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Australian salt basins – options for underground hydrogen storage

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ABSTRACT

As Australia and the world transition to net zero emissions, hydrogen will continue to grow in importance as a clean energy source, with underground hydrogen storage (UHS) expected to be a key component of this new industry. Salt (halite) caverns are a preferred storage option for hydrogen, given their scale, stability and the high injection and withdrawal rates they can support. The use of salt caverns for storing gas is an established industry in North America and Europe but not in Australia, where exploration for suitable storage locations is in the initial frontier stages. Australia's known major halite deposits occur in Neoproterozoic and Paleozoic sequences and are predominantly located in western and central Australia. This analysis has identified potential in eastern Australia in addition to the proven thick halite in the Adavale Basin, Queensland. Building on Geoscience Australia's previous salt studies in the Canning, Polda and Adavale basins, this study expands the portfolio of areas prospective for halite in onshore and offshore basins using both direct and indirect evidence. The study correlates paleogeography and paleoclimate reconstructions with evidence of salt in wells, and in geophysical and geochemical data. Salt cavern design for UHS, the solution mining process, and the preferred salt deposits are also discussed. The results will provide pre-competitive information through a comprehensive inventory of areas that may be prospective for UHS.

Keywords: Adavale Basin, Amadeus Basin, evaporites, halite, Officer Basin, Polda Basin, salt caverns, underground hydrogen storage, UHS.

Introduction

Hydrogen provides flexible options for transporting and storing energy that will enable deep penetration of renewables into the energy mix. It is a clean energy source especially suited for uses that are hard to electrify and/or abate, such as powering heavy vehicles and the manufacturing of iron and steel (BloombergNEF 2020). Australia's energy security will be enhanced by a domestic hydrogen industry that will provide a more diverse and resilient energy supply and less reliance on fuel imports (DCCEEW 2022). Underground hydrogen storage (UHS) is an enabling technology that provides a flexible, short- to long-term energy storage option to complement short- to medium-term energy storage, such as batteries and pumped hydroelectricity schemes for grid stabilisation (Michael *et al.* 2021).

Hydrogen and salt are inextricably linked. Presently, all large-scale storage of commercially produced hydrogen (from unabated fossil fuels) occurs in underground salt (halite) caverns. Salt caverns are typically formed by solution mining cavities in salt rock. This process has been used to develop caverns for liquid-petroleum gas storage in Texas since the 1950s (Gill and Cowan 2008), and it is estimated that there are presently 104 salt caverns (as of 2017) used worldwide for energy storage (Cornot-Gandolphe 2019). For hydrogen, salt caverns provide the advantages of high gas deliverability, low cushion gas requirements and a high sealing capacity, making salt caverns competitive with depleted gas fields, surface tanks and hard rock caverns for large-scale UHS

(BloombergNEF 2019). Globally, there are four salt caverns for hydrogen storage currently in operation (Hévin 2019; Caglayan et al. 2020; Ennis-King et al. 2021), with more caverns planned given the increasing global demand for hydrogen with low carbon emissions (International Energy Agency 2022). For example, the Advanced Clean Energy Storage Delta project in Utah (ACES DELTA 2022) plans to store green hydrogen in two large salt caverns, each capable of storing 150 GWh of energy (~5500 tonnes of hydrogen per cavern). The UK, Germany, Ireland and the Netherlands are pursuing UHS in both onshore and offshore salt accumulations (Caglayan et al. 2020; Chedwynd 2021; dCarbonX 2021; ESB 2021; RVO 2022).

In addition to providing sealing capacity for hydrogen storage, salt may act as a trap for natural (geologic) hydrogen sourced from deep subsurface abiotic processes (Haines and Allen 2020; Boreham et al. 2021). The discovery of a hydrogen gas field in Mali (Prinzhofer et al. 2018) has spurred exploration for this potentially new carbon-free source of energy, with Australia considered one of the most prospective locations (Boreham et al. 2021; Moretti et al. 2021). Free hydrogen and hydrogen in fluid inclusions within salt deposits have been attributed to it being effectively trapped by alternating layers of clays and salt and the inertness of halite to the highly reactive hydrogen. Additionally, the radioactive decay of potassium (present in potash) and its further radioactive decay products (^{40}Ca from ^{40}K) can reduce water to hydrogen (Zgonnik 2020) given suitable porosity and permeability within the salt, which can occur in deep sedimentary basins (Scribano et al. 2017). These associations suggest the possibility that the components of hydrogen plays (Stalker et al. 2022) may incorporate salt as source, reservoir and seal.

Salt caverns for UHS

When developing underground salt caverns for storage purposes, careful consideration to the target salt formation is required to ensure successful hydraulic containment and geomechanical behaviour. Ideally, the salt formation will consist of thick (>200 m) and pure (>90%) halite with minimal non-salt inclusions (e.g. interbedded anhydrite). The salt formation depth often controls the operating pressure envelope for gas (including hydrogen) storage, where deeper caverns can withstand higher storage pressures and higher storage densities than shallower caverns. In general, gas storage caverns target an optimal depth range of approximately 900–1500 m, which maximises the storage capacity while also avoiding problematic geomechanical conditions at deeper depths. Although there can be some site-specific flexibility, gas storage cavern fields are typically recommended to maintain a spacing to diameter ratio of at least four, where the spacing refers to the cavern centre-to-centre distance and the diameter is the average diameter of the two neighbouring caverns.

The solution mining of storage caverns requires both a water source (ideally fresh or brackish) and a disposal method for the produced brine. As a rule of thumb, a freshwater volume to cavern volume ratio of approximately seven will be required to solution mine a cavern. As an example, if the target storage cavern volume is 1 million m^3, solution mining will require a total of 7 million m^3 of freshwater. Consequently, 7 million m^3 of brine will also be produced, which will need to be managed either through production of a commercial salt product (and recovery of water from the brine for the solution mining process) or through deep disposal injection or other methods (e.g. solar evaporation). Depending on the target development timelines, water source and disposal rates often exceeding 200 m^3/h are required, which necessitates a robust water and disposal infrastructure. The typical time required to solution mine a storage cavern often ranges between 6 months and 3 years, depending on the target cavern volume and water injection rates. In the situation where a gas storage cavern gradually loses volume over time due to salt creep, it is often necessary to re-solution mine the cavern to regain the lost volume. Depending on the volumetric goals, these re-solution mining activities typically require a few months or up to a year to complete.

The deformation behaviour of salt is typically dominated by a viscoplastic (i.e. creep) mechanism that increases exponentially with stress and temperature. Therefore, the higher stress and temperature conditions in deeper salt formations will result in enhanced salt creep, which manifests as a more mobile salt that gradually 'flows' inward towards the cavern. This enhanced salt creep decreases the volume of the storage cavern, essentially returning the salt to a pre-cavern-development state. Although not a strict limit, storage caverns are typically limited to a maximum depth of approximately 2000 m. Storage cavern development and operation below this depth are complicated by significant salt creep that can exceed a volume loss rate of 20%/year, which is often not economical for storage operations. Also important is to consider and manage post-injection processes, including increased moisture content in the stored hydrogen with increasing confinement pressure (Lopez-Lazaro et al. 2019) and microbial utilisation of hydrogen with the addition of other gaseous species, such as methane (Schienteie et al. 2022).

Although it is well-established in Europe and North America, there is no gas storage in Australia that utilises salt caverns. Natural gas storage is limited to depleted reservoirs from eight previously producing gas fields and above ground LNG tank facilities.

A sustained exploration phase supported by pre-competitive geoscience data is required to find thick halite in useful locations in Australia. This paper aims to sketch out the search space for UHS in salt, show how our continent-wide geophysical and other datasets can be leveraged to high-grade areas in case studies at prospect, play and frontier reconnaissance levels of understanding.

Evaporite depositional environments

Evaporites are chemical sediments precipitated from concentrating brines in the familiar environments of salt lakes and coastal tidal flats (sabhkas) in warm, dry climates (Warren 2010). Evaporation of seawater yields, with increasing salinity, the marine evaporite sequence of carbonates, gypsum, halite and late-stage bitten salts (K and Mg salts, potash). Marine evaporites fall into two main types: (1) gypsum/anhydrite dominated platform sequences with no or only thin (>10 m) halite and (2) thick, basin-centred halite deposits, termed 'mega-halites' or saline giants (Warren 2010, 2021).

These marine, basin-wide deposits are ideal UHS targets with relatively pure halite beds from hundreds of metres to kilometres thick that can, with later halotectonics process, ductile flow into salt pillows, domes and diapirs, producing suitable geometries for constructing salt caverns. Examples of ancient saline giants that are used for gas storage and that are being developed for UHS include the Permian Rotliegend and Zechstein salts, North Sea, and the onshore Europe and Triassic Northwich Halite, Cheshire Basin, UK (Caglayan *et al.* 2020). In North America, the saline giants used for gas storage include the Silurian Salina Group, Michigan Basin; the Carboniferous Paradox Formation, Paradox Basin in Colorado–Utah, USA; the Permian Salado Salt, Midland Basin; and the Jurassic Louann Salt, Gulf of Mexico Basin (Bruno 2005; Warren 2021). The Cretaceous Maha Sarakham Formation, Khorat Basin, Thailand, is another basin-wide salt being considered for UHS projects (Pajonpai *et al.* 2022).

