vicinity of Waitsia, the most significant structural elements are the Northampton Block/Beagle Ridge to the north and west, and the Dandaragan Trough to the south and east (Fig. 3). The boundary between the Beagle Ridge and Dandaragan Trough is here defined by the north–south trending Mountain Bridge fault and the west–east trending Allanooka fault, both of which have up to 1,400 m of throw.

These large-scale faults developed during Early Permian rifting that resulted in steep planar extensional faulting, often at near-orthogonal angles, and commonly displaying little or no bedding growth. This was followed by an extensive period of thermal subsidence from the Late Permian up to the earliest Jurassic when a new phase of faulting commenced, associated with rifting of the Gondwana super continent and ultimate segmented plate breakup in the Valanginian (Hall et al, 2013). The absence of obvious bedding growth or rotation throughout these phases of extension is likely to be a function of both oblique rifting above a pre-existing Proterozoic fabric (cf. McClay et al, 2002), as has been inferred by Hall et al (2013), and strain partitioning associated with rheological differences between underlying Northampton Complex granites and the overlying sedimentary succession. As a consequence, many faults exhibit components of dip-slip and strike-slip movement.

Volcanism associated with the rifting event in the Bunbury Trough in the southern Perth Basin elevated heat flows throughout the entire basin. More than 1,000 m of denudation occurred on structural highs such as the Northampton Block/Beagle Ridge but there is no apparent erosion in the centre of the Dandaragan Trough. This uplift is an important consideration for charge and fill-spill history in some areas of the basin but has little impact at Waitsia given its long-term location immediately up dip from mature source rocks. With the exception of very minor fault movement associated with the Mio-Pliocene collision of the Australian and Eurasian plates, the Perth Basin remained largely quiescent during the Cenozoic.

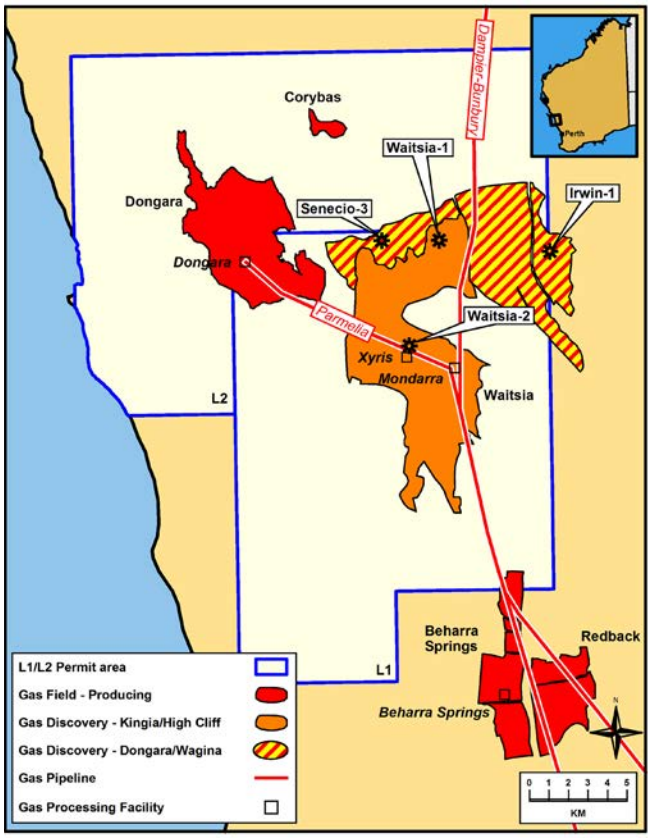

Figure 1. Location map for the Waitsia discovery and nearby fields, onshore north Perth Basin.

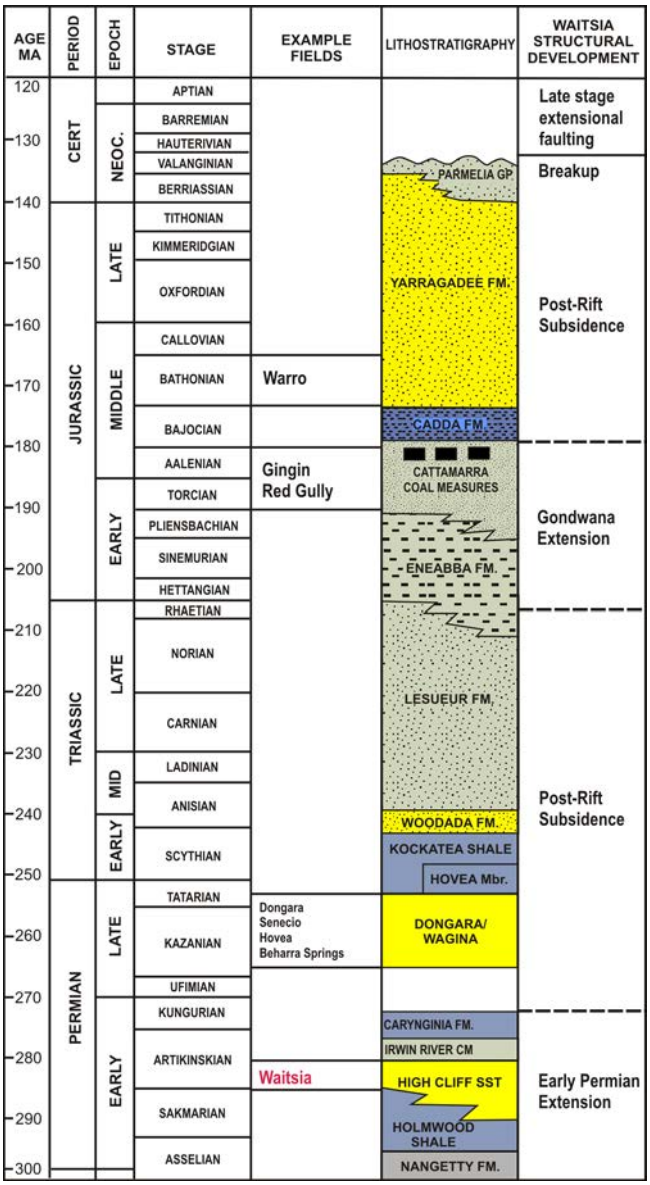

Figure 2. Stratigraphy and structural events for the onshore north Perth Basin with age of example discoveries. Blue denotes marine rocks, green denotes fluvial, grey denotes fluvial-glacial, and yellow denotes key sandstone units.

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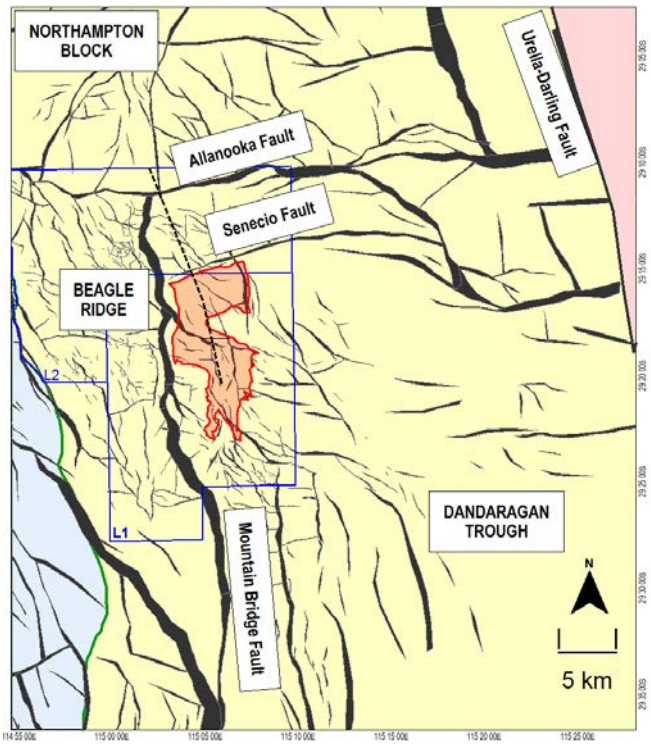

Figure 3. Structural elements for the Waitsia Field area showing Top Dongara fault displacements. Regional seismic line (Fig. 7) location is shown by the black line. Waitsia Field extent is shown by the red outline.

PERMO-TRIASSIC STRATIGRAPHY

The stratigraphy of the onshore Perth Basin is summarised in Figure 2, and detail of the Permian sequence at Waitsia is shown in Figure 4. Biostratigraphic control is poor because palynomorphs tend to be sparse and poorly preserved, particularly in the more sand-prone intervals, and a dinoflagellate zonation has not been established. The definition of formations is therefore predominantly lithostratigraphic and many could be diachronous. Overall, northwest–southeast thickening is observed from seismic and well data, and implies the Darling and Urella faults were active during this period and that the Northampton Block was a persistent structural high controlling sedimentation.

The Permo-Triassic succession commences with the deposition of the Nangetty Formation in a glacial to pro-glacial marine setting and lacks reservoir or source potential. The overlying Holmwood Shale comprises marine siltstone and shale with some potential for gas generation (Thomas and Barber, 2004) but the subordinate sandstone and limestone beds lack reservoir quality. The High Cliff Sandstone was deposited in a higher energy shoreface setting and is dominated by thick beds of quartzose sandstone with minor siltstone inter-beds. The formation has an abrupt transition with the underlying Holmwood Shale and has a total thickness of about 200 m in the Waitsia area.

The authors of this paper have adopted an informal nomenclature to describe the uppermost interval of the High Cliff Sandstone, which has application in the Waitsia Field area but has not been validated for the wider basin (Fig. 4). The Bit Basher Shale and the Kingia Sandstone appear to represent genetically distinct upper units that can be correlated throughout the northern part of the basin. The Bit Basher Shale is interpreted to have been deposited in a lower shoreface to inner shelf environment and comprises highly bioturbated and storm re-worked argillaceous sandstone and siltstone. It has a distinct base and top, but variable thickness (5–50 m). The overlying Kingia Sandstone represents a return to upper shoreface and beach conditions and is characterised by thick bedded quartzose sandstone that is transitional with the overlying Irwin River Coal Measures and the top is difficult to define. Its thickness over Waitsia is consistent within the 25–50 m range. The Kinga and High Cliff sandstones provide the reservoir for the Waitsia Field.

