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PETROLEUM DATA: LEADING THE SEARCH FOR GEOTHERMAL RESOURCES IN WESTERN AUSTRALIA

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ABSTRACT

In Western Australian basins, subsurface drill-hole data, primarily from petroleum exploration, allows the identification of regions of high temperature at depth that may be potential geothermal resources. The extent and economic viability of such resources remain poorly known and require further study. Observed temperatures at depths up to 4.5 km reach 150°C in parts of the Canning, Carnarvon and Perth basins, indicating low-enthalpy resources related to regional heat flow. The greatest potential for hydrothermal resources is in the Perth Basin where subsurface temperatures of 65–85°C are reached at 2–3.5 km depth. Heat-flow modelling of 170 Perth Basin wells shows a range of 30–140 mW/m2, with the highest surface heat-flow values in the northern part of the basin. The median value of 76.5 mW/m2 for this basin exceeds the average reported for the Australian continent—64.5 mW/m2.

Potential hot rocks resources are present in parts of the Canning, Carnarvon and Perth basins where the depth to 200°C is less than 5 km. Knowledge of high subhorizontal stress conditions that can enhance geothermal water flow from engineered reservoirs are based on data mostly from petroleum wells in the Perth Basin. A systematic quantitative assessment of geological, hydrogeological, geophysical, stress orientation and geochemical conditions is required to further delineate and prove these resources. Progressive compilation, validation and interpretation of subsurface data from more than 800 wells is underway, and includes temperature logs of 47 shallow water bores and 30 new thermal conductivity measurements of Perth Basin wells. Data compilation from 580 wells in the Canning, Carnarvon and Perth basins is complete. To date the greatest number of wells indicating high geothermal gradients and temperatures are in the Carnarvon Basin.

KEYWORDS

Geothermal resources, energy, hydrothermal, hot rock, Western Australia.

INTRODUCTION

In January 2008, Western Australia extended a new phase in the search for energy from geothermal resources, with the amendment of the Petroleum Act 1967 to the Petroleum and Geothermal Energy Resources Act 1967. The first geothermal acreage, in the Perth Basin, was released on 22 January 2008 offering 495 blocks, each about 320 km2. The next geothermal acreage release was on 12 August 2008, offering 81 blocks in the Carnarvon Basin, with a block size of about 6,400 km2. The next releases are proposed on 18 May and 7 September 2009 for the southeast and north, respectively (Fig. 1).

Subsurface stratigraphy, temperature and tectonic events control the origin, migration and accumulation of geofluids in petroleum and geothermal systems. The data from the 2,086 petroleum exploration wells drilled between 1902 and mid-2008 in Western Australia are invaluable in the search for geothermal energy as they provide objective information to locate high-temperature areas, and to evaluate potential heat reservoirs and the thermal properties of the sedimentary cover required for trapping heat (Fig. 1). The similarities between petroleum and geothermal exploration data (Narayan et al, 1998) assist in the new energy search, and for the latter, high-temperature logging and different reservoir stimulation techniques necessitate the development of new technologies.

Geological, hydrogeological, electrical, magnetic, geochemical and seismic data can be used to locate potential geothermal resources for exploratory drilling. In 2006, the Geological Survey of Western Australia (GSWA) commenced a study of high-temperature geothermal resources from hot rock systems that are currently economic, i.e., where the depth to 200°C is less than 5 km. The aim is to progressively compile, validate and interpret petroleum well data on temperature and in situ stress conditions of Western Australian basins, in order to identify potential geothermal resources and develop reliable pre-competitive datasets specific to geothermal energy. GSWA has completed this task for more than 580 onshore wells in the Canning, Carnarvon and Perth basins, as well as temperature logs of 47 shallow water bores and 30 new thermal conductivity measurements of Perth Basin wells (Fig. 2).

GEOTHERMAL ENERGY

Geothermal energy includes thermal or electrical power produced from the heat contained in the earth. The earth's