Today some of the thickest salts are accumulating in terrestrial environments in high altitude deserts, such as the Altiplano and Tibetan Plateau (Warren 2021), but with their mixed lithologies, they may be less suitable for UHS. There are no Quaternary analogues of ancient marine saline giants, although they are well represented in the past when thick bedded halite deposits accumulated in hydrographically isolated depressions well below sea-level that still had access to seawater in hot, dry and windy climates. A tectonic driver was needed to preserve kilometres of salt in an actively subsiding depression, such as a rift, foreland depression or intraplate sag (Warren 2021).

However, an alternative to the surface evaporative model has been proposed by Scribano *et al.* (2017), Hovland *et al.* (2018*a*, 2018*b*) and Debure *et al.* (2019), where salt deposits are derived from hydrothermal fluids associated with Wilson cycles. In the 1970s, new information from drilling the Messinian (Late Miocene) salt underlying the Mediterranean supported shallow water deposition of thick salts in deep desiccated basins as an alternative to deep water brine basin models (Hsu 1972). Similarly, the new information from drilling the sub-salt of offshore Brazil has provided new insights into the relationships between evaporite formation and volcanic activity (Szatmari *et al.* 2021). The hydrothermal model (Hovland *et al.* 2018*b*) allows for deep water halite environments (e.g. Dead Sea) and can help explain the common association of giant salt deposits and new ocean basins; perhaps saline giants form in different and hybrid ways beyond the current end-member models.

Australian salt basins

Building on the work of Boreham *et al.* (2021), this study attempts to identify all Australian basins that may be prospective for UHS in salt (Fig. 1). Included are basins with direct evidence of halite (well intersection) plus basins where there is only indirect structural or geophysical evidence of salt. Facies commonly associated with halite deposits (carbonates, especially dolomite, other evaporites and red beds) point to other prospective areas for UHS or at least where evaporite seals for natural hydrogen accumulations may occur.

The inventory of Australian evaporites compiled by Wells (1980) highlighted potash resources for agriculture, and recently, lithium for batteries and other strategic resources in salt lakes has been the focus (Mernagh *et al.* 2013). Now, identifying thick halite deposits for UHS has become a new priority. The Tonian, Early Paleozoic and Devonian were peak times for evaporite deposition in Australia (Table 1). There are some indications of evaporitic facies in Mesoproterozoic and Palaeoproterozoic sequences, such as dolostones in the McArthur and Nathan groups of the greater McArthur Basin (Hall *et al.* 2020), but no thick halite has been reported. Fig. 2 shows some of Geoscience Australia's collection of salt samples from cores and cuttings from petroleum wells.

Tonian evaporites

Salt deposition was most extensive across Australia in the Tonian (~1000–720 Ma) when other saline giants were deposited across Rodinia (Fig. 3; Schmid 2017). The Gillen Formation (Amadeus Basin, Fig. 2*d*), the Browne Formation (Officer Basin) and the Kilroo Formation (Polda Basin, Fig. 2*b*) are all proven thick halite deposits of Tonian age that are discussed in more detail below. The possible salt in the Bremer Sub-basin (Bradshaw *et al.* 2013; Cunneen *et al.* 2019) is also interpreted to be part of this major episode of Neoproterozoic evaporite deposition (Fig. 3). The Amadeus and Officer basins are part of the Centralian Superbasin, (Walter *et al.* 1995) along with the Georgina, Ngalia and Murraba basins (Fig. 3). The known thick Tonian salts (Gillen and Browne formations) are a minor part of the Centralian 1 Supersequence that fills rifts and sags associated with the break-up of the Rodinia supercontinent (Bradshaw *et al.* 2020).

The Adelaide Rift Complex was initiated during this time and was once contiguous with the Centralian Superbasin (Preiss 2000). Numerous diapiric structures (Kernen *et al.* 2021) and modelling by Backé *et al.* (2010) indicate that a relatively thick and extensive halite was once within the Tonian section of the rift. The question remains as to whether

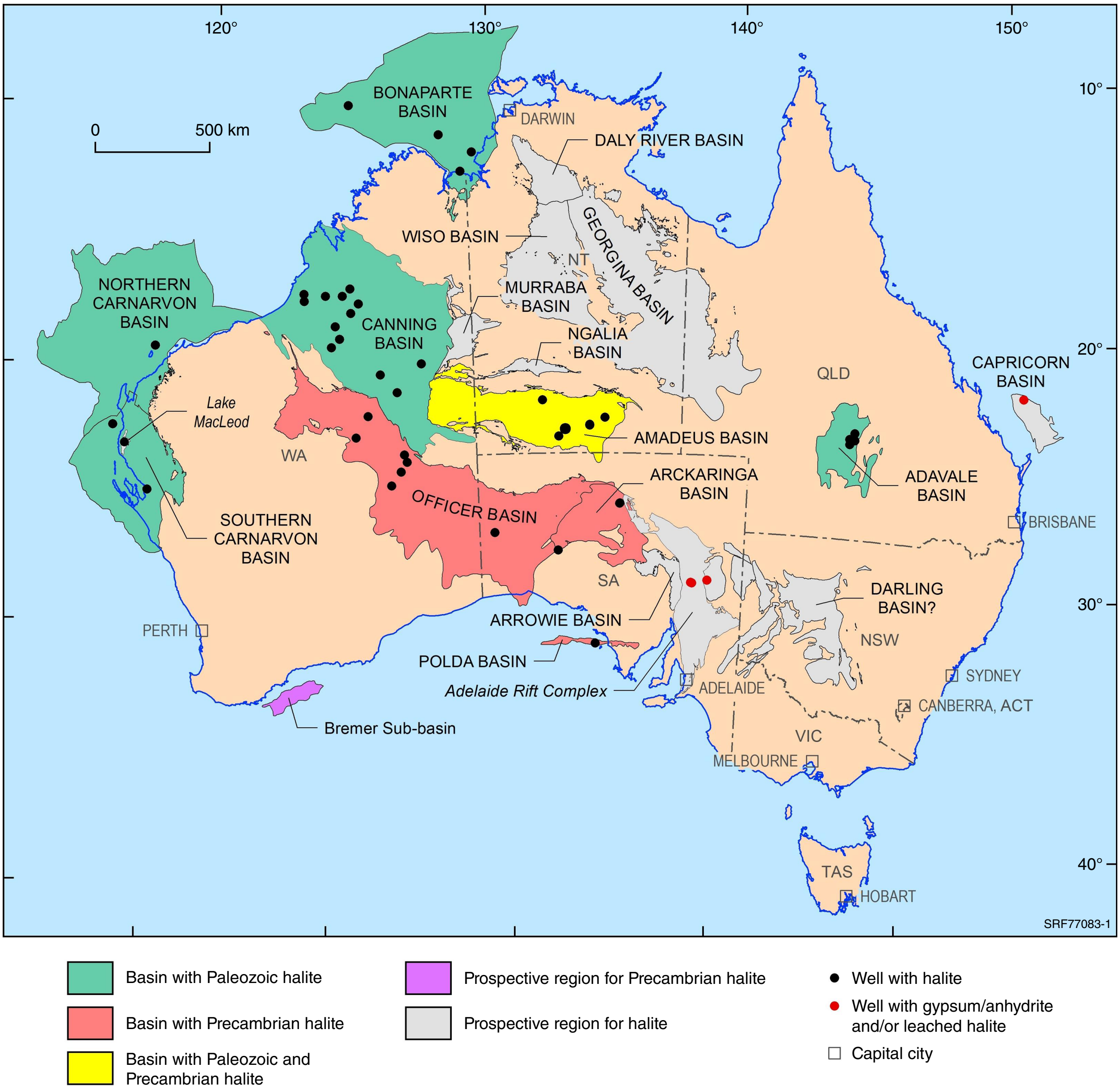

Fig. 1. Australian salt basin modified from Boreham et al. (2021). Grey indicates basins with either minor or limited known occurrences of evaporites. The Bremer Sub-basin is suspected of having Precambrian halite based on structures imaged in seismic data. Note that only the onshore extent of Canning Basin is shown.

any significant salt remains in the subsurface given a post-depositional history of tectonism and dissolution; however, Mernagh et al. (2013) suggest that evaporitic units (Callana Group) could be the source of anomalous hydrogeo-chemistry around Lake Torrens today.

The salt features interpreted on seismic data underlying the Arckaringa Basin (eastern Officer Basin extending to the west of the Adelaide Rift Complex) may also be Tonian in age. Halite has been intersected in Cootanoorina 1 and Wilkinson 1 (Kovalevych et al. 2006). Mulyawara 1, also drilled in the eastern Officer Basin (Rodinia Oil 2011; Boult et al. 2012), intersects two Neoproterozoic halite units. The Murraba Basin (Fig. 3) also has a Tonian section as well as having a structural style that is suggestive of salt tectonics in some local areas (Haines and Allen 2017).

Paleozoic evaporites

Sporadic salt deposition occurred during the Cambro–Ordovician when platform carbonates were a common lithology and some evaporitic facies developed, such as dolomites (Red Hart Dolomite, Georgina Basin; Kalladeina Formation, Warburton Basin). Thin halite beds occur in the Early Cambrian Ouldburra Formation, Officer Basin,

Table 1. Evaporites in Australian basins.

