Author/s:
Beardsmore, GR

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REVIEW ARTICLE

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A review of hot sedimentary aquifer geothermal resources in Australia

Graeme R. Beardsmore

School of Geography, Earth and Atmospheric Sciences, University of Melbourne, Parkville, Australia

ABSTRACT

Numerous currently operating, past and potential future geothermal energy projects in Australia depend on heat from hot sedimentary aquifer (HSA) sources. The relevant aquifers cover a range of geographical and geological settings. Currently operating geothermal energy projects in Australia (excluding ground source heat pumps) predominantly utilise 40–70°C aquifers in the Gippsland Basin, Otway Basin and Perth Basin. Economic assessments have demonstrated that heat from these sources is significantly cheaper than heat from natural gas. Electrical power has previously been generated using 87–99°C water from aquifers in the Great Artesian Basin in South Australia and Queensland, but those generators are now decommissioned. A project to generate power using >150°C groundwater from deep in the Otway Basin in 2010 was suspended and subsequently abandoned when initial production did not meet commercial requirements. Several new projects, particularly in Western Australia, are in the stage of technical and economic pre-feasibility for geothermal power generation from >150°C groundwater. Preliminary techno-economic assessments may be favourable, but existing regulatory constraints pose major impediments to further development of hot sedimentary aquifers in parts of Australia.

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Introduction

Geothermal energy in Australia

The Commonwealth of Australia occupies 7.7 million square kilometres of continental land area and supported a population of 26.5 million in March 2023 (ABS 2023), two thirds of whom (17.5 million people) lived in the eight state and territory capital cities (ABS 2021–2022), with most of the remainder living in regional towns and cities in the southeast of the country (Figure 1; ABS 2011). In spite of its modest population, Australia is an energy-hungry nation, ranking 14th out of 80 countries for energy consumption per capita in 2022 (c.f. New Zealand ranked 23rd) as reported by the Our World in Data organisation (Ritchie 2021). Interest is growing in Australia for domestic energy sources with low greenhouse gases emissions, of which geothermal energy is one option for both heat and electricity.

Located wholly within the interior of the Australian tectonic plate (Figure 1), the Australian continent lacks geological phenomena often associated with large-scale production of geothermal energy (e.g. active volcanoes, fumaroles, geysers, steaming ground, boiling mud), which are commonly found along active tectonic margins. Given a broad definition of geothermal energy as any extractable and useable natural heat in the Earth from the surface downwards, however, Australia's tectonic circumstances do not preclude access to geothermal energy. But they do predominantly limit prospectivity to 'intracratonic basin' and 'crystalline rock / basement' geothermal play types as defined by Moeck and Beardsmore (2014).

In the early part of the twenty-first century, Geodynamics Ltd (GDY) made a serious, though ultimately uncommercial, attempt to generate geothermal power from a crystalline basement geothermal play. Between the late 1990s and the early 2010s, GDY planned and drilled six wells into 250°C fractured crystalline rocks at a depth of about 4.5 km beneath the Cooper Basin in a remote location in central Australia, and ultimately achieved a significant technical milestone by generating geothermal power from a 1 MWe pilot plant for a demonstration period of 160 days. Readers are referred to Hogarth and Holl (2017), Budd and Gerner (2015), Huddlestone-Holmes (2014) and other sources for a fuller history of Geodynamics' project.

There may be future attempts to commercialise geothermal energy production from crystalline basement geothermal plays in Australia. A large portion of the Australian continent, however, is covered by Phanerozoic-aged sedimentary basins (Figure 1), suggesting that intracratonic basin geothermal plays provide an extensive range of opportunities for geothermal energy production. Indeed, this paper

CONTACT Graeme R. Beardsmore g.beardsmore@unimelb.edu.au

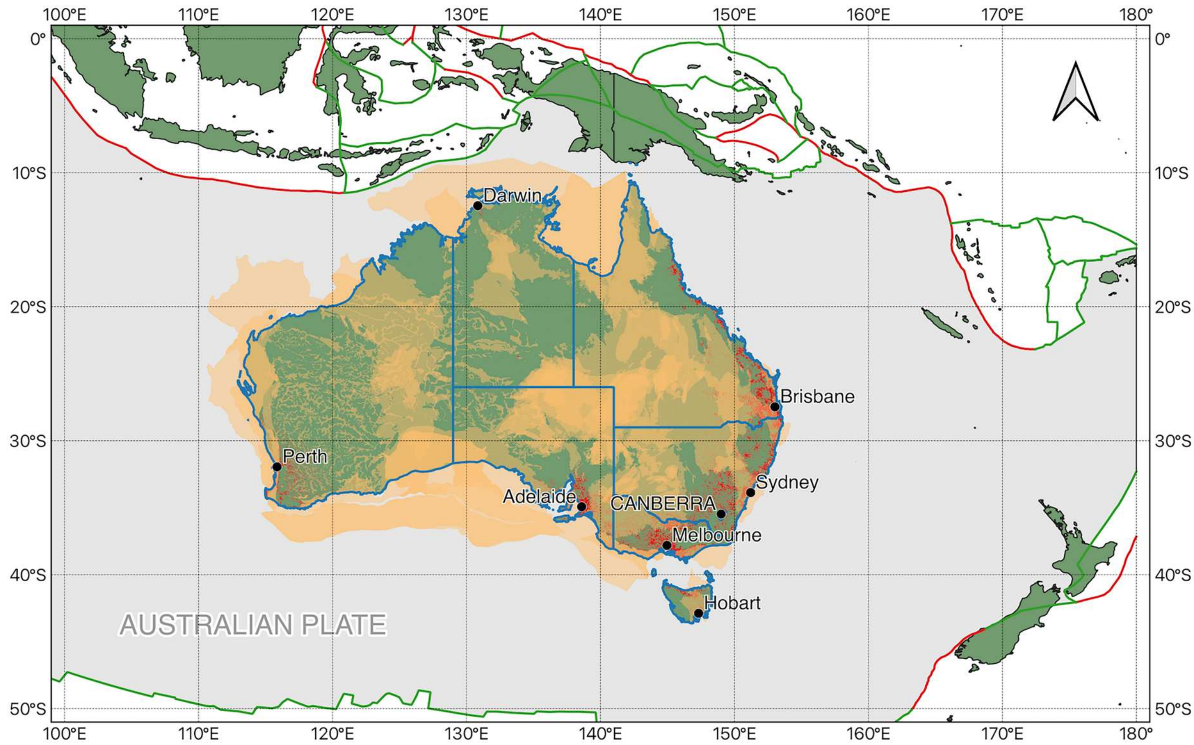

Figure 1. Australia (states and territories outlined in blue with capital cities labelled) lies wholly within the Australian Plate (grey shading). Phanerozoic-aged sedimentary basins with onshore segments (Raymond et al. 2018) are shaded orange. Red shading indicates centres of population (ABS 2011). Regional subduction zones (red lines) and other boundary types (green lines) after Bird (2003).

will demonstrate that all geothermal energy presently being produced in Australia is from intracratonic basin sources. Although the thermal energy theoretically contained in the basins might be enormous, the quantities of geothermal energy currently being produced are small by global standards. Beardsmore et al. (2023a) reported 36 MW_t of installed geothermal heating and cooling capacity in Australia in 2023, representing just 0.02% of the global total geothermal heating and cooling capacity of 173 GW_t (IGA 2023). Beardsmore et al. (2023a) furthermore reported no operating geothermal electricity generators in 2023.

This paper aims to provide a broad review of the past, current and potential future production of geothermal energy from sedimentary aquifers by real or proposed geothermal projects in Australia. Its geographic scope is the full extent of the onshore Australian continental landmass. While the author aimed to be as comprehensive as possible, he does not warrant that it includes every instance of geothermal energy production from sedimentary sources.

Terminology

This paper uses the terminology of the UNFC – the United Nations Framework Classification for Resources (UNECE 2019; IGA 2022). Specifically, the terms 'source', 'resource', 'known' and 'potential' have specific meanings with respect to geothermal energy under UNFC. A reference to a geothermal energy 'source' in this paper means a volume of underground rocks, sediments and pore fluids containing thermal energy which is available for extraction and/or conversion into process heat or electricity. Geoscientists might think of a 'source' as a subsurface reservoir of heat. A reference to a geothermal energy 'resource' means the total quantity of process heat or electricity that a project will produce over its lifetime. The emphasis here is on actual energy to be produced and utilised at the Earth's surface, considering all recoverability and energy conversion processes.

The word 'known' used in this paper in reference to a geothermal energy source means that the ability to commercially produce geothermal energy from the source has been established beyond reasonable doubt through testing, sampling and/or production. The word 'potential', however, means that the existence of recoverable energy and the commerciality of geothermal energy production has not yet been established.

A distinction is often made between 'shallow' and 'deep' geothermal systems (e.g. Stober and Bucher 2021) but the terminology can be misleading because the distinction typically relates to the technology of heat delivery rather than the depth of the geothermal source. By most definitions, 'shallow' geothermal systems require heat pumps to deliver usable heat while 'deep' geothermal systems do not. The author notes there is no global consensus on the depth threshold between 'shallow' and 'deep' geothermal sources. For example, the British Geological Survey defines 'shallow' geothermal sources as shallower than 500 m (BGS 2024) while Goetzl et al. (2020) documented definitions from six other European countries ranging between 100 m and 400 m. This paper focusses on 'deep' geothermal systems within the technology definition above, but assumes no specific depth threshold.

Hot sedimentary aquifers

The scope of this paper is limited to a review of Australian 'Hot Sedimentary Aquifer' geothermal resources (HSAs). The entry for 'Hot Sedimentary Aquifers' in 'Thermopedia' – an online guide to thermodynamics terminology (DOI: 10.1615/thermopedia.010322) – defines HSAs as 'a type of geothermal resource that involves the extraction of geothermal energy from permeable sedimentary rock formations containing hot water or steam'. This paper applies a more restrictive definition. Namely, an HSA is a voluminous, water-saturated, porous and permeable sedimentary rock of sufficient temperature and yield to sustain economic heat production without significant reservoir engineering, either with or without reinjection of the spent water (Figure 2). The author assumes no explicit minimum values for either temperature or yield, or limitations on the processes to which the heat can be applied – power generation, industrial processes or domestic heating. The only requirement is that heat production sustainably meets the technical and economic requirements of the process to which it is applied.

The definition of HSA given above limits the scope of the paper to heat contained within Australian sedimentary basins. It excludes geothermal energy projects which will require (or have required) significant permeability enhancement or closed-loop borehole heat exchangers. High profile projects such as the Habanero 'engineered geothermal system' (EGS) previously developed by Geodynamics Ltd in the basement beneath the Copper Basin (e.g. Hogarth and Holl 2017), the Paralana EGS project previously conducted by Petratherm Ltd (e.g. Reid and Messeiller 2013), the conduction-only 'advanced geothermal system' (AGS) project proposed by Greenvale Mining Ltd in the Millungera Basin in Queensland (e.g. GRV 2023), and other EGS/AGS projects, therefore, are not discussed.

Structure of the paper

Given the purpose and scope of the paper, it logically suits a structure based on a basin-by-basin review. To that end, the paper is divided into sections focussed on individual basins (e.g. Gippsland Basin). For each basin with known or potential HSA geothermal energy resources, the paper describes the geological context of HSAs within the basin sequence, and the past, present and potential future production and utilisation of geothermal energy from the HSA sources. Power and energy quantities are included for some of the basins and projects, but most are described in a qualitative sense. Specific challenges or issues related to the production of geothermal energy are also described for some individual HSAs.

The following review might not cover every known and potential HSA geothermal energy source in Australia, but it aims to present a reasonably comprehensive picture of the regional and end-use diversity of the industrial processes to which HSA geothermal energy has been or could be applied.

