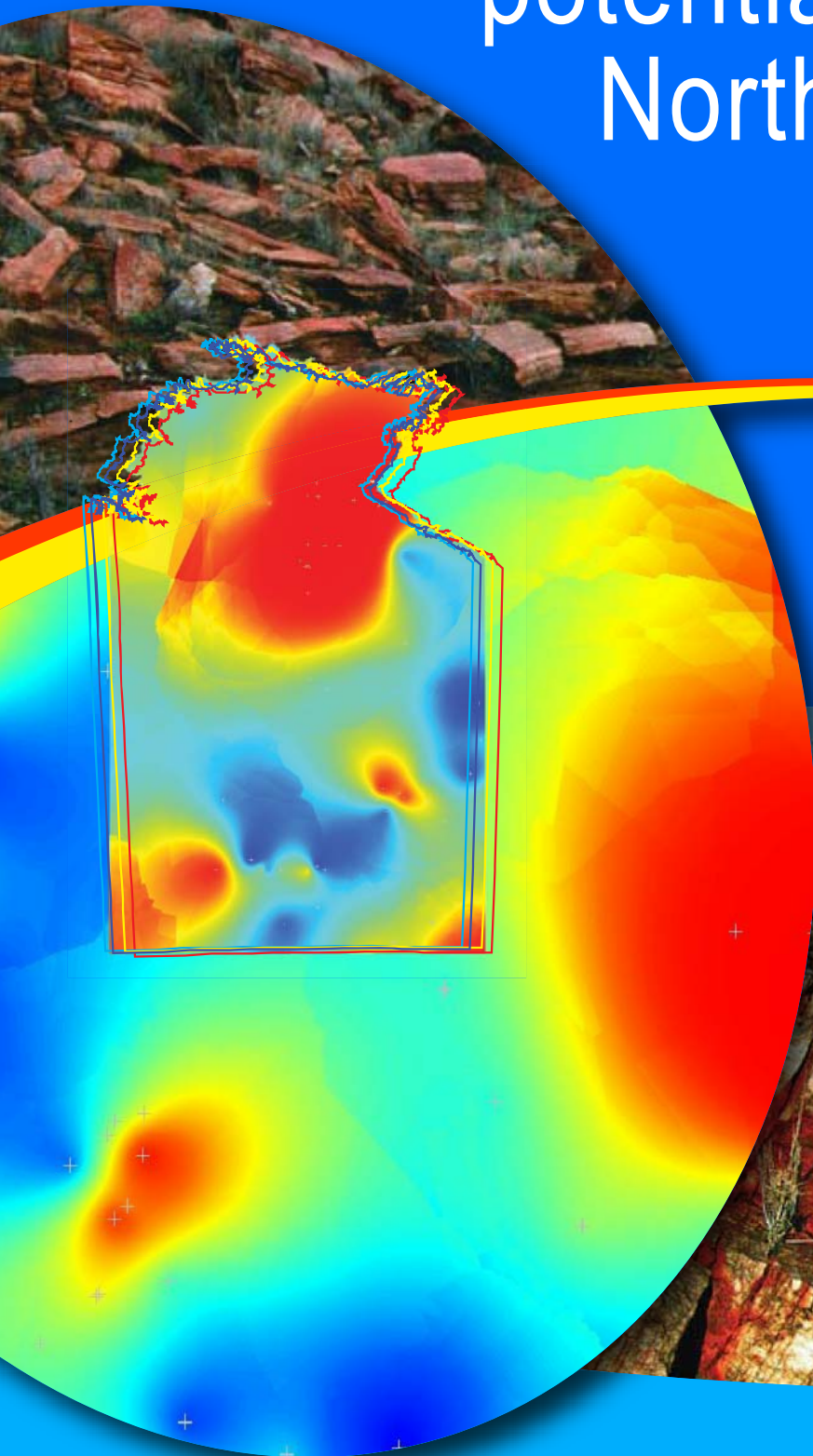


# Geothermal energy potential of the Northern Territory

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Geothermal energy potential of the Northern Territory.

BIBLIOGRAPHIC REFERENCE: Beardsmore G, 2007. Geothermal energy potential of the Northern Territory. *Northern Territory Geological Survey, Record 2007-004*.

(Record / Northern Territory Geological Survey ISSN 1443-1149)

Bibliography

ISBN: 978-0-7245-7164-2

Keywords: Northern Territory, Amadeus Basin, Ngalia Basin, Georgina Basin, McArthur Basin, Beetaloo Sub-basin, Dunmarra Basin, Pedirka Basin, Eromanga Basin, Daly Basin, Wiso Basin, Lander Trough, Bonaparte Basin, Money Shoal Basin, Arafura Basin, Central Australian Heat Flow Province, stratigraphy, sedimentology, geothermal energy, geothermal fields, geothermal gradient, geothermal systems, hot dry rocks, hot fractured rocks, hydraulic fracturing, reservoir rocks, thermal conductivity.

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## ABSTRACT

The Northern Territory is part of the Central Australian Heat Flow Province and possesses all the fundamental requirements for geothermal systems that could be used for hot rock or deep hot aquifer geothermal electricity generation. Crystalline basement rocks beneath the NT's basins are capable of generating high surface heat flows in many areas and adequate thermal insulation is provided by appropriate rock types in overlying sedimentary successions in a number of basins. The whole of the NT is currently in a compressive stress regime, making it attractive for the hydraulic stimulation of hot basement rocks, and basement is at a drillable depth in many areas. Sedimentary formations at depth may also be suitable drill targets, provided they are naturally permeable or susceptible to permeability enhancement.

The NT's onshore sedimentary basins are individually assessed for their hot fractured rock geothermal energy potential. The McArthur Basin, Beetaloo Sub-basin and Dunmarra Basin are prospective for geothermal systems in areas where there is high heat flow and significant insulating sedimentary layers. Basement is deeply buried beneath these basins, but there is potential for *in situ* permeability, or layers that can have their permeability artificially enhanced. The Victoria–Birringudu basins are likely to have high heat flows, but may lack adequate insulating sedimentary layers, reducing the potential for good geothermal systems at drillable depths. Except for northern areas of the Victoria Basin, these basins are also relatively remote from infrastructure. The Daly Basin may host areas of elevated heat flow and is also relatively close to infrastructure and markets. However, sedimentary thicknesses may be insufficient to provide the required thermal insulation, except in parts of the basin that overlap other sedimentary successions. The coastal Bonaparte, Money Shoal and Arafura basins are attractive for exploration because they are underlain by basement with demonstrated high heat flow, they contain potentially insulating intervals of fine-grained sedimentary rocks, and they are also relatively close to infrastructure and/or markets.

The Amadeus Basin contains a thick, but mostly conductive sedimentary succession. However, local areas of basement have exceptionally high heat-generating properties that could elevate surface heat flow to reasonable levels. Thick basement sections occur in shallower portions of the basin on the central ridge and in southern areas; these areas are within drillable depths and are relatively close to infrastructure. The Ngalia Basin has potential for elevated heat flow in areas where basement has high heat-generating properties and the succession has a high proportion of fine-grained sedimentary rocks. This basin is distant from markets, but has relatively good road access. The Georgina Basin contains some areas where crystalline basement rocks are at relatively shallow depths and heat flow is likely to be high. However, the sedimentary fill may not provide adequate thermal insulation and this basin is remote from potential markets. The Pedirka and Eromanga basins are underlain by crystalline basement rocks with high heat-generating potential and the sedimentary succession has excellent potential for thermal insulation. Geothermal targets may be present within drillable depths in some areas, either in basement rocks, or in strata that are naturally permeable or susceptible to permeability enhancement. However, these basins are also distant from potential markets and have limited infrastructure. The Wiso Basin (Lander Trough) is distant from infrastructure and is poorly explored; deeper parts of the basin have not been drilled and its geothermal potential is therefore difficult to assess. However, underlying crystalline basement rocks may provide adequate heat flow and parts of the sedimentary succession may have good thermal insulation properties.

Basins in the north of the NT are relatively close to population centres and electricity power lines from Katherine to Darwin, whereas basins in the south are close to Alice Springs and to north–south rail and road arteries. Remote communities and mining operations in all parts of the Territory could benefit from the development of sustainable geothermal power.



## GEOTHERMAL ENERGY, GEOTHERMAL SYSTEMS AND EXPLORATION

Where high temperatures occur in rocks close to the Earth's surface, the heat can potentially be harnessed to provide useful power for the benefit of humanity. The general term for this resource is *geothermal energy*. Globally, geothermal energy currently provides more than 8900 MW of electrical power (Bertani 2005), as well as direct heat for applications such as space heating and aquaculture. Almost all electrical power is currently generated close to plate tectonic boundaries in regions such as New Zealand, Iceland, South East Asia and the western United States (Table 1). In these regions, naturally occurring hot water and steam is found in permeable rocks close to the Earth's surface. These sorts of systems are sometimes referred to as *conventional* geothermal energy.

*Hot fractured rock* (HFR) geothermal energy differs from conventional geothermal energy in that it does not rely on the rock's natural permeability. Rather, a permeable reservoir, or underground heat exchanger, is artificially created by fracturing hot rocks deep underground (see Tester *et al* 2006, Figure 1). Heat can then be recovered from the hot rocks by passing water through the underground heat exchanger from one borehole to another. The water heats up as it permeates through the hot rocks and flows to the surface through a production bore as superheated water. At the surface, the superheated water is passed through a heat exchanger to vaporise a secondary fluid to drive a turbine. Spent geothermal water is reinjected into the underground heat exchanger to extract more heat, making a closed loop.

The conditions necessary for the extraction of geothermal energy can be described using the concept of geothermal systems. A geothermal system has three components: a heat source, a reservoir and a fluid. All three components must be present before geothermal energy can be produced at the

Earth's surface. The *heat source* can be thought of as a volume of rock at a particular temperature at a drillable depth. The *reservoir* is a volume within the heat source through which a *fluid* can flow to extract heat. In conventional geothermal systems, all three components are naturally present. In HFR operations, the reservoir is artificially created within the heat source and the fluid artificially introduced into the reservoir. The primary aim of geothermal exploration is therefore to locate a heat source in rocks conducive to the natural or artificial development of a reservoir.