Australian salt basins					
Age	**Basin**	**Salt unit**	**Evidence of salt (core, cuttings, well logs, seismic)**	**Facies**	**Reference**
Quaternary	Lake MacLeod	MacLeod Halite	Shallow wells, costeans	Marine platform	Logan (1987)
Paleogene	Capricorn	None identified	Well (anhydrite at Aquarius 1)	Non-marine	Hill (1992)
Early Cretaceous	Fairway – Lord Howe Rise	None identified	Seismic diapir	Marine?	Van de Beuque *et al.* (2003)
Late Devonian	Darling	None identified	Restricted marine, red beds	Marine?	Alder *et al.* (1998)
Givetian (mid Devonian)	Adavale	Boree Salt	Wells (Boree 1, Bury 1, etc.), core, seismic	Saline giant	Paterson *et al.* (2022)
Silurian–Devonian	Bonaparte – Petrel Sub-basin	Silurian–Devonian salt	Wells (Kinmore 1, Pelican 1, Sandpiper 1, etc.), seismic	Saline giant?	Mory (1991)
Pre-Permian	Bonaparte –Vulcan Sub-basin	Pre-Permian salt	Well (Paqualin 1), seismic	Saline giant?	Molyneux and Doyle (2021)
Late Ordovician – Silurian	Carnarvon	Yaringa Salt	Wells (halite at Yaringa 1, anhydrite at Pendock 1, etc.)	Saline giant or marine platform?	Canadian superior oil (1976), Continental oil company of Australia (1966)
	Canning – Kidson Sub-basin	Mallowa Salt	Wells (Kidson 1, Fruitcake 1, etc.), seismic	Saline giant	Connors *et al.* (2022)
Late Ordovician	Canning – Kidson Sub-basin	Minjoo Salt	Wells (Kidson 1, Patience 2, Brooke 1, etc.), seismic, AEM	Saline giant	Connors *et al.* (2022)
Cambrian	Darling –Bancannia Trough	None identified	Well (carbonates at Bancannia South 1)	Marine platform?	Khalifa and Mills (2022)
	Arrowie	None identified	Well (<10 m anhydrite at Moorowie 1)	Marine platform	Delhi Petroleum (1984)
	Amadeus	Chandler Salt	Wells (Mt Charlotte 1, Magee 1, etc.), seismic	Saline giant	Bradshaw (1991)
	Officer	Ouldburra Fm	Wells (<10 m halite in Manya 6, etc.)	Marine platform	Kovalevych *et al.* (2006)
	Georgina	None identified	Dolostones	Marine platform	Dunster *et al.* (2007)
Tonian	Amadeus	Bitter Springs – Gillen Member	Wells (Magee 1, Mt Kitty 1, Magee 1 etc.), seismic	Saline giant	Plummer (2021)
	Murraba	None identified	Carbonates, salt structures?	Marine platform?	Haines and Allen (2017)
	Adelaide Rift Complex	Callana Subgroup	Surface diapirs	Saline giant	Kernen *et al.* (2021)
	Below Arckaringa	Callana Subgroup	Wells (Cootanoorina 1, etc.), seismic	Saline giant	Boult *et al.* (2012)
	Eastern Officer	Alinya Salt	Well (Mulyawara 1), seismic	Saline giant	Rodinia Oil (2011)
	Western Officer	Browne Fm	Wells (Browne 1, etc.), diapirs on seismic and AEM	Saline giant	Carr *et al.* (2012)
	Polda	Kilroo Fm	Well (Mercury 1), seismic	Saline giant	Nelson *et al.* (1986)
	Bremer		Seismic diapirs	Saline giant?	Bradshaw *et al.* (2013)
Mesoproterozoic–Paleoproterozoic	Greater McArthur	None identified	Dolostones	Marine platform?	Hall *et al.* (2020)

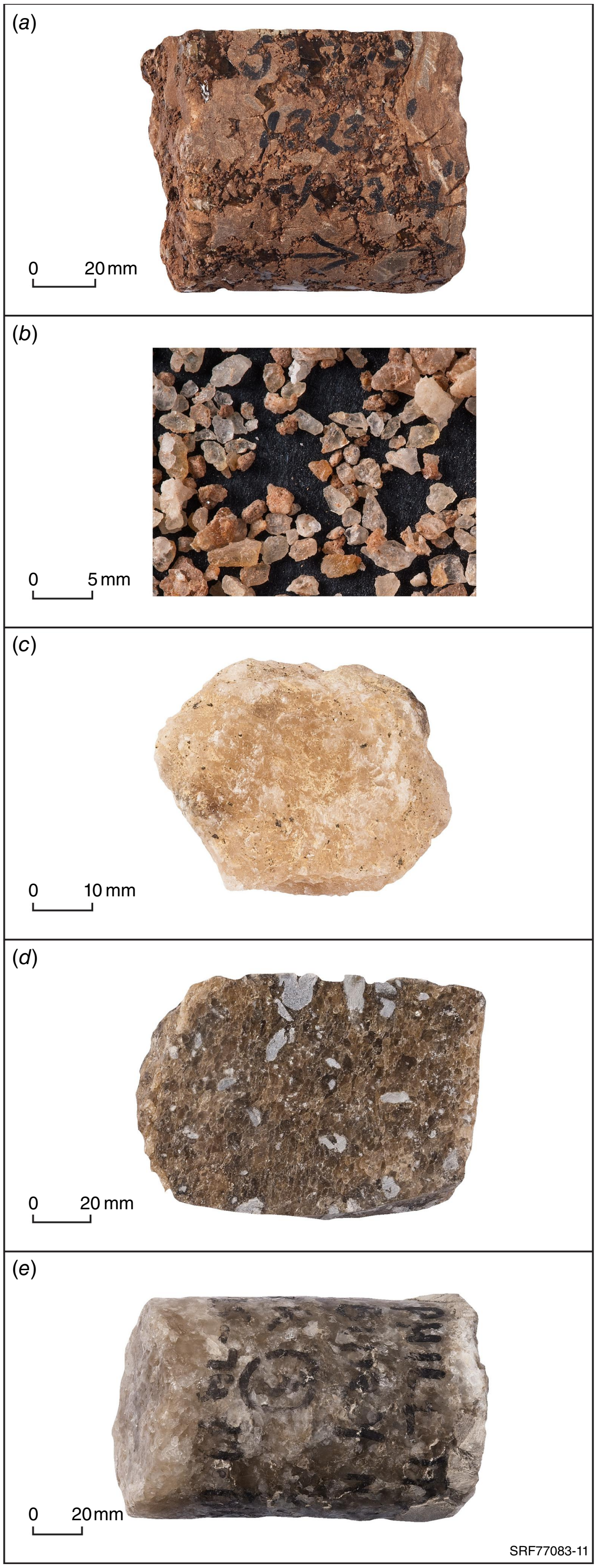

Fig. 2. (*Caption on next column*)

Fig. 2. Photographs of salt core and cutting samples stored at Geoscience Australia, showing (*a*) Ordovician Mallowa Salt, Kidson 1, Canning Basin; (*b*) Neoproterozoic Kilroo Formation, cuttings from Mercury 1, Polda Basin; (*c*) Cambrian Chandler Formation and (*d*) Neoproterozoic Gillen Formation, Mt Charlotte 1, Amadeus Basin; and (*e*) Middle Devonian Boree Salt, Boree 1, Adavale Basin.

(Kovalevych *et al.* 2006) and anhydrite is reported in the early Cambrian of the Arrowie Basin (Moorowie 1, see Table 1). The carbonate facies in Arrowie Basin extends further east into Bancannia Trough underlying the Darling Basin (Khalifa and Mills 2022).

True saline giants occur in the Amadeus (Cambrian Chandler Salt, Fig. 2*c*) and Canning (Late Ordovician Minjoo Salt and Late Ordovician–Silurian Mallowa Salt: Table 1, Fig. 2*a*) basins. Structural control was the key factor in creating the conditions to accumulate and preserve these thick salts, with the Lasseter Shear Zone forming a potential structural barrier restricting circulation between the Canning and Amadeus basins (Bradshaw *et al.* 2020). In the Southern Carnarvon Basin, there are evaporitic facies in the Late Ordovician–Silurian Dirk Hartog Formation, including the Yaringa Salt, which has been penetrated in wells and is up to 37 m thick (Table 1). These occurrences may point to other thick salt bodies, perhaps on the poorly explored Bernier Platform.

By the Devonian, marine conditions had retreated to the western and eastern margins of the continent, though tropical climates still held sway as indicated by the reefal carbonates found in both the Canning and Adavale basins. The Givetian Boree Salt in the Adavale Basin is thick halite that may be suitable for UHS and is discussed further in a case study. On trend to the south are Late Devonian red beds in the Darling Basin (Wilga Downs Group), where palaeographic interpretations of tenuous marine connections (Alder *et al.* 1998; Young and Lu 2020) suggest some potential for evaporitic facies to be present.