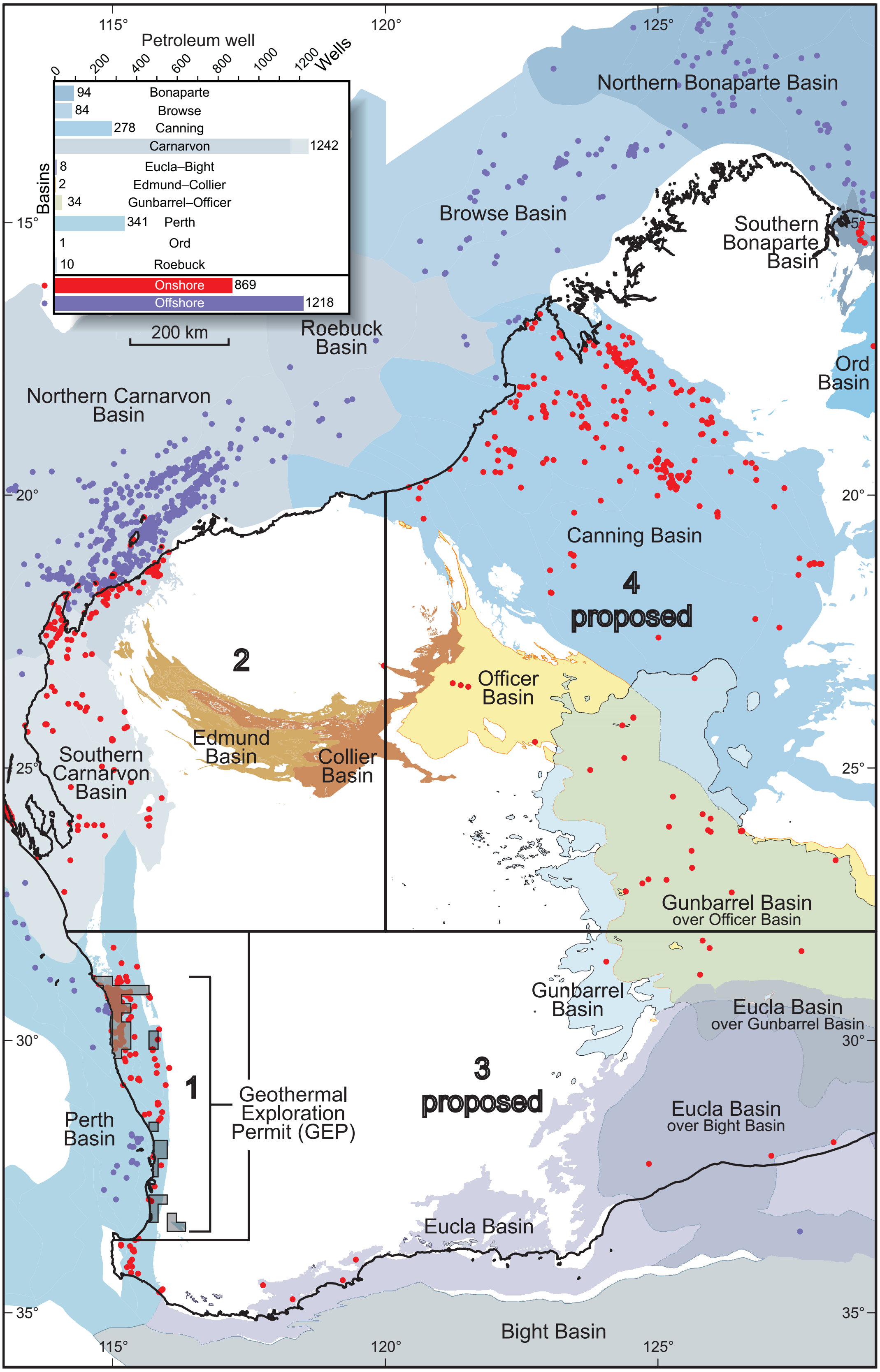

Figure 1. Map showing geothermal acreage areas (released and proposed, 1–4), sedimentary basins, and data available from wells for geothermal energy exploration in Western Australia.

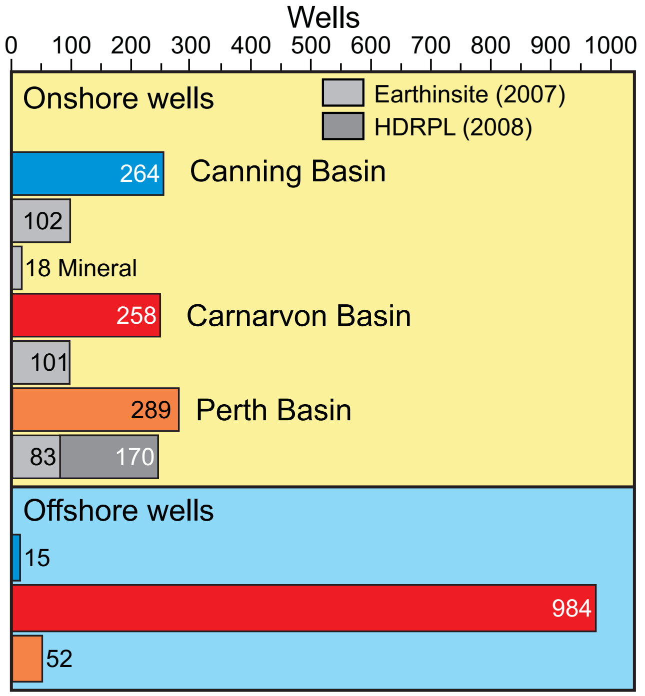

Figure 2. Status of compilation and verification of wells data by Earthinsit.com Pty Ltd (2007) and Hot Dry Rock Pty Ltd (2008) for the Canning, Carnarvon and Perth basins.

heat is reservoired in both rocks and geofluids. Geofluid reservoirs include water-dominated hydrothermal resources, oil- and gas-associated hydro-geothermal resources, and methane-dominated high-pressure geothermal resources. Hot rock systems may or may not contain geofluids. Hot rock resources are the most abundant source of geothermal energy. Generally, low temperature or low-enthalpy resources are suitable for direct geothermal energy use (≤ 100°C), while medium-enthalpy (100–200°C) and high-enthalpy resources (≥ 200°C) are suitable for both electricity power generation and direct use.