Australia's geothermal basins

Overview

The Australian continent is known for its exposed Precambrian shield areas with some of the oldest rocks

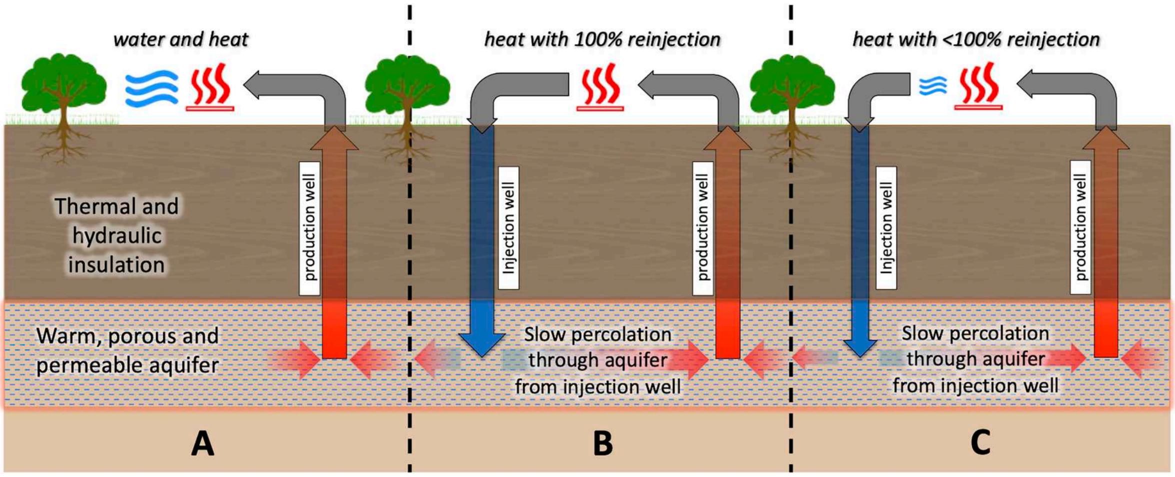

Figure 2. HSAs provide energy through the medium of warm or hot water drawn from naturally porous and permeable aquifers via a production well. When cooled, the water may be wholly consumed (A), disposed of via an injection well into the same or a different aquifer (B), or partially consumed with the balance of water reinjected (C).

(e.g. Hickman-Lewis et al. 2022) and detrital minerals (e.g. Wilde et al. 2001) in the world, but relatively young and undeformed sedimentary basins cover a significant portion of the continent. Data sets from Geoscience Australia (Raymond et al. 2018) and Geognostics (2021) indicate that Phanerozoic sedimentary basins overlie about half the continent (Figure 1). Such basins invariably contain water-saturated formations at temperatures greater than the ambient surface air temperature, and therefore *prima facie* potential for hosting HSA geothermal energy sources.

International experience demonstrates that even small temperature differentials between groundwater and the atmosphere can be exploited for geothermal energy using (for example) groundwater-source heat pumps if market conditions support their development (e.g. Previati and Crosta 2021; Gizzi et al. 2023), but the potential for such exploitation has been poorly researched and little incentivised in Australia. Exploitation of HSA geothermal energy sources in Australia has been (and will be for the foreseeable future) limited to locations where geothermal energy is the cheapest option for industrial heat supply within the competitive local energy market. Figure 3 illustrates the locations and extent of sedimentary basins mentioned in this paper.

The author is unaware of any national collation or synthesis of aquifer permeability or water quality data to simplify a review of HSA geothermal resources in Australia. Some data for individual aquifers and basins, however, are published in disparate sources and formats. The following sections present such data where available.

Eromanga Basin (aka 'Great Artesian Basin')

Geological context

The Australian continent hosts one of the world's largest contiguous groundwater systems. Underlying one million square kilometres (approximately 13% of the exposed continental area of Australia) and comprising the largest portion of the 'Great Artesian Basin' (GAB), the Eromanga Basin (Figure 4) straddles four states and territories and is a critical source of water for pastoral leases, communities and the mining industry in central eastern Australia (Habermehl and Pestov 2002; Alexander and Cotton 2007). The

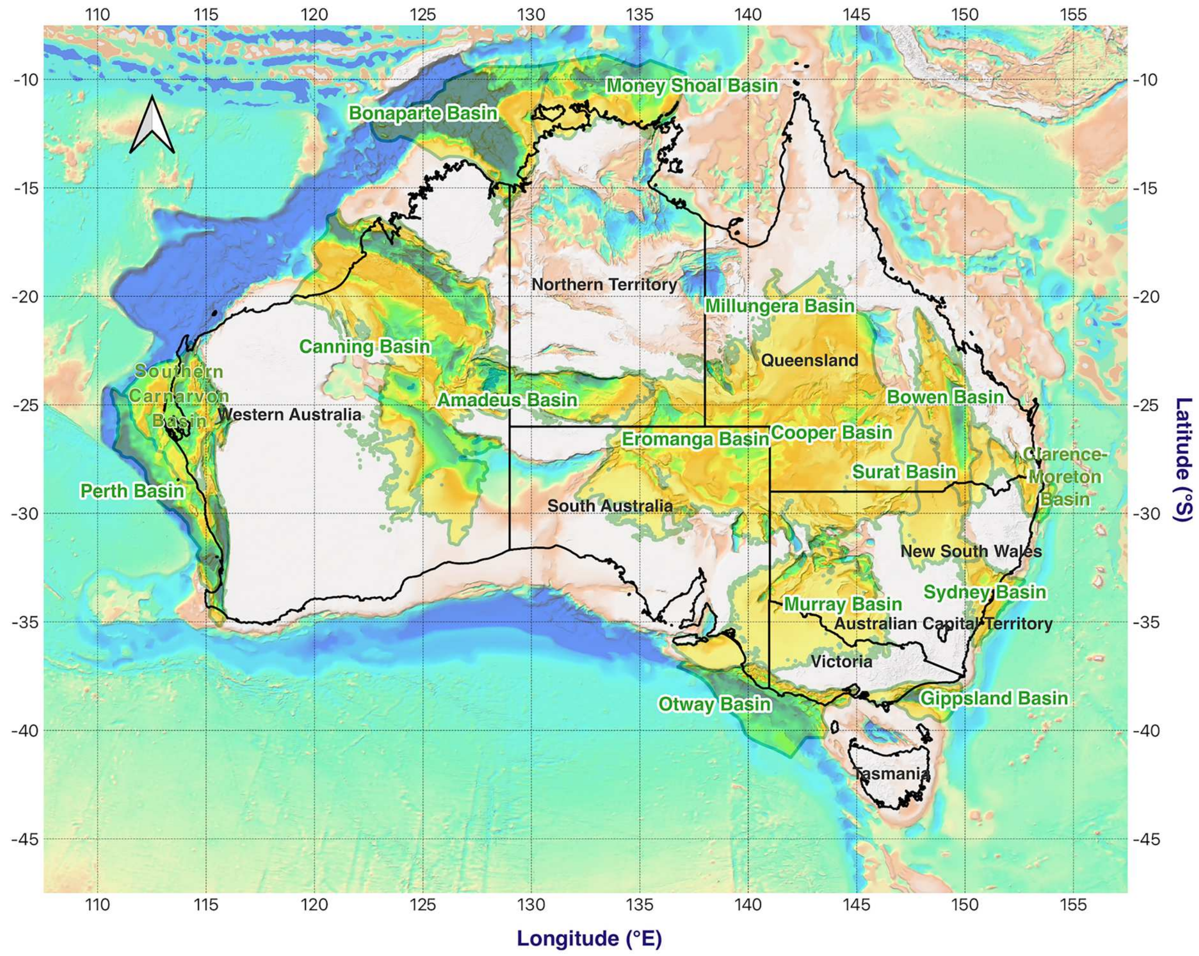

Figure 3. Basins hosting known or potential HSA geothermal energy sources in Australia. Background image is OZ SEEBASE sediment thickness as a relative colour scale, where pale brown represents exposed basement and deep blue represents the thickest sediment (Geognostics 2021). Australian states and territories are shown in black, and basins referred to in the text are highlighted and labelled in green. Basin outlines from Geoscience Australia (Raymond et al. 2018).

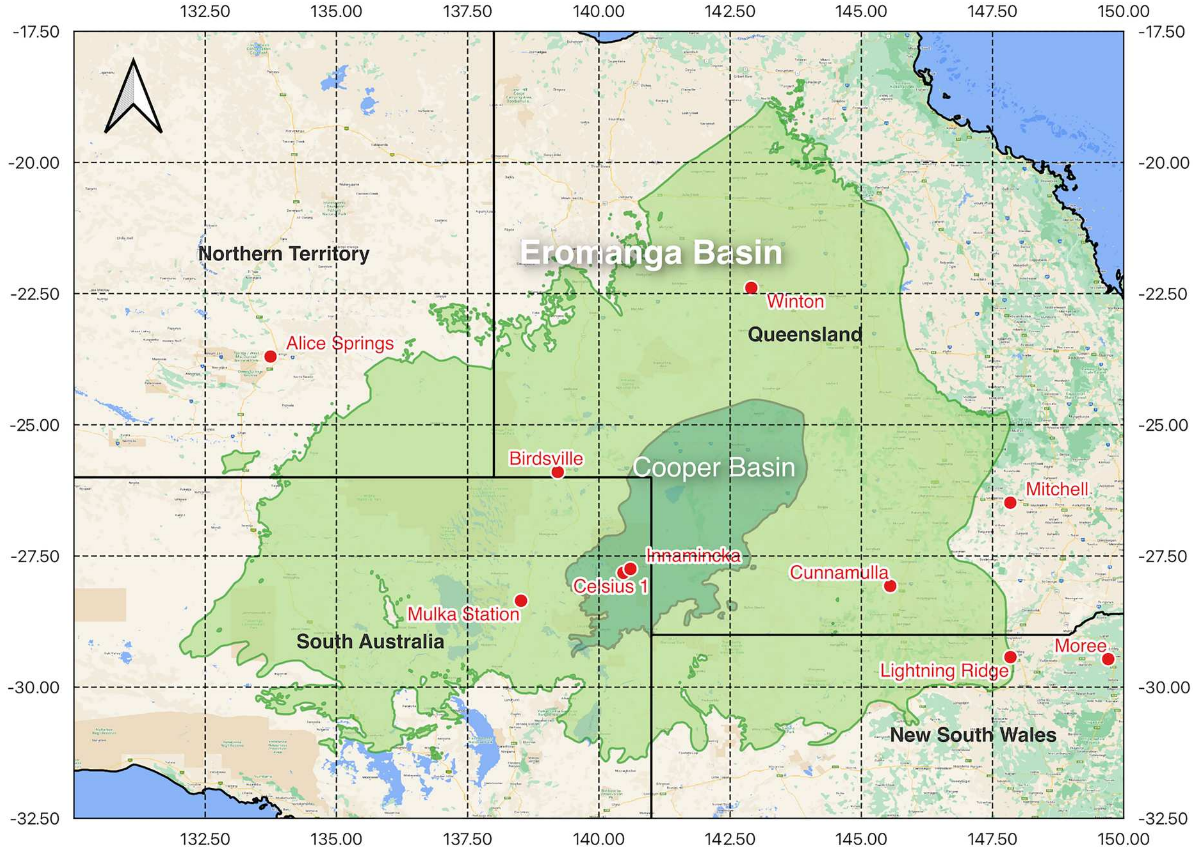

Figure 4. Extent of the Eromanga Basin, the underlying Cooper Basin, and locations mentioned in the text. Australian states and territories are shown in black. Basin outlines from Geoscience Australia (Raymond et al. 2018). Grid is decimal latitude and longitude. Background image is Google Road from https://mt1.google.com/vt/lyrs=m&x={x}&y={y}&z={z}.