Thick salt occurs in the offshore Bonaparte Basin, where salt structures have been drilled in the Petrel (Sandpiper 1, Pelican Is 1, Kinmore 1) and Vulcan (Paqualin 1) sub-basins (Molyneux and Doyle 2021). Investigating the Canning Basin, McNee *et al.* (2021) present seismic data to indicate that the salt diapir drilled by Frome Rocks 1 may be Devonian in age and point to a third thick salt interval in the basin.

Mesozoic and Cenozoic evaporites

For much of the Late Palaeozoic and Mesozoic, Australia was near the South Pole and mostly beyond the mid-latitude arid belt. Clastic sediments deposited in fluvial, deltaic, glacial and marine environments dominate, carbonates are rare, and salt is absent (Boucot *et al.* 2013). However, diapiric features have been noted in seismic data collected on the Lord Howe Rise, in a section interpreted as possibly Early Cretaceous in

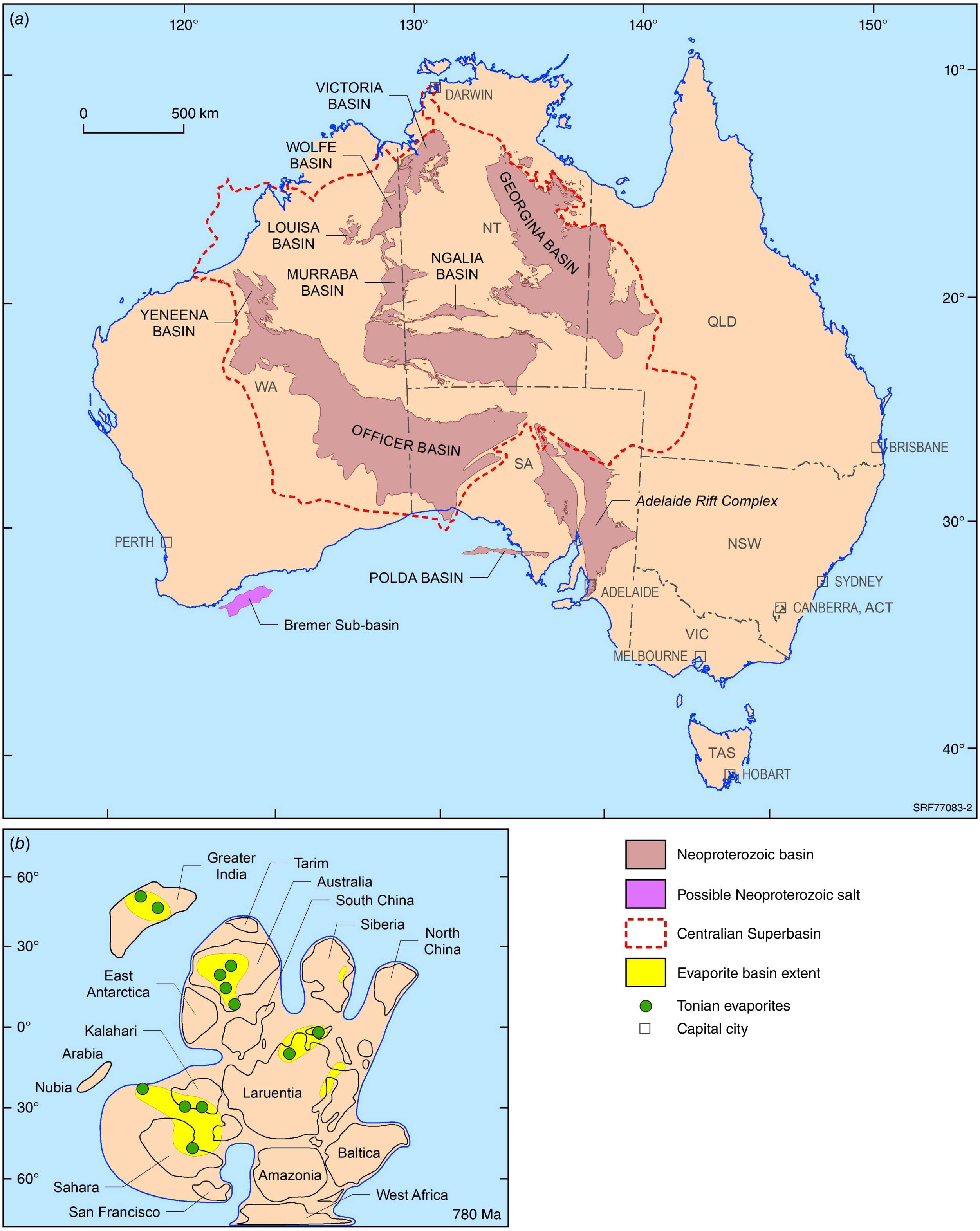

Fig. 3. Neoproterozoic basins and the Centralian Superbasin modified from Haines and Allen (2017) shown in (*a*). The Bremer Sub-basin pre-rift strata (interpreted to contain evaporites) is suspected to be equivalent to the Polda Basin or Officer Basin (Bradshaw *et al.* 2013). Insert (*b*) is distribution of known Tonian evaporite basins and their likely position at 780 Ma (Li *et al.* 2008, as cited in Schmid 2017).

age (Van de Beuque *et al.* 2003), and a thin anhydrite bed was intersected in Aquarius 1, Capricorn Basin (Fig. 1, Table 1), in a section considered to be Paleogene in age (Struckmeyer *et al.* 1994). One of the largest modern examples of a platform marine evaporite is Lake MacLeod, a coastal playa in Western Australia underlain by a graben where a 3–5 m thick Early Holocene bedded halite is overlain by an extensive (2–6 m thick, ~2000 km^2) gypsum deposit (Logan 1987; Mernagh *et al.* 2013).

Recognising salt in the subsurface

The review of Australian salt basins above shows that there are specific time periods and basin settings where evaporite deposition is favoured. However, the uncertainty surrounding the modes of formation of thick halite deposits increases the importance of empirical evidence rather than conceptual models to find salt in the subsurface.

Geophysical evidence

Geophysical methods such as airborne electromagnetic (AEM), seismic, gravity and magnetics can be used as indirect evidence of salt. The AEM method detects electrical conductivity variations (from rock and pore fluid) in the subsurface (Wilford 2022), whereas seismic reflection data measures acoustic impedance contrast (density and velocity) (Bain *et al.* 1991). Gravity and magnetic data estimate lateral changes in density and magnetic mineral content respectively (Bain *et al.* 1991).

Geoscience Australia's recent study in the Canning Basin shows how AEM data can be used to image localised folding/faulting of a shallow conductive unit that may have formed above isolated salt domes (Connors *et al.* 2022). Although the Canning Basin salt units are deeper than the AEM depth of investigation (salt identified at depth >500 m), distinct zones of disruption within the shallow conductive unit from salt dissolution and mobilisation were observed along the margins of the present-day salt occurrence (Connors *et al.* 2022).

Although seismic data has been successfully used to image salt in the Gulf of Mexico (Winker 1996), the Norwegian North Sea (Jones and Davison 2014), the western and central United Arab Emirates (Stewart 2018) and the Canning Basin in Australia (Zhan 2019), there are some cases when seismic data fails to image salt. Reasons for this include poor seismic coverage, which is inadequate to capture salt geometry that may change rapidly in space; only a slight acoustic impedance contrast at the salt-sediment interface; and complex salt structures that dip steeply or are surrounded by faults (Jackson and Hudec 2017). In these cases, gravity gradiometry and high-resolution magnetic data can be used to improve salt imaging (Stadtler *et al.* 2010; Debacker *et al.* 2016).

Other subsurface features, such as mud diapirs, granitic intrusions or gas chimneys, can also be mistaken for salt diapirs. Gas chimneys are seen as vertically disturbed zones with a chaotic reflection pattern inside where the seismic reflections are discontinuous and its amplitudes are weaker (Løseth *et al.* 2009; Virs 2015; Singh *et al.* 2016) (Fig. 4). One major characteristic of gas chimneys that differs from salt is that they are often associated with low-velocity anomalies in seismic profile from the presence of free gas in the sediment, which is identified by the velocity 'push down' feature observed above the chimneys (Virs 2015). The main factor distinguishing igneous bodies from salt is the geometry of sediments around the two features. Salt structures are associated with syn-depositional growth into the structure (e.g. mini basins/rim synclines) or collapse structures (e.g. half turtle structures) where accommodation space is being created while the structure forms (Mauduit *et al.* 1997; Banham and Mountney 2013; Duffy *et al.* 2017) (Fig. 4). In contrast, igneous intrusions have no associated growth or collapse of adjacent sediments. Although mud diapirs can have similar shape to salt diapirs, they usually have no impedance contrast (from lithology) to their surrounding sediment (Jackson and Hudec 2017). Where a mud diapir is over-pressured, the interface may have a negative reflection coefficient and is commonly gradational, unlike the top salt structures that usually have strong reflection (Jackson and Hudec 2017).

Case studies

The case studies below show how geophysical evidence combined with well data and other regional geological information can be used to develop prospects and plays for UHS.