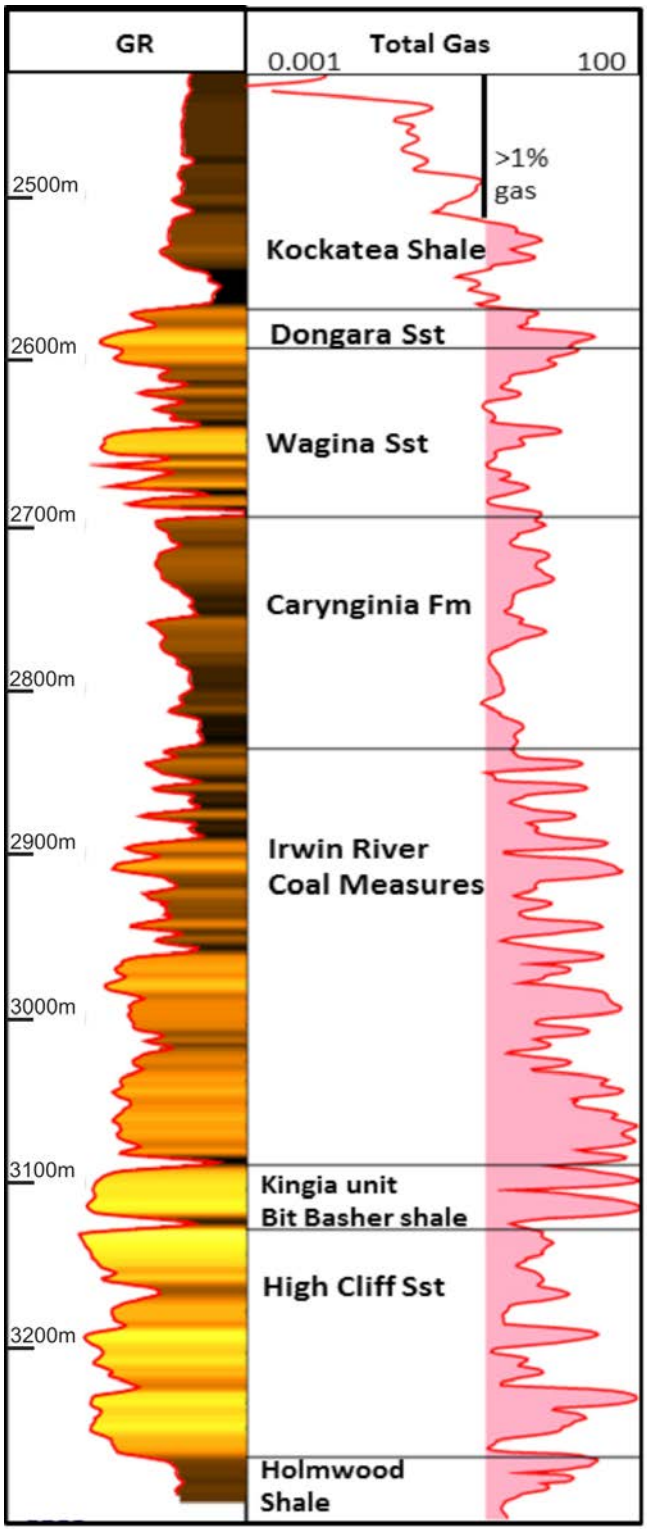

Figure 4. Senecio–3 gamma ray log and gas show profile showing the Dongara/Wagina (Senecio Field) and Kingia/High Cliff (Waitsia Field) reservoirs.

The Irwin River Coal Measures comprise interbedded argillaceous sandstone, siltstone, shale and thin coal deposited in a coastal or lower delta plain environment. The sequence is believed to act as a significant source for gas and in the Waitsia Field constitutes a potentially significant unconventional gas resource with a gross thickness of about 250 m. The shale dominated Carynginia Formation represents a return to marine shelfal conditions and acts as a major regional seal except where eroded over the Beagle Ridge and the Northampton Block. The Carynginia Formation is believed to be a source for gas (Thomas and Barber, 2004) and a potential unconventional gas resource (Cooper et al, 2015). The sequence is about 150 m thick in the Waitsia area.

The Dongara and Wagina Sandstones were deposited in shoreface settings (Tupper et al, 1994) and have a combined thickness of about 120 m in the Waitsia area. These reservoirs have been the main oil and gas producing intervals in the Perth Basin (e.g. the Dongara, Beharra Springs and Hovea fields) and in the Senecio Field that directly overlies the northern culmination of the Waitsia Field. A regional transgression, commencing in the late Permian and continuing into the Early Triassic, resulted in the deposition of the Kockatea Shale, which is the main source for oil and a significant source for gas in the basin. Deposition appears to be continuous across the Permo-Triassic boundary in basinal areas although a rapid onset of anoxic conditions is observed (Thomas and Barber, 2004). The Kockatea Shale is a major regional seal and is also a potential unconventional oil and gas resource (Cooper et al, 2015).

PREVIOUS EXPLORATION

The onshore Perth Basin has been explored for more than 50 years, resulting in eight significant producing gas fields and five oil fields prior to the discovery of Waitsia in 2014. Excluding Waitsia, the total ultimate proved and probable reserves for these fields are estimated at 740 BCF of gas and 14 MMBBL of oil, of which more than 95% has been produced (based on data published by the Department of Mines and Petroleum [2015]). Creaming curve analysis showing the size and timing of discoveries suggested that the onshore basin was mature for conventional exploration (Fig. 5) and that tight gas or unconventional resources provided the best opportunities for future exploitation (Cooper et al, 2015). The Permo-Triassic petroleum system, principally the Dongara or Wagina play, contains 97% of historical discovered reserves.

Exploration for Permo-Triassic targets has been strongly influenced by the perceived distribution of good-quality reservoir in the Dongara and Wagina sandstones. Where present depth of burial is less than about 3,000 m, valid structural closures are usually charged with oil or gas, and good flow rates have been achieved. Few sizeable Dongara/Wagina prospects, however, remain undrilled at these depths. At depths greater than 3,000 m, reservoir quality in the Dongara and Wagina sandstones is generally poor due to pervasive quartz cementation except where diagenesis has locally preserved primary porosity (Tupper et al, 1994). Exploration to date indicates that this diagenetic enhancement may be restricted to the Beharra Springs/Redback area with all other deep well penetrations encountering tight sandstone. Nevertheless, these tight quartzose sandstones are considered to be suitable targets for hydraulic stimulation with a good chance of achieving commercial flow rates.

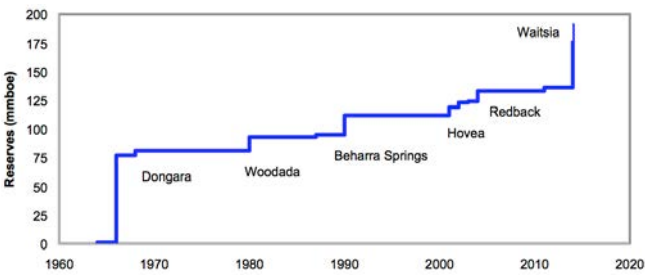

Figure 5. Discovery timing and conventional cumulative field size distribution for the onshore north Perth Basin. All fields are 2P reserves estimates excluding Waitsia (2P reserves plus 2C contingent resources for good-quality reservoir facies).

Exploration for older Permian objectives principally targeted the High Cliff Sandstone (including the more recently defined Kingia Sandstone) with more than 20 wells intersecting the formation but without commercial success. Many of these penetrations had some intervals with good reservoir quality, and some have flowed hydrocarbons (e.g. Hovea–2), but all occur at depths less than 3,000 m (Ferdinando et al, 2007). Most of these wells were drilled on the Beagle Ridge where top seal, cross-fault seal and access to charge are assessed to be problematic for Early Permian objectives. It was generally assumed that equivalent sandstones in the deeper parts of the basin would be tight and therefore not viable as conventional exploration targets.

For these reasons, the L1/L2 joint venture was focused on further evaluation of tight gas objectives in the Dongara/Wagina interval. The Senecio–3 appraisal well was drilled in 2014 to further evaluate the gas-bearing Dongara reservoir encountered in the 2005 Senecio–1 discovery well. Due to encouraging gas shows while drilling, a decision was made to deepen the Senecio–3 well to evaluate the unconventional potential of the Early Permian section at a low incremental cost. This resulted in the conventional Waitsia discovery and definition of a new commercial play type for the onshore Perth Basin.

SENECIO–3 RESULTS

The Senecio Field is reservoired in the Dongara Sandstone and the trap is mapped as a low-side fault closure defined by the Mountain Bridge fault in the west and the Senecio fault in the north (Figs 1 and 3). Cross fault seal is provided by offset against crystalline basement and the Carynginia Formation, respectively. Senecio–1, and its side-track Senecio–2, encountered gas bearing but tight Dongara Sandstone at a depth of around 3,200 m. Senecio–2 was tested without stimulation in 2005 and flowed at an initial rate of 2.5 MMCFGD, which declined to 0.6 MMCFGD during the test period. Re-entry of the well in 2012, and hydraulic stimulation, resulted in an improved stabilised gas flow of 1.35 MMCFGD. The subsequent acquisition of 3D seismic data demonstrated that Senecio–1 and Senecio–2 were drilled in a localised fault zone and that reservoir quality could improve significantly elsewhere in the closure. Senecio–3 validated this theory by encountering better-quality Dongara reservoir although this interval has not yet been flow tested.