Eromanga Basin sequence was deposited between the Early Jurassic and the Late Cretaceous within a broad continental down-warp (Figure 5; Cotton et al. 2007), and includes a series of Early Jurassic to Early Cretaceous confined sandstone aquifers which have been heavily exploited for groundwater (Habermehl and Pestov 2002). Literally thousands of bores have been drilled into those aquifers to an average depth of about 500 m, but with individual bores reaching as deep as 2000 m. Most bores intersect and produce from the Early Cretaceous (Neocomian to early Aptian) Cadna-owie Formation (Figure 6), it being the shallowest productive aquifer in the sequence. Alexander et al. (2007) described the depositional settings of the Cadna-owie Formation as non-marine (lacustrine), coarsening upward into shoreface, beach and marginal marine environments. They described the lithology as predominantly pale grey siltstone with very fine to fine-grained sandstone interbeds and minor carbonaceous claystone.

Relatively high production temperatures from the Cadna-owie Formation, ranging between 30°C and 100°C (Habermehl and Pestov 2002), have been attributed to elevated crustal heat flow and overlying thermal insulation (Beardsmore 2004). The heat brought to the surface with the groundwater has been exploited as HSA geothermal resources in several locations, described below. Deeper sandstone units – Namur Sandstone, Algebuckina Sandstone, Adori Sandstone, Hutton Sandstone (Figure 6) – represent other potential HSA geothermal energy sources, although a test of the Hutton Sandstone as a geothermal energy source in 2011 (described below) was commercially unsuccessful.

Smerdon and Ransley (2012) reported an average permeability of 96 milli-Darcies (mD) for the Cadna-owie Formation in the central portion of the Eromanga Basin, increasing to the northeast. They noted that other sandstone aquifers in the Eromanga Basin have average permeability values between 100 and 1000 mD, with similar values in Surat Basin aquifers to the east (e.g. average 426 mD for the Hutton Sandstone.)

Smith et al. (2015) reported relatively fresh to brackish water quality in the Eromanga Basin aquifers, specifically citing mean values for total dissolved solids (TDS) of 2766 mg/L (range 1810–4766 mg/L) within the Namur Sandstone; 3497 mg/L (range unavailable) for the Adori Sandstone; and 2630 mg/L (range 959–5729 mg/L) for the Hutton Sandstone. They made a qualitative note that '… water from the Namur and Adori sandstones is generally of better quality than the Cadna-owie Formation'.

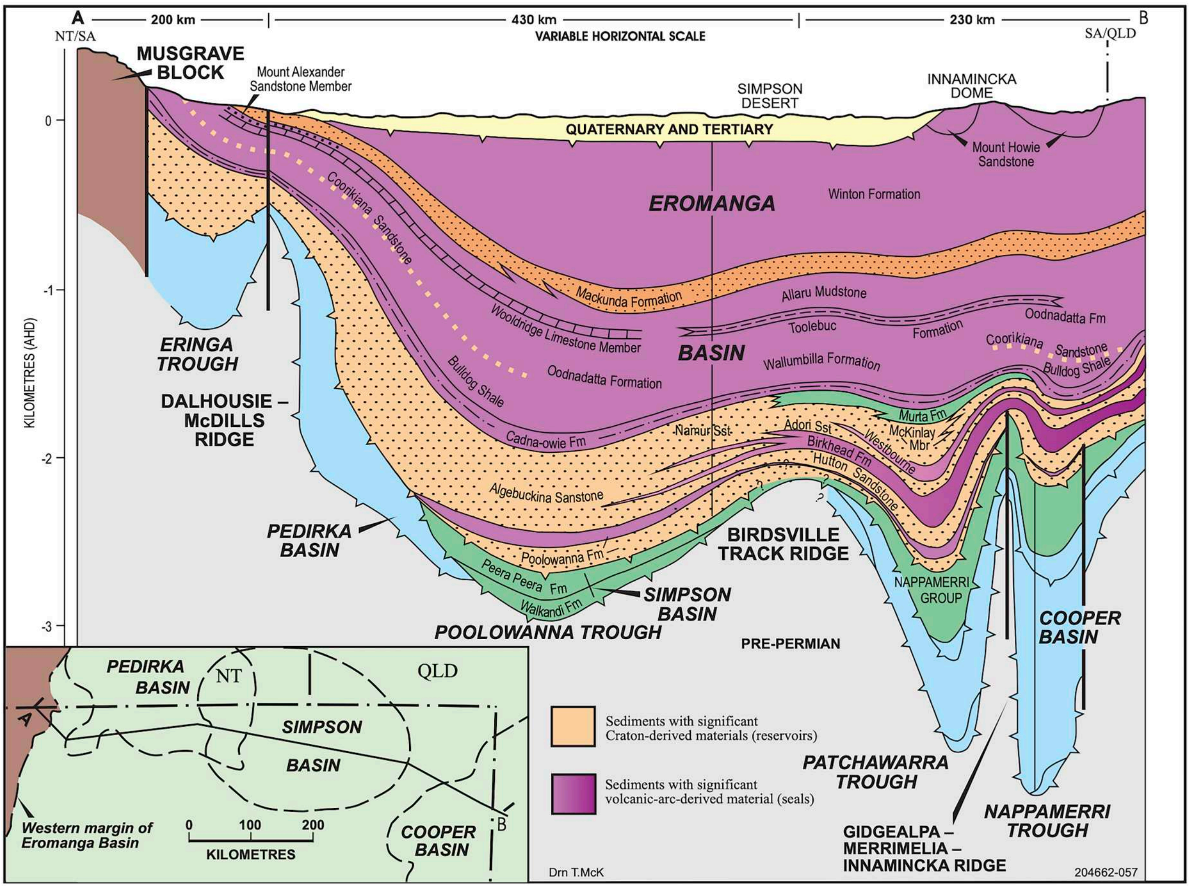

Figure 5. West-to-east cross section across the South Australian portion of the Eromanga Basin. Reprinted with permission of the Government of South Australia, Department of Energy and Mining, from https://tinyurl.com/yd9frbmp, accessed 15 November 2023.

Examples of geothermal energy use: past, present and potential

The Cadna-owie Formation has provided the HSA source for three separate geothermal power plants, and several direct use projects in the form of hot spring tourism operations. The deeper Hutton Sandstone has been unsuccessfully tested for power generation at one location but remains a potential HSA source elsewhere.

Mulka Station, South Australia: Many bores in the GAB produce water greater than 80°C (Habermehl and Pestov 2002), but most are used only for watering stock. In most bore locations, the thermal energy in the water is a liability because the water must be significantly cooled before the stock can drink it. In mid-1986, however, enterprising engineers at a company called Enreco Pty Ltd in Alice Springs (Northern Territory) adapted a 15 kWe ‘organic rankine cycle’ (ORC) generator originally designed for a solar pond to be driven instead by 86°C water flowing at up to 10 litres per second from a 1300 m deep domestic artesian bore at Mulka cattle station in South Australia. Not only did the generator provide cheap electrical power for the station homestead and operations, easily meeting the maximum load demand of 3.5 kWe, but it also provided the added benefit of cooling the bore water (Burns et al. 2000). The experimental generator ran continuously for three and a half years until ceasing operation in late 1989 when a mining company bought Mulka Station and had no use for the ORC generator (Popovsky 2013).

Birdsville, Queensland: On the back of the technical success at Mulka, Enrico Pty Ltd took the concept to the town of Birdsville in Queensland (Burns et al. 2000), where a 1221 m deep bore flowed 99°C at up to 30 litres per second. An initial ORC plant designed to generate 100 kWe (net) using Freon as a working fluid commenced operation in October 1992, feeding power directly to the town of Birdsville. The plant ran until the end of 1994 when Freon was banned under the Montreal Protocol for its detrimental impact on the ozone layer. Generation from the geothermal plant was suspended for several years while various modifications were implemented. Generation recommenced in June 1999 using isopentane as a working fluid (Burns et al. 2000), and provided about 80 kWe (net) power (Huddlestone-Holmes 2014) almost continuously for the next 19 years until the plant’s owner – state-owned energy company Ergon Energy – decommissioned it in 2018 in favour of solar photovoltaic generation with battery storage (Beardsmore et al. 2021). Vorrath (2018) reported Ergon at the time as saying,

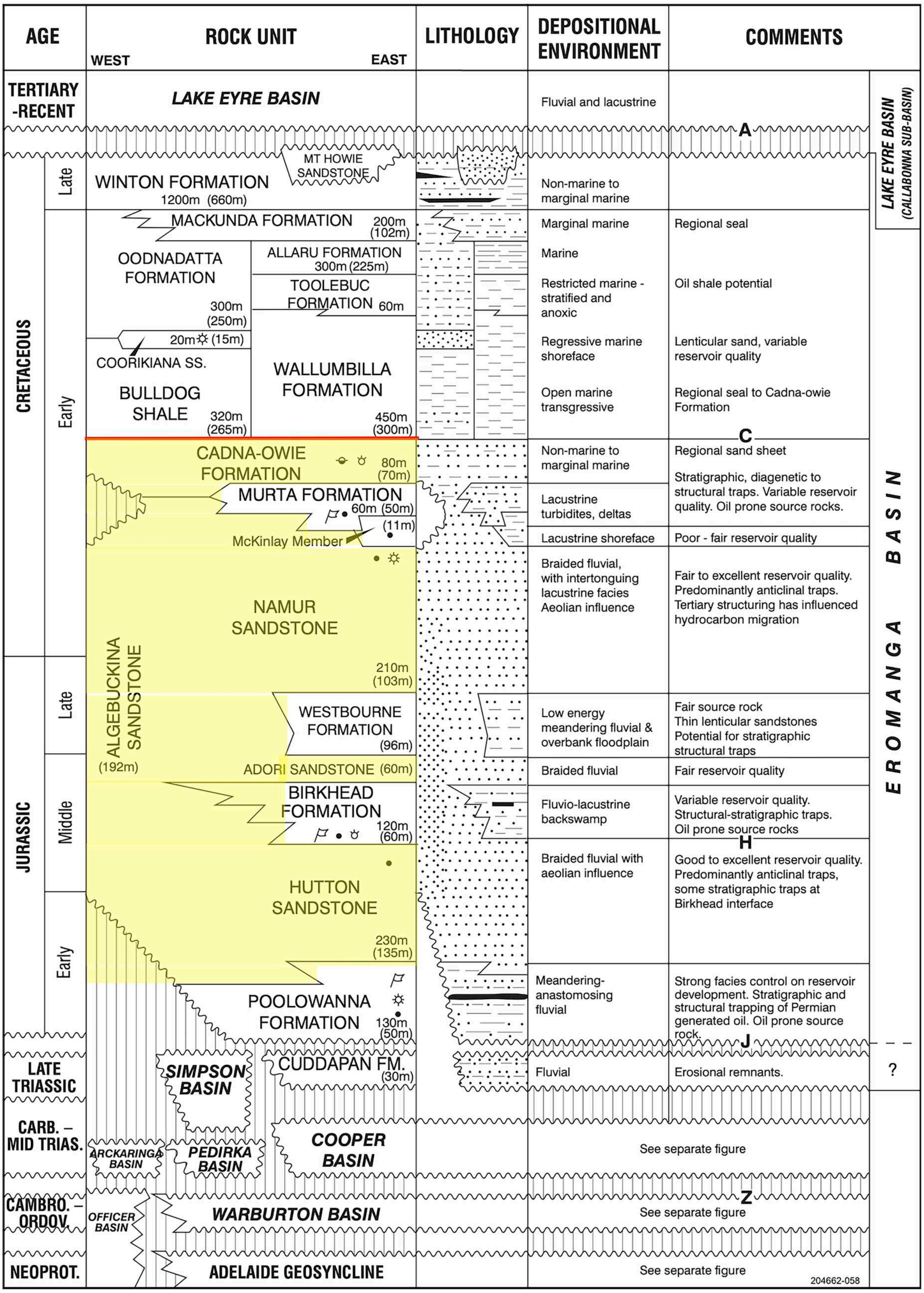

Figure 6. Geological summary of the Eromanga Basin in northeast South Australia, with known and potential HSA geothermal source formations highlighted in yellow. Reprinted with permission of the Government of South Australia, Department of Energy and Mining, from https://tinyurl.com/yd9frbmp, accessed 15 November 2023.

