LITHIUM

Critical mineral potential of South Australia

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SOUTH AUSTRALIA

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As guests on Aboriginal land, the Department for Energy and Mining (DEM) acknowledges everything this department does impacts on Aboriginal country, the sea, the sky, its people, and the spiritual and cultural connections which have existed since the first sunrise. Our responsibility is to share our collective knowledge, recognise a difficult history, respect the relationships made over time, and create a stronger future. We are ready to walk, learn and work together.

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CONTENTS

TABLES

FIGURES

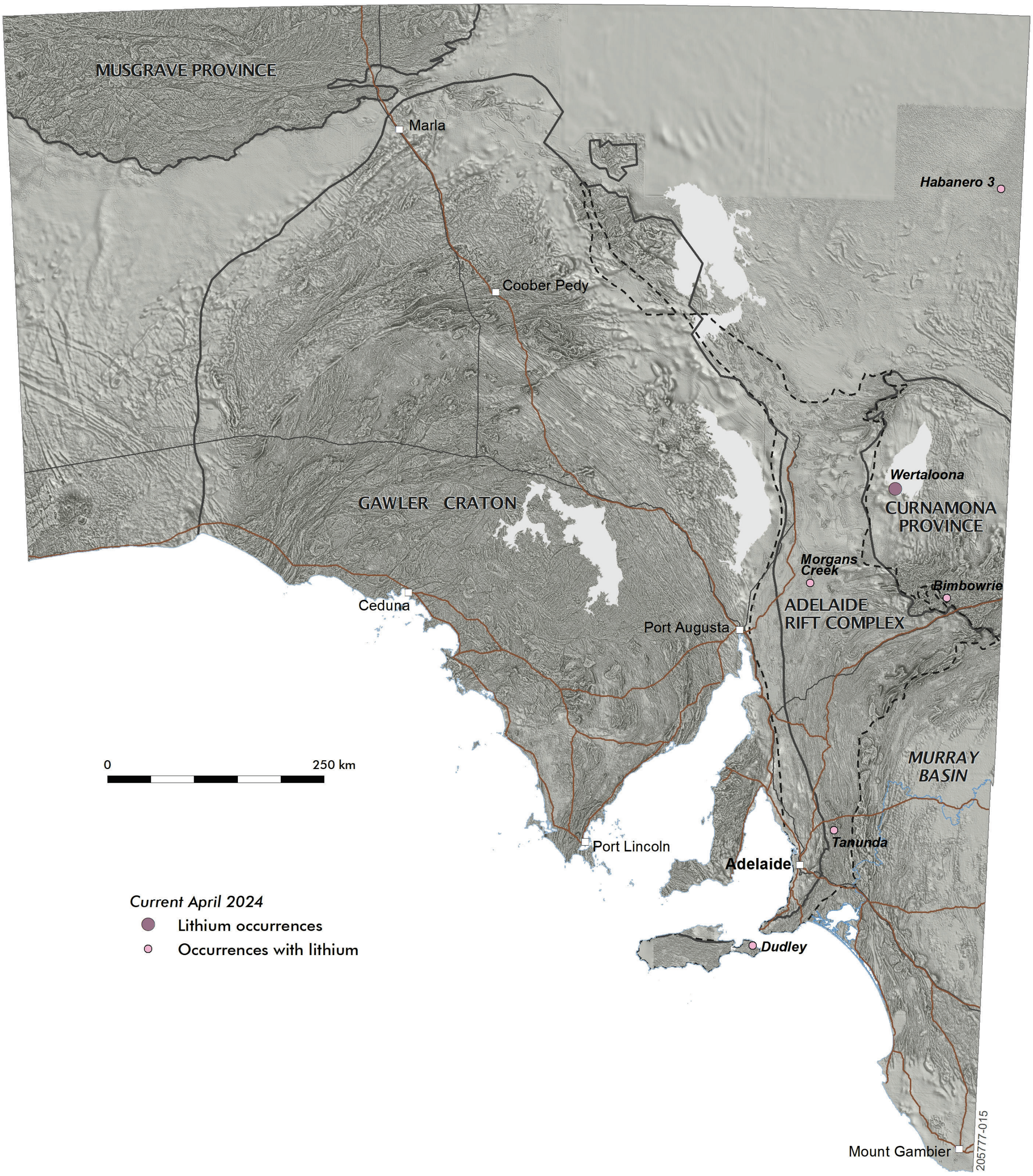

Figure 1. Occurrences of lithium and occurrences with associated lithium in South Australia. (205777-015 PDF 5.5 MB)