The planned total depth for the Senecio–3 well was 50 m into the underlying Carynginia Formation. A decision, however, was taken to deepen the well after observing continuous very high gas shows (Fig. 4) and recognising that the Carynginia Formation and possibly other older intervals have significant unconventional potential (Cooper et al, 2015). Good hole conditions and under-budget cost performance facilitated this decision. As a result the well was deepened by nearly 600 m to reach a total depth of 3,300 m TVD SS (true vertical depth subsea) in the Holmwood Shale (Fig. 4) and encountered a combination of good-quality and tight gas pay in the Kingia and High Cliff Sandstones. Appraisal drilling in Waitsia–1 and Waitsia–2 subsequently demonstrated the lateral continuity of these reservoir intervals and the existence of a large gas accumulation.

It is noteworthy that 19 wells have been drilled for Dongara/Wagina objectives directly above the mapped Waitsia closure since the early 1960s. Deepening of any one of these would have resulted in much earlier discovery of the Waitsia Field.

WAITSIA FIELD OVERVIEW

The Waitsia Field is a low-side fault trap set up by the same faults that create the overlying Senecio accumulation (Fig. 6). Interpretation of the 3D seismic defines a closure area of about 50 km^2 with distinct north and south culminations. Pressure data, gas composition and the defined gas/water contacts demonstrate that the Waitsia and Senecio fields are separate with the intervening Carynginia Formation acting as a regional seal. Based on the continuity of gas shows, the Irwin River Coal Measures could constitute part of a greater Waitsia accumulation but the tightness of the reservoir has so far prevented the acquisition of pressure data or samples to prove this (Fig. 4). The gross column height for the proven Kingia-High Cliff accumulation is more than 350 m, which demonstrates the effectiveness of top and cross-fault seals.

The tight and non-reservoir intervals in the Kingia and High Cliff sandstones of the Waitsia Field are caused by pervasive quartz cementation that is also the case for the Dongara and Wagina sandstones in the deeper parts of the basin. Interestingly, the good-quality reservoir intervals result from the same process as observed for the Wagina Sandstone in the Beharra Springs Field (Tupper et al, 1994) and for reservoirs of the same age in the Petrel Field in the Bonaparte Basin (Bhatia et al, 1984). The presence of thin clay rims has locally prevented the formation of widespread quartz overgrowths and preserved excellent primary porosity and permeability at significant depths in the Waitsia Field. This mechanism has previously been recorded for the Kingia Sandstone at shallow depths in Hovea–2 and Corybas–1 (Ferdinando et al, 2007).

STRUCTURAL INTERPRETATION

The Waitsia Field is covered by contiguous 3D seismic data from the Irwin (2013), North Dongara (1994), Denison (2005) and Hovea/Hibbertia (2001) surveys. Data quality is moderate to poor for the Early Permian section due to a number of factors including variable surface conditions, shallow carbonates and energy absorption associated with the Cattamarra Coal Measures. Significant differences in seismic image quality exist within and between the various surveys with areas proximal to the Mountain Bridge fault being the worst affected. Synthetic seismograms and recently acquired vertical seismic profiles provide a reasonable match between well logs and the Permian seismic events associated with the Top Dongara and Top Kingia horizons and these can be mapped with some confidence (Fig. 7). Re-processing of all the 3D surveys covering the Waitsia Field has commenced in an attempt to improve resolution and to deliver a homogeneous data set across the entire field area. The reprocessing workflow, which includes pre-stack depth migration is expected to improve fault definition, horizon continuity and depth control, and could potentially generate seismic attributes for mapping the thicker good-quality sandstone intervals.

Depth control to the Top Dongara Formation is excellent, based on 40 well intersections in the vicinity of the Waitsia Field. The Top Kingia Sandstone penetrations, however, only exist on the downthrown side of the Mountain Bridge fault at Senecio–3, Waitsia–1, Waitsia–2 and Irwin–1 (Fig. 6). Despite the uncertainty associated with the amount of regional uplift, a predictable time versus present-day depth relationship is apparent, with no obvious velocity perturbations.

The Waitsia Field is bound to the west by the north–south trending Mountain Bridge fault, which has up to 1,400 m of throw down to the east such that the Kingia and High Cliff reservoirs are likely to be adjacent to Pre-Cambrian basement (Fig. 8). Basement intersections at Hovea–2 and Allanooka–2 are granites and gneisses of the Northampton complex and these rocks are interpreted to underlie the northern part of the Beagle Ridge. This is consistent with the high present-day heat flows in the footwall of the Mountain Bridge and related faults in the Waitsia area (Cooper et al, 2015).

To the north, the field limit is defined by the west–east trending Senecio fault, which has mapped throw of 150–300 m down to the south (Fig. 8), implying some degree of sand-on-sand juxtaposition rather than full offset against the Nangetty Formation or the Holmwood Shale (Fig. 7). Shale gouge, cataclasis or fault-plane cementation must therefore be invoked to provide seal along the Senecio fault. Regionally, the principal maximum horizontal stress in the basin is oriented west–east with some local perturbations associated with faults in the Waitsia area (Bailey et al, 2012; Cooper et al, 2015). Based on orientation alone, the Senecio fault would be regarded as being susceptible to reactivation in the present-day stress regime and should not provide an effective seal. This is clearly not the case and suggests that the Senecio and other faults are not stress sensitive, which has significant positive implications for exploration elsewhere in the basin. Closure to the east and the south is defined by structural dip into the Dandaragan Trough.

Despite the relatively poor-quality seismic reflection data, numerous other faults are interpreted within the field area. The faults trend north–south, northwest–southwest and west–east, and some have significant throw of up to 250 m (Fig. 6). It is predicted that many of these other faults could act as barriers or baffles during production. This particularly applies to the west–east Xyris fault that divides the Waitsia closure into distinct northern and southern culminations.

Throw analysis demonstrates that the major extensional faults were initiated in the Early Permian with growth up to the end of Kungurian or Top Carynginia time. This was followed by a second period of growth in the Early to Middle Jurassic associated with Gondwana rifting and terminating around the Bajocian or near top Cattamarra Coal Measures time. Extension, however, continued on some faults after the Bajocian with some showing offset of the Yarragadee Formation. This is particularly the case for larger faults, such as the Mountain Bridge fault, which exhibits further extension in Valanginian to Early Tertiary times (Fig. 8). This late phase of extensional faulting appears to be penecontemporaneous with regional denudation associated with the Valanginian break-up (Cooper at al, 2015). This infers the uplift is not associated with inversion or reverse movement on faults, but with broad regional tilting and possibly isostatic rebound of the footwall of the Mountain Bridge fault. Some late fractures (filled and unfilled) are observed in core and interpreted from image logs but more work is required to determine whether they have any significance for reservoir performance.

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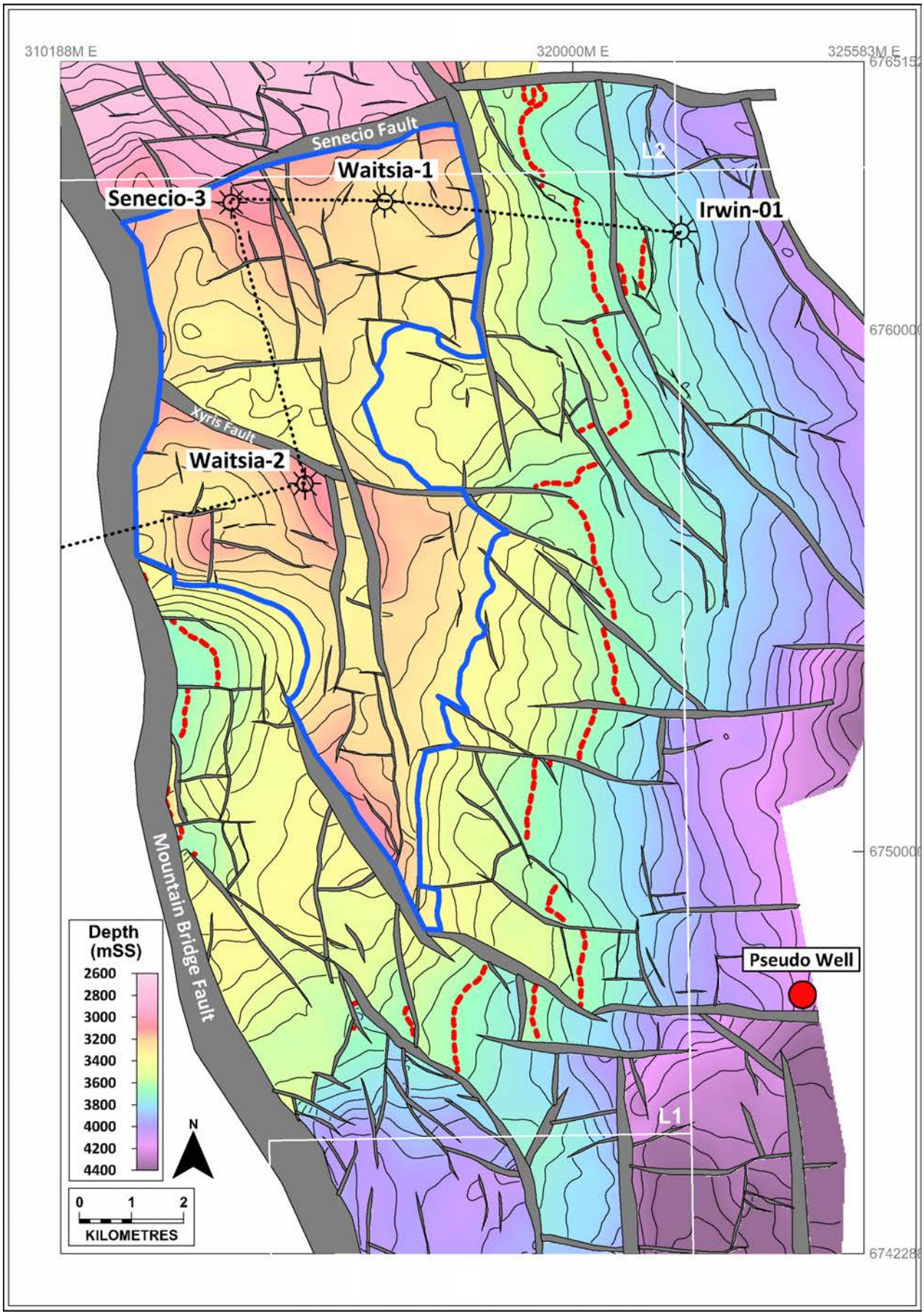

Figure 6. Depth structure map for the Top Kingia sandstone, Waitsia Field, showing gas/water contact (blue line). Maturity threshold (>1.2 Ro%) for the onset of gas expulsion is shown for the base of the Irwin River Coal Measures (red line). Thermal modelling pseudo-well location (Fig. 15) is shown by the red dot. Well correlation line location (Fig. 9) is shown in black.