Active volcanism in areas such as plate boundaries generates high-enthalpy or high-energy content in hydrothermal resources, whereas deep sedimentary basins generate low-enthalpy resources where the regional heat flow heats the reservoired ground water (hydro-geothermal). In hydro-geothermal systems, water temperature depends on the depth of the aquifer and the geothermal gradient in the area. Such systems in sedimentary basins without active volcanism or tectonism are generally in the range of 50–100°C at less than 3 km depth. Hydrothermal resources are used for producing electricity and heat for direct application, in about 71 countries. Figure 3 summarises primary energy production and the increasing trend in direct and power generation application of geothermal energy worldwide. In Australia, geothermal energy is used for electricity generation at Birdsville, Queensland, and direct heat applications at various places, but on a very small scale. The Birdsville operation is a 150 kW power plant utilising hydro-geothermal resources at about 98°C in the Great Artesian Basin from a water bore producing about 30 litres of water per second from 1,173–1,220 m depth (Burns et al, 2000; Hills et al, 2004). Western Australian geothermal resources originate from regional heat and are low-enthalpy hydro-geothermal and hot rock resources.

Generally, hot rock systems are artificially created, using enhanced geothermal systems (EGS) technologies to enhance permeability in formations that are either too dry or too impermeable to transmit water at the required rates. Hydraulic fracturing and/or stimulation are used, which involve high-pressure injection of a fluid into the reservoir to crack and enlarge pre-existing fractures. EGS technologies are considered a major option for broadening geothermal resources to almost anywhere on the earth, as well as for expanding the capabilities of existing geothermal developments (International Energy Agency, 2008). Extensive drilling for petroleum, geothermal and mineral resources has demonstrated that the largest heat resource in the earth's crust is contained in rocks of low natural permeability (tight gas sand, hot sedimentary and basement rocks).

Geological evaluation of heat source, reservoir, and sealing rocks for extracting heat at drillable depths (3–5 km), using a water source are necessary to select suitable sites for utilising hot rock geothermal energy. The basic requirements are: a high heat source shown by high geothermal gradients (>50°C/km); rock formations at over 200°C composed of a homogenous lithology with subhorizontal fractures to provide a good reservoir; and a thermal cover over 3 km thick of low thermal conductivity sedimentary rocks to provide a heat trap, or seal. Geological, geophysical, and geochemical information available from deep oil and gas wells are the best source for identifying areas of high geothermal gradients, which help in:

a) selecting a test well site;
b) identifying reservoir lithologies and structural stresses for enhancing porosity and permeability; and,
c) evaluating both depth of reservoir and thickness of thermal cover.

Australia's most significant geothermal resources suitable for electricity generation appear to be from hot rock resources. The highest potential is in the Cooper Basin, followed by the McArthur, Otway, Carnarvon, Murray, Perth, Canning, East Queensland and Sydney basins (Somerville et al, 1994). The high geothermal gradient recorded in petroleum wells provided the first indication for hot rocks potential (Chopra and Holgate, 2005). Fluid temperature and flow rate control the rate and economics of energy production. Existing EGS projects in Australia, Germany, France, Switzerland and the USA help to explain the successes and problems related to high fluid flow rate and temperature (Massachusetts Institute of Technology, 2006; International Energy Agency, 2006, 2008). The South Australian Habanero project is the best guide for new Australian hot rock projects; to date circulation tests have been successful, and plans are underway to install the first stage power station.