Lithium

Peter Keller, Alexander Corrick, Jarred Lloyd, Adrian Fabris, Carmen Krapf and Alicia Caruso

Lithium is the first metal on the periodic table being recognised as an element in 1817 (Evans 2014; Lithium Australia NL 2019). It is a soft silvery-white to grey alkali metal that floats on water and can ignite when exposed to air. It is also the lightest of all the metals and has excellent electrical conductivity. Lithium does not occur freely as a native element, rather it forms compounds such as silicates, as a chloride complex in brines and in some clay minerals (Evans 2014). The average crustal abundance of lithium is 17 ppm while in comparison, seawater has an average concentration of 0.18 ppm (Evans 2014). The principal lithium minerals are spodumene ($LiAlSi_2O_6$), petalite ($LiAl(Si_4O_{10})$,) amblygonite ($LiAl(PO_4)F$) and the lithium mica series minerals polylithionite-trilithionite (KLi_2 $Al(Si_4O_{10})F$ $OH)_2$), often referred to as lepidolite in literature. The mineral spodumene is the most sought-after source of lithium due to its relatively high Li content of approximately 8% (Zhang et al. 2022). Australian production of lithium in 2022 was 61,000 tonnes and accounted for nearly half of the world's supply of 130,000 tonnes in 2022. Chile, China, Brazil and Argentina are the other principal global producers (Jaskula 2023).

USES

Lithium is primarily used to manufacture rechargeable Li-ion batteries (80%), with other minor uses including ceramics/glass (7%), lubricating greases (4%), continuous casting mould flux powders (2%), air treatment (1%), medications (1%) and other uses (5%) (Jaskula 2023).

ECONOMIC DEPOSIT TYPES

Key deposit types with proven or growing economic potential include:

- Brine deposits (continental/oilfield/geothermal)
- Lithium-caesium-tantalum (LCT) pegmatites and rare metal granites
- Lithium-rich clay deposits
  - Smectite and illite deposits
  - Jadarite deposits
  - Lithium-rich volcanic deposits

Most of the global lithium supply is sourced from salt lake/continental brines and LCT type deposits (Bradley et al. 2017). Secondary deposits produced by weathering of hard rock deposits (i.e., deeply weathered crusts and alluvial or placer deposits) may also be of economic interest, as they can be further enriched in lithium and more cost-effective to mine. However, given these deposits typically form in proximity to the primary deposit, they are not considered as separate deposit types here.

There is also potential to extract lithium from an even wider range of sources, such as desalination brines, mine water, coal fly ash and iron-manganese nodules/crusts. These potential future sources of lithium are not considered in this report.

BRINES

Continental brines

Continental brine deposits are excellent sources of lithium compared to hard rock deposits due to their significant resource size, lower capital and operating costs (Tabelin et al. 2021), however, continental brine extraction can typically take up to 10 months of evaporation time to produce a concentrate. The lithium content of brines is typically provided in mg/L (1 mg/L = 1 ppm). Most economic continental brines contain average lithium concentrations of between 200–1400 mg/L

(Gruber et al. 2011; Munk et al. 2016), however, lithium concentrations can vary by hundreds to thousands of mg/L across a salt lake or salt crust, requiring widespread sampling to determine a reliable average concentration. Brines with low magnesium/lithium ratios (Mg/Li <6) are also preferable, as Li^{+} and Mg^{2+} ions are of similar size and therefore difficult to separate, increasing production costs. Alternative processing techniques for high magnesium brines is an area of ongoing development (Liu et al. 2020). Brines can also be a source of potash, magnesium, bromine and boron.