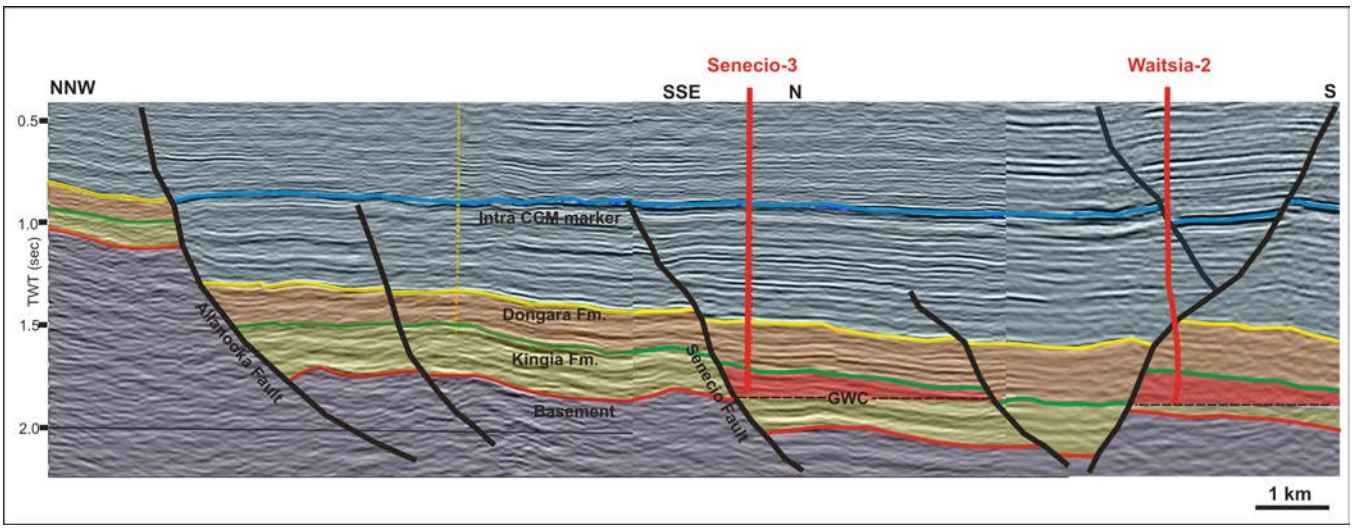

Figure 7. North–south seismic line from the Allanooka fault and across the Waitsia Field through Senecio–3 and Waitsia –2 (see Fig. 3 for line location). Waitsia Field gas column is highlighted in red with GWC (gas water contact). Note that the throw on the sealing Senecio fault (up to 350 m) is not sufficient to prevent cross fault sand-on-sand juxtaposition in the Kingia Sandstone.

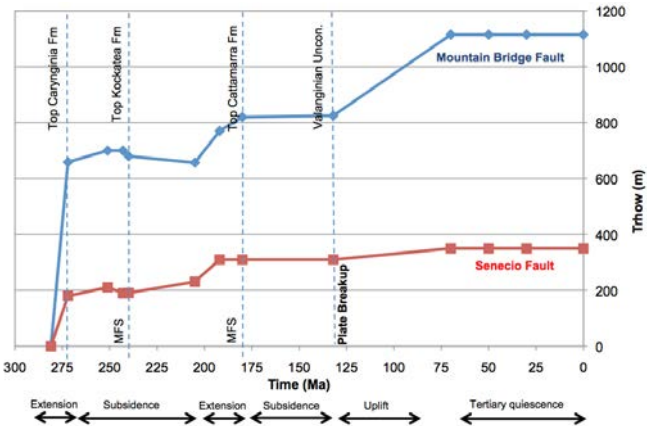

Figure 8. Displacement histories for the Mountain Bridge and Senecio faults based on interpreted throw for representative locations at the Top Kingia horizon.

KINGIA AND HIGH CLIFF SANDSTONE RESERVOIR DESCRIPTION

Gross sand distribution

The High Cliff Sandstone appears to be present throughout the north Perth Basin. In the outcrop type section, east of the Urella fault, the formation is only 26 m thick but in the subsurface is typically 50–150 m (Mory and Iasky, 1996). Generally, the formation is thickest in the northeast and thins to the south and west with a maximum penetrated thickness to date of nearly 200 m in the Waitsia area (Fig. 9).

At Waitsia, the High Cliff Sandstone comprises thickly bedded sandstone with minor conglomerate and siltstone, and has an abrupt transition with the underlying Holmwood Shale. The sandstones are typically medium grained and medium-well sorted consistent with their interpreted deposition in a predominantly high-energy environment in a shoreface or shallow marine setting. The quartz arenite to sub-arkose composition reflects a predominance of monocrystalline quartz grains with minor feldspar and rare rock fragments, and implies derivation from a pre-existing sandstone or granitic source material. The top of the High Cliff Sandstone is transitional with the Irwin River Coal Measures, which are defined by the appearance of carbonaceous material and finer grained, more argillaceous sandstone, and the disappearance of obvious marine affinities.

Description of the outcrop by Mory and Haig (2011) confirms that bioturbation is widespread with high-energy (*Skolithos* type) and low-energy (*Planolites* and *Rosselia* types) forms abundant. A cool-water open marine fauna of foraminifera, bryozoans, brachiopods, bivalves and gastropods has been recorded. Virtually the entire High Cliff Sandstone has been cored in Waitsia–2 and when fully evaluated should assist in further defining its environment of deposition and better understanding its relationship with overlying and underlying strata.

The authors of this paper and some other workers have found it useful to differentiate two informal units in the upper part of the High Cliff Sandstone. As previously described, the Bit Basher Shale appears to be a correlatable event across a wide area of the basin and has been used as a stratigraphic datum in Figure 9. The uppermost interval, the Kingia Sandstone, appears to be a discrete unit with different reservoir characteristics and therefore its definition has practical application in the Waitsia Field. More study, however, is required to understand its full regional and chronostratigraphic significance.

Diagenetic history

Diagenesis is the main control on reservoir quality. Where early clay rims are present around detrital grains, quartz overgrowths have been inhibited and excellent primary porosity is preserved (Fig. 10A). Where the clay rims are incomplete or absent, however, quartz cementation is pervasive and most primary porosity is lost (Fig. 10B). Dissolution of feldspar and lithic grains has created some secondary porosity in both reservoir types but this tends to be poorly connected and does not contribute to permeability. Late stage calcite has locally further reduced remaining porosity and is concentrated where quartz cement is not abundant (Fig. 10C). The relative sequence of diagenetic events is shown in Table 1.

Thin section and scanning electron microscope analyses demonstrate that the clay cements formed during deposition or soon thereafter as they occur before any significant compaction and pre-date all other diagenetic events (Table 1). From X-ray diffraction, the composition of the clay is an iron-rich chlorite that is chemically compatible with marine pore waters but requires proximity to a source of iron such as discharge from a river. It is possible that the rims have a glaucony precursor and were formed as oolitic layers around detrital grains on the sea bed before recrystallisation during early burial (Tupper et al, 1994). This is supported by the occasional presence of detrital chlorite