This decision was made due to a rapidly changing energy market driven by our customers' adoption of renewable energy such as PV and the continued reduction in energy storage costs, which is expected to substantially alter the energy requirements of our isolated communities in the future.

Winton, Queensland: At the time of Ergon Energy's decommissioning of the Birdsville Geothermal Power Plant, Winton Shire Council (also in Queensland) had committed to build a 310 kWe (gross) geothermal power plant to be driven by an existing bore flowing 86°C water. Construction of the plant was completed in 2020 (Beardsmore et al. 2023a). At the time of writing (December 2023), however, the plant is not operating and is the subject of an ongoing legal dispute reported by O'Neal (2023).

Celsius 1, South Australia: In 2011, towards the end of the period in which Geodynamics Ltd was pursuing its EGS project at Innamincka in northeast South Australia, Geodynamics' joint venture partner, Origin Energy, drilled a 2,417 m well called Celsius 1 in the same region to test the potential of the Hutton Sandstone as an HSA geothermal source for ORC power generation (Budd and Gerner 2015). Celsius 1 encountered temperatures in excess of 145°C in the target formation – easily hot enough for ORC power generation – but failed to produce water at a commercial rate. Origin Energy (ORG 2011) reported simply that the 'reservoir permeability is below target'. After examining physical samples and the thermal history of the aquifer rocks, IMER (2014a) concluded that 'diagenetic factors have made the deep, hot water reservoirs less permeable than hoped', but 'it may be possible to identify more permeable zones [in other locations] using seismic and petrology'. The Hutton Sandstone therefore remains a potential HSA geothermal energy source at other locations.

Bathing, New South Wales and Queensland: Commercial or semi-commercial hot spring bathing and recreation centres draw water from HSA sources in the Eromanga Basin at many locations, especially in regional towns throughout north-western New South Wales and western Queensland. Some of the better known examples are at Lightning Ridge, NSW (Walgett Shire Council 2023) and Cunnamulla, QLD (Paroo Shire 2023), while similar centres at Moree, NSW (Moree Plains Shire Council 2023) and Mitchell, Queensland (Maranoa Regional Council 2023), draw water from equivalent aquifers in the adjacent Surat Basin and Bowen Basin, respectively, to the east.

Perth Basin

Geological context

Geoscience Australia describes the Perth Basin as an onshore and offshore sedimentary basin extending about 1300 km along the southwestern margin of the Australian continent, formed during the breakup of the supercontinent Gondwana during the Permian to early Cretaceous (https://tinyurl.com/mrrduu8b, accessed 21 November 2023.) The basin takes its name from the capital city of the state of Western Australia, which sprawls across the basin plains between the Indian Ocean and the Darling Scarp (Figure 7). The main HSA geothermal energy sources of note are the Yarragadee Aquifer around the Perth Metropolitan Region in the central south part of the basin, and the 'Kingia Sandstone' further north.

The Yarragadee Aquifer lies within highly permeable, coarse sandstones of the Early Cretaceous Gage Formation, and the Mid-Jurassic Yarragadee Formation, Cadda Formation and Cattamarra Coal Measures (Figure 8A; Pujol et al. 2015). The top of the aquifer, defined by the base of the South Perth Shale, varies between about 400 m and 900 m depth (Figure 9). Geothermal bores typically target the Yarragadee Aquifer between 750 m and 1150 m depth, aiming for production temperatures between 40°C and 52°C and production rates of 10–40 litres per second (Pujol et al. 2015). The full thickness of the aquifer has only been penetrated once in the vicinity of Perth – by the petroleum exploration well Cockburn 1 – where the combined thickness of Yarragadee and Cadda Formations was 1600 m (Smith 1967; the Gage Formation and Cattamurra Coal Measures were absent in Cockburn 1). Pujol et al. (2015) reported permeability ranging between 0.4 darcy (D) and 8.8 D for the production intervals of 21 bores in the Yarragadee Aquifer, with an average of 3.4 D and a standard deviation of 2.5 D. They furthermore characterised the aquifer's salinity as 'fresh' at shallow depths and near the recharge zone north of Perth, to increasingly brackish and saline towards the south and at greater depths. Salinity observed in a bore about 50 km south of Perth, for example, ranged from 10.6 g/L at 385 m depth near the top of the aquifer to 26.3 g/L at 780 m depth.

'Kingia Sandstone' is an informal name for an upper unit of the High Cliff Sandstone (Figure 8B) deposited in a fluvial to marginal marine environment in the Early Permian. It is a potential HSA geothermal energy source being investigated for commercial power generation in the north of the basin. Ballesteros et al. (2020) identified the Kingia Sandstone as a potential HSA geothermal energy source based on high porosity and permeability, and formation temperatures exceeding 150°C, observed in at least three natural gas reservoirs ('Waitsia', 'West Erregulla' and 'Beharra Springs Deep'; Figure 7) at depths between 3 km and 5 km. Ferdinando (2007) reported permeability values ranging from 0.86 mD to 1466 mD for ten Kingia Sandstone core samples from a nearby gas exploration well, and attributed preservation of the higher values to the inhibition of quartz overgrowths on matrix grains by a coating of illite/smectite related to depositional conditions. Whether or not the favourable reservoir characteristics extend into water-saturated zones downdip from the gas reservoirs is yet to be confirmed, as is the salinity of the water.

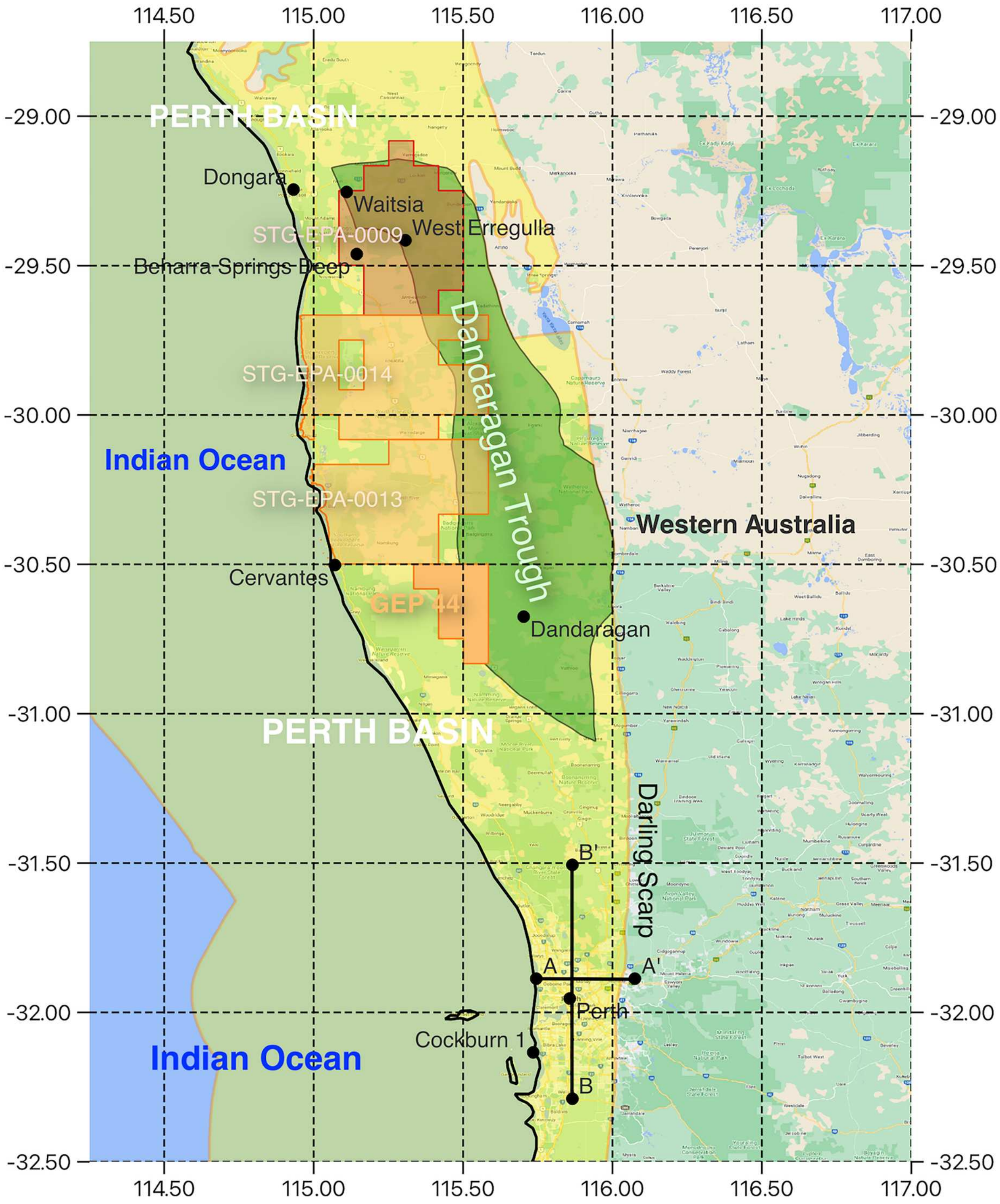

Figure 7. Region of interest in the Perth Basin (yellow shading), and locations mentioned in the text. Basin outline from Geoscience Australia (Raymond et al. 2018). Grid is decimal latitude and longitude. A–A′ and B–B′ are locations of cross sections illustrated in Figure 9. Labelled red and orange polygons are geothermal licence areas referred to in the text. Background image is Google Road from https://mt1.google.com/vt/lyrs=m&x={x}&y={y}&z={z}. Coastline is black.

Geothermal energy use: past, present and potential

Historical geothermal energy use from the Yarragadee Aquifer: The earliest production of geothermal energy from the Yarragadee Aquifer dates back to 1898, when heat was recognised as a useful by-product of groundwater produced primarily for consumption. Pujol et al. (2015) mentioned users as diverse as the South Perth Zoological Gardens (for heating the reptile enclosure), a commercial laundry (for direct hot water), a wool processing plant (for drying wool), and an open air bathing pool (the result of uncontrolled artesian flow from an uncapped bore). None of these early uses continue in the present day. There is little explanation in readily-accessible literature to explain why, but the author surmises that the respective late-nineteenth-century artesian water bores reached the end of their functional lives and were either not replaced, or were replaced in a way that precluded the co-production of geothermal energy.