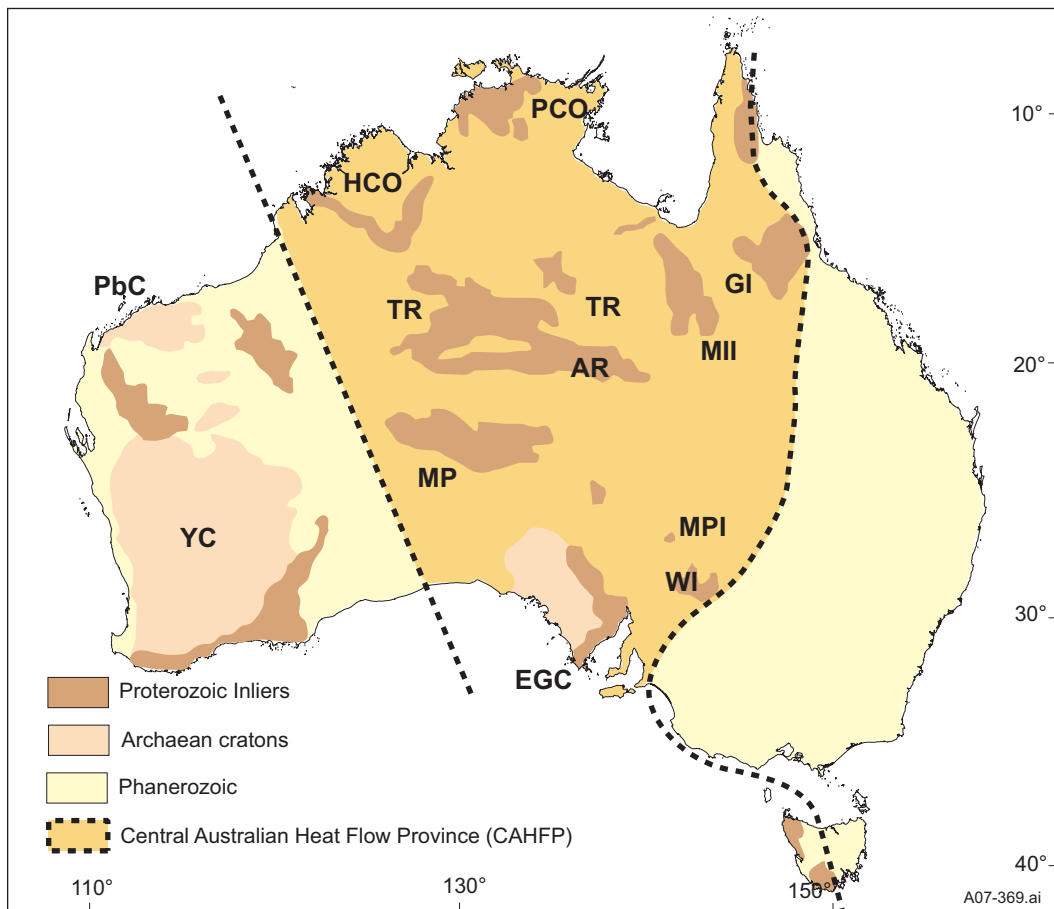
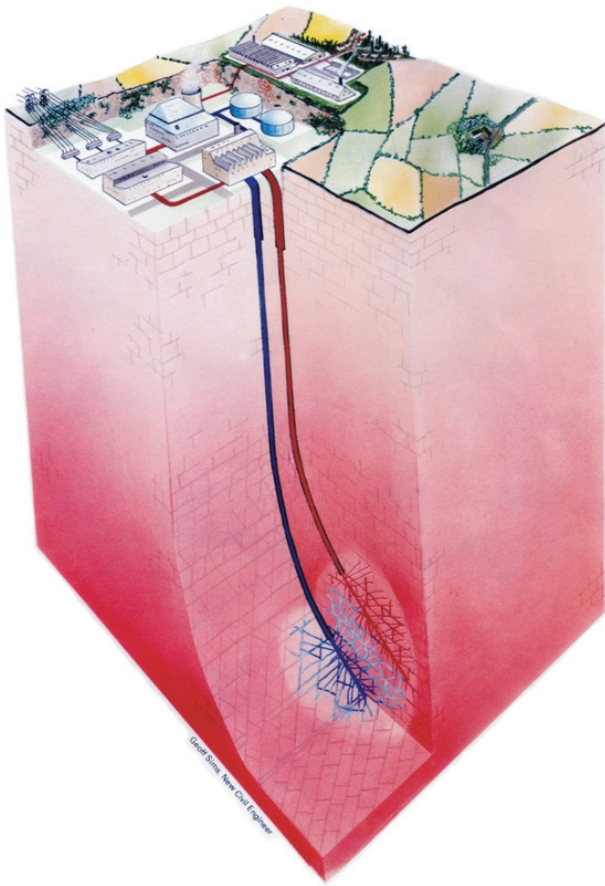
Temperatures suitable for HFR electricity generation exist beneath every point on the Earth's surface. However, the cost of drilling to access that heat will typically be lowest at locations where a high geothermal gradient exists. Geothermal gradient is directly proportional to heat flow and inversely proportional to thermal conductivity. That is, high geothermal gradients are found in regions with high heat flow and low thermal conductivity. Exploration for a heat source should focus on locating regions with high heat flow and low-conductivity surface layers.

The magnitude of heat flow in a region is the sum of heat flowing from the mantle and heat generated within the crust. McLaren *et al* (2003) demonstrated that the heat flow from the deep crust and mantle beneath the Central Australian Heat Flow Province (CAHFP), which includes the entire Northern Territory (Figure 2), is about 40 MW/m<sup>2</sup>. On its own, heat flow of this magnitude is unlikely to generate high temperatures at drillable depths. However, McLaren *et al* (2003) also concluded that the upper crust within the CAHFP is prone to generating a considerable amount of heat from the natural radiogenic decay of uranium, thorium and potassium isotopes. Therefore, it is very likely that heat flow in parts of the Northern Territory is of sufficient magnitude to generate attractive geothermal targets, especially where high heat flow coincides with insulating sedimentary layers.

Country	1990 (MWe)	1995 (MWe)	2000 (MWe)	2005 (MWe)
Argentina	0.67	0.67	0	0
Australia	0	0.17	0.17	0.2
Austria	0	0	0	1
China	19.2	28.78	29.17	28
Costa Rica	0	55	142.5	163
El Salvador	95	105	161	151
Ethiopia	0	0	8.52	7
France (Guadeloupe)	4.2	4.2	4.2	15
Germany	0	0	0	0.2
Guatemala	0	33.4	33.4	33
Iceland	44.6	50	170	202
Indonesia	144.75	309.75	589.5	797
Italy	545	631.7	785	790
Japan	214.6	413.71	546.9	535
Kenya	45	45	45	127
Mexico	700	75	755	953
New Zealand	283.2	286	437	435
Nicaragua	35	70	70	77
Papua New Guinea	0	0	0	6
Philippines	891	1227	1909	1931
Portugal (The Azores)	3	5	16	16
Russia (Kamchatka)	11	11	23	79
Thailand	0.3	0.3	0.3	0.3
Turkey	20.6	20.4	20.4	20.4
USA	2774.6	2816.7	2228	2544
<b>Total</b>	<b>5831.72</b>	<b>6833.38</b>	<b>7974.06</b>	<b>8912</b>

**Table 1.** Conventional geothermal power generation by year and country. Data from the International Geothermal Association.

**Figure 1.** Schematic of a “hot fractured rock” system (after Dickson and Fanelli 2004, figure 8).



**Figure 2.** Location of Proterozoic metamorphic belts and Archaean cratons. The Central Australian Heat-Flow Province is shown in brown tones. HCO = Halls Creek Orogen; MII = Mount Isa Inlier; TR = Tennant Region; MPI = Mount Painter Inlier; AR = Arunta Region; TR = Tanami Region; WI = Willyama Inlier; MP = Musgrave Province; EGC = Eastern Gawler Craton and Stuart Shelf; PCO = Pine Creek Orogen; GI = Georgetown Inlier; YC = Yilgarn Craton; PbC = Pilbara Craton (slightly modified after McLaren *et al* 2003).

## Thermal conductivity

Different types of rocks have different thermal conductivities (Beardsmore and Cull 2001). For example, coal has a very low thermal conductivity compared to most other rocks, and is therefore an excellent thermal insulator. Fine-grained porous or mafic rocks such as basalt, shale and mudstone are also relatively good insulators. Rocks such as quartzite and dolostone, on the other hand, are typically poor insulators. The ratio of coaly/shaly layers to sandy/dolomitic layers in a sedimentary interval gives a reasonable first-pass idea of the interval's insulating properties.

## Heat generation

Ignoring the horizontal dissipation of heat, a 1 km thickness of rock, generating heat at a rate of  $1 \mu\text{W}/\text{m}^3$ , contributes  $1 \text{ MW}/\text{m}^2$  to surface heat flow. Surface heat flow is the sum of heat generated in crustal rocks combined with mantle heat flow. McLaren *et al* (2003) demonstrated that within the CAHFP, most heat is generated on average in the top 13 km of crust. It follows that an average  $5 \mu\text{W}/\text{m}^3$  is sufficient to generate surface heat flow of over  $100 \text{ MW}/\text{m}^2$  in the CAHFP, equivalent to the heat flow in the vicinity of Geodynamics Limited's Habanero HFR development (Beardsmore 2005). **Table 2** summarises heat generation data derived from geochemical analyses of basement rocks in a number of Northern Territory Proterozoic and Archaean terranes. It is apparent that there are rocks in each of the terranes that are capable of generating sufficient heat for  $>100 \text{ MW}/\text{m}^2$  surface heat flow.

## Stress field

From the viewpoint of energy extraction, the optimum orientation for a geothermal reservoir is horizontal. In order to hydraulically enhance the permeability of horizontal fractures, the minimum compressive stress direction in the crust must be close to vertical. This can only be achieved in regions under tectonic compression. Hillis and Reynolds (2000) showed that the whole of the Northern Territory is currently in a compressive stress regime, making it attractive for hydraulic stimulation of basement rocks.

## ASSESSMENT OF INDIVIDUAL BASINS

The remainder of this document includes a first-pass assessment of the potential for geothermal targets to be

found in each of a number of sedimentary provinces in the Northern Territory (**Figure 3**). Prospectivity is assessed on the basis of the potential for high heat flow (ie high heat generation in the crust), the insulating properties of the sedimentary rocks (including thickness and shale content), the potential for a natural or artificial reservoir, proximity to infrastructure, and any other relevant factors.

More information on the Northern Territory's onshore basins can be found in Ambrose (2006) and Munson and Ambrose (2007). For the coastal Bonaparte, Money Shoal and Arafura basins, refer to articles in Ellis *et al* (2004). Key references are also provided in sections on individual basins.

Drillholes referred to in this report are located on **Figure 3**.

### Amadeus Basin

*Age:* Neoproterozoic (Cryogenian)–Carboniferous.

*Summary structure:* Large, intracratonic sedimentary basin.

*Thickness:* Up to 14 km.

*Lithology:* Dolostone, limestone, shale, sandstone, siltstone, quartzite, evaporite, diamictite, conglomerate.

*Summary relationship:* Overlies the Warumpi Province and Aileron Province of the Arunta Region to the north and Musgrave Province to the south (**Figure 4**). Overlain by Pedirka Basin to the southeast and Eromanga Basin to the east. It is a tectonic remnant of the large intracratonic Centralian Superbasin (Walter *et al* 1995), which was a contiguous entity during the late Neoproterozoic and early Palaeozoic.