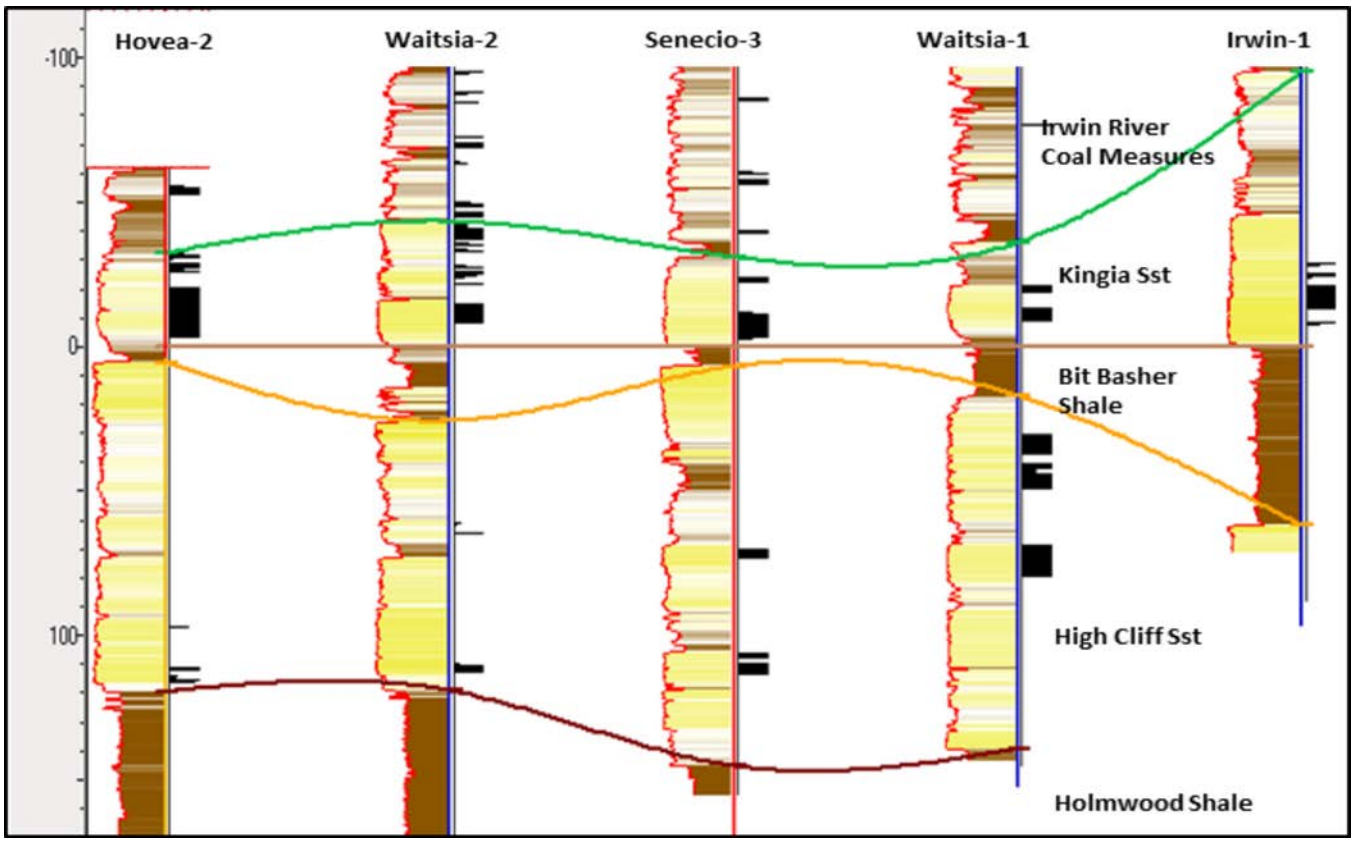

Figure 9. Correlation of the Kingia and High Cliff sandstones from Hovea–2 to Irwin–1 (see Fig. 6 for section location). For each well, gamma ray response and a net sand marker for the good reservoir facies (porosity >11%) are displayed.

grains with indistinct concentric or oolitic layering (Fig. 10C). The formation and preservation of the clay rims would require relatively quiescent conditions during deposition and early burial consistent with a mid-shoreface, estuarine or tidal setting.

Based on visual inspection, quartz overgrowths comprise up to 20% of the total rock volume in the Kingia and High Cliff sandstones that lack protective clay rims. This cementation appears to pre-date deep burial because compaction effects and sutured grain contacts are not observed. The source of the silica is interpreted to be through fluid expulsion associated with deep burial diagenesis of the same quartzose sandstone intervals in the Dandaragan Trough further to the east. Calcite is sporadically developed as an infill of the remaining primary and secondary porosity and is occasionally observed as infill of small-scale fractures, but is not believed to have a significant impact on overall reservoir quality.

Reservoir characterisation

A comprehensive suite of formation evaluation data has been acquired for the Senecio–3, Waitsia–1 and Waitsia–2 wells (Table 2) but not all of the data has been fully analysed and interpreted at the time of writing. There is, however, sufficient information to establish the main controls on reservoir quality and to build a preliminary static reservoir model for reserves estimation and development planning. The acquisition of large-size sidewall cores proved highly beneficial given the erratic conventional core recovery from some of the relatively unconsolidated good-quality reservoir intervals. Wireline formation testing, specifically the mini drill stem test tool, was also very effective in measuring pressures and recovering gas samples in the tighter reservoir intervals.

The integrated available well data have been used to define two broad hydraulic flow units for the Kingia and High Cliff sandstones; essentially good reservoir and tight reservoir facies determined from their provisional core porosity-permeability relationship (Fig. 11). A porosity of 11% appears to equate with a permeability of about 1 mD and this has been adopted as an interim threshold for differentiating good-quality reservoir that may not require hydraulic stimulation from tight reservoir that is expected to require stimulation to achieve commercial flow rates. This threshold appears to coincide with the presence or absence of clay rims and quartz cements, but more analysis is required to determine whether there are other controls on reservoir performance such as grain size, texture or depositional facies. Note that approximately 80% of the gross combined Kingia/High Cliff sandstone is classified as non-pay based on wireline log derived porosity of less than 7% (Fig. 12). These intervals require further evaluation but could represent significant incremental unconventional resource potential.

The thickness of the Kingia good reservoir facies is reasonably consistent (6–9 m) and has an average porosity of 15% (Fig. 9). The equivalent facies in the High Cliff is more variable, ranging from just 1 m in Waitsia–2 to 22 m in Waitsia–1 with a normalised mean porosity of 17%. This represents an average of just over 10% of the gross sand thickness. The productivity of the good-quality reservoir has been demonstrated by unstimulated production testing of the Kingia, which flowed at a rate of 12.3 MMCFD in Senecio–3 and 25.7 MMCFD from Waitsia–1, which was constrained by tubing size. Flow from the High Cliff was more variable with a rate of 0.3 MMCFD achieved in Senecio–3 and 24.7 MMCFD from Waitsia–1, constrained by tubing size (AWE, 2015a, 2015b, 2015c, 2015d). Waitsia–2 is also interpreted to have high flow potential in the Kingia but will not be tested before production start-up.

The gas-bearing tight reservoir (nominally permeability less than 1 mD) has an aggregate thickness totalling 1–9 m in the Kingia and 4–18 m in the High Cliff. The average porosity of 9% is reasonable but mostly comprises small and weakly connected primary pores that remain after quartz cementation. The relatively low proportion of detrital and authigenic clays, however, indicates that these sandstones are suitable targets for stimulation. None of these low-permeability intervals have been tested to date.

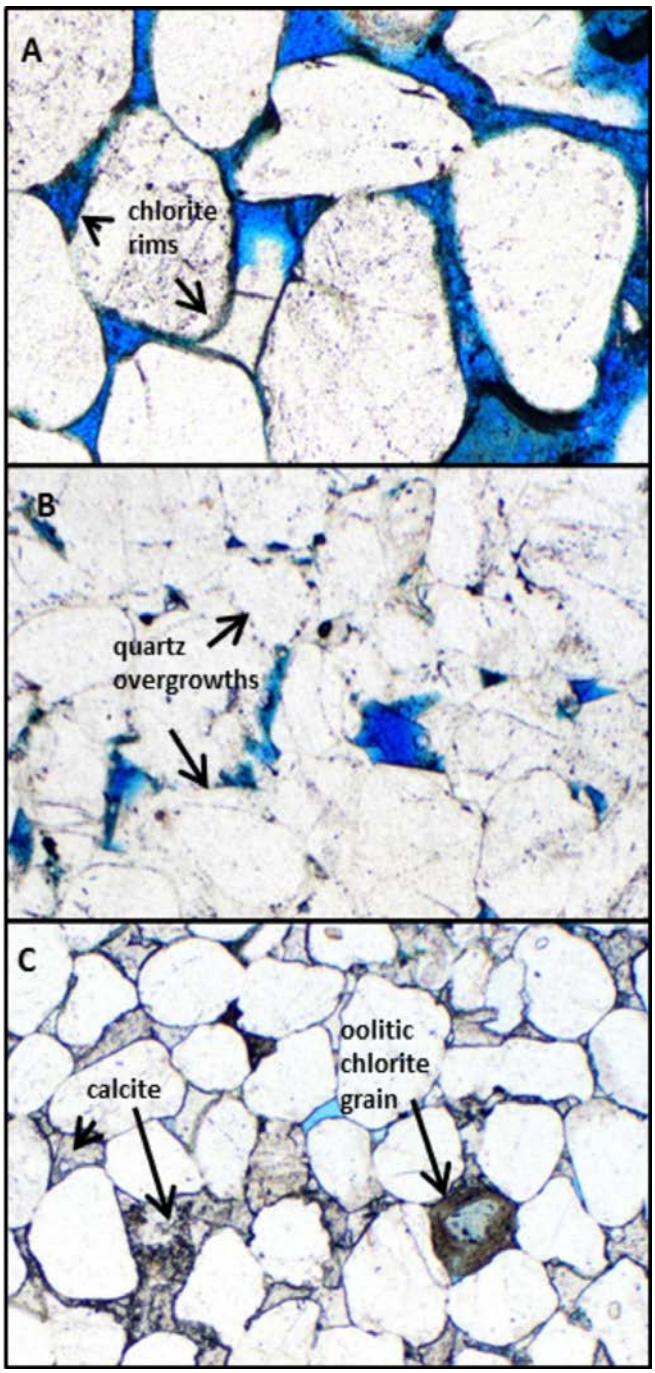

Figure 10. Thin section photomicrographs from selected Kingia samples from Senecio–3. A) Good-quality reservoir where chlorite clay rim cement has prevented formation of quartz overgrowth cement and preserved abundant primary porosity (blue). Field of view is 1.5 cm. B) Tight reservoir where pervasive quartz overgrowth cement has filled most porosity with only rare isolated primary pores remaining (blue). Field of view is 3 cm. C) Good-quality reservoir with oolitic chlorite grain that suggests clay rim cement could originate from a glaucony precursor. Elsewhere, poikilotopic calcite cement has locally filled most porosity with only residual primary pores remaining (blue). Field of view is 3 cm. Photomicrographs provided by Julian Baker.

Table 1. Diagenetic sequence for Kingia and High Cliff sandstones good-quality and tight reservoirs, Waitsia Field.

Reservoir class	Good	Tight
Porosity (%)	>11	7–11
Permeability (mD)	>1	<1
Diagenetic sequence	Chlorite rim cements	
	Minor quartz overgrowths	Pervasive quartz overgrowths
	Unstable grain dissolution	
	Minor fracture formation localised calcite cement	Minor fracture formation
	Gas entrapment	

Table 2. Formation evaluation data for the Kingia and High Cliff sandstones, Waitsia Field (includes only valid tests and recovered samples).