When Li-rich brines evaporate at the surface, the lithium is incorporated within common salt minerals. The sole exception to this rule is the deposit at Zabuye Lake in the Autonomous Region of Tibet, China, which naturally precipitates the lithium salt - zabuyelite (Munk et al. 2016; Bradley et al. 2017). Other examples of continental brine deposits currently producing lithium can be found in Chile, Bolivia, China, Argentina and the USA (Kesler et al. 2012; Bowell et al. 2020). A review of the Li-enriched brine deposits of Salar de Atacama (Chile) and Clayton Valley (USA) is provided by Munk et al. (2016). Processing costs can be reduced by extracting additional co-products or by-products, such as potassium/potash, magnesium, bromine and boron, which may be in higher concentrations than lithium (Gruber et al. 2011; Kesler et al. 2012).

Understanding the environmental, social, and governance (ESG) impacts of lithium extraction from continental brines is an important consideration in these type of projects (Moran et al. 2022). By their nature, these deposits require the extraction of significant fresh and saline water resources over a large area which can impact groundwater levels and potentially affect local freshwater supply for communities, with knock-on effects on biodiversity and ecosystems. This may be exacerbated by changing water recharge rates and increasing aridity as a result of climate change and competing water demands.

The potential for saline lake deposits to contain lithium-enriched brines is often determined by certain geological and geographical requirements such as (Munk et al. 2016):

1. an arid climate
2. a closed basin containing a salar (salt crust), a salt lake, or both
3. associated igneous and/or hydrothermal activity
4. tectonically driven subsidence
5. suitable lithium sources
6. sufficient time to concentrate lithium in the brine.

Oilfield brines

Deep oilfield brines have been reported to contain lithium concentrations as high as 700 ppm (Bradley et al., 2017), however, economic extraction of lithium from these brines is limited by the cost associated with pumping the brine from much greater depths (>1 km) than continental brine deposits. The ability to utilise solar evaporation ponds to reduce the brine may be an important factor affecting the viability of a project (Bradley et al. 2013).

The most advanced oilfield brine project aims to commercially extract lithium from brines within the Jurassic Smackover Formation, which spans several states including Arkansas, Louisiana, Mississippi, and Alabama, in the USA. The brine, which is already pumped to the surface to recover bromine, is hosted within the limestone unit and is approximately 200 m thick at depths between 1800–4800 m. This formation contains lithium brines with concentrations between 50–692 mg/L (Collins 1976; Bradley et al. 2017). Standard Lithium has been operating an industrial-scale demonstration plant using a proprietary extraction technique to extract lithium from Smackover Formation brine since May 2020 and undertaken feasibility and engineering studies towards construction of a commercial lithium plant (Standard Lithium 2023).

Geothermal brines

In geothermal power plants, fluids pumped from the subsurface for power generation may be enriched in dissolved minerals which may corrode components within the power plant (Al Radi et al. 2022). Therefore, treatment of the wastewater to extract these dissolved minerals has been considered as a possible source of lithium, in addition to a variety of other elements such as boron, arsenic, silica and sulphur (Al Radi et al. 2022).

Analysis of Salton Sea and Imperial Field geothermal brines from California, USA, are reported to contain typical lithium concentrations of 230 and 327 ppm, respectively (Duyvesteyn 1992)., however, not all geothermal brines are similarly enriched. Reported values from New Zealand, Iceland and Chile all contain lithium concentrations <50 ppm (Evans 2014).