*Key references:* Korsch and Kennard (1991), Ambrose (2006), articles in Munson and Ambrose (2007).

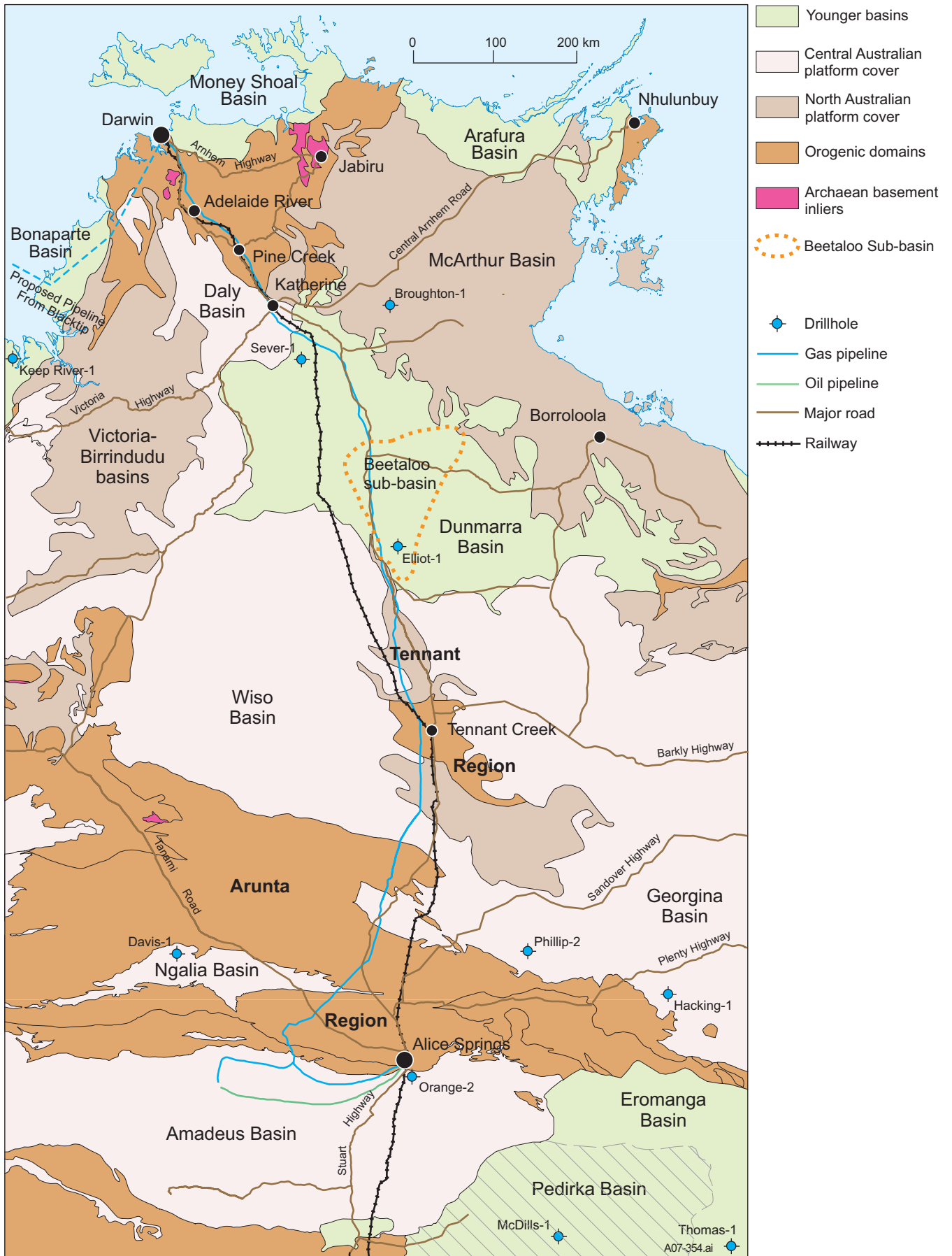
*Example well:*

Orange-2 (Jackson *et al* 1985; depths in metres; finer-grained stratigraphic intervals in bold)

0–9	unconsolidated red/brown/orange sandstone with some calcite cement
9–283.5	Pertnajara Group (sandstone, siltstone, conglomerate, some limestone)
283.5–622	Mereenie Sandstone
622–730.5	Stairway Sandstone

Region name	Heat generation ( $\mu\text{W}/\text{m}^3$ )				
	#data	Mean	Median	Max.	Min.
Aileron Province (Arunta Region)	136	4.52	3.39	18.7	0.23
Warumpi Province (Arunta Region)	10	3.67	3.41	7.49	0.82
Warramunga Province (Tennant Region)	15	4.10	3.24	14.8	2.94
Pine Creek Orogen	423	61.1	3.01	5110	0.35
Archaean basement	22	2.12	1.93	6.70	0.55
Davenport Province (Tennant Region)	91	3.29	3.42	6.01	0.70
Murphy Inlier	34	4.09	3.44	10.6	2.11
<b>TOTAL</b>	<b>731</b>	<b>37.0</b>	<b>3.21</b>	<b>5110</b>	<b>0.23</b>

**Table 2.** Summary of heat generation data from Northern Territory basement rocks.



**Figure 3.** Principle tectonic regions of the Northern Territory, showing infrastructure, locations and drillholes referred to in the text.



730.5–791	<b>Horn Valley Siltstone equivalent (mudstone-rich sedimentary rocks)</b>
791–1175	Pacoota Sandstone
1175–1320	Goyder Formation (yellow-brown, partly micaceous kaolinitic sandstone)
<b>1320–1720</b>	<b>Shannon Formation (siltstone, shale, limestone, dolostone)</b>
<b>1720–1977.5</b>	<b>Hugh River Shale</b>
1977.5–2276.5	Giles Creek Dolostone
2276.5–2286.5	Dingo Member of Giles Creek Dolostone
2286.5–2500	Chandler Formation (limestone, dolostone, chert)
2500–2522.5	Todd River Dolostone equivalent
2522.5–2909	Arumbera Sandstone
2909–2930	Julie Formation equivalent (pale brown to red-brown sandstone)
<b>2930–2948.2</b>	<b>Pertatataka Formation (fine kaolinitic sandstone)</b>

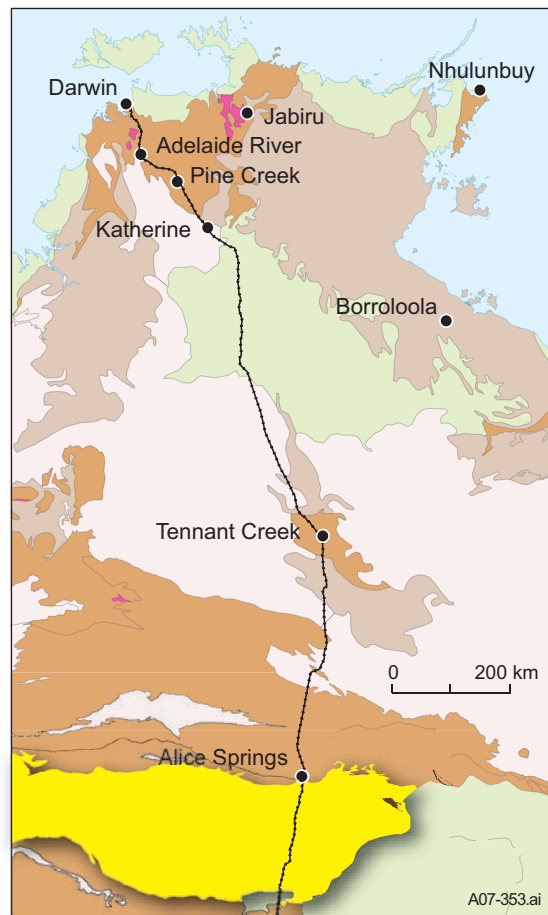
*Potential for high heat flow:* The underlying basement of Warumpi Province and Musgrave Province rocks provides ample potential for high crustal heat generation. The ten data points from the Warumpi Province (Table 2) include values up to  $7.5 \mu\text{W}/\text{m}^3$ . If the broader Arunta Region is taken as representative, the average heat generation may be as high as  $4.5 \mu\text{W}/\text{m}^3$ , with local values exceeding  $15 \mu\text{W}/\text{m}^3$ . This study provides no new heat generation data for the Musgrave Province, but McLaren *et al* (2003) provided data which suggested that the upper 10 km of the Musgrave Province generates  $5\text{--}6 \mu\text{W}/\text{m}^3$ . These data suggest that local areas, if not broad regions, within the Amadeus Basin may have surface heat flow exceeding  $100 \text{ MW}/\text{m}^2$ .

*Potential for insulating sedimentary rock:* The sedimentary fill of the Amadeus Basin is biased towards high-conductivity rock types such as quartzite, dolostone and sandstone. The example well (Orange-2) reveals about 730 m of shale and fine-grained rocks over its 3 km section. Other areas of the basin may have a higher proportion of fine-grained rocks, but in general, the limited insulation provided by the cover succession is the largest exploration risk in this basin.

*Potential for a natural or artificial reservoir:* Basement crystalline rocks are buried deeply beneath much of the Amadeus Basin. They may present a target for fracturing where they exist at shallower levels in the central ridge and southern flanks of the basin. However, within the sedimentary succession itself, there is evidence that some of the quartzite layers may preserve some natural permeability at depth (eg Young and Ambrose 2007).

*Proximity to infrastructure:* The Amadeus Basin is home to the onshore petroleum production industry in the Northern Territory. Alice Springs is situated on the northern margin of the basin and the Adelaide to Darwin railway and highway pass through it (Figure 3).

*Summary:* Localised areas of basement with exceptionally high heat-generating properties could elevate surface heat



**Figure 4.** Amadeus Basin in the Northern Territory.

flow to levels that counteract the negative impact of the conductive cover successions. The thick basement sections required for this scenario are most likely to be found in the shallower portions of the basin, on the central ridge and in southern parts, within drillable depths. These areas are also close to infrastructure.

### **Ngalia Basin**

*Age:* Cryogenian–Carboniferous.

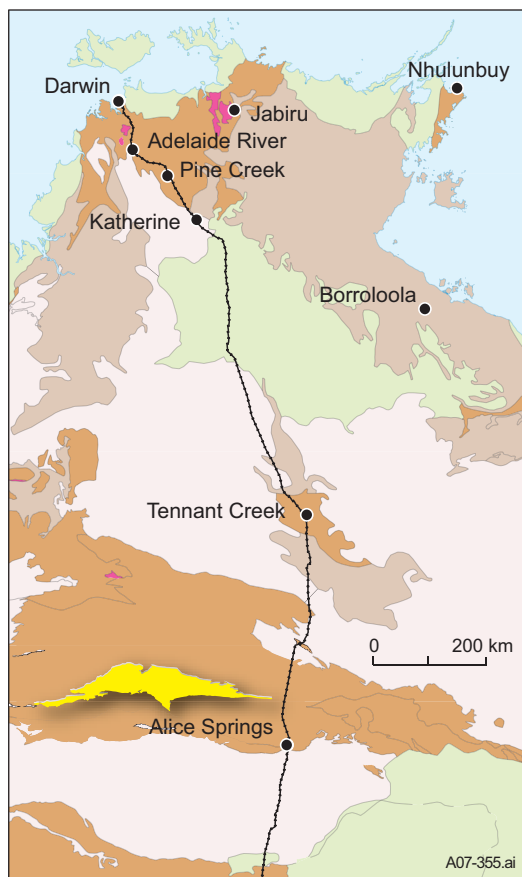
*Summary structure:* East–west-oriented, elongate intracratonic basin.