Polda Basin – UHS prospect in a proven thick salt in an offshore basin

Hydrogen storage in offshore basins salt caverns has received little attention in Australia but is under active consideration in the Netherlands (Innovation Origins 2022), and Ireland is developing three offshore UHS projects (Chedwynd 2021; dCarbonX 2021; ESB 2021). In Australia, the Polda Basin has the potential for UHS in the Neoproterozoic Kilroo Formation. The intracratonic Polda Basin extends 350 km from the Eyre Peninsula to the centre of the Great Australian Bight and contains Proterozoic–Jurassic sedimentary fill (>5000 m), including halite of the Kilroo Formation (Fig. 5) (South Australia Department for Energy and Mining 2021). The Kilroo Formation was deposited in an arid terrestrial fluvial and endorheic playa lakes environment (South Australia Department for Energy and Mining 2021) and is another Tonian saline giant roughly coeval with those in the Amadeus and Officer basins. Salt interpreted from seismic data in the undrilled Bremer Sub-basin (west of the Polda Basin) is also proposed to be part of the Tonian evaporite deposition (Bradshaw *et al.* 2013;

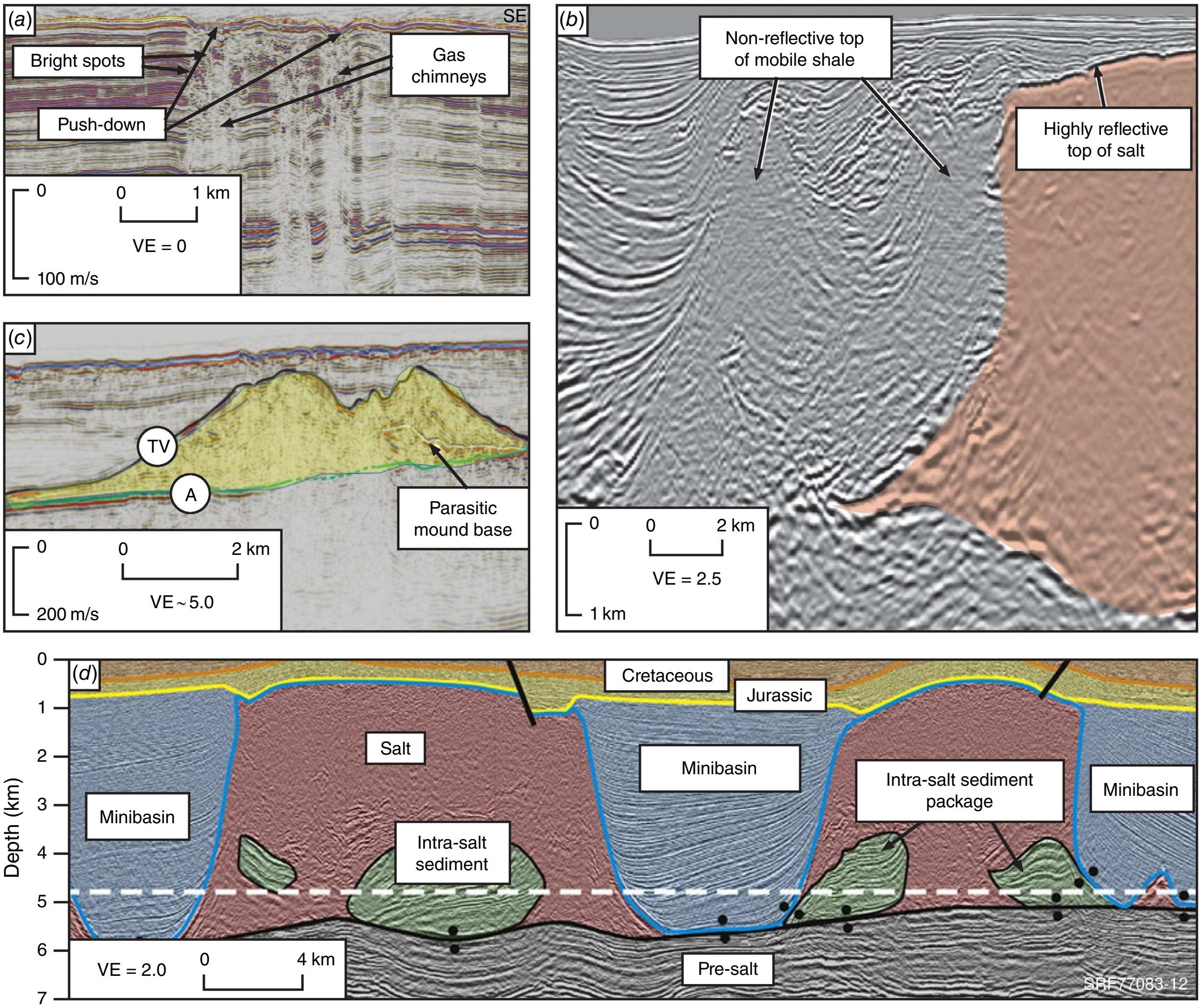

Fig. 4. Seismic signatures of various subsurface events that may be mistaken as salt. (*a*) Gas chimneys seismic signature with push-down feature and chaotic reflection pattern inside the chimneys modified from Virs (2015). (*b*) Vertical seismic section showing mud/shale diapir (non-reflective) and salt diapirs (strong reflection at the top of salt) modified from Jackson and Hudec (2017). (*c*) Vertical seismic section showing volcanic intrusion (yellow) modified from Magee *et al.* (2013). (*d*) Interpreted seismic cross-section of salt and associated minibasins feature in southern Precaspian Basin from Duffy *et al.* 2017). VE, vertical exaggeration.

Cunneen *et al.* 2019) (Fig. 6). The salt was first identified on seismic data pre-drill (Nelson *et al.* 1986). Three wells drilled down to the Kilroo Formation (Columbia 1, Mercury 1 and Kilroo 1A), but only Mercury 1 penetrated the halite body with a net halite thickness of 1000 m (Feitz *et al.* 2022).

Feitz *et al.* (2022) conducted UHS feasibility analyses on the Kilroo Formation in the anticlinal Mercury structure in the central Polda Basin (Fig. 7). The Mercury structure, located 60 km offshore and 200 km away from Port Lincoln, has a net halite thickness >1000 m and total potential area of 217 km^2 (Feitz *et al.* 2022). Well data from Mercury 1 suggests the basin has a low thermal gradient (1.7–2.1°C/100 m) and an overburden pressure gradient of approximately 18 pounds per gallon, providing effective gas operation pressure for UHS. The Caglayan *et al.* (2020) methodology was used to estimate a UHS capacity for a conceptual design of cylindrical halite caverns with 60 m and 100 m diameters for a depth range of 1650–2000 m with a water depth of 77 m. The storage capacities of these conceptual caverns were estimated to be 240 GWh and 665 GWh, respectively (Feitz *et al.* 2022). To put energy storage scale into perspective, one of Australia's largest energy storage resources, the Snowy 2.0 pumped hydro project, will have a storage capacity of 350 GWh once operating in 2026 (Snowy Hydro 2020).

Adavale Basin – UHS prospects in a proven thick salt in an onshore basin

The Boree Salt in the Adavale Basin is the only proven thick halite in eastern Australia and presents a potential option for