Data	Senecio–3	Waitsia–1	Waitsia–2
Logging while drilling	Gamma, resistivity	Gamma, resistivity	Gamma, resistivity
Wireline logs	Conventional suite plus NMR* and IGS*	Conventional suite plus NMR* and IGS*	Conventional suite plus NMR* and IGS*
Image logs	Acoustic	Resistivity	Resistivity
Vertical seismic profile	No	Yes	Yes
Side wall cores	15 × 1.5" samples	15 × 1.5" samples	None
Core interval (m)	None	Kingia: 33 m (rec. 83%) HCS: none	Kingia: 43 m (rec. 100%) HCS: 86 m (rec. 100%)
Wireline formation testing	3 pre-tests	15 pre-tests	13 pre-tests
		7 Saturn Mini DSTs	4 Saturn Mini DSTs
	No gas samples	2 gas samples	4 gas samples
Well tests: perforated interval and gas flow rate	Test 1: HCS: 3,254–59 m 0.3 MMCFD	Test 1: HCS: 3,254–59 m 24.7 MMCFD	Pending tie-in for production
	Test 2: Kingia: 3,173–83 m 12.3 MMCFD	Test 2: Kingia: 3,173–83 m 25.7 MMCFD	

*NMR: nuclear magnetic resonance; IGS: induced gamma spectroscopy.

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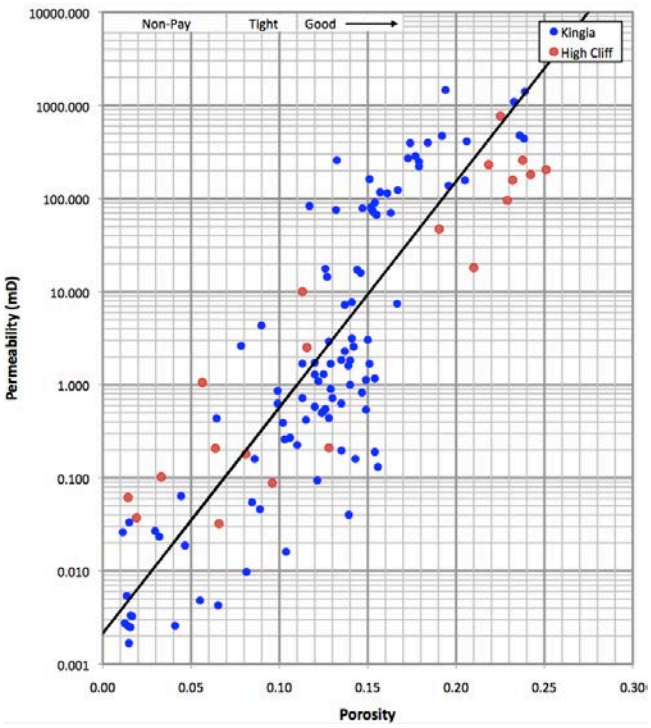

Figure 11. Porosity versus permeability relationship based on ambient core and sidewall core analyses from Kingia and High Cliff reservoirs in Senecio–3, Waitsia–1, Drakea–1 and Corybas–1.

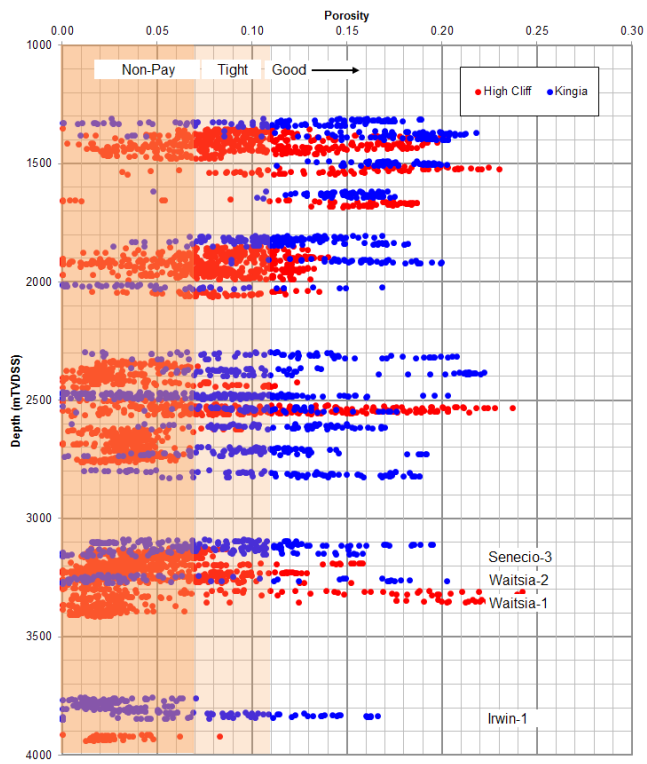

Figure 12. Porosity versus present-day depth based on log interpretation of Kingia and High Cliff reservoirs from wells in the Waitsia Field and surrounding area .

PRESSURE DATA AND FLUID CONTACTS

Gas and aquifer pressure data from the wireline formation tester and drill stem tests are shown in Figure 13. A common gas gradient of 0.245 psi/m (1.689 kPa/m) for initial datum reservoir pressure and temperature conditions has been derived from the laboratory measured specific gravity of a gas sample from the Kingia drill stem test in Senecio–3. A common water leg pressure gradient of 1.383 psi/m (9.535 kPa/m) is based on a log-derived average salinity value of 22,500 ppm NaCl and a Kingia Sandstone water sample recovered from the offset well Corybas–1. These gradients provide a close fit to the measured wireline formation and drill stem test pressures obtained for Senecio–3, Waitisia–1 and Waitsia–2.

A gas-water contact was penetrated in Waitsia–1 at 3,351 m TVDSS within the lower High Cliff Sandstone and is precisely defined by gas pressure, aquifer pressure and log data. This could represent a single field-wide contact for all sandstones across the entire field closure, although the data obtained so far indicate the possibility of some variation between component fault blocks. For Waitsia–1, gas pressures from the Kingia, upper and lower High Cliff plot on a single gradient and hence 3,351 m TVDSS probably represents a common contact for all three good-quality reservoir intervals in this structural block (Fig. 13). A slightly deeper contact of 3,377 m TVDSS, however, could be applied to the Kingia and upper High Cliff sandstones in the less likely circumstance that these intervals are in communication with the higher aquifer pressures encountered in the down-dip exploration well Irwin–1. The Senecio–3 gas gradient is closely aligned with the Waitsia–1 data (6 psi or 41 kPa offset) and therefore it is expected that the Kingia and High Cliff sandstones have a similar contact in this area of the field. The Waitsia–2 gas gradient, however, is 30 psi or 207 kPa lower than Waitsia–1, which would translate to a slightly higher gas-water contact at 3,325 m TVDSS if the Waitsia–1 water pressure gradient is applicable (Fig. 13).

Overall, it is probable that all of the reservoirs in the northern culmination (Senecio–3 and Waitsia–1 fault bounded structural blocks) are in communication with each other and have a single gas-water contact. The difference in pressures observed in Waitsia–2 (a more southerly structural block) indicates that gas columns in the southern culmination, or individual fault bounded blocks, may not be in direct pressure communication.

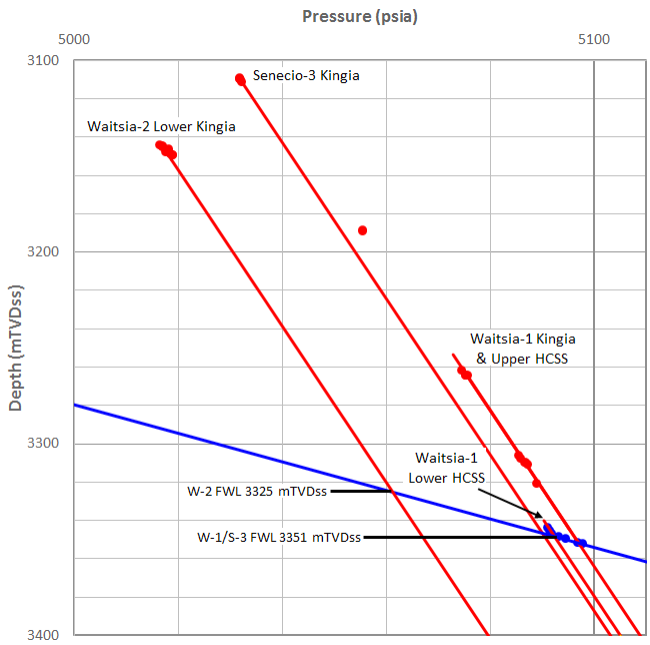

Figure 13. Gas and aquifer pressure data interpretation for the Waitsia Field showing the most likely free water level or gas-water contact for each well.

GAS COMPOSITION

Gas samples from Senecio–3 and Waitsia–1 show a consistent dry gas composition with 93% methane and about 4% carbon dioxide. Gas in the overlying Senecio Field has a slightly higher liquids content (89% methane) and lower carbon dioxide (3%), supporting the geological and pressure interpretations that they are separate accumulations and represent discrete petroleum plays.

Carbon isotope analysis of samples from Senecio–3 has been used to identify the source for the Senecio Field and Waitsia Field gases. Studies by Boreham et al (2000; 2001) demonstrated that the isotope values for the hydrocarbon components of Perth Basin gases can be used to differentiate an Early Permian (Irwin River Coal Measures) from an Early Triassic (Kockatea Shale) source probably reflecting the proportion of terrigenous to marine kerogens. Isotube samples of mud gas (i.e. the gas entrained in drilling mud and returned to surface) were used to build an isotopic profile of the gas shows released on drilling the Early Permian to Early Triassic sequence. Samples for the Kockatea and Dongara formations are isotopically light for the methane to *n*butane components (Fig. 14) and plot within the general range for gasses believed to be derived from a Kockatea Shale source. Likewise, the isotopically heavier Irwin River Coal Measures, Kingia and High Cliff gasses appear to be similar to those reservoired in the Irwin River Coal Measures in the Yardarino Field that are attributed to an Early Permian source (Boreham et al, 2000; 2001).