*Thickness:* Up to 6 km.

*Lithology:* Shallow-marine and fluvio-glacial siliciclastic, carbonate and evaporitic rocks, overlain by fluvial to continental sandstone, greywacke and siltstone.

*Summary relationship:* Unconformably overlies and is surrounded by basement rocks of the Aileron Province of the Arunta Region (Figure 5). The basin is a tectonic remnant of the large intracratonic Centralian Superbasin (Walter *et al* 1995), which was a contiguous entity during the late Neoproterozoic and early Palaeozoic.

*Key references:* Questa Australia (1989a), Wells and Moss (1983), Young *et al* (1995).



**Figure 5.** Ngalia Basin.

*Example well:*

Davis-1 (Baarda and Buckingham 1982; depths in metres; finer-grained stratigraphic intervals in bold)

0–996.7	Mount Eclipse Sandstone
996.7–1120.4	Kerridy Sandstone
<b>1120.4–1261.3</b>	<b>Djagamara Formation (siliceous sandstone interbedded with green shale)</b>
<b>1261.3–1410.3</b>	<b>Mount Doreen Formation (green to red-brown siltstone)</b>
<b>1410.3–1858.4</b>	<b>Rinkabeena Shale</b>
1858.4–1898.6	Patmungala beds (quartzite, siltstone, metatuff, chert conglomerate)

*Potential for high heat flow:* The underlying basement of the Ngalia Basin probably has a significant proportion of granite, as this outcrops extensively in the surrounding Aileron Province. The Aileron Province hosts some of the most energetic granites in the Northern Territory, with mean and maximum heat generation values greater than those of most other regions (Table 2). These data suggest that local areas, if not broad regions, within the Ngalia Basin may have surface heat flow exceeding 100 MW/m<sup>2</sup>. An uncorrected bottom hole temperature of about 68°C in Davis-1 suggests an equilibrium thermal gradient of only around 25°C/km, which for the given lithological succession, may equate to a heat flow of about 90 MW/m<sup>2</sup>. This suggests that Davis-1 may not be located in the hottest part of the basin.

*Potential for insulating sedimentary rock:* The sedimentary fill of the Ngalia Basin is biased towards high-conductivity

rock types such as quartzite, dolostone and sandstone, but there are a number of formations with reasonable potential for thermal insulation. The example well (Davis-1) has 600 m or more of shale and fine-grained rocks over its 1.9 km section. This well lies in a relatively shallow section of the basin (Figure 3), but if the same proportion of fine-grained rocks occurs throughout thicker sections, they may provide enough insulation to generate relatively high thermal gradients. Likewise, if other parts of the basin have thicker sections of Rinkabeena Shale, for example, then insulation may also be sufficient.

*Potential for a natural or artificial reservoir:* Basement crystalline rocks are buried beneath much of the Ngalia Basin. As the maximum thickness of sediments is in the order of 6 km, basement probably lies at drillable depths beneath large parts of the basin and this may present a target for fracturing.

*Proximity to infrastructure:* The Tanami Road, which connects the Tanami goldfields to Alice Springs, passes through the centre of the Ngalia Basin and provides easy logistical access. Alice Springs is some 150 km from the eastern end of the basin (Figure 3).

*Summary:* Localised areas of basement with high heat-generating properties could coincide with parts of the succession that have a high proportion of fine-grained sedimentary rocks, resulting in the elevation of subsurface temperatures to attractive levels. These conditions have not been intersected in the two wells drilled to date in the basin. Distance from markets may be an impediment to the commercial development of geothermal energy, but road access to the region is relatively good.

### Georgina Basin

*Age:* Neoproterozoic (Cryogenian)–Devonian.

*Summary structure:* Polyphase intracratonic basin.

*Thickness:* Up to 3.7 km.

*Lithology:* Dolostone, limestone, shale, sandstone, siltstone.

*Summary relationship:* The Georgina Basin is a tectonic remnant of the large intracratonic Centralian Superbasin (Walter *et al* 1995), which was a contiguous entity during the late Neoproterozoic and early Palaeozoic (Figure 6).

*Key references:* Dunster *et al* (2007), articles in Munson and Ambrose (2007).

*Example well:*

Phillip-2 (Wakelin-King and Weste 1988; depths in metres; finer-grained stratigraphic intervals in bold)

2.5–26	Quaternary surficial deposits
26–242	Dulcie Sandstone
<b>242–569</b>	<b>Kelly Creek Formation and Tomahawk Formation (quartzose and glauconitic sandstone; minor dolostone, mudstone)</b>

	and conglomerate; upper part dominantly limestone with lesser interbedded sandstone, marl at top)
569–786	upper Arrinthrunga Formation (dolostone, limestone; minor quartz sandstone, siltstone, shale, marl and conglomerate)
786–831	Eurowie Sandstone Member of Arrinthrunga Formation
831–1025	lower Arrinthrunga Formation (dolostone, limestone; minor quartz sandstone, siltstone, shale, marl and conglomerate)
1025–1304	Chabalowe Formation (quartz arenite: dolomitic; interbeds of dolostone and siltstone, stromatolitic)
<b>1304–1381</b>	<b>Arthur Creek Formation</b> (upper: dolostone, limestone)
1381–1473	Red Heart Dolostone
1473–1489	unnamed siliciclastic rocks
1489–1493	Proterozoic basement

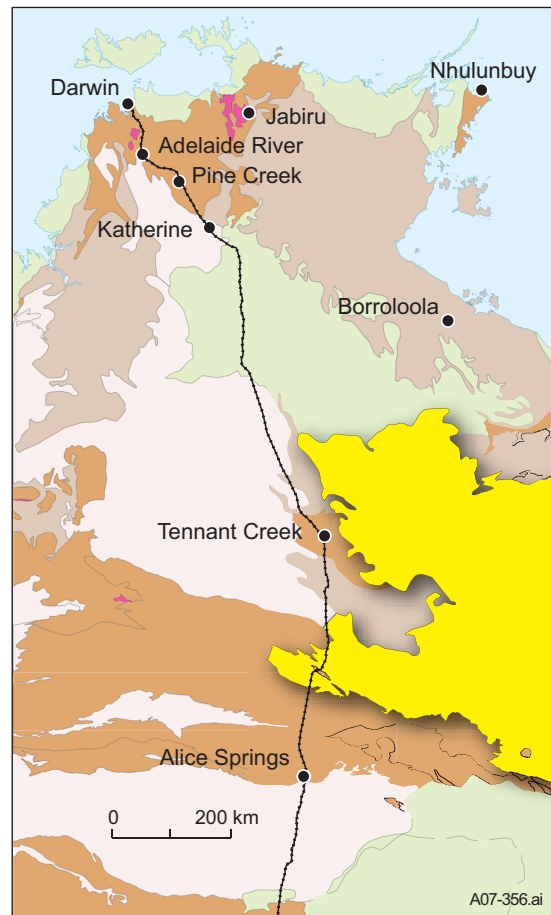
*Potential for high heat flow:* A number of granitic bodies have been interpreted in the basement of the southern Georgina Basin (Dunster *et al* 2007). Any of these bodies could potentially be high heat-producing granites. Average thermal gradients of greater than 35°C/km have been reported for at least three petroleum exploration wells in the basin (Dunster *et al* 2007), suggesting that some areas do, in fact, have elevated levels of heat flow.

*Potential for insulating sedimentary rock:* Black foetid pyritic-carbonaceous shale of the lower part of the Middle Cambrian Arthur Creek Formation, present in numerous southern Georgina Basin drillholes but not in Phillip-2, has the greatest potential for insulation. Although the formation is relatively thin in the example well, the stratigraphic well Hacking-1 intersected 457 m of the formation (see Dunster *et al* 2007). To a lesser extent, the Early Cambrian Adam Shale may also contribute to insulation. However, in general, insufficient thermal insulation represents an exploration risk.

*Potential for a natural or artificial reservoir:* Granite bodies interpreted in the basement are potential targets for artificial stimulation of a reservoir. Given the relatively shallow depth of the basin, there is a lower likelihood of *in situ* permeable layers hosting fluid at elevated temperature, although the permeability of the sedimentary rocks in the very deepest parts of the basin may be susceptible to artificial enhancement.

*Proximity to infrastructure:* The Stuart Highway, the north–south Adelaide–Darwin railway and the gas pipeline between Darwin and the Amadeus Basin all pass over the western margin of the Georgina Basin (Figure 3).

*Summary:* Some basement within the Georgina Basin is at relatively shallow depths and can be accessed through drilling, and there are good reasons to expect high heat flow in a number of areas. Risks lie in the ability of the sedimentary rocks to trap the heat, and the challenge of delivering power from a geothermal discovery to the market.



**Figure 6.** Georgina Basin in the Northern Territory.

### **McArthur Basin / Beetaloo Sub-basin / Dunmarra Basin**

*Age:* Palaeoproterozoic–Mesoproterozoic (McArthur Basin); Mesoproterozoic–Neoproterozoic (Beetaloo Sub-basin); Jurassic–Cretaceous (Dunmarra Basin).

*Summary structure:* Part of the North Australian Platform Cover.

*Thickness:* Up to 12 km (total).

*Lithology:* Dolostone, sandstone, shale, felsic and mafic volcanic rocks, minor microgranite (McArthur Basin); sandstone, shale, mudstone (Beetaloo Sub-basin); sandstone, mudstone (Dunmarra Basin).

*Summary relationship:* The McArthur Basin unconformably overlies the Palaeoproterozoic Pine Creek Orogen to the northwest, Murphy Inlier to the southeast and Arnhem Inlier to the northeast (Figures 7, 8, 9). The Beetaloo Sub-basin overlies the western portion of the McArthur Basin. The Dunmarra Basin overlies both.

*Key references:* McArthur Basin: Rawlings (1999), Scott *et al* (2000); Beetaloo Sub-basin: Ambrose (2006), Silverman (2007); Dunmarra Basin: Kruse *et al* (1994), Krassay (1994).



Figure 7. McArthur Basin in the Northern Territory.