Development of consistent procedures and environmental considerations for the economic extraction of dissolved minerals from geothermal brines is still in its infancy, with additional research required before any processes can be widely adopted (Al Radi et al. 2022). Simbol Materials reportedly extracted lithium from the Salton Sea geothermal brine using a proprietary extraction process (Bradley et al. 2017). More recently, Vulcan Energy announced their Zero Carbon Lithium Project, which intends to extract lithium from geothermal brines from the Upper Rhine Valley in Germany. Brines extracted from the area contain an average lithium content of 153–181 mg/L with the intention of commencing production in 2025 (Vulcan Energy 2023). While conventional aluminium absorbent extraction processes require a minimum lithium grade of >300 mg/l, a new ion-exchange process developed by Lilac Solutions has enabled lithium grades of 50 mg/l to be economical (Lilac Solutions 2024). New technology may indeed provide further impetus for lithium production from these types of brines.

LITHIUM-CAESIUM-TANTALUM (LCT) PEGMATITES AND RARE METAL GRANITES

Lithium-caesium-tantalite (LCT) pegmatites are primarily sought as a source of spodumene, as it occurs in significant quantities and has well established beneficiation methods (Tadesse et al. 2019). A compilation of world-class lithium pegmatite deposits, which includes examples from Western Australia, Brazil, Canada and Zimbabwe, provide lithium grades between 6040–11,800 ppm (Bowell et al. 2020).

Other than LCT pegmatites, certain rare metal/greisen granites can also contain economic concentrations of lithium minerals and other metals. For example, the topaz-lepidolite phase of the Yichuan granite, a rare-metal granite in the Jiangxi province in China, was found to contain an average lithium concentration of 5,243 ppm (Yin et al. 1995). Because granites contain more complex mineralogy they tend not to be seen as an economic source of lithium compared to LCT pegmatites, however, many recent global assessments of lithium resources do not distinguish between the two (Bradley et al. 2017). New processing technologies being developed to treat lithium micas may result in more granites and pegmatites being re-evaluated (Cornish Lithium 2023).

Lithium-rich pegmatites have a wider global distribution than continental brines, and therefore reduce the reliance on geographically restricted deposits, a risk commonly associated with many other critical minerals. LCT pegmatites can be multi-commodity deposits also containing tin, tantalum and beryllium (Gruber et al. 2011; Kesler et al. 2012). The recovery of these other commodities may become an important factor affecting the profitable extraction of lithium.

LITHIUM-RICH CLAY DEPOSITS

Smectite and illite deposits

Currently, there are no lithium-rich smectite/illite deposits being exploited, however, there are two deposits in advanced stages of development. The Thacker Pass Project (also known as the Kings Valley Deposit), Nevada, USA, has begun construction for approved mining operations (Lithium Americas Corp. 2022), and the Sonora lithium deposit, Mexico, has completed a feasibility study and is progressing towards construction (Cadence Minerals 2023).

The Thacker Pass deposit contains a combined measured and indicated mineral resource estimate of 1.457 Gt with an average of 2,070 ppm Li and a combined proven and probable mineral reserve of 217.3 Mt with an average lithium content of 3,160 ppm (Lithium Americas Corp. 2022). Lithium is hosted within the clay minerals smectite and illite (Lithium Americas Corp. 2022). The deposit is thought to have formed in two stages, with an initial phase of lithium-rich, magnesian smectite clays forming in a closed basin environment as a result of a reaction of volcanic glass with a highly alkaline aqueous solution. This was followed by a secondary enrichment phase, due to the alteration of smectite by hydrothermal lithium-rich fluids (Benson et al. 2023).

The Sonora lithium deposit contains an open pit reserve of 243.8 Mt with an average Li grade of 3,480 ppm (Ausenco Services Pty Ltd 2018). Lithium is hosted in two clay-rich units separated by an ignimbrite and constricted by basal and capping basalts (Ausenco Services Pty Ltd 2018; Verley 2014). The clay intervals are comprised of illite or smectite, with their formation attributed to either supergene alteration or diagenetic alteration of volcanic ash (Verley 2014).

Jadarite deposits

The only known deposit of the mineral jadarite ($LiNaSiB_3O_7)H$) occurs in the Jadar basin, Serbia (Bradley et al. 2017). The deposit contains 85.4 Mt of indicated resources at 1.76% Li_2O and an additional 58.1 Mt of inferred resources at 1.87% Li_2O (Rio Tinto 2022). The deposit is considered a potential economic source of lithium but has yet to be exploited.