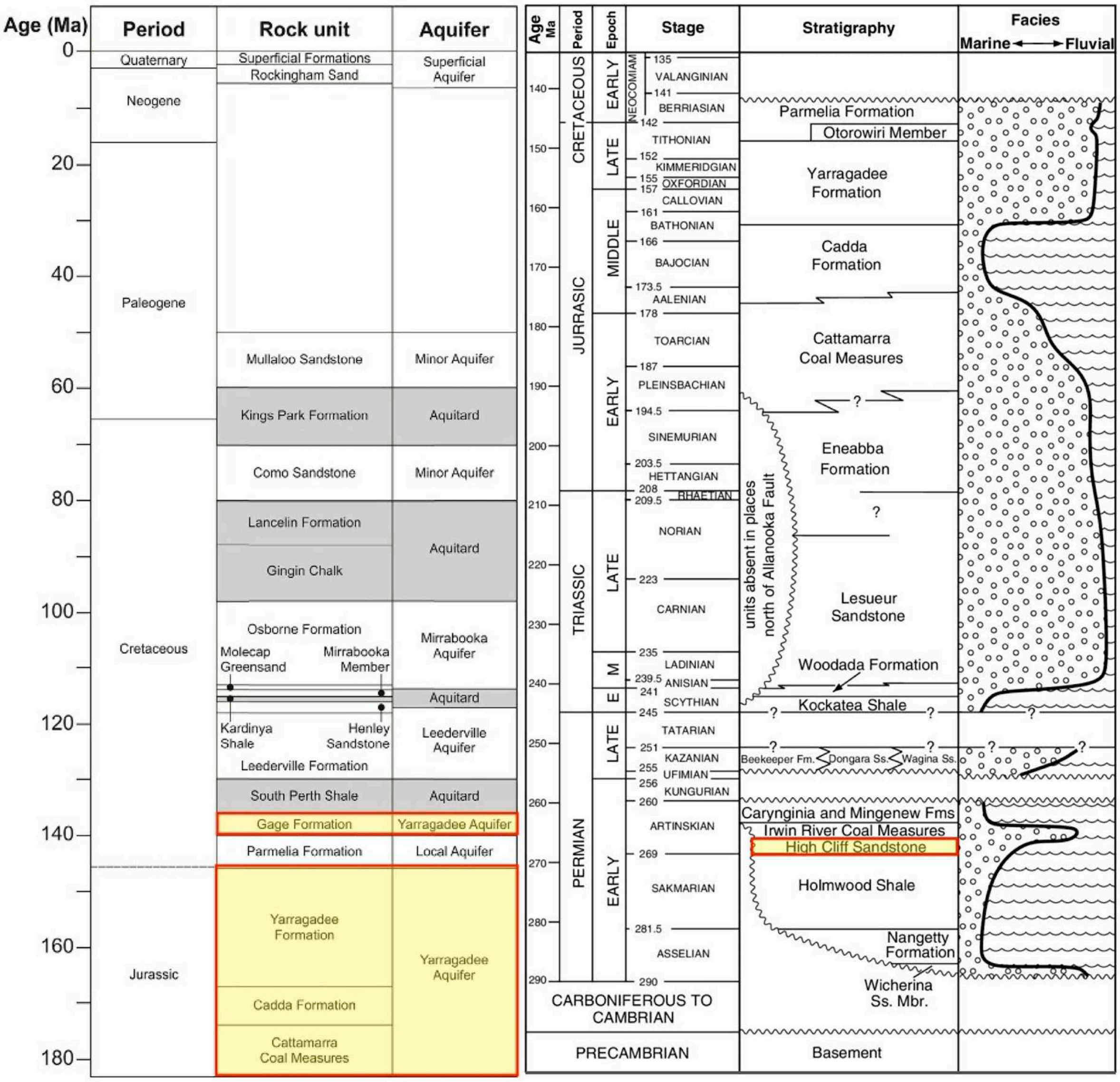

Figure 8. A, Generalised shallow stratigraphy of the Perth Basin in the Perth Metropolitan Region, indicating aquifers (white background) and aquitards (grey background). Yarragadee Aquifer highlighted in yellow. Modified after Pujol et al. (2015) with permission of Elsevier. **B**, Stratigraphy of the northern Perth Basin, with the High Cliff Sandstone highlighted in yellow. Modified after Mory and Iasky (1996) under licence CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/legalcode).

Aquatic centres in the Perth Metropolitan Region: A new wave of geothermal energy development of the Yarragadee Aquifer began in the late 1990s, focussed on leisure and aquatic centres. Beardsmore et al. (2021) listed fourteen geothermal energy systems built to heat buildings and pools between 1997 and 2018, with production temperatures ranging from 38.3°C to 50.6°C and maximum production rates ranging from 8 to 48 litres per second. Collectively, the systems provide an estimated 247 TJ_t of geothermal energy per year. Regulations require 100% reinjection of the cooled fluid, although reinjection is typically into a shallower part of the Yarragadee Aquifer to maintain pressure while protecting the deeper temperatures (Pujol et al. 2018).

Strike Energy Ltd: At the time of writing (December 2023), Strike Energy Ltd was awaiting the granting of an geothermal exploration licence applied for over the Kingia Sandstone in the north Perth Basin (application STG-EPA-0009) encompassing the three productive natural gas reservoirs (Figure 7). STX acquired rights to apply for the acreage from Midwest Geothermal Power Pty Ltd in May 2021, citing possible applications for geothermal heat in urea and hydrogen production plants proposed for the region (STX 2021). STX subsequently issued a resource statement in May 2022 (STX 2022), in which STX estimated (with 50% – P50 – likelihood) a potential to generate 6780 MW_e-years of electricity from the HSA geothermal source within STG-EPA-0009.

VRX Silica Ltd/Steam Resources Ltd: VRX Silica Ltd announced in July 2023 that it had been granted Geothermal Exploration Permit GEP44 in the north Perth Basin (Figure 7) through a competitive tender process run by the Government of Western Australia (VRX 2023a). A subsequent announcement by VRX

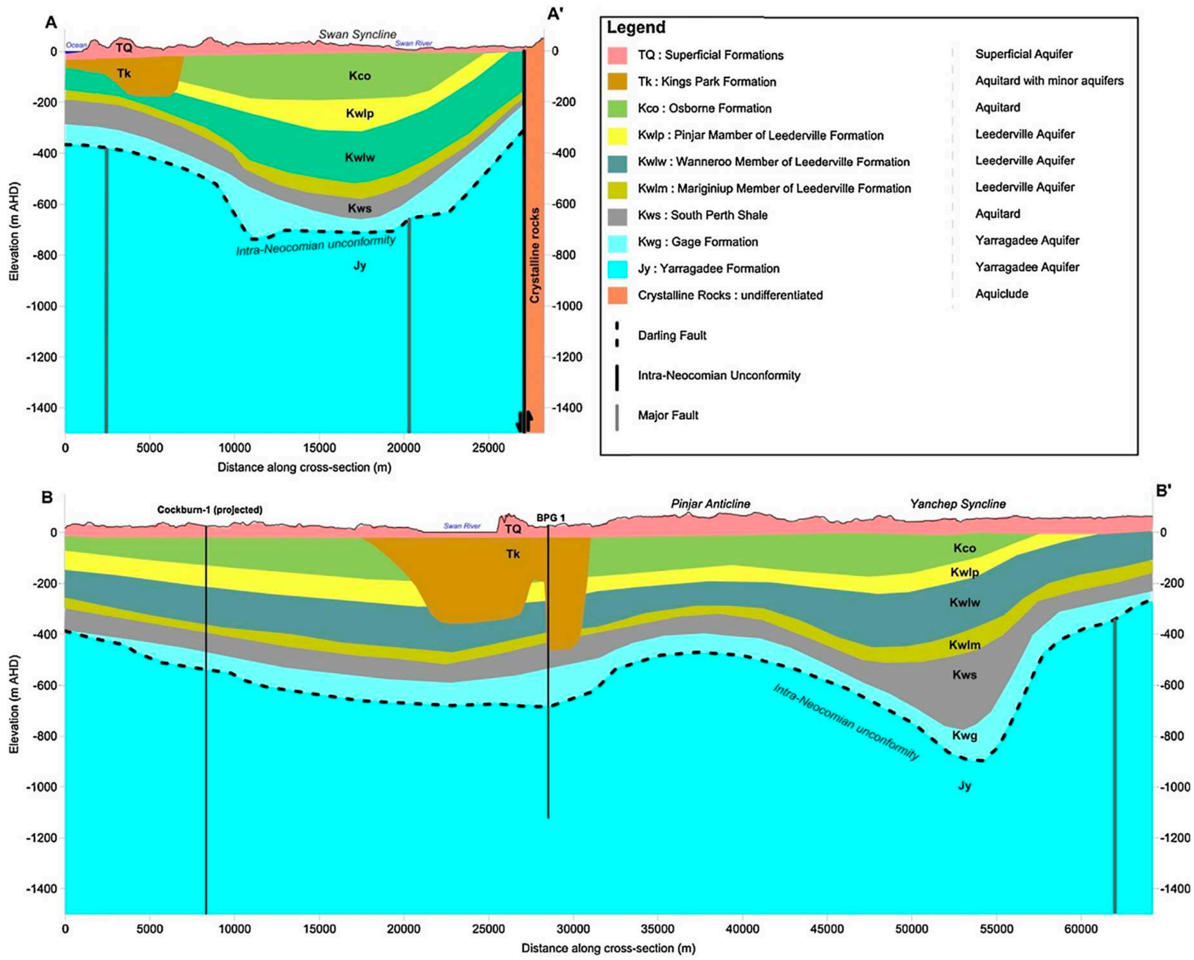

Figure 9. Geological west–east (A–A′) and south–north (B–B′) cross sections from surface to the Yarragadee Formation in the Perth Metropolitan Region. Pale blue colours represent the Yarragadee Aquifer. See Figure 7 for cross section locations. Reprinted from Pujol et al. (2015) with permission of Elsevier.

in November 2023 explicitly stated that it had entered a joint venture agreement with Steam Resources Ltd to explore for HSA geothermal energy sources to generate low-emissions electricity to power electrolysers to produce hydrogen for glass furnaces (VRX 2023b).

Gippsland Basin

Geological context

The onshore portion of the Gippsland Basin underlies approximately 15,000 km^2 of the state of Victoria in the southeast of Australia (Figure 10). HSAs have been known in the area since Australian Paper Manufacturers (APM) discovered 70°C water in a 529 m deep bore drilled at Maryvale at the western end of the basin in 1945 (Southern States Drilling Co Pty Ltd 1945). Jenkin (1962) subsequently compiled and published the Maryvale discovery along with many other 'occurrences of high temperature waters in East Gippsland'.

Relatively thin fluvial sands and gravels of the Pliocene to Pleistocene Sale Group cover much of the onshore Gippsland Basin. These overlie brown coal and marine carbonates (predominantly marls) of the early Oligocene to late Miocene Seaspray Group (Figure 11). The coal (thickest in the west) and carbonates (thickest in the east) thermally insulate the underlying rocks resulting in significantly higher temperatures than would otherwise be expected (Rawling et al. 2013).

The Palaeocene to Eocene Latrobe Group immediately underlies the Seaspray Group and includes alluvial and fluvial sandstones in the Traralgon Formation and Yarram Formation (Figure 11). These sandstones host a highly productive regional aquifer referred to as the 'Lower Aquifer' by Southern Rural Water – the local water management authority (SRW 2012) – and the 'Lower Tertiary Aquifer' (LTA) by GHD (2012). This paper adopts GHD's terminology.