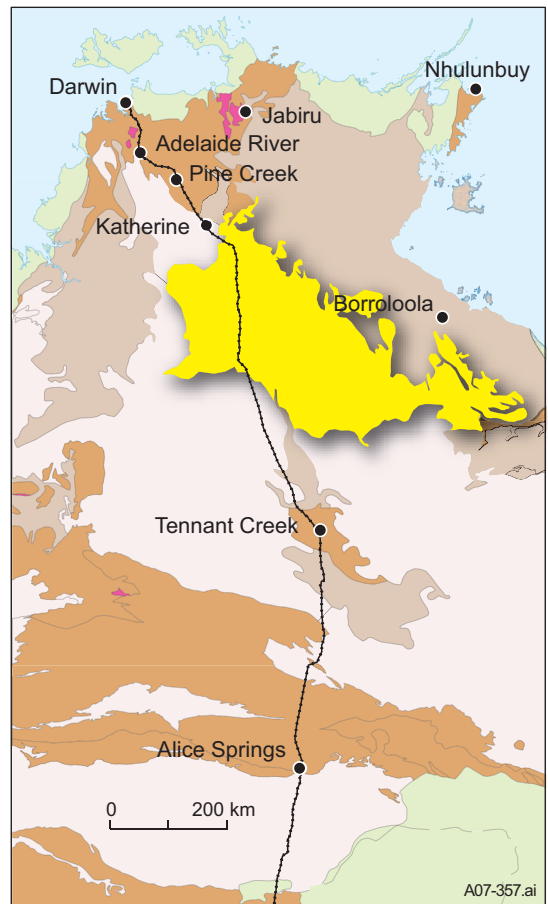


Figure 9. Dunmarra Basin.

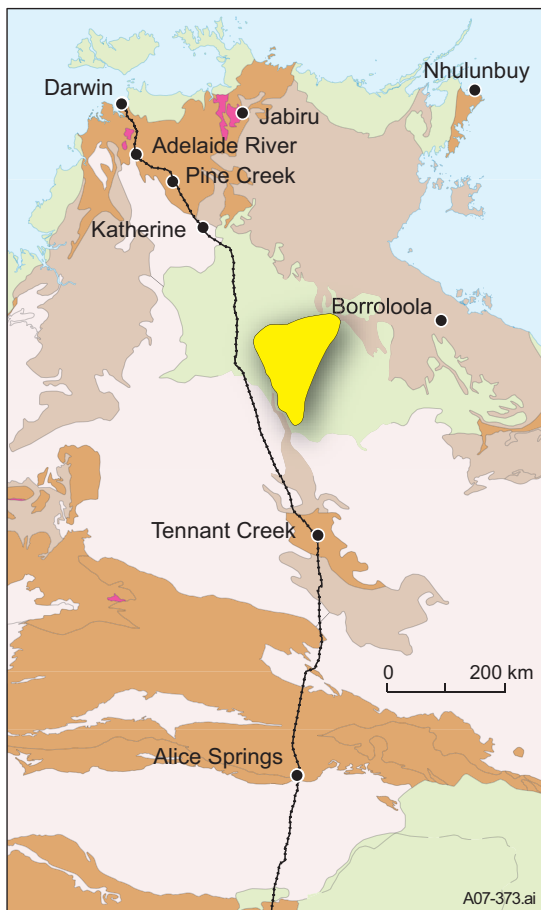


Figure 8. Beetaloo Sub-basin.

*Example wells:*

Broughton-1 (McArthur Basin; Ledlie and Torkington 1988; depths in metres; finer-grained stratigraphic intervals in bold)

<b>0–82</b>	<b>Corcoran Formation (mudstone; fine sandstone at top)</b>
82–105	Munyi Member of Corcoran Formation
105–129	Hodgson Member of Abner Sandstone
129–148	Jalboi Member of Abner Sandstone
148–249	Crawford Formation (sandstone, mudstone, siltstone)
<b>249–439</b>	<b>Mainoru Formation (siltstone, shale, fine sandstone)</b>
439–478	Limmen Sandstone
478–563	Mantungula Formation (mudstone, fine sandstone, dolostone)
563–1000	Nathan Group (dolostone, chert, dolomitic sandstone, siltstone)

Elliott-1 (Beetaloo Sub-basin / Dunmarra Basin; Pacific Oil and Gas 1992a; depths in metres)

<b>0–119</b>	<b>undivided Cenozoic/Cretaceous</b>
119–323.5	Jinduckin Formation (sandstone-siltstone interbeds, dolostone; evaporite common in siltstone and some sandstone)
323.5–524	Tindall Limestone
524–664.7	Jamieson Sandstone
<b>664.7–1322.3</b>	<b>Kyalla Formation (sandstone, siltstone)</b>
1322.3–1729.2	Moroak Sandstone



*Potential for high heat flow:* Although no heat generation data are available for the Arnhem Inlier, there is evidence of high heat generation in the other two underlying orogenic blocks. In particular, a number of extremely high values have been reported from metasomatised rocks in the Pine Creek Orogen. Although these values distort the statistics in **Table 2**, the data include values greater than  $10 \mu\text{W}/\text{m}^3$  from unaltered granite. There is real potential for high heat flow through parts of these nested basins.

*Potential for insulating sedimentary rock:* The Roper Group (represented by the Mantungula to Corcoran formations in Broughton-1 and Moroak to Jamieson sandstones in Elliot-1) and overlying Hayfield Mudstone of the Beetaloo Sub-basin contribute at least 2 km of shale to the total thermal insulation. The overlying Dunmarra Basin contributes more shale. Fine-grained insulating rocks are likely to comprise a considerable portion of the overburden, if considering a target depth of about 5 km, proving ample thermal insulation.

*Potential for a natural or artificial reservoir:* Although basement beneath these nested basins is likely to be too deep to be easily reached by drilling, there is some potential for finding units within the sedimentary succession that are either naturally permeable (eg Bessie Creek Sandstone; Ambrose 2006) or susceptible to artificial permeability enhancement.

*Proximity to infrastructure:* The Beetaloo Sub-basin straddles the gas pipeline that connects the Amadeus Basin to Darwin, and the Stuart Highway also passes across it. The north–south Adelaide–Darwin railway passes over the Dunmarra Basin to the west of the Beetaloo Sub-basin. Tennant Creek is about 250 km south of the Beetaloo Sub-basin, and Katherine is about the same distance to the north (**Figure 3**).

*Summary:* There is good evidence that all the elements of a good geothermal system may be present somewhere within this nested sequence of basins. Heat flow is likely to be locally high, and the average thermal gradient will be high where these zones coincide with significant thicknesses of shale in the Beetaloo Sub-basin and Dunmarra Basin. There is a low probability of basement at drillable depths beneath the thick insulating layers, but there is potential for *in situ* permeability, or layers that can have their permeability artificially enhanced. Parts of the broader McArthur Basin are close to the electricity line that extends to Katherine, but adequate thermal insulation represents a significant risk in these areas.

### **Pedirka / Eromanga basins**

*Age:* Carboniferous–Permian (Pedirka Basin); Jurassic–Cretaceous (Eromanga Basin).

*Summary structure:* Intracratonic sedimentary basins.

*Thickness:* Up to 5.5 km (total).

*Lithology:* Sandstone, siltstone, mudstone, coal, shale, redbeds.

*Summary relationship:* The Eromanga Basin unconformably overlies the Pedirka Basin. Both basins are unconformable on metamorphic rocks of the Arunta Region and Musgrave Province (**Figures 10, 11**).

*Key references:* Ambrose (2006); Pedirka Basin: Middleton (2007); Eromanga Basin: Questa Australia (1990).

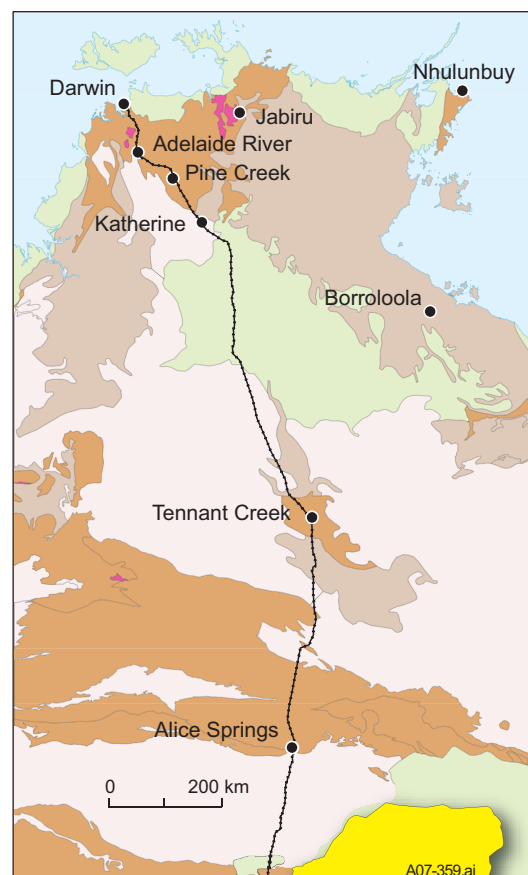
*Example wells:*

Thomas-1 (Eromanga Basin; Wiltshire 1983; depths in metres; finer-grained stratigraphic intervals in bold)

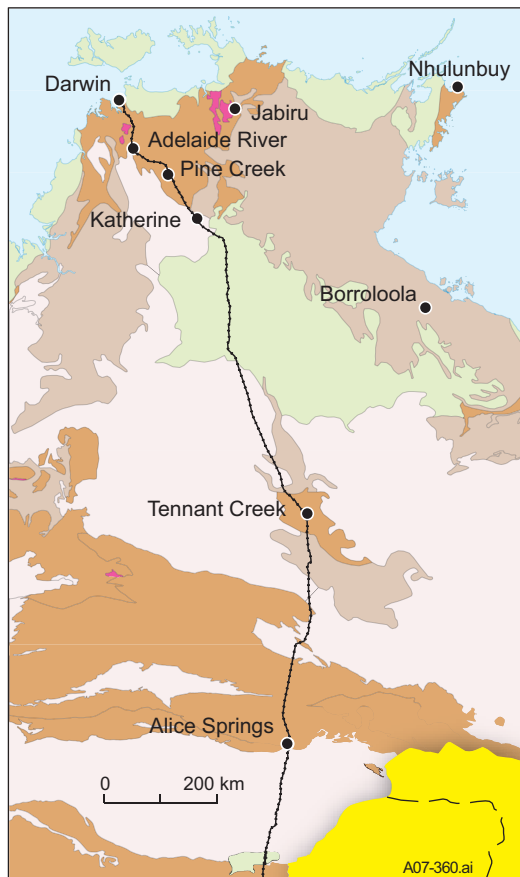
<b>0–190.5</b>	<b>Eyre Formation (carbonaceous sandstone, siltstone, mudstone)</b>
<b>190.5–804</b>	<b>Winton Formation (sandstone, siltstone, mudstone; minor conglomerate, coal; predominantly alluvial deposits)</b>
<b>804–1107</b>	<b>Oodnadatta Shale</b>
<b>1107–1159</b>	<b>Toolebuc Formation (limestone, calcareous bituminous shale)</b>
<b>1159–1395.5</b>	<b>Bulldog Shale</b>
1395.5–1455	Cadna-owie Formation (sandstone, siltstone)
1455–2075	Algebuckina Sandstone
2075–2280	Poolowanna beds (?)
2280–2363.5	Peera Peera beds (?)
2363.5–2420	unnamed redbeds
2420–2460	unnamed unit

McDills-1 (Pedirka Basin; Beach Petroleum and Amerada Petroleum 1965; depths in metres)

0–30.9	Quaternary sandstone
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**Figure 10.** Pedirka Basin in the Northern Territory.