A model for jadarite deposits has yet to be defined, so understanding key features and geologic processes is imperative when searching for comparable deposits elsewhere (Bradley et al. 2017; Stefanović N et al. 2023). The deposit is comprised of metre-scale layers of jadarite (Stanley et al. 2007), which are interpreted to have formed during the deposition or early diagenesis in an extensional tectonic setting of Miocene-aged lake sediments in the Jadar Basin (Bradley et al. 2017). Mineralisation is possibly the result of geothermal-hydrothermal fluid alteration of volcanic-sedimentary deposits (Bowell et al. 2020).

Lithium-rich volcanics

Felsic to intermediate volcanics are widely considered the source of lithium for enriched brines or clay deposits, as lithium in volcanic glass is easily leached. However, volcanic deposits typically do not contain sufficient lithium to be exploited. The Falchani deposit in Peru may represent an exception to this rule. The deposit is comprised of a lithium-rich volcanoclastic tuff overlain by breccia and rhyolite units (DRA Pacific 2024). Although lithium grades are highest within the tuff interval, significant resources are also reported in the upper and lower breccia structures of the deposit (Burling et al. 2019). American Lithium Corporation have provide an indicated resource of 61 Mt with a grade of 2,706 ppm Li (American Lithium 2024).

The exact nature of the Falchani deposit remains poorly understood, with insufficient evidence to form a reliable deposit model. Based on drill core and outcrop observations, DRA Pacific (2020) currently favours a primary lithium mineralisation model but do not discount the possibility that the high lithium concentrations are associated with alteration by groundwater or hydrothermal fluids. Conversely, a review of lithium deposits by Bowell et al. (2020) stated that the Falchani deposit is comprised of uranium-lithium-rich hydrothermal clays within altered rhyolites. No mineralogy information on the deposit has been published to date and the review provides no associated reference or data to support this interpretation. Given the lack of understanding around this relatively new deposit type, additional research is required to determine the key characteristics and geologic processes responsible for lithium enrichment to promote future exploration.

OCCURRENCES IN SOUTH AUSTRALIA

The occurrence of lithium micas, elbaite, and petalite in Delamerian-aged pegmatites, occur within the Tapannapa Formation of the Kanmantoo Group at the Dudley deposit (MinDep no. 529) on Kangaroo Island. These pegmatites were historically worked for gem quality tourmaline (1890s) and feldspar, kaolin and silica (1905–1910). An economic review was carried out by the Department of Mines and Energy in 1987. Eight shallow trenches were cut across the strike of one pegmatite to evaluate its gem potential (Keeling and Rachmat 1987). The review determined that there was some merit in further investigation of the area as a source for potassium feldspar and gem tourmaline. Rock chip and float assays from exploration in the area have returned lithium concentrations up to 0.43% Li_2O and 770 ppm tantalum (Lithium Australia NL 2019). Without further geological and geochemical data, it is difficult to determine the potential for lithium in this district.

Early Delamerian gneiss, granites and mafic intrusive rocks occur to the southeast of Tanunda in the Barossa Valley. The I-type Tanunda Creek Gneiss may host the 'Spodumen-Granite' at 'Jacob's Glen, Barossa' referred to in Johannes Menge's book *The Mineral Kingdom of South Australia* (Menge 1847). The area would certainly benefit from further geological and geochemical work to determine its potential for lithium and other elements.

Drilling of mafic intrusions in 2021 by Taruga Minerals Ltd at their Morgan's Creek REE prospect (MinDep no. 11900) approximately 20 km southeast of Hawker in the Flinders Ranges, returned assay values of 15 m at 0.16% Li_2O, including 7 m at 0.2% Li_2O (Taruga Minerals Ltd 2021). While REE is the current primary target here, there is some potential to also produce lithium.

PROSPECTIVITY IN SOUTH AUSTRALIA

While there are no current lithium projects being developed in South Australia, there is significant potential. Regions most favourable for lithium exploration include the Olary district in the Curnamona Province, the Cooper Basin, the Gawler Craton and the Delamerian intrusives within the Adelaide Rift Complex.