The LTA is the main HSA geothermal energy source in the region, although shallower aquifers within the overlying coal seams also represent potential HSA sources. The LTA extends across approximately 6000 km^2 of the Gippsland Basin – from Morwell, Maryvale and Traralgon in the west to Metung in the east; and from Maffra and Bairnsdale in the north to Yarram and the coast in the south

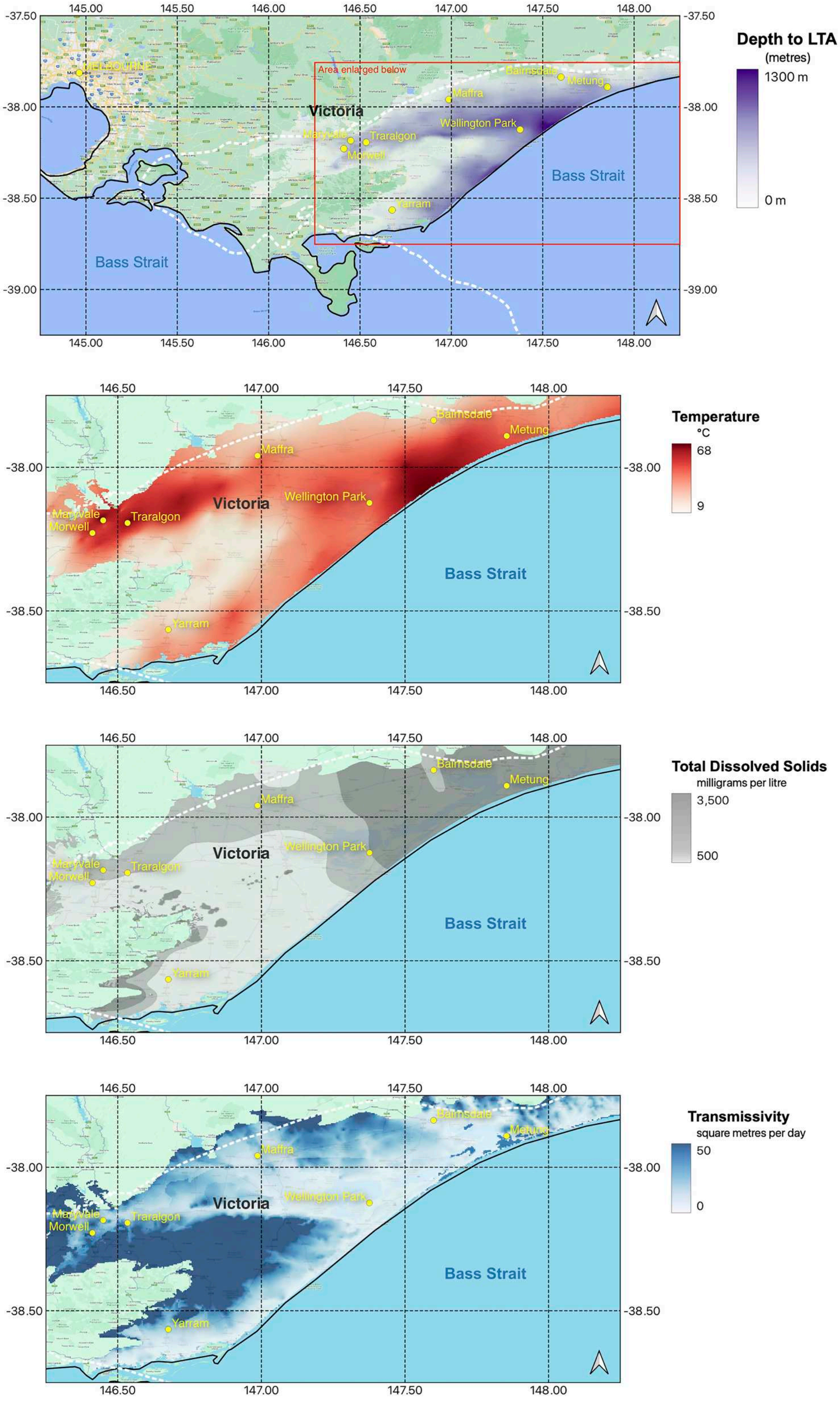

Figure 10. Properties of the LTA as mapped by O'Neill et al. (2022): Depth to top LTA, temperature at top LTA, salinity (TDS), and transmissivity, as labelled. For all maps: Extent of the onshore Gippsland Basin (white dashed line); locations mentioned in the text (yellow dots). Coastline is black. Grid is decimal latitude and longitude. Basin outline from Geoscience Australia (Raymond et al. 2018). Background image is Google Road from https://mt1.google.com/vt/lyrs=m&x={x}&y={y}&z={z}.

(Figure 10) – and typically produces water in the range 30–70°C (SRW 2012).

In 2022, the Geological Survey of Victoria compiled and published new borehole data and maps approximating the depths, temperatures and hydrological properties of each of the aquifers hosted within the Cenozoic sequence across the extent of the onshore Gippsland Basin (O'Neill et al. 2022). While the maps were generated by interpolating values recorded within a relatively sparse set of bores, they represent

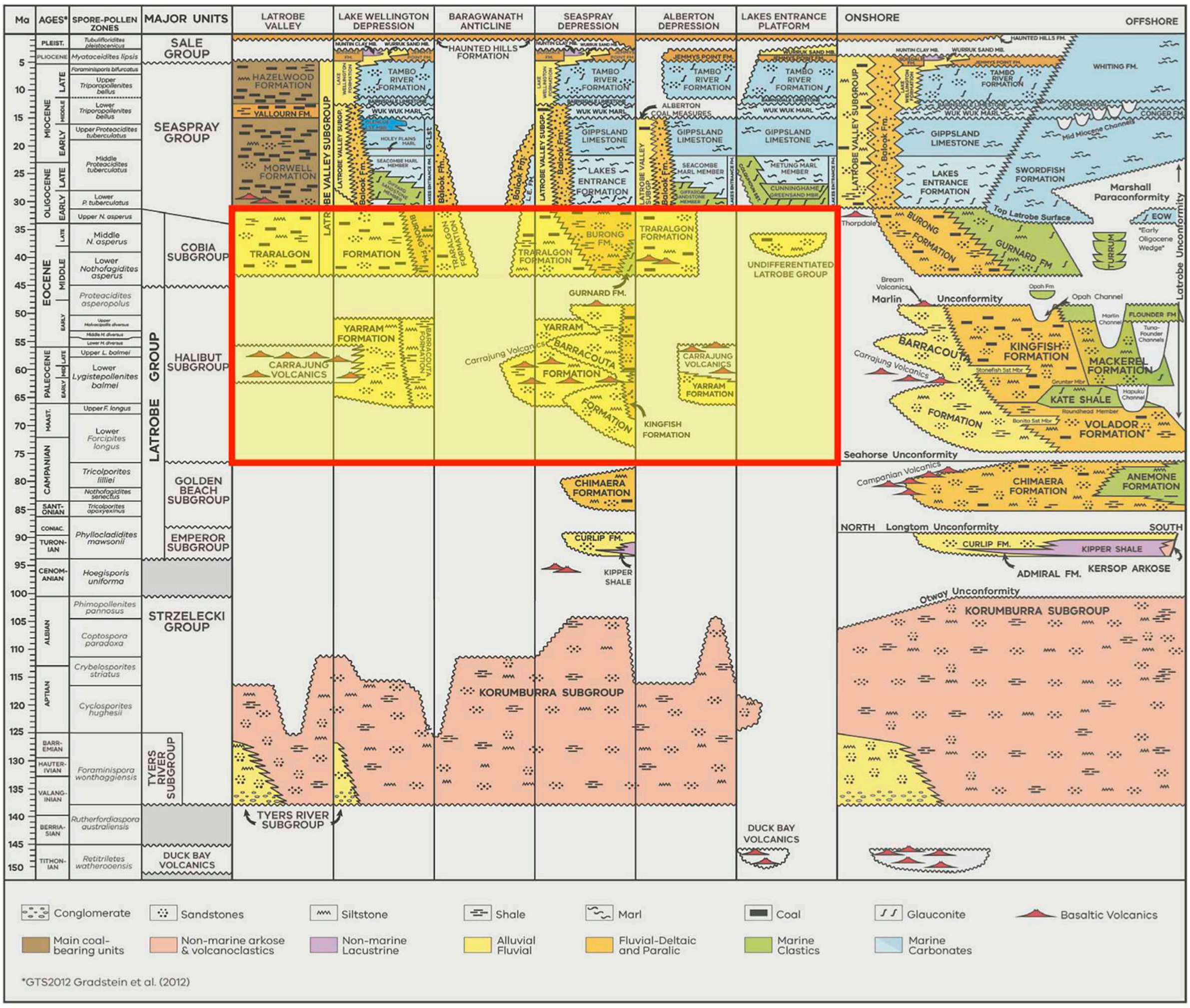

Figure 11. Generalised stratigraphy of the Gippsland Basin with host formations of the 'Lower Tertiary Aquifer' (GHD 2012) highlighted in the red box. Modified after Powell et al. (2020) under licence CC BY 3.0 (https://creativecommons.org/licenses/by/3.0/au/).

the best available information about the LTA as a HSA geothermal energy source at the time of writing (December 2023). They indicate (Figure 10) that water quality is fresh in the west, decreasing to brackish in the east, and that transmissivity is approximately in the range 5–25 m^2/day in the warmer parts of the aquifer.

The LTA is vertically constrained by an Oligocene unconformity at the base of the Seaspray Group, and underlying volcaniclastics of the Early Cretaceous Strzelecki Group. The Strzelecki Group lies at a depth of about 750 m around Morwell, Maryvale and Traralgon, and deepens eastwards to 1200 m or more at the coast. The Strzelecki Group might in places be as much as 3000 m thick above Palaeozoic igneous and folded sedimentary basement, and include a basal unit (the Tyers River Subgroup; Figure 11) of porous and permeable alluvial conglomerates and fluvial sandstones (Powell et al. 2020). The Tyers River Subgroup represents a potential HSA geothermal energy source for power generation, but a significant exploration and drilling program would be required to test the hypothesis.

Geothermal energy use: past, present and potential

Historical uses: APM utilised geothermal heat in its paper manufacturing processes at Maryvale from the discovery of 70°C groundwater in 1945 until significant dewatering of the aquifer by nearby brown coal mining operations led APM to abandon the bore sometime before 1987 (King et al. 1987; RPS Aquaterra and Hot Dry Rocks 2012).

Gippsland Regional Aquatic Centre: The Gippsland Regional Aquatic Centre ('GRAC') at Traralgon (see Figure 10 for location) was the first project to specifically target and utilise geothermal energy from the LTA. Commissioned by the local municipal government – Latrobe City Council (LCC) – and opened in March 2021, the public recreational facility uses geothermal energy from 68°C water drawn from a depth of about 650 m to heat its swimming pools and buildings as an substitute for natural gas combustion (Beardsmore et al. 2023b). Produced water passes through a heat exchanger at up to 25 litres per second before 100% of the cooled water is reinjected into the LTA approximately 500 m from the production bore.

Fu et al. (2023) analysed the capital costs and twelve months of production data and operational costs for the GRAC's geothermal heating system, and found the system delivered 23.7 TJ_t of heat over that period. They furthermore determined that the geothermal heating system had a positive net present value for any natural gas price greater than 10.80 AU$/GJ (11.70 NZ$/GJ in December 2023). The natural gas tariff paid by LCC at the time of the study was 31.0261 AU$/GJ, representing substantial cost savings for LCC and a pay-pack period less than five years.

Metung Hot Springs: Metung Hot Springs (https://www.metunghotsprings.com/) opened its first stage of operations at Metung in East Gippsland in late 2022. Natural geothermal water is drawn from the LTA at about 42°C and fed directly into pools (personal conversation with Adrian Bromage, 15 November 2023) for bathing and wellness. None of the spent water is reinjected, but instead used to irrigate a local golf course.

Nunduk: While less advanced in development, Nunduk Spa Retreat at Wellington Park (https://www.nunduk.com/) also plans to supply hot water from the LTA to a bathing and wellness resort. The most recent public information available at the time of writing (December 2023) was from 28 July 2022 when Nunduk's developer posted on Facebook.com that exploratory drilling would commence in early 2023 (https://www.facebook.com/NundukSpaRetreat/).

Smart Geothermal Industrial Loop: Cariaga (2023) reported online that the University of Melbourne and commercial partners received a grant from the Government of Victoria to research the optimal design and cost of a 'Smart Geothermal Industrial Loop' (SGIL) for a site near Morwell. The project entailed geological modelling, engineering studies, and an assessment of legislation and regulation that could impact the commercial sale of heat. If developed, the SGIL would be Australia's first project to deliver geothermal energy from an HSA source to multiple independent end users.