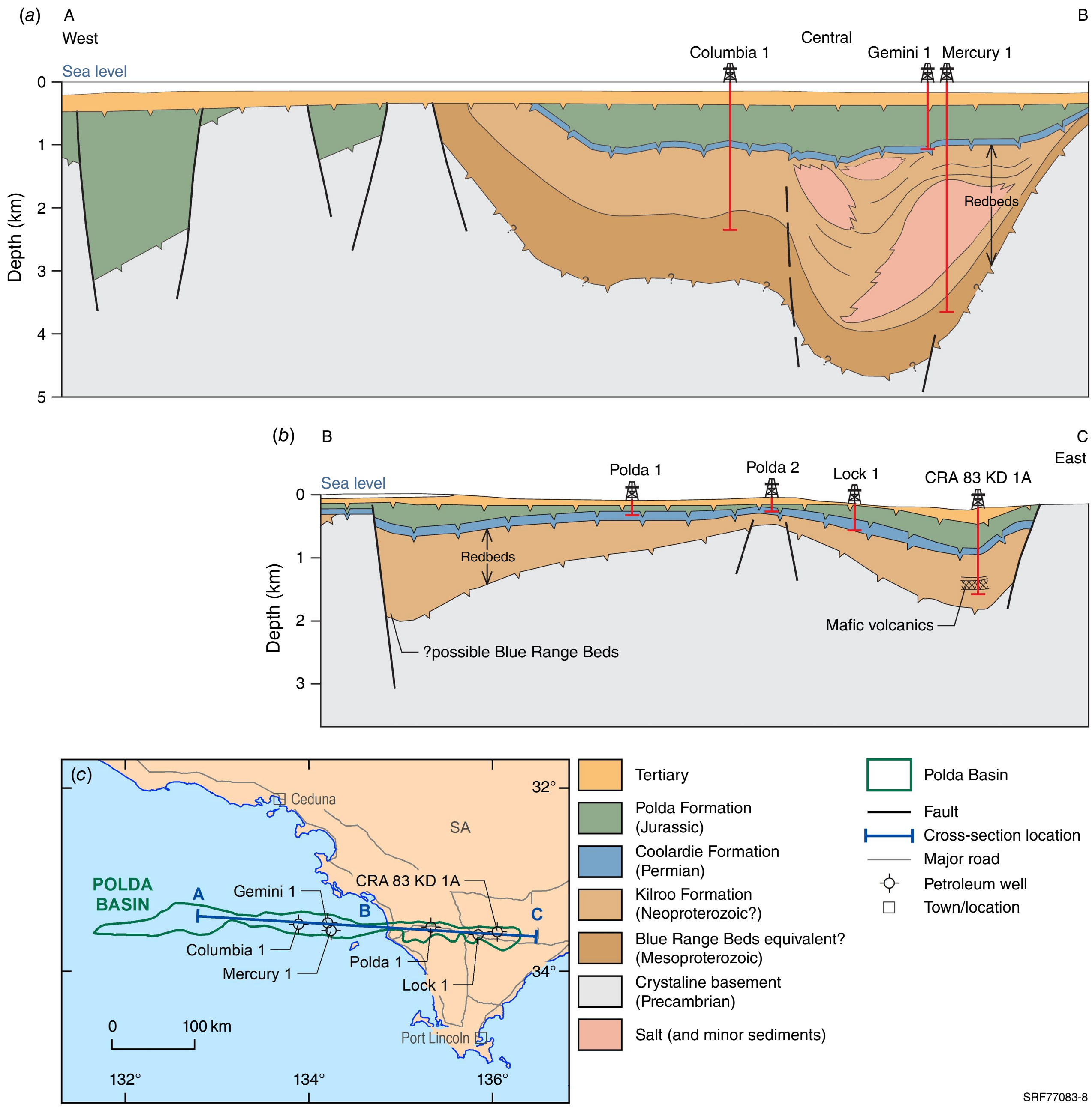

Fig. 5. (*a*) and (*b*) are the Polda Basin cross-section from west to east and wells locations (South Australia Department for Energy and Mining 2021). (*c*) Map showing the Polda Basin location and the cross-section A-B-C line shown in (*a*) and (*b*). Mercury 1 is located offshore, approximately 60 km from the Eyre Peninsula.

onshore UHS, given the basin's strategic location relatively close to industrial infrastructure, existing pipelines and good renewable energy sources. A preliminary 3D model by Paterson *et al.* (2022) identified three main salt bodies that may be suitable for salt cavern construction and UHS (Fig. 8*a*). The 3D model was generated by integrating well log interpretations, time-based maps from the 1960s, 2D seismic lines from the 1980s and the results of Boyd Petrosearch's (2010) investigation on potash and salt in the region (Paterson *et al.* 2022). The largest salt body, intersected by four wells (Bury 1, Alva 1, Bonnie 1 and Stafford 1, Fig. 8*b*), appears to be a suitable target for further characterisation and potential construction of salt caverns (Paterson *et al.* 2022). Additional salt bodies were intersected at Rosebank 1 and Boree 1. The salt in Boree 1 is >500 m, but its depth (1923–2426 m) requires careful planning for constructing UHS at this location. Ennis-King *et al.* (2021) reported that high pressure and temperature below 1800 m might lead to salt deformation and cavern instability issues.

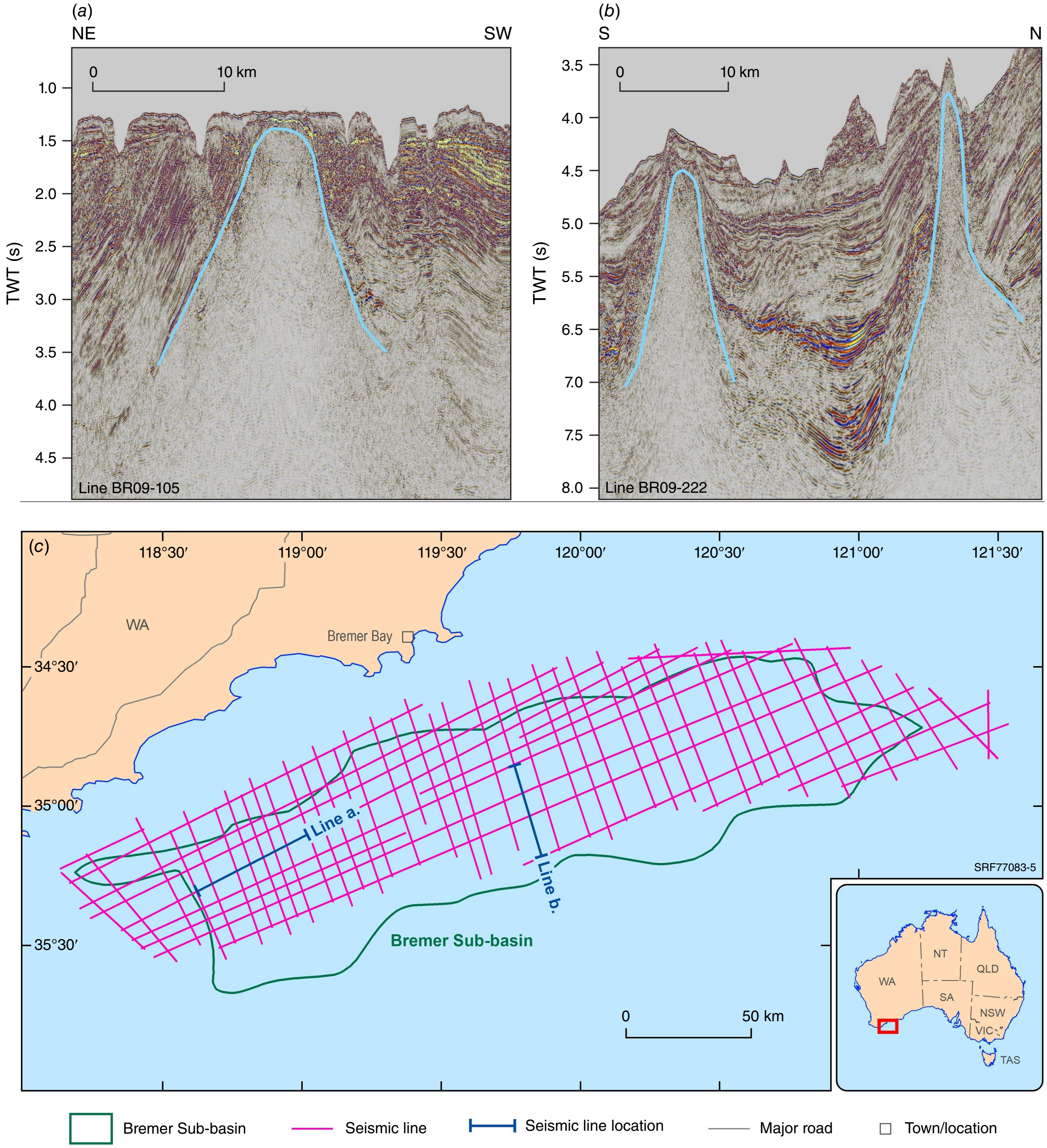

Fig. 6. (*a*) and (*b*) are salt-lead features on 2D seismic cross-sections identified in deep-water (>2.2 km depth) in the central Bremer Sub-basin. These salt-lead structures are suspected to be older than the six Mesozoic seismic stratigraphic units (Bremer 1–6) identified by Bradshaw (2005). (*c*) Shows 2009 Arcadia 2D seismic survey over the Bremer Sub-basin in offshore Western Australia. TWT (s), two-way time in seconds.

Officer Basin – onshore frontier basin for UHS

Evaporites in the Tonian Browne Formation have been intersected in seven wells in the western Officer Basin (Browne 1, BMR Madley 1, GSWA Lancer 1, GSWA Empress 1, Kanpa 1, Yowalga 3 and Kutjara 1), and halite has also been drilled in the eastern Officer Basin. Previous studies (Simeonova and Iasky 2005; Carr *et al.* 2012) have identified shallow expressions of possible salt diapirism in the western Officer Basin. Frontier, regional-scale