Exploratory drilling for evaporites by Comalco in 1979 near Lake Frome, north-eastern South Australia, demonstrated anomalous lithium values. In 2011, ERO Mining Ltd continued this exploration with further drilling at the Wertaloona prospect (MinDep no. 10709), returning values of 10–70 ppm Li in most drillholes, although concentrations of up to 250 ppm were reported from the south-western margin of the lake (ERO Mining Ltd 2011). The project did not move beyond the initial assessment stage.

Geoscience Australia conducted a review of the economic mineral potential of Australian salt lakes in 2016 (Mernagh et al. 2016). Although lacking directly measured lithium concentrations within groundwaters feeding into many lake systems, the review concluded the inland salt lake systems of Lake Frome and the Central Gawler Region, may have potential for lithium in addition to other commodities such as potash, boron, or calcrete-hosted uranium (Mernagh et al. 2016). Preliminary assessment of cores at Lake Eyre indicated lithium concentrations were subeconomic (ERO Mining Ltd 2011).

Rock chip sampling of LCT pegmatite outcrops by Stelar Metals north of Broken Hill, NSW, in 2023, identified amblygonite-montbrassite, as the main source of anomalous lithium at its Trident Lithium Prospect (Stelar Metals 2023). Although a continuation of these pegmatites into South Australia has not yet been identified, anomalous lithium concentrations have been noted in rock chip and drill hole samples in the area south of Radium Hill (MinDep no.962) and in the vicinity of the Portia Cu-Au prospect (MinDep no. 4504). Notably, pegmatite outcrops reported in the Olary/Bimbowrie region of the Curnamona Province have been interpreted as LCT-type (Pollard

2017). Any further assessment of pegmatites in the State, is hindered by a lack of reliable data on their spatial distribution and mineralogy, which would help to constrain areas with economic potential.

Brines within the Habanero 3 well (PEPS SA no. 2330) in the Cooper Basin, were assessed for their geothermally potential by Geodynamics Ltd (currently Renu Energy Ltd) in 2008. Brine analysis demonstrated elevated values of up to 202 ppm Li and 43.7 ppm Cs (Geodynamics Ltd 2008). These brines are thought to originate from a radiogenic granite intersected at the base of the drillhole. The economic significance of this occurrence is uncertain. The potential for other developing sources of lithium from oilfield brines, lithium-rich clays and volcanics in South Australia, are difficult to reliably assess as there are not many economic deposits of these types worldwide, and because they are still poorly understood.

Table 1. Summary of deposit types which may be enriched in lithium and regions of interest in South Australia with potential for these deposits.

Key deposit types	Regions of interest in South Australia
LCT-type pegmatites and Li-rich granites	• Pegmatites in the Olary region of the Curnamona Province classified as LCT-type (Lottermoser and Lu 1997; Pollard 2017). • Dudley Pegmatite, Kangaroo Island (Lithium Australia NL 2019). • Delamerian granitoids, Jacobs Creek district – Barossa Valley (Turner et al. 2022; Pollard 2017).
Lithium-rich clay deposits	• Morgans Creek REE deposit, Flinders Ranges (Taruga Minerals Ltd 2021).
Continental brines	• Inland salt lakes; Lakes Eyre, Torrens and Frome (Mernagh et al. 2016).
Geothermal brines	• Cooper Basin area (Geodynamics Ltd 2008).

