World's oldest regional salt seal in the Amadeus and Officer Basins: implications for subsalt helium and hydrocarbons

by

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Introduction

Thick salt (halite or anhydrite) accumulations within sedimentary basins can exert controls over the structural development of fluid traps and provide the highest quality seals. Sealing capacity becomes particularly important when prospecting for relatively early generated hydrocarbons trapped in old, long-stable sedimentary basins. Old salt seals also have particular significance for the trapping of He, a light, inert and highly mobile element that largely escapes through less efficient seals over geological time. Helium is constantly generated in the crust as a daughter product of the radioactive decay of U and Th and can also be sourced from the mantle; most commercial He is extracted as a minor byproduct during commercial hydrocarbon production. Although low concentrations of He may be commercially extracted from shale-sealed traps, high concentrations (>1%) typically require very effective seals and long accumulation times, favouring traps in old, stable salt-bearing basins. Components of the Centralian Superbasin, particularly the Amadeus and Officer Basins of central and west Australia (Fig. 1), contain widespread deposits of Tonian (early Neoproterozoic) salt believed to be the oldest regionally extensive salt deposits in the world. At the time of deposition, these basins were at least partly linked, as attested by similar stratigraphy, biostratigraphy and depositional history, but were separated during late Neoproterozoic and younger tectonism (Walter et al., 1995; Munson et al., 2013). Exploration for subsalt hydrocarbons and He in this extensive province is in its infancy, but early results from the eastern Amadeus Basin are encouraging.

Salt in the Centralian Superbasin

Amadeus Basin

The Tonian stratigraphy of the Amadeus Basin (Fig. 2) starts with a basal sandstone-dominated unit, the Heavitree Formation in the north and laterally equivalent Kulail Sandstone and Dean Quartzite in the southwest, although this package is locally absent in the southeast. These units are overlain by the Bitter Springs Group comprising the Gillen Formation (mudstone, carbonate and halite-dominated evaporites), Loves Creek Formation (stromatolitic carbonate) and Johnnys Creek Formation (evaporitic dolomitic redbeds, carbonate and minor mafic volcanics), in ascending order. The youngest Tonian unit, the Wallara Formation, comprises mixed sandstone, carbonate and shale facies.

Officer Basin

In the central Western Australian Officer Basin, the entire Tonian succession is within the Buldya Group (Fig. 2), with basal sandstone-dominated Townsend Quartzite present locally. The overlying and more extensive Browne Formation contains two halite-dominated evaporite units (Fig. 3), separated by stromatolitic carbonates of the Woolnough Member. The siltstone-dominated Lefroy Formation lies between the Townsend and Browne Formations locally in outcrop, but has not yet been recognized in drillholes. The upper Buldya Group (Hussar, Kanpa and Steptoe Formations) is a mixed sandstone, mudstone and carbonate succession, with local evidence of evaporites and mafic volcanics.

Age and correlations

The Tonian successions of the Amadeus and Officer Basins have a similar depositional history and can be correlated using biostratigraphy and chemostratigraphy (Fig. 2). The carbonate-dominated Loves Creek Formation and Woolnough Member are correlated based on the stratigraphically restricted *Acaciella australica* Stromatolite Assemblage (Grey et al., 2012) and the presence of the globally recognized $\delta^{13}C$ Bitter Springs Anomaly. However, the boundaries of this isotope anomaly are strongly facies controlled in the Amadeus Basin, so may not correlate in entirety to this c. 800 Ma isotope anomaly elsewhere (Klaebe et al., 2017). These constraints imply that Gillen Formation salt correlates with the lower Browne Formation salt, while the less extensive upper Browne Formation salt may correlate with the evaporitic redbeds (with halite pseudomorphs) of the Johnnys Creek Formation, although no preserved salt is known at this level in the Amadeus Basin. The post-salt succession can likewise be correlated between the