**Figure 11.** Eromanga Basin in the Northern Territory.

<b>30.9–437.7</b>	<b>Rumbalara Shale</b>
437.7–462.8	Cadna-owie Formation
462.8–717	De Souza Sandstone
717–910.4	Crown Point Formation (?)
910.4–1155.2	Idracowra Sandstone
<b>1155.2–1240.5</b>	<b>Horseshoe Bend Shale</b>
1240.5–1767.8	Langra Sandstone
1767.8–2161	Polly Conglomerate
2161–2502.4	Mereenie Sandstone
2502.4–2750.5	unnamed unit
2750.5–3205.2	Todd River Dolostone

*Potential for high heat flow:* There are good reasons to expect high heat flow in parts of these basins, because they overlie the Arunta Region and Musgrave Province. Average heat generation in the Arunta Region may be as high as  $4.5 \mu\text{W}/\text{m}^3$ , with local values exceeding  $15 \mu\text{W}/\text{m}^3$ . This study provides no new heat generation data for the Musgrave Province, but McLaren *et al* (2003) provided data that suggest that the upper 10 km of the Musgrave Province generates  $5\text{--}6 \mu\text{W}/\text{m}^3$ .

*Potential for insulating sedimentary rock:* The total thickness and general composition of the sedimentary succession indicate excellent potential for thermal insulation, particularly in coal-rich units within Permian and Cretaceous formations. Other shale units also contribute to the total insulation.

*Potential for a natural or artificial reservoir:* With a maximum thickness of 5.5 km, there are likely to be areas

where basement is within drillable depth. Some of the deeper sedimentary units may provide opportunities for artificial permeability enhancement.

*Proximity to infrastructure:* At its nearest point, the Pedirka Basin is about 200 km from Alice Springs (Figure 3). A limited amount of infrastructure currently exists within the boundaries of the two basins.

*Summary:* Geologically, there are good reasons to expect the presence of geothermal systems, or the opportunity to create artificial systems. Distance from potential markets and limited infrastructure create potential risks.

### Victoria–Birrindudu basins

*Age:* Palaeoproterozoic–Mesoproterozoic.

*Summary structure:* Stacked basins with a largely undeformed and unmetamorphosed sedimentary succession, forming part of the North Australian Platform Cover. Correlated with the McArthur Basin.

*Thickness:* The stacked basins probably originally contained in excess of 8 km of section.

*Lithology:* Dolostone, sandstone, limestone, minor shale.

*Summary relationship:* The stacked basins unconformably overlie the Palaeoproterozoic Pine Creek Orogen to the north and Palaeoproterozoic metasediments and granites of the Tanami Region to the south. The basins are unconformably overlain by the Palaeozoic Daly Basin to the north, Ord Basin to the west and Wiso Basin to the east (Figure 12).

*Key references:* Dunster *et al* (2000), Cutovinos *et al* (2002).

*Stratigraphic column:* No single drillhole penetrates much of the succession of these stacked basins, so the generalised stratigraphy is illustrated in Figure 13.

*Potential for high heat flow:* The Pine Creek Orogen that underlies the northern part of these basins hosts metasomatised rocks with extreme values of heat generation (Table 2). Although no new data are available for the Tanami Region in this review, McLaren *et al* (2003) suggested that average heat generation values in that domain may be as high as, if not higher than those of the Pine Creek Orogen. This clearly points to the strong likelihood that parts of the basins have high heat flow.

*Potential for insulating sedimentary rock:* The Birrindudu and Tolmer groups are dominated by coarse siliciclastic sedimentary rocks. The Limbunya Group is dominated by carbonate and siliciclastic rocks. The Wattie Group is predominantly a siliciclastic succession with minor carbonate intervals. The Bullita Group includes several carbonate units and sandstones, with only minor thin black shale units. The Tjunna Group consists of sandstone and mudstone, but is only up to 300 m thick. The Auvergne Group is composed of sandstone, siltstone and evaporitic carbonate rocks. The lack

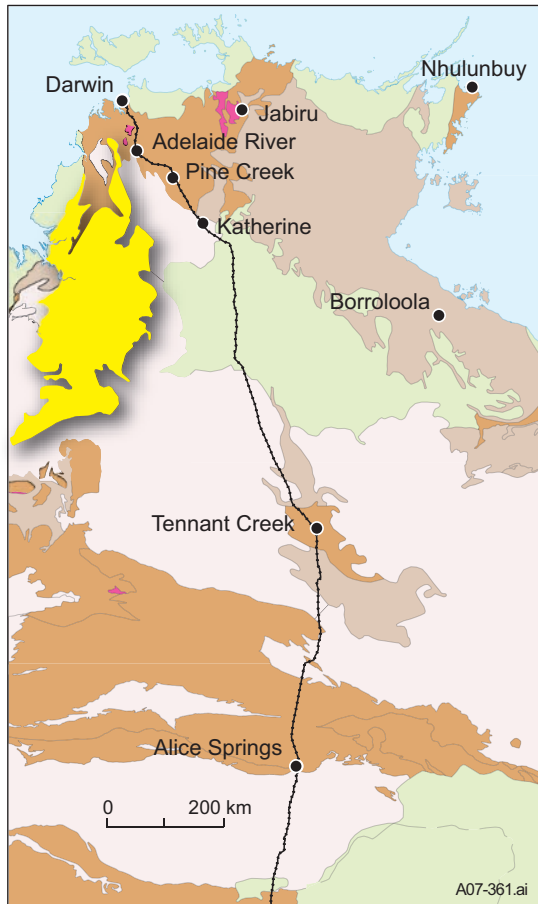


Figure 12. Victoria-Birrindudu basins.

of a thick shale or mudstone unit represents an exploration risk from the viewpoint of thermal insulation, although extreme values of heat flow could counteract this risk to some extent.

*Potential for a natural or artificial reservoir:* Granite basement has been intersected within a number of drillholes in these basins, providing the possibility of hot granites being located at drillable depths. The dominance of siliciclastic units also suggests a possibility of locating *in situ* permeability, or identifying units susceptible to artificial permeability enhancement.

*Proximity to infrastructure:* These basins are relatively remote, although their northernmost extent approaches infrastructure in the form of road and rail (Figure 3).

*Summary:* A lack of adequate insulation would appear to be the dominant risk in these basins. The prospect for high heat flow seems good, given the nature of the underlying basement, and the northern sections of the basins are relatively close to infrastructure.

### Daly Basin

*Age:* Cambrian–Ordovician.

*Summary structure:* Intracratonic basin forming part of the Central Australian Platform Cover.

*Thickness:* Up to 1 km.

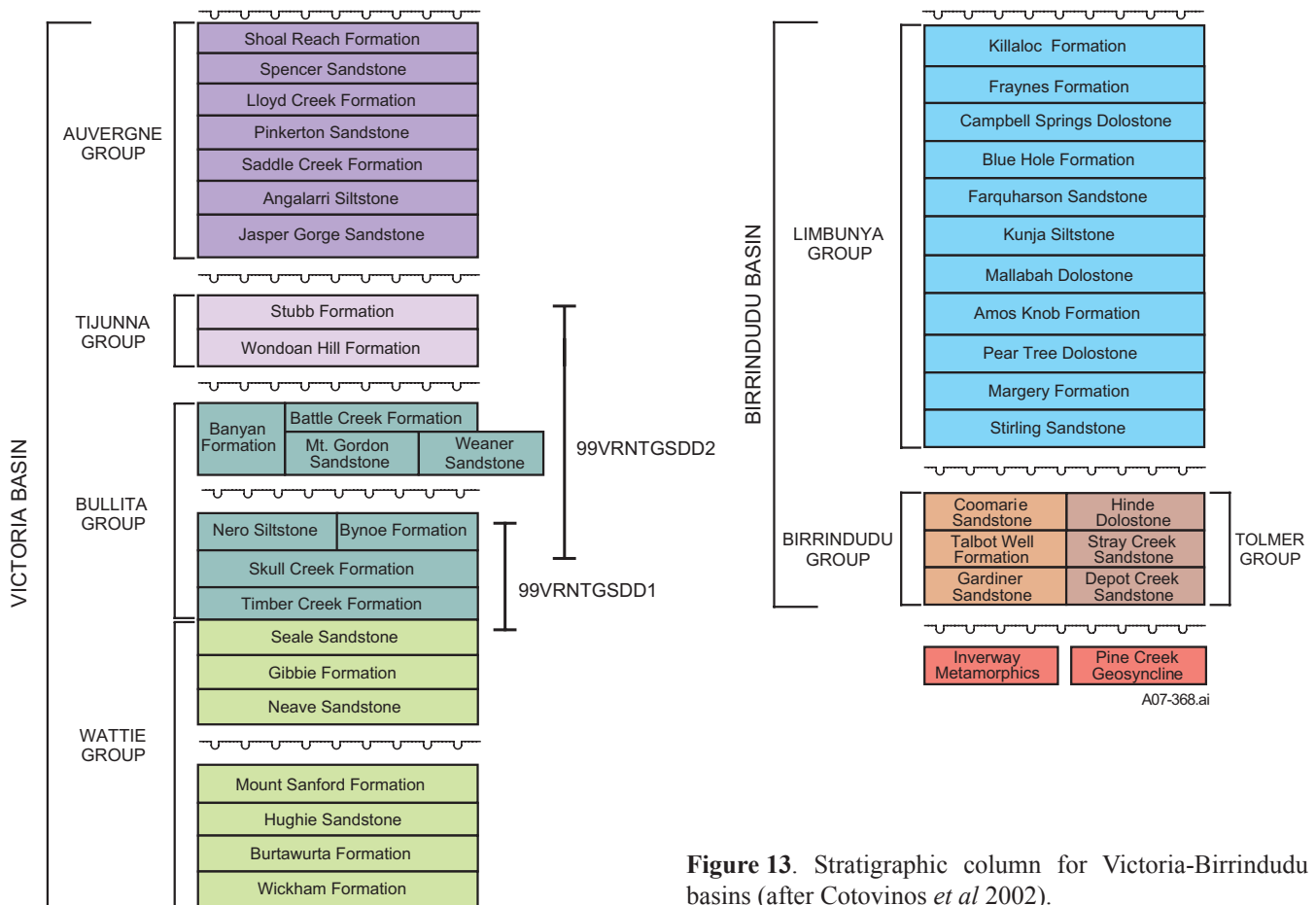


Figure 13. Stratigraphic column for Victoria-Birrindudu basins (after Cotovinos *et al* 2002).