The maturity derived from isotope analysis of the Early Permian samples at Senecio–3 ranges from ~1.4–2.0 Ro%, which is moderately more mature than the in situ source rock at the well (c. 1.1 Ro%). This is consistent with thermal modelling, which predicts that the Waitsia gas has migrated from mature Early Permian source rocks immediately down dip to the east of the structure.

Geochemical analysis of further samples is required, but the data acquired to date strongly indicate that the Permo-Triassic petroleum system does comprise two separate plays. Oil and gas in the Dongara/Wagina is derived from the Kockatea Shale and gas in the Kingia/High Cliff is being sourced from the Irwin River Coal Measures and supplemented by the Carynginia Formation, with the latter acting as an effective regional seal between them. This is discussed further in the gas charge section of this paper.

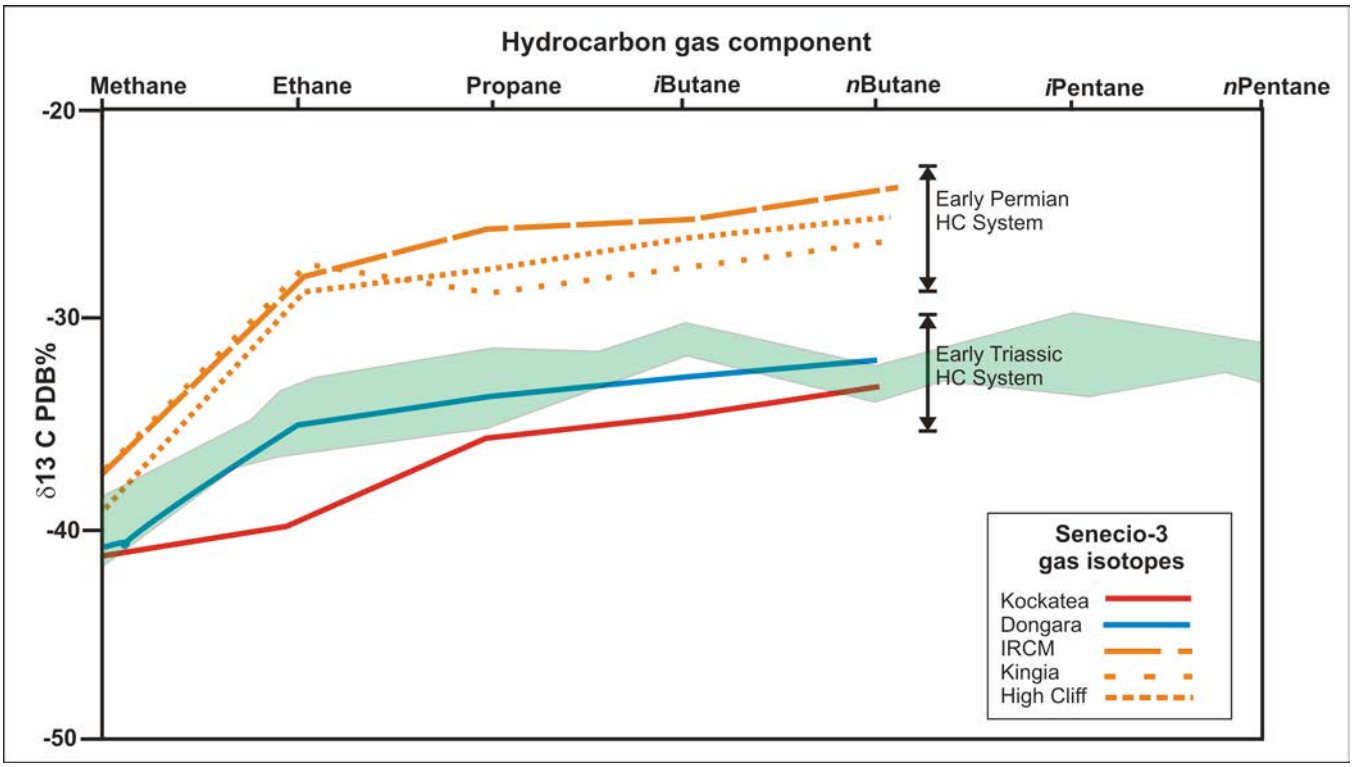

Figure 14. Carbon isotope data for the hydrocarbon gas components of isotube samples from Senecio–3 and comparison with published data from Boreham et al (2000; 2001) shown as the green band for Perth Basin samples from a Kockatea/Hovea source. Data indicate that Waitsia Field gas (Kingia/High Cliff reservoir) has a different source to the Senecio Field gas (Dongara/Wagina reservoir).

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KINGIA/HIGH CLIFF PLAY DEFINITION

Success at Waitsia has defined a new commercial play for the Perth Basin. The key elements are the regional extent of good-quality reservoir in the Kingia and High Cliff sandstones, the presence of a suitable trapping mechanism, cross-fault seal, and access to charge (Table 3).

Reservoir distribution

Overall, the onshore Perth Basin has a relatively unfavourable porosity-depth relationship compared with other hydrocarbon basins due to significant uplift and high heat flow in some areas of the basin. Regional studies indicate that the Kingia Sandstone generally includes some good-quality reservoir (nominally with porosity greater than 11%) where its present depth of burial is less than about 3,000 m. The equivalent depth for the High Cliff Sandstone appears to be about 2,000 m (Fig. 12).

Below these depths, the existence of good reservoir depends on the presence of suitable depositional and diagenetic conditions for the formation of clay rim cements and preservation of significant primary porosity. Existing well control indicates that the Kingia Sandstone has at least one interval of good-quality reservoir wherever it has been intersected with a deepest penetration to date of 3,760 m TVDSS in Irwin–1 (Fig. 9). This implies that the depositional and diagenetic conditions required to preserve porosity are widespread and may represent a regional sequence stratigraphic event or a repeat of a specific facies. The extent of good-quality reservoir in the High Cliff Sandstone is far less predictable, with two thick intervals penetrated in Waitsia–1 but only thin zones in Senecio–3 and Waitsia–2. More exploration is needed to determine whether the High Cliff component of the play is localised or has wider regional extent.

Table 3. Kingia/High Cliff critical play elements based on Waitsia success.

Play rank	Trap	Reservoir	Seal	Charge
1	Low-side fault closures with large throw	Good-quality reservoir <3,000 m	Carynginia top seal plus favourable fault offsets	Mature source in large drainage cell; limited late uplift/tilting
2	Low or high-side fault closures with lesser throw	Good-quality reservoir 3–4,000 m; with diagenetic porosity preservation	Carynginia top seal but some faults with sand-on-sand juxtaposition	Longer distance migration involving spill from pre-existing traps
3	Four-way dip closures	Tight reservoir <4,000 m	Large closure height to offset potential impact of IRCM waste zone	
4	Potential diagenetic traps	Unconventional reservoirs <4,000 m	IRCM seal if Carynginia is absent	

Note: yellow highlights key play elements for Waitsia discovery.

Structure and seal

The Carynginia Formation is believed to provide the ultimate vertical seal for the Kingia/High Cliff play and the seal potential could be supplemented by shales in the Irwin River Coal Measures (Fig. 4). This seal is likely to be effective throughout the Dandaragan Trough where the Carynginia Formation is thickly preserved, but could be problematic over the Beagle Ridge where the interval is thinned or removed by erosion. Small gas accumulations have been encountered (e.g. Kingia Sandstone at Hovea–2) but these pools appear to be limited to local four-way dip closures. The pressure continuity of the Kingia and High Cliff sandstones in Waitsia indicates that the intervening Bit Basher Shale does not act as a seal despite its apparent semi-regional extent.

It is possible that undrilled four-way dip closures could still exist in areas of the basin covered by sparse seismic data. The degree of faulting observed in areas with 3D seismic control, however, suggests fault-bound structures are more likely to be present and will be larger than four-way dip closures. Fault traps with large throws and favourable cross-fault juxtaposition (e.g. Mountain Bridge fault) would be considered low risk, but low-side and high-side closures with smaller throw are more prevalent. Fault dependent closures with likely cross-fault sand-on-sand juxtaposition should be pursued given the very effective seal on the Senecio fault although the mechanism did not work at the Kingia Sandstone level in the Irwin–1 exploration well. Fault re-activation does not appear to be a risk factor in the onshore basin and therefore fault orientation is not an issue. For all trap types, there is some risk that the overlying Irwin River Coal Measures could act as a tight gas waste zone for prospects that are seal or charge limited.

Gas charge

The source of the gas in the Waitsia Field is believed to be the Irwin River Coal Measures and the Carynginia Formation, as indicated by gas isotope data and regional studies (Thomas and Barber, 2004). 3D thermal modelling suggests that gas charge from the Irwin River Coal Measures alone may not be volumetrically sufficient to achieve the observed fill history for the Waitsia Field, and that additional charge from the Carynginia Formation is also required. Both source rocks are gas-prone (Thomas and Barber, 2004; Cooper et al, 2015) and regional studies indicate they are mature for expulsion at a vitrinite reflectance maturity greater than 1.2 Ro%. This threshold equates to a depth of 3,650 m for the base Irwin River Coal Measures and is located only 2 km down dip from the Waitsia gas-water contact (Fig. 6). The large in-place volumes for the conventional and unconventional reservoirs at Waitsia indicate that expulsion and charge are efficient, but also reflects trap location immediately up dip from a regionally extensive source kitchen in the Dandaragan Trough.

Thermal maturation modelling indicates that peak generation and expulsion in the drainage area for Waitsia commenced in the Late Jurassic and continued to about the Mid Cretaceous (155–80 Ma) although expulsion declines significantly after about 110 Ma as heat flow diminishes (Fig. 15). Very minor expulsion continues through the Cenozoic to the present-day in the deepest parts of the Dandaragan Trough. Comparable temperature history modelling for quartz cementation indicates that this period of peak expulsion is coincident with maximum burial and elevated heat flow in the Late Jurassic to Early Cretaceous (155–132 Ma).