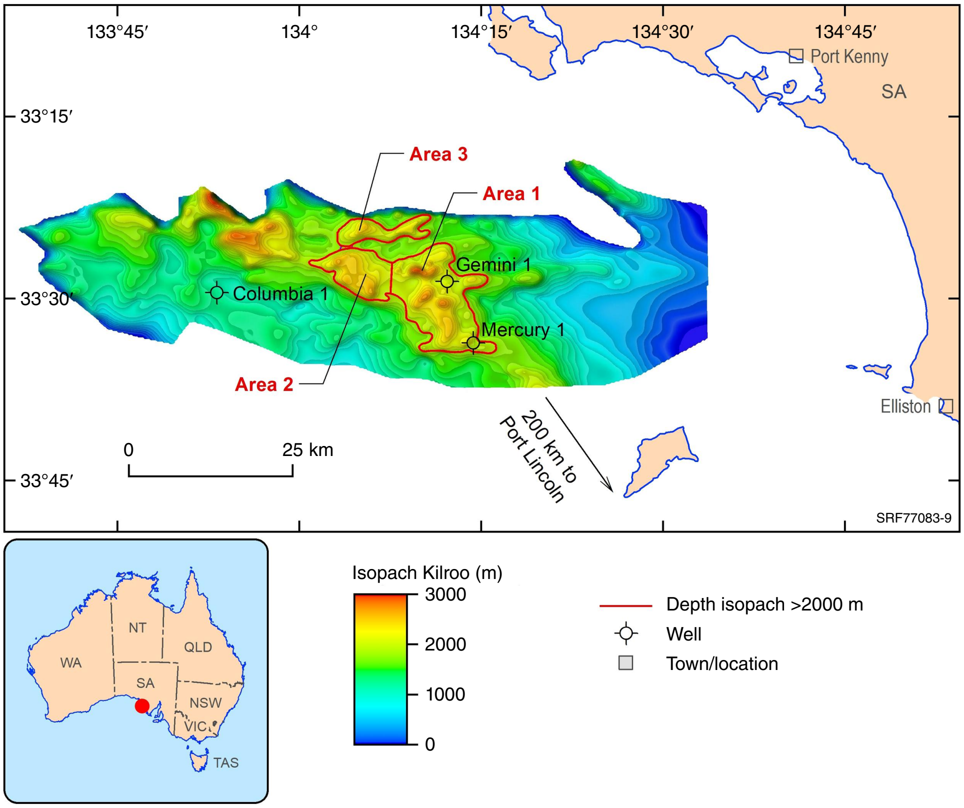

Fig. 7. True vertical depth of the Kilroo Formation in the offshore Polda Basin. Red polygons represent three potential UHS areas within the Mercury structure salt deposits identified by Feitz *et al.* (2022).

reconnaissance of 2D seismic profiles identified a first-pass inventory of possible large salt leads suitable for UHS. Although the area is only covered by broadly spaced 2D seismic profiles of mixed recording vintage and image processing quality, the sampling was sufficient to reveal the scale and depth of potential salt structures (Fig. 9). To date, the crests of the shallowest possible salt-related features occur around 500 m depth in the subsurface.

A preliminary investigation on the recently acquired Geoscience Australia AEM dataset (Ley-Cooper 2020, 2021) has shown a correlation between anomalies in AEM conductivity sections to the areas of known and potential salt features over the western Officer Basin. The AEM data was compared to potential salt leads identified in seismic (Fig. 9) and the Salt Intrusions dataset from the Geological Survey of Western Australia's Western Australian Petroleum and Geothermal Management System (WAPIMS). Other supporting datasets, such as borehole data, geological maps, gravity, magnetics and elevation data, were included in the assessment. Areas identified as hosting salt intrusions in the WAPIMS dataset correlated with potential salt-related features observable in the seismic and AEM data (Fig. 10). Several AEM conductivity sections showed truncation of horizontal conductive horizons by more resistive geology in areas highlighted by the Salt Intrusions dataset and seismic interpretation. In most cases, these features also correlated with anomalous features observed in the gravity and magnetics datasets.

Integration of seismic and AEM methods has helped to refine the subsurface distribution of such features, where they can be observed extending across several of the nominally 20 km-spaced AusAEM (Ley-Cooper 2021) lines. In some cases, the distribution of the potential salt features can be extended a significant distance (over 40 km) from the current extent highlighted in the Salt Intrusions dataset by integrating the AEM data with other datasets.

Given the regional sparsity of subsurface data, a multi-parameter, play-based, common-risk segment mapping approach, similar to that used with other resource types, could elucidate key subsurface uncertainties and risks. De-risking requires a multi-disciplinary approach that includes a combination of geophysical methods and an increase in survey density and perhaps regional hydrogeochemistry. Integrated geophysical data interpretation (seismic, AEM, gravity and magnetic with shallow seismic images) could help change the subsurface understanding at both a play and prospect level. Although new seismic acquisition would improve the current subsurface understanding, a considerable cost-effective uplift could be gained through selected reprocessing of key seismic profiles, particularly given that most seismic data is over 20 years old.

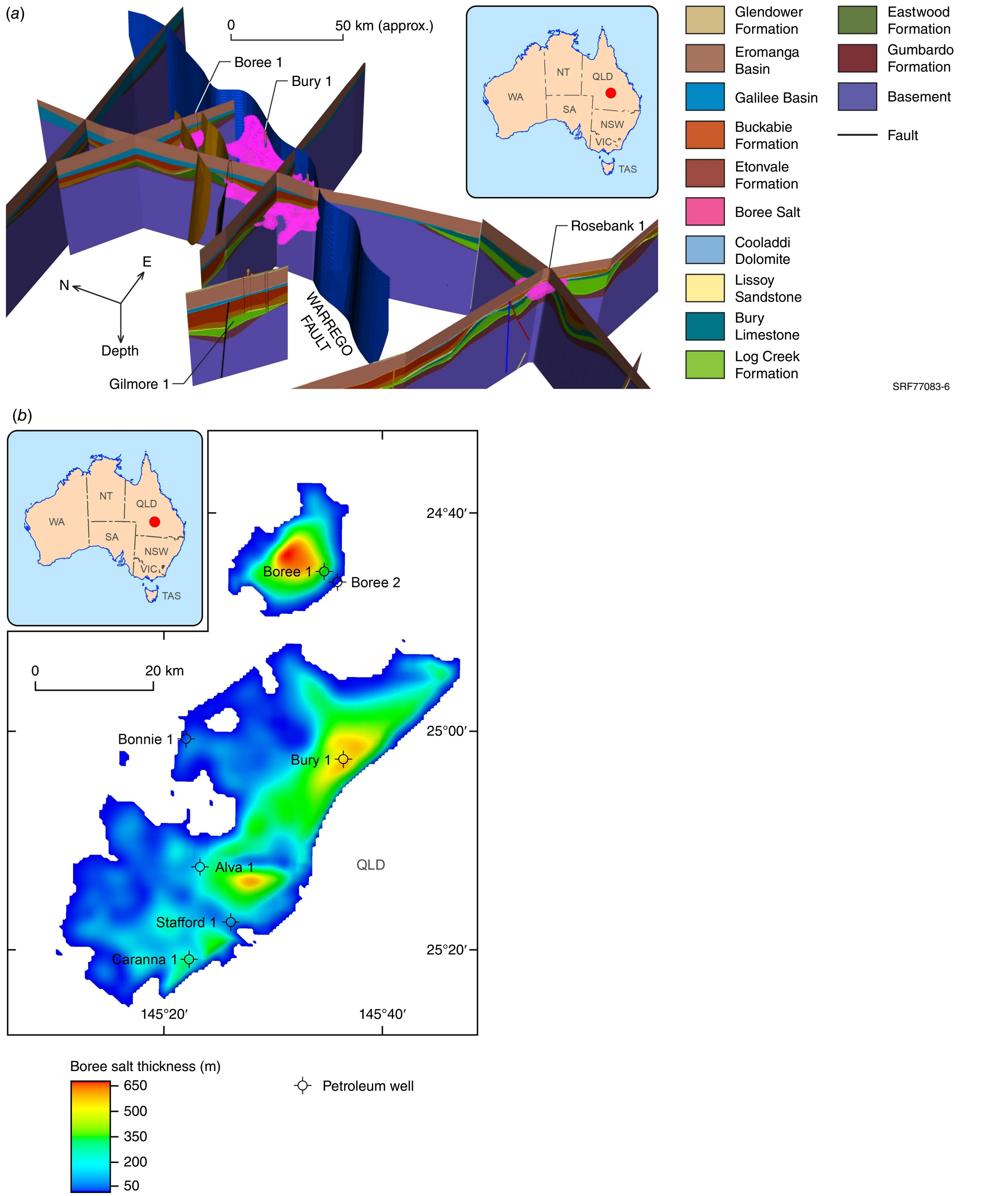

Fig. 8. (*a*) Adavale Basin 3D view of geological transects, three Boree Salt bodies and faults from Paterson *et al.* (2022). Bury 1 well intersected the main salt body. (*b*) Thickness of Boree Salt in the Adavale Basin.