*Lithology:* Limestone, dolostone, sandstone, siltstone, flood basalt.

*Summary relationship:* Unconformably overlies the Pine Creek Orogen and McArthur Basin to the north and east, and Victoria Basin to the west. Cretaceous rocks of the Dunmarra Basin cover its southern margin (**Figure 14**).

*Key references:* Kruse *et al* (1990, 1994).

*Example well:*

Sever-1	(Pacific Oil and Gas 1992b; southern Daly Basin in a region overlapped by the Dunmarra Basin; depths in metres; finer-grained stratigraphic intervals in bold)
0–28	undivided Cenozoic / Cretaceous
28–46	Tindall Limestone
<b>46–151.5</b>	<b>Antrim Plateau Volcanics (20–60 m-thick basalt flows)</b>
151.5–331.4	McMinn Formation (sandstone, mudstone; minor conglomerate and ironstone)
<b>331.4–1167</b>	<b>Velkerri Formation (carbonaceous mudstone and siltstone)</b>
1167–1227.7	Bessie Creek Sandstone
<b>1227.7–1259.9</b>	<b>Corcoran Formation (laminated mudstone and siltstone)</b>

*Potential for high heat flow:* Data from the underlying Pine Creek Orogen suggest great potential for high heat flow through the Daly Basin. Some of the metasomatised Pine Creek Orogen rocks have extreme values of heat generation

(**Table 2**) and such deposits, buried beneath the basin, could generate significant levels of heat flow through the overlying sedimentary rock.

*Potential for insulating sedimentary rock:* The thickness of the Daly Basin on its own is not great, but total sedimentary thickness approaches 2.5 km in places where it overlaps the McArthur and Victoria basins. The example well includes formations assigned to the Dunmarra, Daly and McArthur basins, and demonstrates the potential for significant thicknesses of insulating sediment in this region (over 900 m of insulating units, including basalt, in the example well).

*Potential for a natural or artificial reservoir:* A range of lithology and formations could be encountered in the 4–5 km depth interval beneath the area defined as the Daly Basin. In some places, the basin is underlain by crystalline basement rocks, and in others, by sedimentary rocks assigned to the McArthur and Victoria basins. Reservoirs could be generated by artificially fracturing natural crystalline basement, or by artificially enhancing the permeability of existing sedimentary units.

*Proximity to infrastructure:* The Daly Basin is well placed relative to infrastructure (**Figure 3**). The town of Katherine lies at its northeastern flank, and the electrical powerline connection between Katherine and Darwin passes along the eastern edge of the basin. The Adelaide–Darwin railway and Stuart Highway are located along the eastern edge of the basin and there is minor road access to most areas.

*Summary:* The Daly Basin appears to be well placed to host areas of elevated heat flow, and it is also well placed relative to infrastructure and markets. Sedimentary thickness may be inadequate to provide the required thermal insulation in some parts of the basin, but in areas where the Daly Basin overlaps other sedimentary successions, this may be less of an issue.

### Wisio Basin (Lander Trough)

*Age:* Cambrian–Devonian.

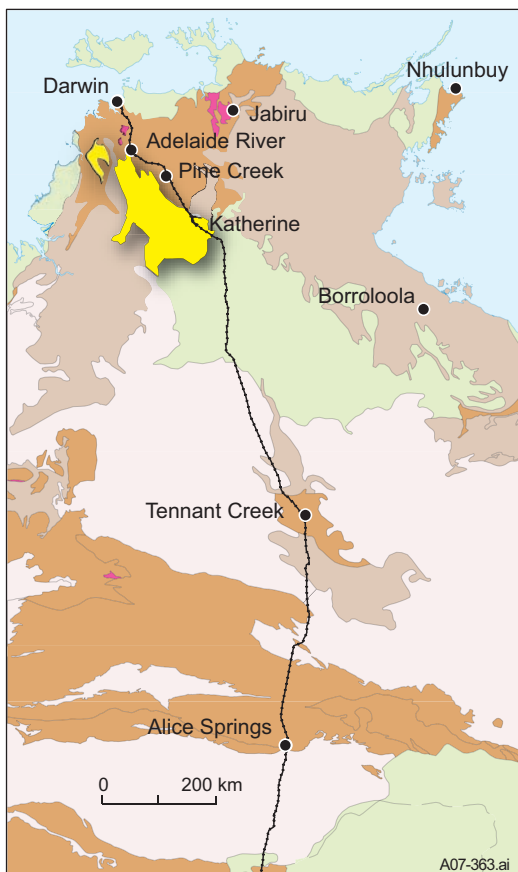
*Summary structure:* Intracratonic basin.

*Thickness:* Seismic and gravity survey data suggest 2000–3000 m of sedimentary strata within the Lander Trough, and about 300 m of section in the remainder of the Wisio Basin.

*Lithology:* Dolostone, limestone, shale, sandstone, siltstone.

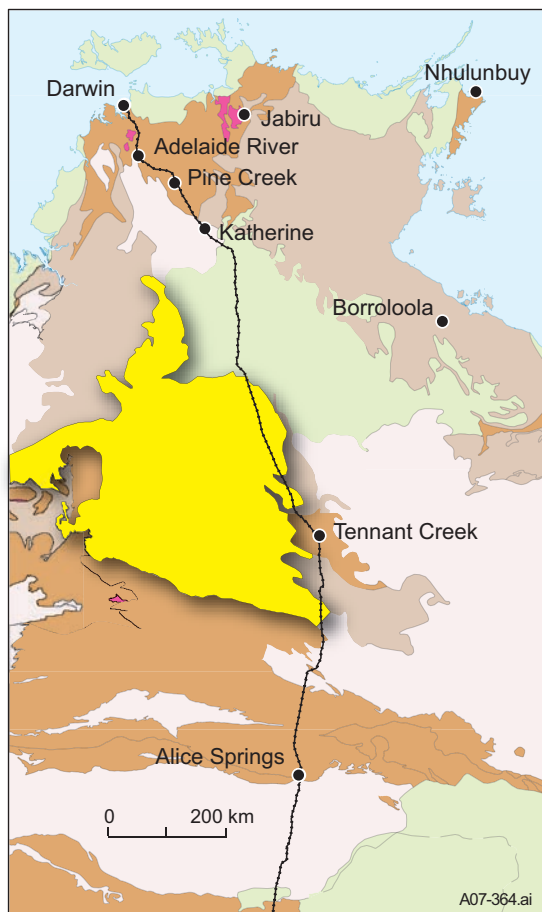
*Summary relationship:* Unconformably overlies the Aileron Province of the Arunta Region to the south, Tanami Region and Victoria-Birrindudu basins to the west, and Tennant Region to the east. Cretaceous rocks of the Dunmarra Basin cover its northern margin (**Figure 15**).

*Key references:* Kennewell *et al* (1977), Questa Australia (1989b), Ambrose (2006).



**Figure 14.** Daly Basin.





**Figure 15.** Wiso Basin.

*Example well:* No wells have yet been drilled in the Lander Trough, although several shallow holes have been drilled through condensed sections in other parts of the basin and some seismic data are available. Kennewell *et al* (1977) interpreted the Lander Trough to consist of three ‘sequences’, with the following probable stratigraphy (top to base):

Sequence I	?Late Palaeozoic Lake Surprise Sandstone; up to 250 m thick
unconformity	
Sequence II	Cambrian–Ordovician, partly marine, probable dolostone, shale, dolomitic shale, sandstone; up to 800 m thick :
unconformity	
Sequence III	Proterozoic basement. Includes probable Ediacaran Central Mount Stuart Formation (800 m thick) and Palaeoproterozoic Hatches Creek Group (several thousand metres thick). The Central Mount Stuart Formation outcrops in the Georgina Basin, where it is a sandstone-rich succession consisting of arkose, subarkose, quartz arenite and siltstone. The Hatches Creek Group outcrops extensively in the Tennant Region, where it is a predominantly volcanosedimentary succession consisting of sandstone, felsic and mafic volcanic rocks, subordinate siltstone and conglomerate, and minor carbonate rocks.

*Potential for high heat flow:* The underlying basement of Arunta Region crystalline rocks provides ample opportunity for high heat flow regions within the Lander Trough, even though no wells have been drilled to test this.

*Potential for insulating sedimentary rock:* The nature of the sedimentary fill in the Lander Trough is poorly understood, due to a lack of drillhole data, so the potential for significant thicknesses of insulating sedimentary rock in the basin is uncertain. The probable succession appears to be predominantly coarse-grained, although thermal insulation might be provided by volcanic rocks and some finer-grained intervals. If Palaeoproterozoic Ooradidgee Group rocks are also present towards the base of the succession, then these could include a relatively thick succession of fine-grained sedimentary rocks (eg Rooneys Formation, or possible distal equivalents of other lithostratigraphic units exposed in the Tennant Region; N Donnellan, NTGS, pers comm 2007), which might provide good insulation.

*Potential for a natural or artificial reservoir:* The potential for natural reservoirs in the deep sections of the Lander Trough is unknown. The depth of the sedimentary pile, about 3 km, is attractive for basement penetration, provided heat flow is high and the sedimentary rocks are insulating.

*Proximity to infrastructure:* The Lander Trough, and the Wiso Basin in general, are relatively remote in terms of accessible infrastructure (**Figure 3**).

*Summary:* The untested nature of the Lander Trough makes it difficult to judge the likelihood of geothermal systems being present. Its distance from infrastructure and lack of existing exploration data render it unattractive as an initial focus for geothermal exploration, even though the fundamental geological prerequisites might all be in place.

### Coastal basins (Bonaparte, Arafura, Money Shoal)

*Age:* Cambrian–Cenozoic (Bonaparte Basin), Ediacaran–Carboniferous (Arafura Basin), Jurassic–Eocene (Money Shoal Basin).

*Summary structure:* Composite basin on northwestern coastline of the NT (Bonaparte Basin); pericratonic basin on Arnhem Land coastline (Arafura Basin, Money Shoal Basin).

*Thickness:* At least 5 km onshore (Bonaparte Basin); up to 5 km (Arafura Basin); up to 4 km (Money Shoal Basin).

*Lithology:* Limestone, sandstone, siltstone, basalt, coal, coarse siliciclastic rocks (Bonaparte Basin). Dolostone, limestone, sandstone, siltstone, basalt, coal (Arafura Basin). Sandstone, coal, shale, claystone, marl, carbonate rocks (Money Shoal Basin).