Kingia/High Cliff structures on trend with Waitsia at the edge of the Dandaragan Trough are assigned a low charge risk

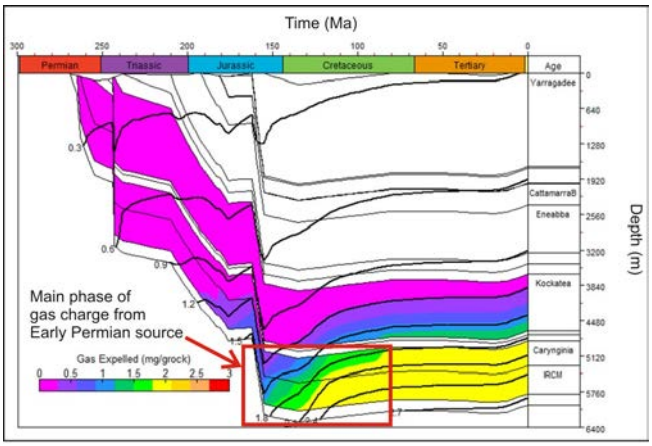

Figure 15. Thermal maturation model for a pseudo-well location in the drainage area of the Waitsia Field. Peak generation and expulsion for Early Permian source rocks is estimated for the period 140–80 Ma. The onset of significant expulsion is modelled at a vitrinite reflectance equivalent of 1.2 Ro%. Model location is shown in Figure 6.

although the continuity of reservoir conduits could be disturbed by excessive cementation or faulting. Valanginian uplift and tilting for this part of the basin is believed to be relatively modest (<200 m) and therefore is unlikely to cause significant spill and re-migration. Given the seal effectiveness and regional extent of the Mountain Bridge fault, it may act as a regional migration barrier for gas expelled from Early Permian source rocks such that the Kingia/High Cliff play on the Beagle Ridge may not be charged. If, however, any Early Permian derived gas does cross the fault, it is expected to have a complicated fill and re-charge history due to the substantial uplift and tilting in that area.

WAITSIA RESERVES AND RESOURCES

Reserves and contingent resource estimates for the Waitsia Field, as reported on 21 August 2015 (AWE, 2015e), are summarised in Table 4. Reserves have been allocated to the good-quality reservoir intervals (porosity greater than 11%) in areas of the field that have been delineated by Senecio–3, Waitsia–1 and Waitsia–2. A range of 1P, 2P and 3P reserves for the Kingia and High Cliff sandstones was derived by applying uncertainty ranges to the key parameters such as gross rock volume, net pay thickness, porosity, hydrocarbon saturation, recovery factor, and elevation of the gas-water contact.

Two classes of contingent resources have also been estimated. For the good reservoir, 1C, 2C and 3C resources have been estimated by application of the same uncertainty ranges but to areas of the structural closure not yet penetrated by wells. Further contingent resources have also been allocated to the tight reservoir intervals (porosity 7–11%) by applying a range of reservoir and fluid parameters across the entire mapped field area. Further evaluation of the low porosity Kingia/High Cliff intervals (<7% porosity), the Irwin River Coal Measures and the Carynginia Formation is required to determine whether these can be quantified as unconventional contingent resources.

The best technical estimate for the size of the good-quality reservoirs in the Waitsia Field is the 2P reserve for the drilled areas (178 BCF) plus the 2C contingent resource for the undrilled areas (149 BCF) for a total of 327 BCF. It is believed that the 2C contingent resource associated with tight reservoir (157 BCF) also has a good chance of ultimate development and this would provide a combined volume of 484 BCF. Further appraisal drilling is planned for early 2017 to validate these estimates and further address the significant remaining upside.

Table 4. Reserves and contingent resource estimates for the Waitsia Field at 21 August 2015 (AWE, 2015e).

Reservoir interval	Gross reserves (BCF)			Gross contingent resources (BCF)		
	1P	2P	3P	1C	2C	3C
Kingia/High Cliff >11% porosity	101	178	242	110	149	203
Kingia/High Cliff 7–11% porosity				110	157	204
TOTAL	178			306		

FIELD DEVELOPMENT

The field development plan may comprise at least three stages to maximise recovery from all of the reservoir types and to ensure that the production ramp-up is managed to fit with domestic gas demand. Stage 1A involves early production testing and gas sales utilising the presently suspended Senecio–3 discovery well and the successful Waitsia–1 appraisal well. These wells will be connected by short pipelines (6 km) to the existing Xyris processing facility from where gas will be exported to southwest WA markets through the Parmelia pipeline (Fig. 1). The purpose of this development stage is partly to generate early cash flow, but also to more accurately define the average well drainage volume for optimising full field development. Production and pressure data will be valuable to identify any flow barriers associated with faults or reservoir heterogeneities, and will be used to determine expected recovery per well and field-wide recovery factors.

Information from Stage 1A development will be integrated with further appraisal drilling results to finalise the development plan for Stage 2 or full field production. Preliminary conceptual studies point to 15–20 vertical production wells ultimately being required. Given the high productivity of wells tested to date (Senecio–3 and Waitsia–1) it is expected hydraulic stimulation will not be necessary and that plateau production for the combined Stage 1 and 2 could be at least 100 MMCFD. This gas may be processed by upgrading an existing plant such as Dongara, or alternatively one or more new gas plants may be constructed. Multiple gas export and supply options are under consideration.

While progressing Stage 2, the tight gas resources in Waitsia and adjacent fields (Senecio, Irwin) will be further evaluated as a Stage 3 development opportunity. This could involve an extension of field life by utilising the Stage 2 facilities, or may instigate a further upgrade to processing and domestic export capacity. It is expected that any development wells will require hydraulic stimulation to achieve commercially acceptable flow rates. Some new wells will be needed but others may be re-completions of depleted wells from the Stage 2 development. Any implementation of Stage 3 would be subject to satisfying all regulatory requirements and securing full stakeholder engagement.

CONCLUSIONS

The Waitsia discovery resulted from a decision to deepen the Senecio–3 tight gas appraisal well to evaluate secondary targets given the presence of very high gas shows at the planned total depth of the well. These deeper potential targets were previously discounted in the mistaken belief that reservoir quality would be universally poor below 3,000 m, and that offset on the northern bounding fault would be insufficient to seal a large accumulation. The presence of good-quality reservoir in the Kingia and High Cliff sandstones, and a gross gas column of 350 m, clearly demonstrates the importance of considering all possible geological scenarios and being prepared to test ideas with the drill bit.

The Waitsia Field represents the largest conventional gas discovery onshore Australia for the past 30 years and is a significant new commercial play for the Perth Basin. Appraisal to date has demonstrated material reserve and contingent resource potential in good-quality and tight reservoirs, which can be quickly and economically developed using existing infrastructure. It is expected that the Waitsia success will encourage further exploration and appraisal in the Perth Basin and may stimulate re-evaluation of conventional opportunities in the other under-explored basins of onshore Australia.

ACKNOWLEDGEMENTS

AWE Perth Pty Ltd and joint venture partner Origin Energy Developments Pty Ltd are thanked for encouraging and authorising the publication of this paper.

The Waitsia discovery would not have been made without the long-standing efforts of Greg Smith and Mark Fabian, on behalf of AWE and previously Arc Energy Ltd, to emphasise the potential of the Perth Basin and to promote further exploration.

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Neil has more than 30 years of industry experience, having worked in a variety of technical and managerial positions for Santos, Enterprise Oil, Origin Energy and BP. He has operating experience in the basins of Australia, PNG and Indonesia, plus good working knowledge of Southeast Asia, New Zealand, the US, UK and North Africa.

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Gareth graduated with a BSc (Hons) (Wollongong) degree in 1990, and a PhD (Monash) in 1995.

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Tim Hicks is a development geologist for AWE Ltd. Tim attended Queensland University of Technology where he completed a BAppSc(Hons) in geology, and an LLB and an LLM in natural resources law. Tim has been employed in the Australian resources sector since 1995 in various capacities, ranging from field exploration projects through to legal advisor. Tim presently works on AWE's development and production assets as Staff Development Geologist.

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Eric Matthews is a petroleum geologist with more than 30 years' experience in oil exploration, primarily in Australia and New Zealand. He first worked for Shell in Taranaki in 1975 before completing higher degrees in geology and working for a year with the New Zealand Oceanographic Institute. In 1982 he joined New Zealand Oil and Gas (NZOG) and was Exploration Manager for both NZOG and sister company Pan Pacific Petroleum from 1994. In his time with NZOG he was instrumental in a number of discoveries, notably Kupe, Ngatoro and, more recently, the Tui oil discovery.

In 2004 Eric joined AWE as Asset Manager, responsible for the company's New Zealand exploration activities, and is presently Chief Geologist. Eric has BSc, MSc and PhD degrees in geology. Member: AAPG, SPE and PESA.

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Andy Furniss joined AWE in 2009 as Principal Geophysicist. In his present role as Exploration Manager he is responsible for the technical oversight and management of AWE's diverse portfolio and joint ventures. Andy also acts in a functional capacity as AWE's Chief Geophysicist.

Andy has more than 25 years of experience, having worked in a variety of technical and managerial roles for Chevron, WAPET and Paradigm Geophysical. His exploration expertise has been applied across the UK North Sea, North Atlantic margins, Gulf of Mexico, Southeast Asia and Australian onshore and offshore basins. His technical expertise lies in advanced seismic imaging, reservoir characterisation and exploration portfolio management.

Andy has a MSc in exploration geophysics, and a BSc (Hons) in geological sciences.

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Suzanne Hunt has a PhD in geomechanics, a BSc in geophysics with mathematics, and a MSc in mining geology. She has more than 18 years' experience in the petroleum sector in geophysics, field development planning, reserves estimation, and production and facilities engineering. Suzanne has published more than 50 papers in production engineering, field development planning, reservoir engineering, micro-seismicity, and geomechanics. Suzanne is Engineering and Development Manager at AWE. Member: SPE.

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