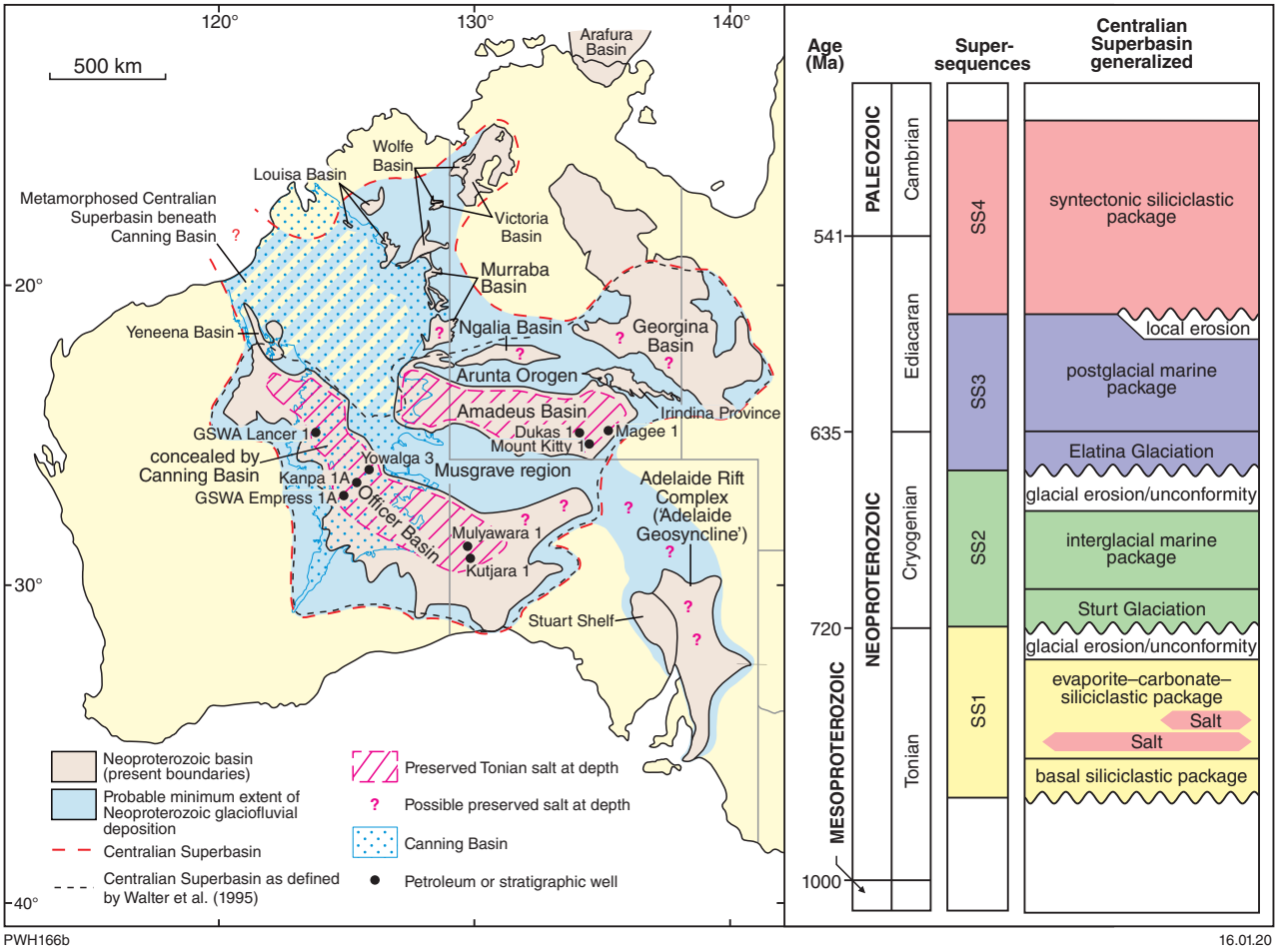

Figure 1. **Map of the Centralian Superbasin and component basins (modified after Munson et al., 2013), with generalized Neoproterozoic stratigraphy on the right indicating the position of the main Tonian salt units. Known and inferred distribution of preserved subsurface salt in the Amadeus and Officer Basins is based on seismic data and drilling, where available, or extrapolated beyond, while possible occurrences in other basins are also indicated. The selected petroleum and stratigraphic wells are referred to in the text**

basins based on stromatolites (*Baicalia burra* Stromatolite Assemblage) and microfossils (Grey et al., 2012). The current constraints suggest the oldest salt horizon is somewhat older than 800 Ma.