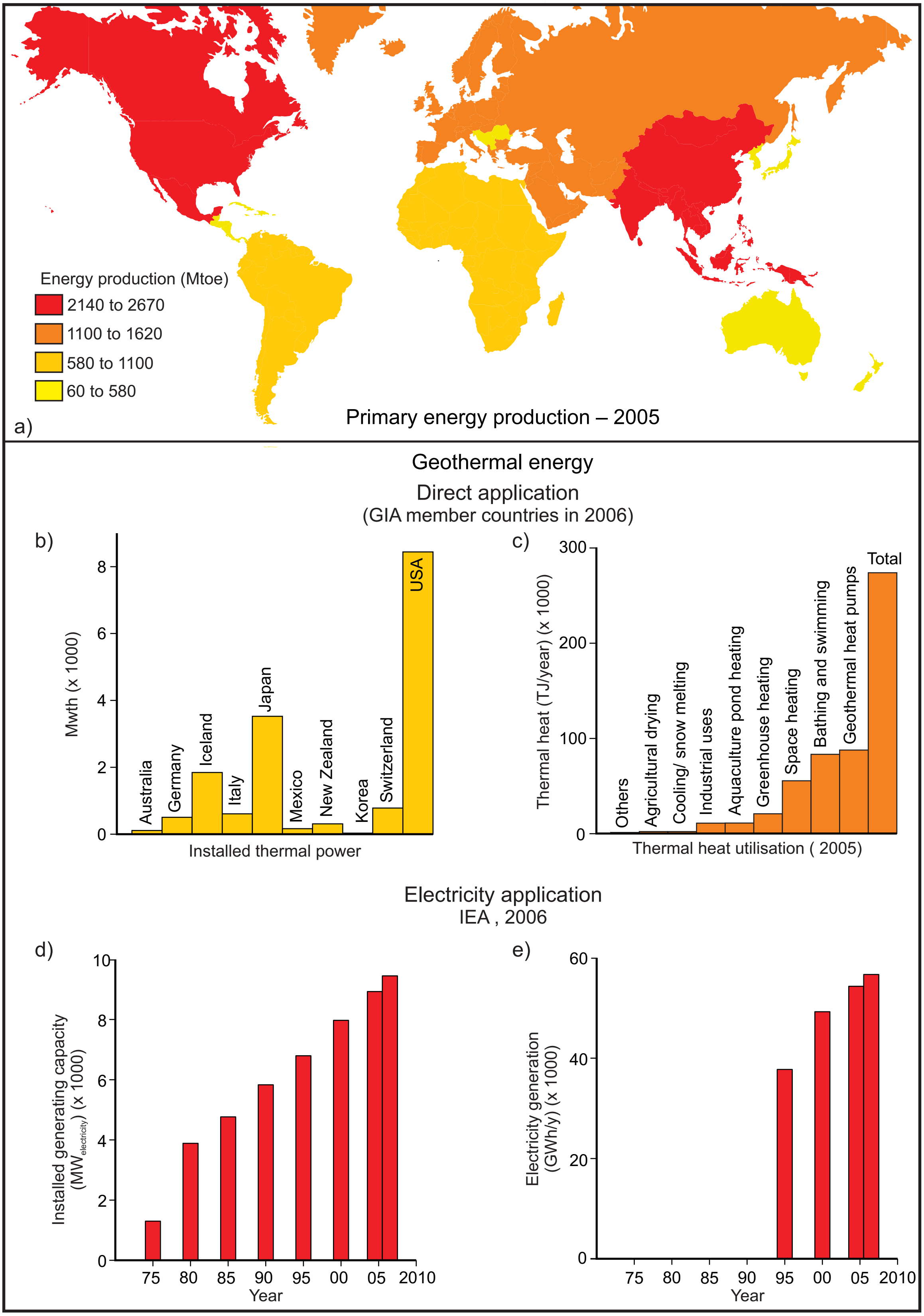

Figure 3. Worldwide primary energy production and geothermal energy application for electricity generation and direct heat use (International Energy Agency, 2008).

WESTERN AUSTRALIA

The search for geothermal resources from hot rock systems in Australia effectively started in 2006 as part of Australian membership to the International Energy Agency–Geothermal Implementing Agreement (IEA–GIA). In Australia's basins, high crustal temperatures are usually associated with local high-heat production below rocks of low thermal conductivity (Chopra and Holgate, 2007). In Western Australia, the study of hydrothermal resources began in the 1980s (Bestow, 1982) but was largely moribund until the mid-2000s. The geothermal systems of Western Australia are both hydro-geothermal and hot rock systems, related to regional heat flow rather than volcanic activity. Since 2006, the focus in GSWA has been on high-enthalpy hot rock resources. To date, three GSWA studies specific to the geothermal energy potential in Western Australia are available (Bestow, 1982; Chopra and Holgate, 2007; Hot Dry Rocks Pty Ltd, 2008).

In the 1980s, Bestow (1982) identified low-enthalpy hydro-geothermal resources with temperatures ranging from 65°C to 85°C at depths ranging from 2 km to 3.5 km, with the best economic potential in the Perth Basin. The study mainly focussed on low-temperature geothermal reservoirs up to 100°C, and applied the available heat flow, geothermal gradient and hydrogeology data to the Archean Yilgarn Craton, and the Eucla/Bight, Gunbarrel/Officer, Canning, Carnarvon and Perth basins. The study was qualitative rather than quantitative and concluded that geothermal and hydrogeological conditions for developing a geothermal resource for both direct use and power generation are present. The hydrogeological and geothermal conditions were found to be similar to overseas basins such as the Paris Basin, France, where the geothermal energy was exploited from 2 km depth, with an annual cost saving of 6–14% compared with other alternative energy sources during the 1980s (Bestow, 1982). At the time, the potential benefit of geothermal energy sources was not realised and the next study was not commenced until 2006. Similar hydro-geothermal resources to those found in Western Australia also are exploited in the Pannonian Basin of Hungary, the Williston Basin of USA, and many Chinese basins (Eggle and Sametinger, 2008).

Chopra and Holgate (2007) and Hot Dry Rocks Pty Ltd (2008) found that the temperature and in situ stress conditions found in the Canning, Carnarvon and Perth basins indicate favourable conditions in parts of these basins. Their results are discussed further and evaluated below.

Subsurface temperature

The first priority of the current GSWA study was to identify high-heat generating areas, based on temperature and geological information accumulated during the search for petroleum in Western Australia (Fig. 1). Initial compilation of raw temperature data from 580 onshore petroleum wells was followed by calculation of temperature gradients, and mapping of gradients was completed to select areas for detailed studies by geothermal consultants (Fig. 4). Next, Earthinsite.com Pty Ltd evaluated 273 petroleum wells from the Canning (100 wells), Carnarvon (90 wells), and Perth Basins (83 wells), as reported by Chopra and Holgate (2007). In the third phase in 2008, Hot Dry Rocks Pty Ltd (HDRPL) evaluated 170 Perth Basin wells (Fig. 2). The aim was to map and identify the most suitable areas within these basins that may have potential to develop geothermal energy from hot rocks, as well as to develop a reliable dataset of subsurface temperatures, basement depths, rock types, and in situ stress conditions for future studies. The full reports are available online at <http://www.dmp.wa.gov.au/801.aspx>. The conclusions of these studies are discussed below.