Others: The successful development and operation of the geothermal heating system at the GRAC demonstrated the technical and financial viability of geothermal heating from the LTA. In addition to the SGIL investigation mentioned above, the author is aware of pre-feasibility studies into geothermal district heating systems by two other municipal governments in the region, as well as commercial interest in geothermal energy for process heat by industries as diverse as protected cropping (greenhouses), poultry farming, aquaculture, meat and dairy processing, fertiliser manufacturing, and others. Beardsmore et al. (2023b), however, reported that a consistent regulatory framework does not yet exist in the state of Victoria for producing and reinjecting groundwater for the purpose of geothermal energy production, resulting in long delays for potential new geothermal projects.

Otway Basin

Geological context

The Otway Basin onlaps some 500 km of the southeast coastline of Australia straddling the states of Victoria and South Australia to the west of Melbourne (Figure 12). It is effectively a series of passive margin basins formed as a result of rifting between Antarctica and Australia in the Jurassic to Late Cretaceous, overlain by a regionally extensive Palaeocene to Miocene cover sequence and younger volcanics (Boult 2002; Figure 13).

Two formations are of interest as HSA geothermal energy sources – the Dilwyn Formation and the Pretty Hill Formation (Figure 13). The Dilwyn Formation was deposited in fluvial and deltaic environments during the Eocene and extends broadly across the South Australian and Victorian parts of the basin. It thickens from north to south, contains intervals of porous and permeable sandstones, and gives its name to the Dilwyn Aquifer which is an extensive confined sandstone aquifer and an important source of groundwater across both states (e.g. Paydar et al. 2009). The Dilwyn Aquifer is utilised in several locations as an HSA geothermal energy source of low grade heat. Dahlhaus et al. (2002) estimated the hydraulic conductivity (lateral permeability) of the Dilwyn Aquifer to range between 10^{-2} and 10^{2} metres per day, its transmissivity to be generally less than 1000 m^2 per day, and its salinity generally less than 1500 mg/L.

IMER (2014a) described the Early Cretaceous Pretty Hill Formation of the Crayfish Group as a thick sandy sequence deposited over a silty flood plain with localised lakes and swamps. The Pretty Hill Formation is up to 2000 metres thick in both South Australia and Victoria, and the average measured porosity is 10%. The deeper sections of the formation are predominantly clean sandstone while the shallower portions are typically interbedded feldspathic litharenite, carbonaceous siltstone and mudstone (IMER 2014a). Temperatures between 85°C and 175°C have been measured in petroleum wells drilled into the Pretty Hill Formation, which is thermally insulated and hydraulically sealed by thick shale, siltstone and coal in the overlying Laira and Eumeralla Formations. Goldie-Divko (2015) reported average permeability values for the Pretty Hill Formation ranging from 231 mD to 758 mD, based on measurements from samples in gas fields in sedimentary troughs. Saline formation water (14,000 ppm) was recovered from a drill stem test of the Pretty Hill Formation in its 'discovery' well Pretty Hill 1 (Bain 1962). The Pretty Hill Formation represents a potential HSA geothermal energy source for direct heat and power generation. Geothermal energy use: past, present and potential.

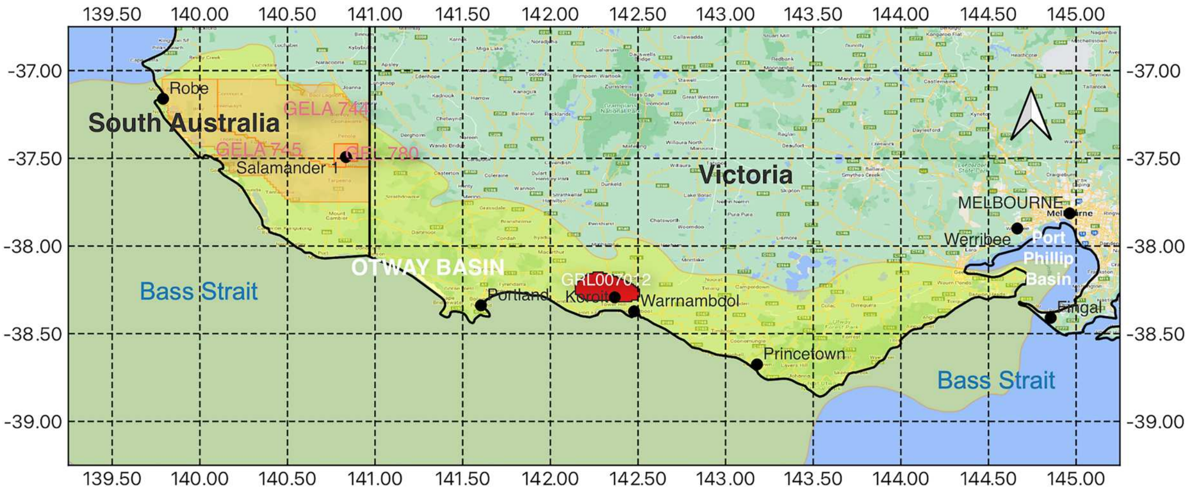

Figure 12. Onshore extent of the Otway Basin (yellow shading), and locations mentioned in the text (black dots). Red and orange polygons are geothermal licence areas referred to in the text. Coastline and state borders are black. Basin outline from Geoscience Australia (Raymond et al. 2018). Grid is decimal latitude and longitude. Background image is Google Road from https://mt1.google.com/vt/lyrs=m&x={x}&y={y}&z={z}.

District heating: The local municipal government – Glenelg Shire Council – operated a geothermal energy district heating system in the town of Portland on the west coast of Victoria between 1983 and 2006. A reticulated hot water pipe network delivered an estimated 8857 GJ_t of geothermal energy per year to 13 council properties – an outdoor swimming pool, hospital, police station, civic hall and others – from a 1400 m deep bore in the Dilwyn Aquifer producing 58°C water at 65 litres per second (Burns et al. 2000). The wholesale price in Victoria for natural gas with an equivalent heat content would be approximately AU $100,000 (NZ$108,000) per year in 2023. After passing through the reticulation system extending 1700 m from the production bore, spent water was returned to a cooling tower adjacent to the production bore where it was further cooled to between 26°C and 34° before being delivered into Portland's town water supply (Burns et al. 1995). No water was reinjected.

The geothermal heating system operated successfully for 23 years until the production bore was decommissioned in 2006 for environmental reasons – cooled water was by then being discharged into a surface stream after a new bore was drilled at a different location to supply Portland's town water (Beardsmore and Hill 2010). Glenelg Shire Council shortened the reticulation system and replaced the heat source with a natural gas furnace. The former geothermal heat source was economic because it utilised an existing water bore. The economics of drilling two new 1400 m deep bores for production and injection to re-establish a supply of geothermal energy remain challenging while Glenelg Shire Council has access to natural gas through the national distribution network. Geothermal energy becomes more competitive, however, as the price of natural gas and the imperative to decarbonise increase.

Industrial process heat: At least two commercial businesses utilise geothermal energy from the Dilwyn Aquifer HSA source in the Otway Basin for industrial process heat. While the water is the primary consumable in both cases – there is no reinjection – the heat in the water provides each business with an economic advantage in terms of avoided energy costs. The two businesses are:

- Robarra Pty Ltd, which farms barramundi (edible tropical sea bass) at Robe in South Australia in tanks directly filled with 29°C water from a 335 m bore into the Dilwyn Aquifer. The bore delivers over 43 TJt of heat per year (Beardsmore and Hill 2010) representing hundreds of thousands of dollars of annual avoided energy costs relative to natural gas prices;
- Midfield Group, which realises an energy saving at its meatworks near Warrnambool in Victoria by using 'preheated' 42°C geothermal water produced at about one megalitre per day from about 700 m depth in the Dilwyn Aquifer. Midfield uses the water as feedstock for a gas-fired furnace producing 82°C water for a sterilisation circuit (Boyce c.2010). The geothermal energy allows Midfield to avoid hundreds of thousands of dollars in natural gas costs per year.

Hot spring resorts: At the time of writing (December 2023), one hot spring resort utilises geothermal energy from the Dilwyn Aquifer HSA source in the form of natural warm bathing water, and another is currently in the planning stage. The Deep Blue Hot Springs resort in Warrnambool, Victoria, utilises 43°C water at up to 50 litres per second from a 735 m bore (no reinjection) for its 15 bathing pools and for space heating in its 122 hotel rooms (RPS Aquaterra and Hot

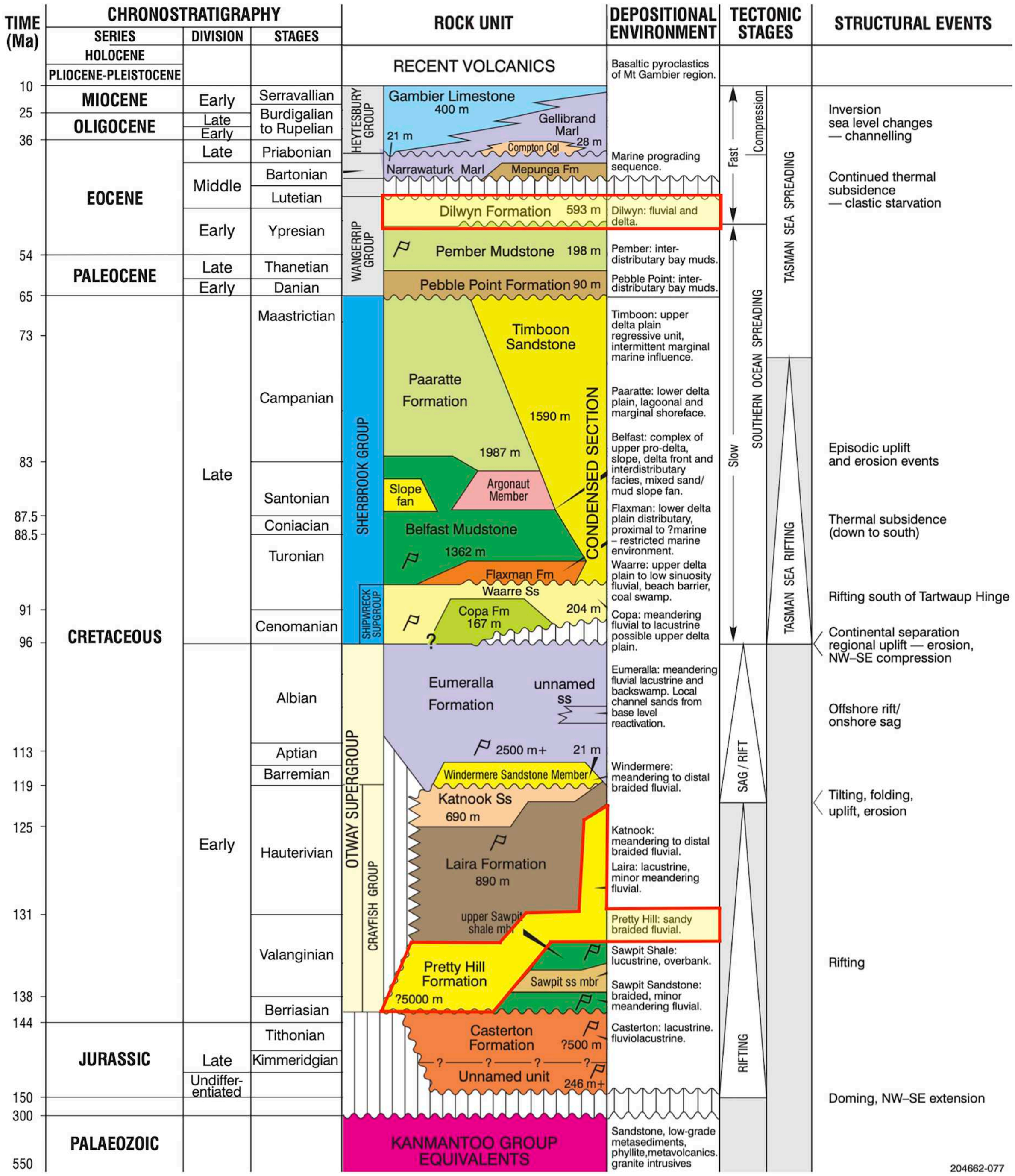

Figure 13. Geological summary of the South Australian portion of the Otway Basin with key HSA formations highlighted in yellow with red outlines. Reprinted with permission of the Government of South Australia, Department of Energy and Mining, from https://tinyurl.com/m84rc793, accessed 28 November 2023.