Subsalt exploration

Two wells drilled to basement beneath Gillen Formation salt in the eastern Amadeus Basin, Magee 1 and Mount Kitty 1, both flowed hydrocarbon gas to the surface, demonstrating the existence of a subsalt hydrocarbon system in this area, presumably sourced from organic-rich shales in the lower Gillen Formation. Lower Gillen Formation shales have a total organic carbon content of up to 1.8% (Jarrett et al., 2016). Both wells had exceptional He contents; 6.2% in Magee 1 (Wakelin-King, 1994) and 9% in Mount Kitty 1 (Boreham et al., 2018; McInnes et al., 2017), the latter being one of the highest recorded He concentrations for any well. Such extraordinary He values demonstrate the integrity of the salt seal and suggest gas accumulation since the Neoproterozoic. The Mount Kitty 1 gas composition (9% He, 61% N_2, 13% CH_4, 4% C_2H_6 and 11% H_2) is particularly unusual; the high H content possibly resulting from either hydrocarbon oxidation, or an abiogenic breakdown product of hydrocarbons in the granite reservoir (McInnes et al., 2017). Despite being technically successful, both wells suffered from poor reservoir quality. Magee 1 produced gas from a very thin (4.5 m) fine-grained sandstone (inferred as Heavitree Formation by Wakelin-King, 1994) overlying crystalline basement, while Mount Kitty 1 lacked any subsalt sandstone, producing gas from fractured and weathered crystalline basement. Drilling of a third subsalt exploration well, Dukas 1, was suspended at the time of writing. No deep drilling has been undertaken in the Western Australian Amadeus Basin; however, salt is inferred to extend into this area based on structural interpretations and significant thicknesses of subsalt shale and sandstone are expected based on extrapolation from outcrop (Haines and Allen, 2019). Despite poor outcrop of the basin in Western Australia, the Tonian succession can be confidently correlated with the better known eastern part of the basin with the aid of stromatolite biostratigraphy (Allen et al., 2012; Allen and Haines, 2019).

Within the Western Australian Officer Basin, there has been no serious exploration for subsalt traps. Fully cored Geological Survey of Western Australia (GSWA) stratigraphic wells GSWA Lancer 1 and GSWA Empress 1A reached basement beneath lower Browne Formation salt, but lacked significant subsalt reservoir and were not drilled on recognized traps. Two deep exploration wells, Yowalga 3