Chopra and Holgate (2007) evaluated the quality and quantity of available subsurface temperature data to calculate reliable true formation temperatures and estimate the equilibrium geothermal gradient for 273 wells. Quality and type of data for estimating the true formation temperature (TFT) (used to estimate the equilibrium geothermal gradient) varies from well to well. They use a Horner correction method to estimate the true formation temperature for wells with a series of temperature measurements at similar depths and different times with recorded circulation and lag time in wells where only lag time is available a semi-log plot (SLP) method was applied. Estimated TFT and mean annual surface temperature (MAST) were used to estimate equilibrium geothermal gradient, the details of which are discussed in Holgate and Chopra (2005). Higher than normal geothermal gradients in many wells provided the first indication of high heat flow (Fig. 5). Estimates of the equilibrium geothermal gradient and the depth to basement are used to predict the temperature at the top of the basement and the depth at each well location required to reach the 200°C isotherm (Fig. 6). The Carnarvon Basin has the greatest number of wells with high present-day geothermal gradients where this isotherm appears to be less than 5 km deep, followed by the Canning and Perth basins (Figs 5 and 6). At present, detailed geochemical information on the basement rocks intersected by the wells studied is not available to calculate the heat-generating potential.

HDRPL (2008) evaluated the quality and quantity of available subsurface temperature data for 170 wells in the Perth Basin, measured thermal conductivities of 30 samples and performed one-dimensional (1D) heat flow modelling of these wells. Of the 170 wells, 162 have good-quality temperature data that were corrected using a Horner correction (Hermanrud et al, 1990). The Perth Basin's corrected temperatures, measured thermal conductivities, and surface temperature from annual mean air data of the Australian Bureau of Meteorology were used in 1D heat flow modelling. Modelled surface heat flow ranges from 30–140 mW/m^2, with a median value of 76.5 mW/m^2 for the Perth Basin (Hot Dry Rocks Pty Ltd, 2008). HDRPL generated isotherm maps at 100°C, 150°C, 200°C, and temperature at 5 km depth, from interpreted subsurface temperatures in 250 wells of the Perth Basin. Figure 7 shows geographic distribution of heat flow values and temperatures at 5 km within the Perth Basin, indicating that heat flow increases