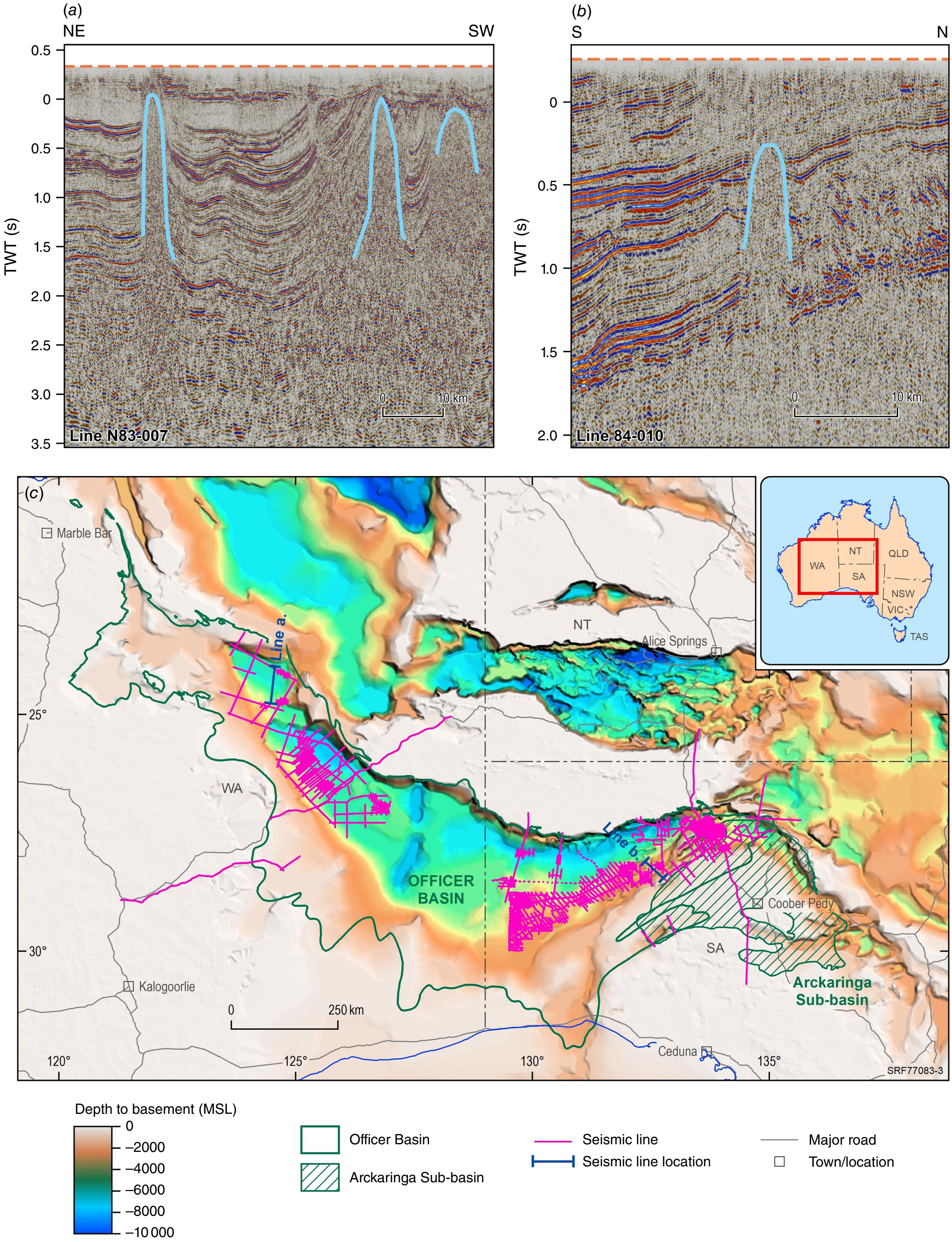

Fig. 9. (a) and (b) are salt-lead features on 2D seismic cross-sections identified in the western and eastern regions of the Officer Basin. (c) A map showing 2D seismic surveys over the Officer Basin and Arckaringa Sub-basin with OZ SEEBASE (Geognostics 2021) map in the background. MSL, mean sea level; TWT (s), two-way time in seconds.

Amadeus Basin – options for UHS and natural hydrogen play development in an onshore basin

The Amadeus Basin has two thick halite sequences: (1) the Cambrian Chandler Formation and (2) the Tonian Gillen Formation (Livesey 2015). The Chandler Formation salt is an extensive evaporite deposit with an average halite grade of 88.6%, with individual layers of high-grade halite (~98%) (Livesey 2015; Scrimgeour 2015). Although its structure can be flat-lying at Mt Charlotte 1 and Magee 1 (thickness varying between 200 and 261 m) (Livesey 2015), the Chandler Formation salt also exists as diapirs at Bluebush 1 (>400 m) (Fig. 11). This salt deposit has been targeted as an underground salt mine and deep geological waste repository under the Chandler Project (Scrimgeour 2015; Tellus Holdings 2022).

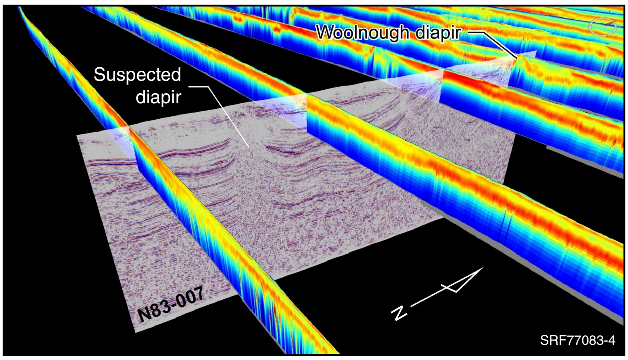

Fig. 10. The Woolnough diapir that was identified as hosting salt intrusions in the seismic dataset correlated with potential salt-related features observable in the AEM data.

The Tonian Gillen Formation contains a massive halite in between anhydrite/dolostone units (Plummer 2021). The evaporites outcrop in the northern Amadeus Basin and occur as diapiric structures and salt pillows at depths below 1900 m at Magee 1, Murphy 1 and Mt Charlotte 1 in the southern Amadeus Basin (Plummer 2021) (Fig. 11). The thickness also varies from approximately 200 m at Magee 1 and Mt Charlotte 1 to >700 m at Murphy 1 (Livesey 2015).

The potential for UHS construction in the Amadeus Basin is likely to be in the diapiric structures. However, further analysis is required to determine UHS feasibility in the Gillen Formation and Chandler Formation salts. Natural hydrogen and helium have been reservoired in the Amadeus Basin at Mt Kitty where sealed by thin anhydrite (Boreham *et al.* 2018).

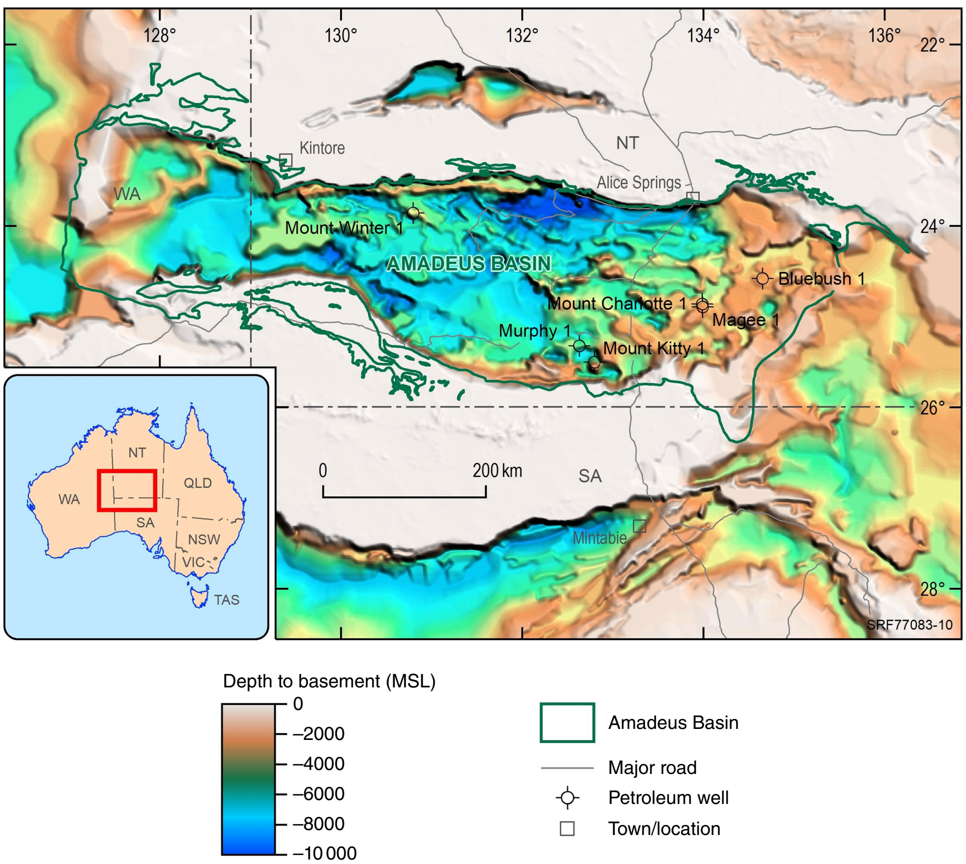

Fig. 11. Petroleum wells with halite in the Amadeus Basin with OZ SEEBASE (Geognostics 2021) map on the background.

Discussion and conclusions

Australia has many examples of saline giants with thick halite sequences and salt structures that may be suitable for UHS. The age, facies and structural setting of rock packages can give a guide to where evaporites may extend beyond the proven well intersections. However, geophysics (seismic, AEM) will be the primary exploration tool, followed by drilling to test the thickness and purity of the interpreted salt bodies. Some basins (Amadeus and Canning) have more than one proven salt 'play' as well as the potential for natural hydrogen accumulations. The subsurface data sets, skills and exploration strategies developed by the petroleum industry can be repurposed for these new targets – thick salt for UHS and salt as a seal for natural hydrogen accumulations.

Economic and engineering considerations can high-grade identified prospects, and the Hydrogen Economic Fairways Tool (Geoscience Australia 2022) can be used for an initial screening of locations. For example, the Darling Basin in western NSW has no proven salt in the subsurface except for two intervals (Cambrian and Devonian) where evaporitic facies may have developed, and it is located closer to where UHS may be needed than proven salts in the western Officer Basin.

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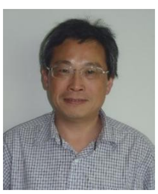

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