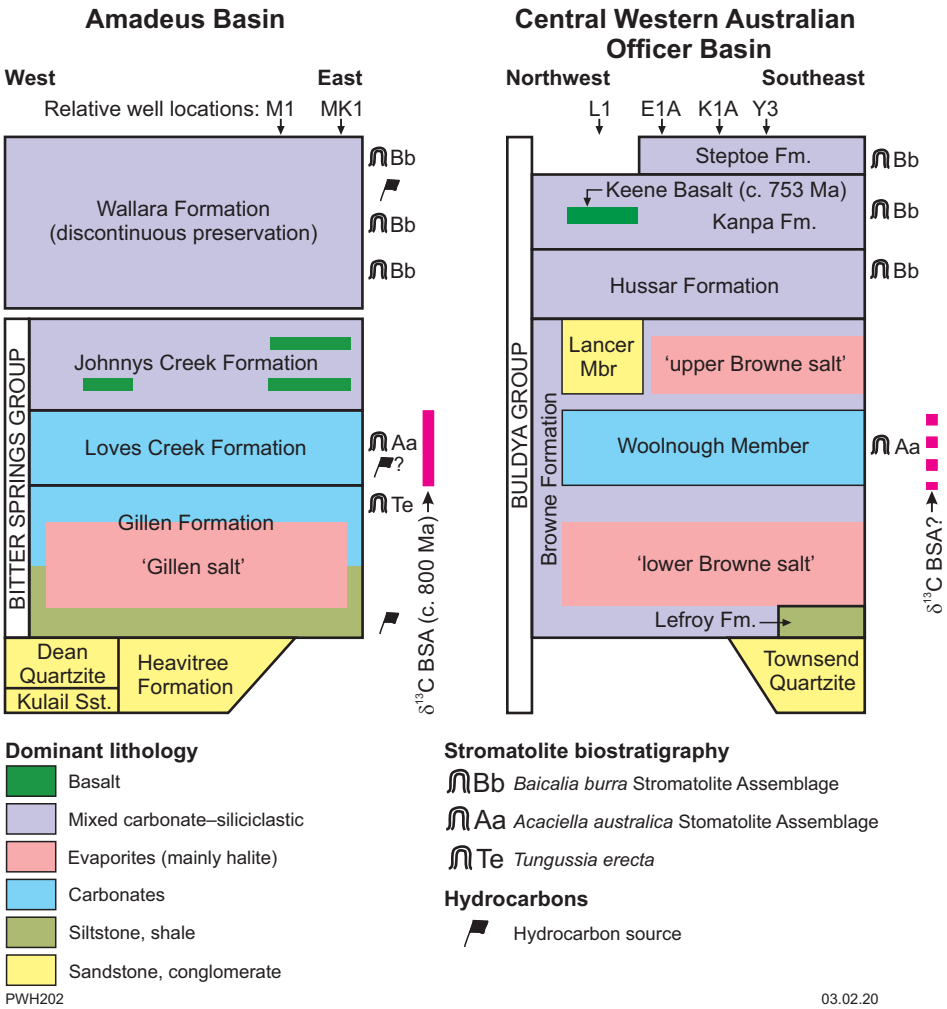

Figure 2. **Stratigraphic correlation between the Tonian successions of the Amadeus and central Western Australian Officer Basins with the main stromatolite biostratigraphic ties and the extent of the $\delta^{13}C$ Bitter Springs Anomaly (BSA) indicated. Well positions: M1, Magee 1; MK1, Mount Kitty 1; L1, GSWA Lancer 1; E1A, GSWA Empress 1A; K1A, Kanpa 1A; Y3, Yowalga 3**

and Kanpa 1A, drilled beneath Browne Formation salt but also failed to intersect subsalt reservoirs. Yowalga 3 drilled a salt-tectonic structure and did not reach the level of the Townsend Quartzite (potential reservoir), whereas Kanpa 1A was probably outside of the deposition or preservation limit of this unit, drilling through an unconformity into likely Mesoproterozoic rocks beneath the Browne Formation (Simeonova and Iasky, 2005).

Two exploration wells drilled in South Australia near the Western Australian border, Mulyawara 1 and Kutjara 1, intersected equivalents of Browne Formation salt overlying subsalt shale and sandstone units. The presence of numerous minor gas shows below and above the salt suggests the presence of a hydrocarbon system at this level in the area, but it is possible the salt is locally too disseminated to form an effective seal. There is considerable scope for future exploration for subsalt traps in the Officer Basin, particularly in the extensive area between deep wells in the central Western Australian part of the basin and the South Australian border, an area where subsalt reservoirs and shales are considered more likely based on adjacent outcrop, but where there is currently very little subsurface information.

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Figure 3. Interbedded halite (orange-brown) and dolomite (pale grey to grey-brown) in the lower Browne Formation in GSWA Lancer 1 (1454.14 – 1458.75 m). Significant halite dissolution during drilling is indicated near the bottom of the core tray

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