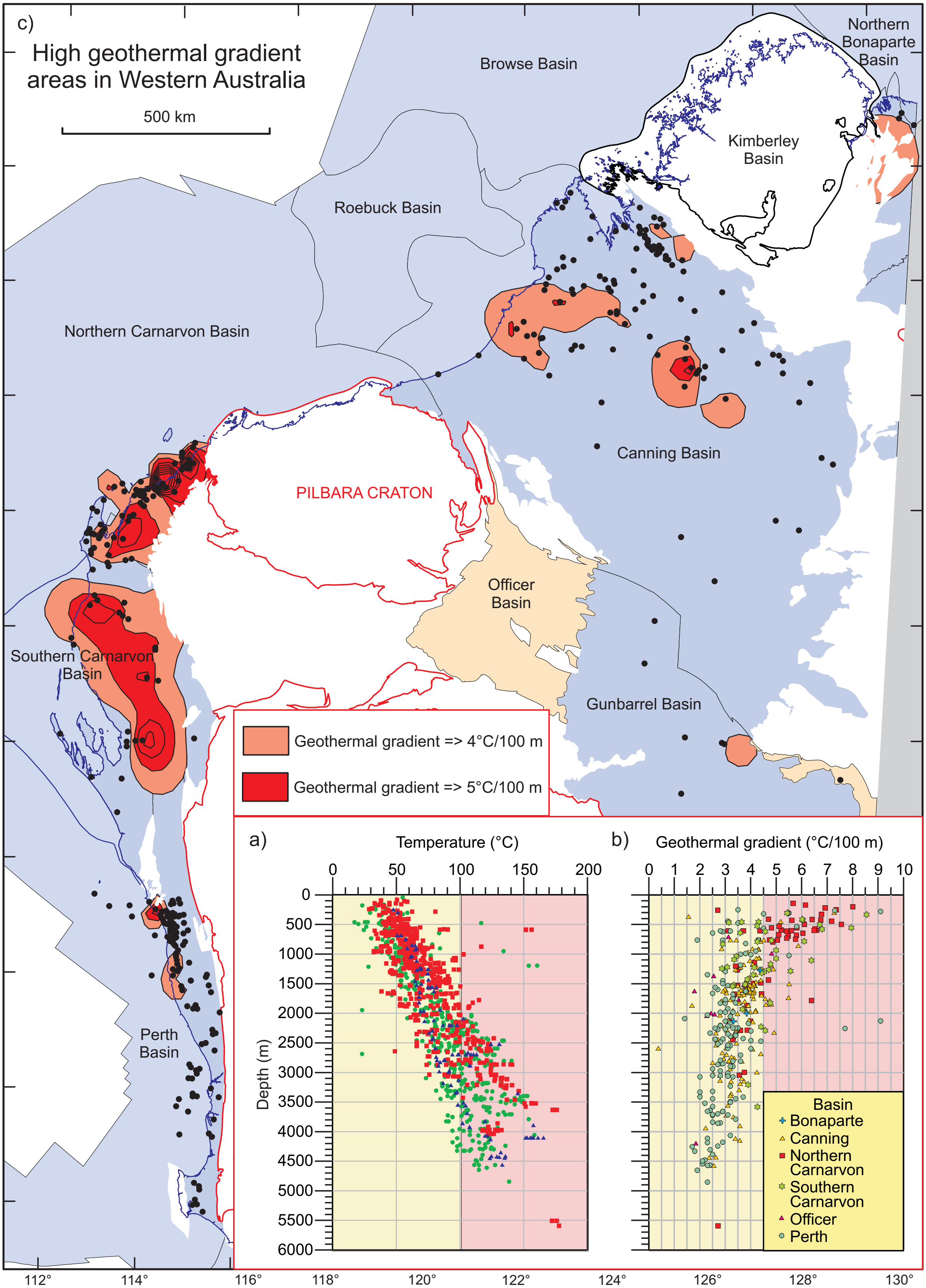

Figure 4. Initial evaluation of subsurface temperatures and geothermal gradients distribution in six Western Australian basins.

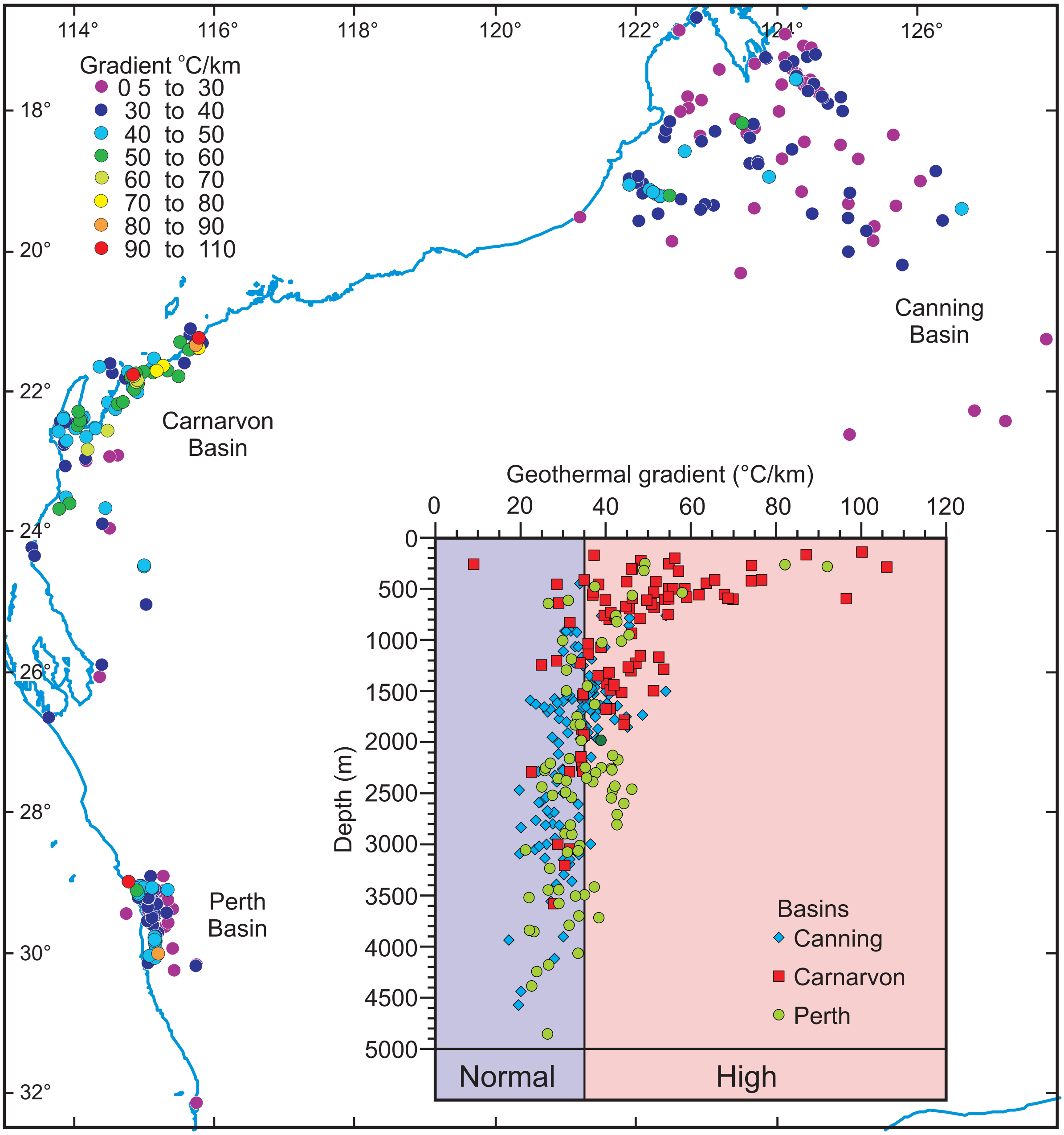

Figure 5. Present-day geothermal gradients in selected petroleum wells in the Canning, Carnarvon and Perth basins verified by Chopra and Holgate (2007) and modified from Ghori (2008a).

and depth to 200°C decreases from south to north, with the highest heat flow and shallowest depth to 200°C around the Eneabba area.