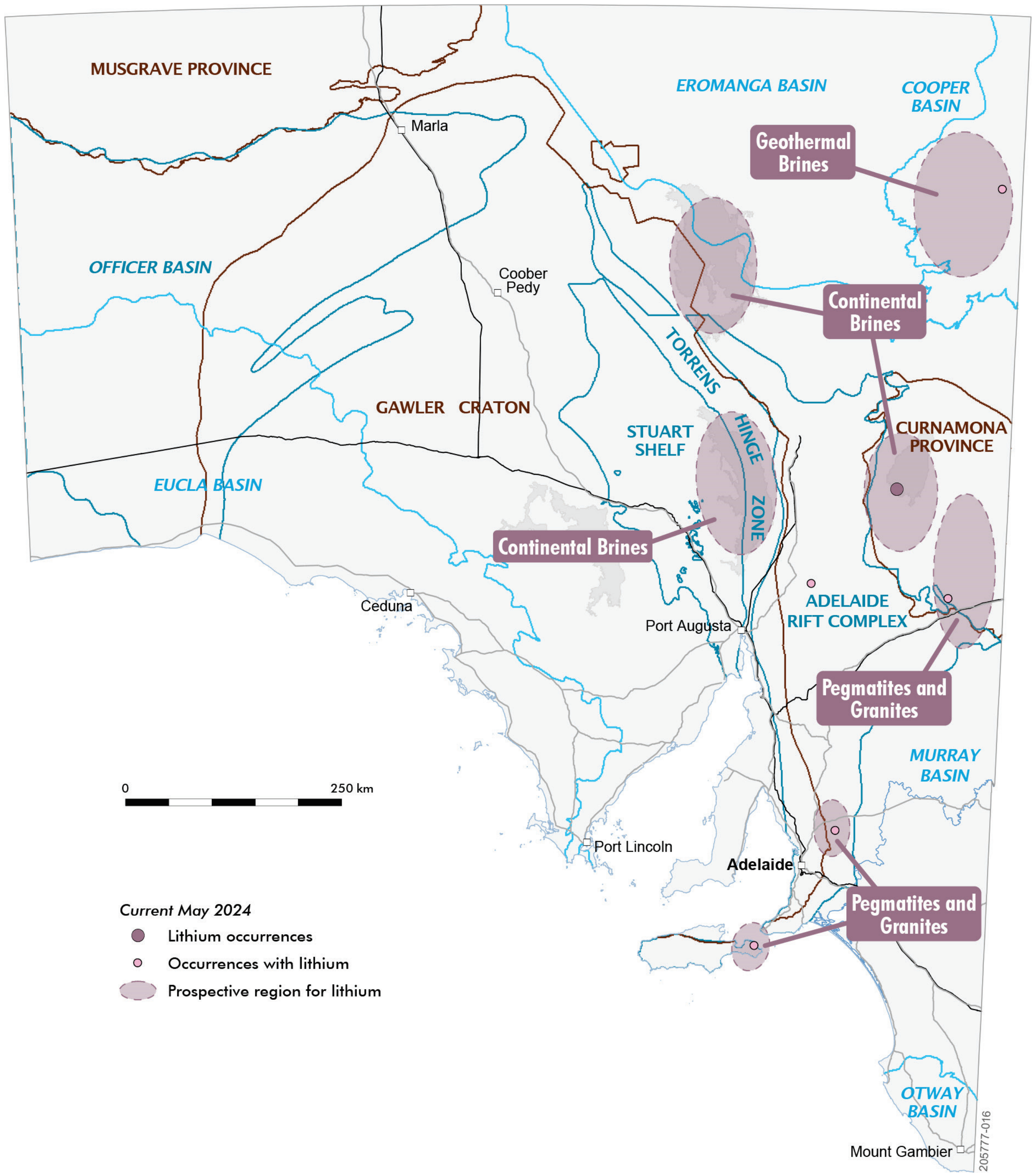

Figure 2. Location of South Australia's lithium occurrences and characteristic lithium forms. (205777-016 PDF 187 KB)

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Critical Minerals South Australia project
https://www.energymining.sa.gov.au/industry/geological-survey/gssa-projects/critical-minerals-south-australia

South Australia’s Mineral Deposit (MinDep) database
https://minerals.sarig.sa.gov.au/MineralDepositSearch.aspx

APPENDIX

OCCURRENCE DATA

Combined data available from South Australia’s Mineral Deposit (MinDep) database as displayed in Figure 1 (as at December 2023).
Click to open attachments panel.