Dry Rocks 2012). A similar style of resort received planning permits and a bore licence in 2023 to begin development at Princetown about 80 km along the coast to the southeast of Warrnambool. The '12 Apostles Hot Springs' reportedly plans to utilise geothermal water from about 1,000 m depth for hot pools and heating for up to 150 accommodation rooms (Schlesinger 2023).

Power generation: Panax Geothermal Ltd (PAX) completed drilling Salamander 1 to a depth of 4025 m near Penola in South Australia in March 2010, intersecting 1125 m of Pretty Hill Formation (PAX 2010a). PAX reported a bottom hole temperature of 171.4°C two months after drilling concluded (PAX 2010b), but it was evident by July 2010 that well productivity was much lower than predicted (PAX 2010c). With an average porosity and permeability-thickness of about 12% and 6.7 darcy-metres, respectively, interpreted from petrophysical logs, PAX remained optimistic as late as October 2010 that Salamander 1 could be reconditioned to supply energy to a demonstration power plant (PAX 2010d). Faced with increasingly tight capital markets during the 'global financial crisis' (Budd and Gerner 2015), PAX was unable to make further progress on the project and Salamander 1 was eventually plugged and abandoned. IMER (2014a) concluded that deep burial and heating has significantly reduced primary porosity and permeability in the Pretty Hill Formation, but that it may be possible to predict locations with better reservoir characteristics by jointly interpreting existing petrological, geochemical, seismic and well log data. IMER (2014b, 2014c) furthermore concluded that the drilling and completion program for Salamander 1 probably caused irreversible formation damage, and recommended techniques and workflows to avoid similar damage during future drilling programs.

Given IMER's conclusions summarised above, the Pretty Hill Formation in the Otway Basin remains a potential HSA geothermal energy source for power generation. It is the likely exploration target in southeast South Australia for holders of geothermal exploration licence GEL780 and geothermal exploration licence applications GELA744 and GELA 745, and in Victoria for the holder of geothermal retention licence GRL007012, all current at the time of writing (December 2023; Figure 12).

Port Phillip Basin

Geological context

Taking its name from the body of water adjacent to Melbourne (the capital city of the state of Victoria), the Port Phillip Basin lies geographically between, and formed contemporaneously with, the Otway and Gippsland Basins (Figure 14). The top sedimentary layers comprise Pleistocene basaltic flows of the New Volcanics and aeolian sediments of the Bridgewater Formation. These overlie Late Miocene to Pliocene shallow marine carbonates and clastic sediments, which themselves unconformably overlie Miocene coals and deeper marine carbonates of the Fyansford Formation (Holdgate et al. 2002). Deeper again, the Late Oligocene to lower Miocene Werribee Formation hosts a confined (historically artesian) aquifer in highly permeable clean sands and gravels (Anderson 1992). The Werribee Aquifer represents a regional HSA geothermal energy source.

Pujol and Bolton (2019) reported transmissivities of 365 m^2 per day and 375 m^2 per day, respectively, for two injection bores intersecting the full thickness of Werribee Formation at Fingal, south of Melbourne, and Pujol et al. (2021) reported brackish salinity of about 3000 mg/L from bores at the same location (see Figure 12 for location.)

Geothermal energy use: present

Aquaculture: Mainstream Aquaculture Pty Ltd operates the world's largest barramundi hatchery and grow-out facility in a southwest suburb of Melbourne – Werribee (Figure 12) – from where it reportedly exported to 31 countries in 2023 (Mainstream Aquaculture 2023). Mainstream fills its tanks with 28°C water drawn directly from a single bore several hundred metres deep in the Werribee Aquifer, disposing of cooled spent water into a surface drain. Mainstream specifically purchased the property in 2003 so it could access the warm water (Beardsmore et al. 2016), demonstrating the commercial value of the geothermal energy resource.

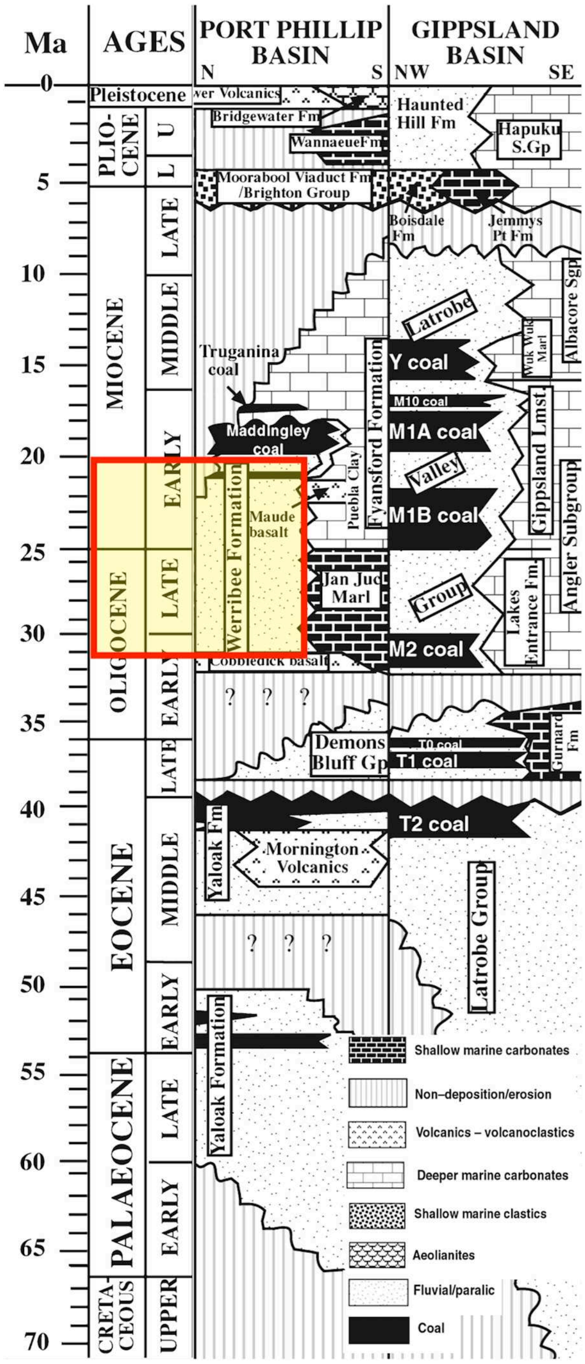

Figure 14. Stratigraphy of the Port Phillip Basin correlated with the Gippsland Basin. Key HSA formation highlighted in red box. Modified after Holdgate et al. (2002), reprinted by permission of Taylor & Francis Ltd (http://www.tandfonline.com).

Hot spring resorts: Peninsula Hot Springs (PHS) and Alba Thermal Springs and Spa are both located at Fingal on the Mornington Peninsula south of Melbourne (Figure 12), and both draw their geothermal water from the Werribee Formation. PHS operates two production bores drawing 47°C water from 640 m depth, and disposes of 100% of produced geothermal water into three reinjection bores (Pujol et al. 2021). Alba accesses the aquifer at a similar depth and temperature through a single production bore, and also reinjects 100% of the produced water.

Other potential HSA geothermal energy sources

Clarence Moreton Basin: In 2009, Planet Gas Ltd announced an intent to explore for HSA geothermal energy sources in the Clarence Moreton Basin at the eastern extremity of Australia (Figure 3; PGS 2009). The conceptual target is yet to be tested because PGS discontinued its geothermal exploration program during the contraction in the industry in the early 2010s.

Coproduced water: Hot water co-produced with petroleum at up to one megalitre per day from Cooper Basin sedimentary formations (Department for Water 2011) or elsewhere represent a potential source of geothermal energy (RPS Aquaterra and Hot Dry Rocks 2012). Commercial challenges in terms of energy production rates and market demand are much greater than geological risks for such co-production of geothermal energy in Australia (e.g. Evans and Peck MTG Ltd 2014).

Other conventional petroleum basins: By definition, sedimentary basins supporting significant conventional petroleum production contain porous and permeable reservoir formations. The petroleum-bearing sections of those formations typically occupy a finite volume corresponding to a local depth minimum. Hydrocarbon pore fluids preclude those volumes as potential HSA geothermal energy sources but the same formations may represent potential HSA geothermal energy sources if they extend downdip to deeper, hotter and volumetrically large water-saturated zones. Little research has been conducted into such potential in Australia with the exception of IMER's review of HSA potential in the Eromanga and Otway Basins (IMER 2014a, 2014b, 2014c). Other potential basins of interest include the Canning Basin and Southern Carnarvon Basin in Western Australia, the Amadeus Basin in the Northern Territory, and the Bowen Basin in Queensland (see Figure 3 for locations).

Greenfields basins: Being a large and sparsely populated country, many parts of Australia remain relatively underexplored for resources including HSA-hosted geothermal energy. Beardsmore (2007), for example, noted that the onshore portions of the Cambrian to Cenozoic Bonaparte Basin and Jurassic to Eocene Money Shoal Basin in the Northern Territory (see Figure 3 for locations) may host HSA geothermal energy sources because they are underlain by the high heat-producing Pine Creek Orogen, contain potentially thermally insulating formations, and are relatively close to infrastructure and/or markets. The potential in these basins remains to be tested.

Summary and concluding remarks

With the exception of a 160-day demonstration of power production by Geodynamics Ltd from the Habanero engineered geothermal system project near Innamincka in South Australia in the early 2010s (Hogarth and Holl 2017), all other production of geothermal energy in Australia historically, currently, and for the foreseeable future has drawn on HSA sources less than 100°C. The Eromanga, Perth, Gippsland and Otway Basins have been the principal focal points for geothermal energy production and utilisation. It is notable that all projects have operated within prevailing energy markets without significant government subsidies or incentives, demonstrating that HSA geothermal energy resources represent the lowest cost source of low grade heat in many locations. The general upward trajectory of domestic natural gas prices will likely see an expansion of locations where this holds true, and thus an increase in the number of projects drawing heat from HSA sources.

The author has been involved in numerous pre-feasibility studies for geothermal energy utilisation from HSA sources in Australia, and has personally observed regulatory challenges with respect to building and operating geothermal energy projects. The details of those challenges vary between jurisdictions, but generally arise from overlapping mineral/energy resource, groundwater, and environmental protection regulations. The vague space in which direct-use geothermal energy projects often sit with respect to legislative responsibility in Australia can result in significant delays to projects and/or the imposition of onerous compliance conditions. Optimal utilisation of HSA geothermal energy resources in Australia may only be realised through streamlined and/or nationally harmonised regulatory processes. Meanwhile, individual projects will continue to come online driven by positive economic returns on investment.

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Data availability statement

The author confirms that the data supporting the findings of this study are available within the article or its referenced materials.

ORCID

Graeme R. Beardsmore http://orcid.org/0000-0003-4812-1146

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