*Summary relationships:* The Bonaparte Basin overlies the Pine Creek Orogen and Victoria Basin (**Figure 16**). The Arafura Basin overlies the Pine Creek Orogen and McArthur Basin and is unconformably overlain by the Money Shoal

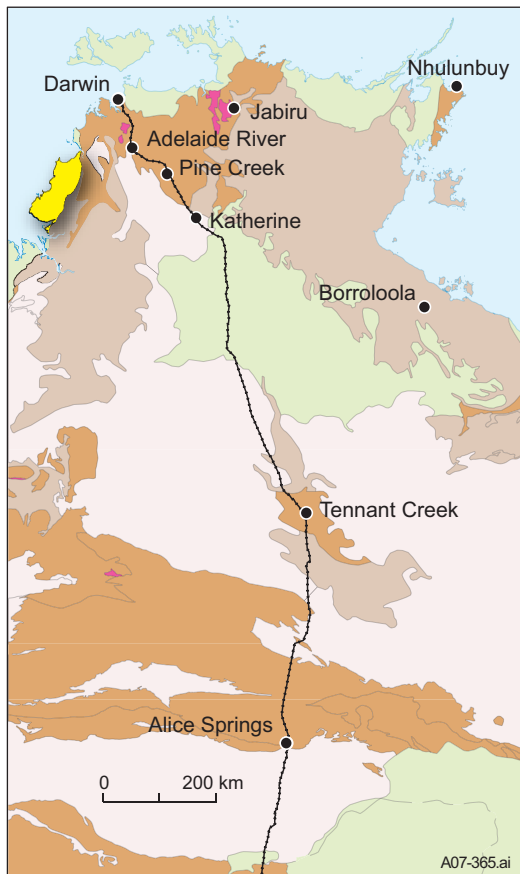


Figure 16. Onshore Bonaparte Basin.

Basin (Figure 17). The Money Shoal Basin overlies the Arafura Basin and offshore is continuous with the Bonaparte Basin in the west (Figure 18).

*Key references:* Articles in Ellis *et al* (2004); Bonaparte Basin: Petroconsultants Australasia (1990); Arafura Basin: Petroconsultants Australasia (1989), Struckmeyer (2006); Money Shoal Basin: Struckmeyer (2006).

*Example well:*

- Keep River-1 (Bonaparte Basin; Caye 1969; depths in metres; finer-grained stratigraphic intervals in bold)
- 0–480.1 Kulshill Formation (subarkose)
  - 480.1–755.9 Tanmurra Formation (sandy limestone, calcareous sandstone)
  - 755.9–2895.6 Milligan Formation (shale, siltstone, minor sandstone)**
  - 2895.6–3221.7 Septimus Formation (limestone, calcarenite, minor sandstone)
  - 3221.7–3445.8 Enga Formation (sandstone, siltstone, shale, limestone)**
  - 3445.8–3570.7 Burt Range Formation (calcarenite grading into sandstone)
  - 3570.7–3712.5 unnamed formation
  - 3712.5–4736.6 Ningbing Limestone
  - 4736.6–4761.9 quartzitic basement rocks

*Potential for high heat flow:* All three of these basins overlie the Pine Creek Orogen, a crustal unit identified as having

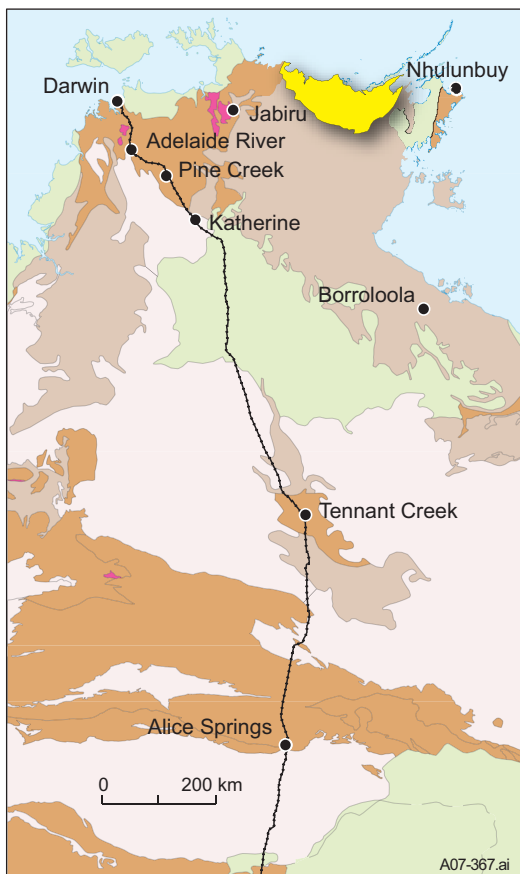


Figure 17. Onshore Arafura Basin.

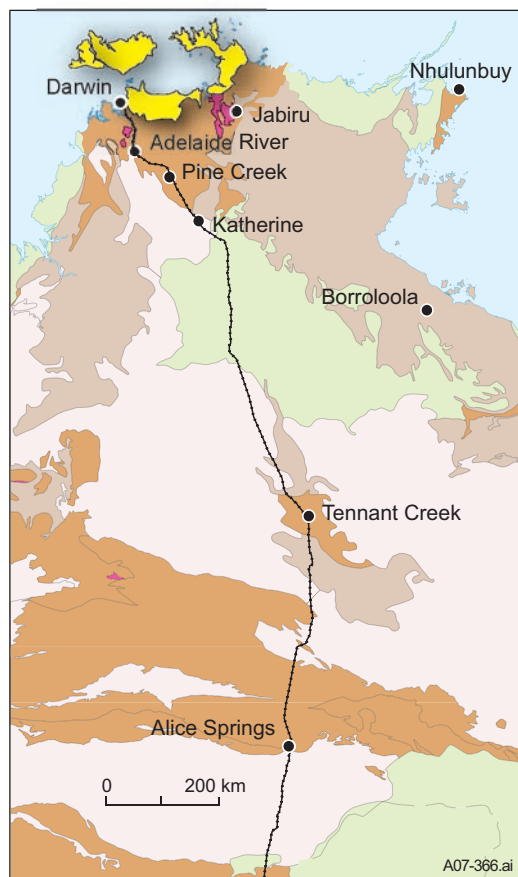


Figure 18. Onshore Money Shoal Basin

high heat generation (Table 2). Therefore, it is reasonable to expect that there will be areas of high heat flow within each basin.

*Potential for insulating sedimentary rock:* The example well from the Bonaparte Basin indicates a significant thickness of Milligan Formation shale and siltstone. Together with the Enga Formation, this suggests that up to half the sedimentary succession might be insulating fine-grained rocks. Ediacaran strata of the Arafura Basin include shallow-marine sandstone, mudstone and minor carbonate units. Younger sedimentary rocks are dominated by carbonate and non-marine siliciclastic rocks. Thermal insulation would rely on an adequate thickness of mudstone, with a possible contribution from coal in the younger successions. The Money Shoal Basin is dominated by sandstone with minor coal, shale, claystone and marl, overlain by carbonate rocks. The degree of thermal insulation would depend on the proportion of coal, shale and claystone in the total succession.

*Potential for a natural or artificial reservoir:* The metamorphic rocks of the underlying Pine Creek Orogen may provide opportunities for developing artificially fractured reservoirs. There may also be permeable hot layers within the sedimentary successions of each of these basins, or sedimentary layers amenable to artificial permeability enhancement.

*Proximity to infrastructure:* The Bonaparte and Money Shoal basins are located close to Darwin and to infrastructure associated with that population centre (Figure 3). The Arafura Basin, although generally further from established infrastructure, lies less than 100 km from a major bauxite mine and alumina refinery on the Gove Peninsula, near Nhulunbuy. This mine and refinery represent a significant potential market for electrical power.

*Summary:* The coastal basins are attractive for exploration because they are underlain by the Pine Creek Orogen, contain potentially insulating layers of fine-grained sedimentary rocks, and are relatively close to infrastructure and/or markets. Challenges to exploration include a relative lack of drillhole data in onshore areas of the Money Shoal and Arafura basins.

## SUMMARY

Geological evidence suggests that all the fundamental requirements for geothermal systems exist within the Northern Territory. In particular, the nature of the basement beneath most of the NT's basins suggests that many areas should have high surface heat flow. The sedimentary basins in the NT include many fine-grained formations capable of providing thermal insulation. High heat flow and adequate thermal insulation are the necessary requirements for high temperature heat sources.

The crust within the NT is in a state of tectonic compression, and the basement is at a drillable depth beneath many parts of the sedimentary basins. These are ideal requirements for locating crystalline basement rocks susceptible to hydraulic permeability enhancement.

In addition, in many of the basins there are sedimentary formations at depth that may be naturally permeable or susceptible to permeability enhancement, thus making basement intersections unnecessary.

Basins in the north of the NT are relatively close to population centres and the electricity power lines from Katherine to Darwin. Basins in the south are close to Alice Springs and the north–south rail and road arteries. In addition, remote communities and mining operations in all parts of the NT could benefit from the development of sustainable, base load geothermal power, especially if it offsets the use of expensive diesel generators.

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## **NORTHERN TERRITORY GEOTHERMAL POTENTIAL – GIS COMPILATION SUMMARY**

This GIS compilation is the result of the commissioning of Hot Dry Rocks Pty Ltd by the Northern Territory Geological Survey (NTGS) to undertake a geothermal potential study of the Northern Territory. Data have been sourced from Geoscience Australia (GA), NT Department of Natural Resources, the Environment and the Arts (NRETA) and NTGS for this compilation.

The Northern Territory GIS Compilation layers are provided in MapInfo .tab format, or ER Mapper .ecw/.ers formats and consist of the following themes:

- Depth to basement grids, images and contours.
- Shale thickness maps for sedimentary basins within the Northern Territory.
- Heat production derived from whole-rock geochemical analysis.
- Drillhole temperature data from deep waterbores.

- Total count radiometric images for K, Th, U and K-Th-U composites.
- Magnetic images for Total Magnetic Intensity (TMI) and 1st Vertical Derivative (1VD).
- Gravity images.
- SRTM elevation images.
- Geological units and geological regions at 1:2.5M scale.
- Natural springs.
- Austermap (estimated temperature at 5 km depth).
- Infrastructure layers.
- Cross-sections and seismic line.

This dataset will be augmented over time as more data is collected, analysed and interpreted.

All layers are accompanied by GA-standard metadata in htm format which detail the lineage, accuracy, consistency, datum and projection and other information concerning the data.

No guarantee is given for the quality or completeness of the layers, and it is recommended that clients regularly visit the NTGS website ([www.minerals.nt.gov.au/ntgs](http://www.minerals.nt.gov.au/ntgs)) to check for recent releases of NTGS datasets.

A full list of NT GIS layers and descriptions can be accessed via the [NT\\_Geothermal\\_GISCompilation.xls](#) file.

Please refer any data quality, integrity or accessibility issues to the Northern Territory Geological Survey (address details on reverse title page).

Compiled 2006–2007 by Hot Dry Rocks Pty Ltd and Mark Asendorf (NTGS, Alice Springs).