Stress field

Present-day stresses are important to both petroleum- and geothermal-energy production as well as for the geological storage of CO_2. Tectonic stress is an important control on the development of artificially created heat reservoirs and water pathways (exchanger or engineered) by EGS techniques in hot rock systems. Generally, where the principal maximum stress is horizontal it facilitates the development of stacked subhorizontal reservoirs, which require assessment of in situ stress orientation and magnitude of all three components (Sh_{max}, Sh_{min} and S_v) at prospect level. Besides controlling heat exchange, in situ stress also affects well stability, fluid flow, seal integrity and structural reactivation or tectonism.

For the Western Australian region, stress indicators include individual borehole breakout, drilling induced tensile fracture, cross-sectional shape of the entire well and single earthquake focal mechanism solution. Most stress data is from the northern Perth Basin, with data

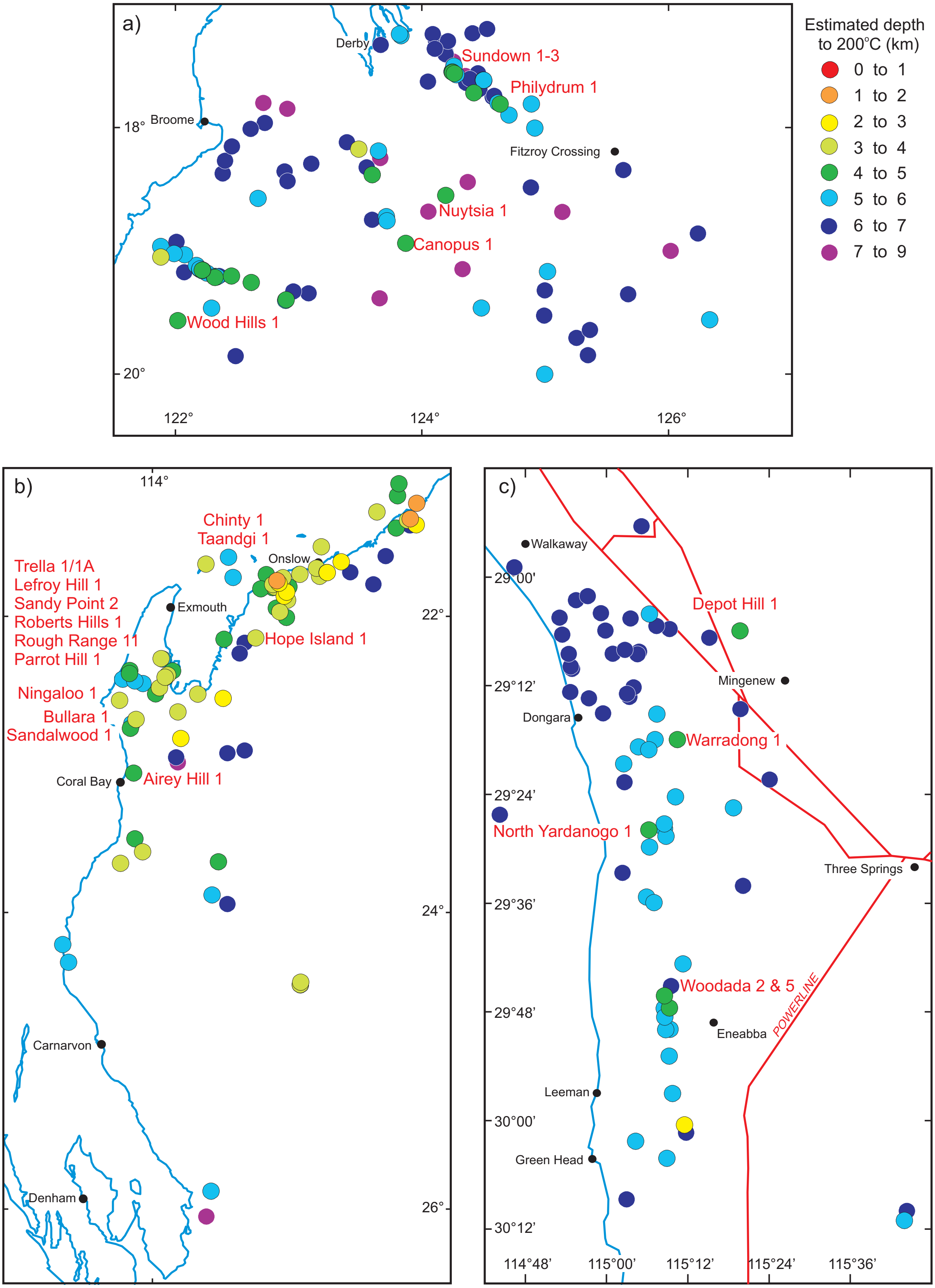

Figure 6. Wells with estimated depth to 200°C shallower than 5 km in a) Canning Basin; b) Carnarvon Basin; and, c) Perth Basin, modified from Ghori (2008a).

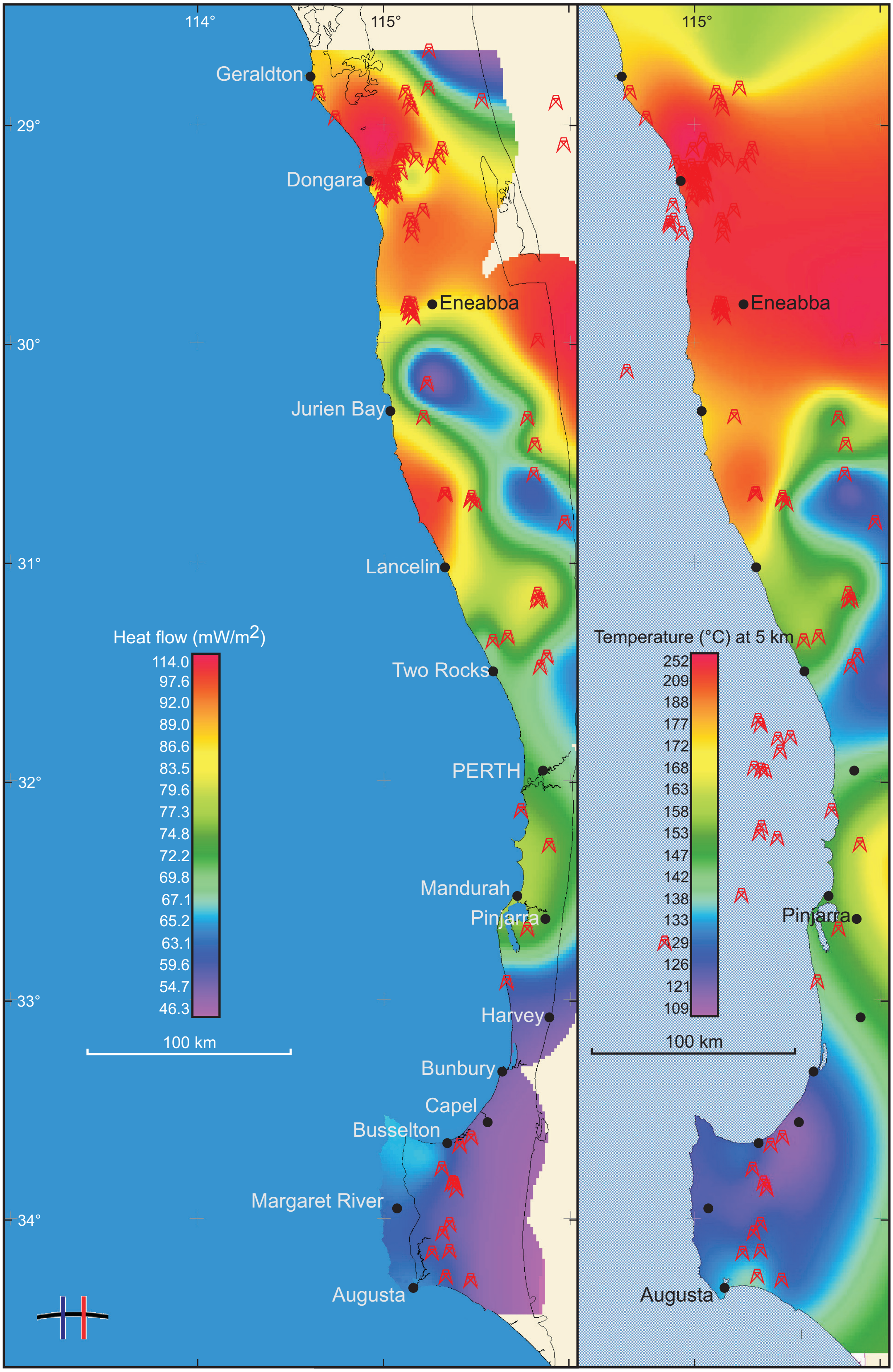

Figure 7. Geographic distribution in the onshore Perth Basin of a) heat flow values; and, b) temperature at 5 km depth, modified from Hot Dry Rocks Pty Ltd (2008).

from only 13 locations for the Canning Basin and offshore petroleum wells in the Carnarvon Basin. Figure 8 and Table 1 summarise Western Australian stress orientation data compiled from release 2008 of the World Stress Map (Heidbach et al, 2008).

Most of the studies from the Perth Basin indicate an east–west maximum horizontal stress orientation—recently confirmed by King et al (2008)—based on borehole breakouts and drilling induced tensile fractures using a Formation Micro-Imager log, which is more reliable than the dipmeter-based studies by Hillis and Reynolds (2000, 2003). However, borehole breakouts and drilling induced tensile fracture do not provide information on stress magnitudes, which must be estimated from leak-off tests and minimum fracture test data. The regional trend of east–west maximum horizontal stress is consistent with stress-field modelling of the Indo-Australian Plate (Coblentz et al, 1995, 1998; Reynolds et al, 2002). There are three fault-controlling events in the Perth Basin: early rifting during the Late Carboniferous to Early Permian, Early Cretaceous Gondwana breakup and the present-day stress regime (Mory and Iasky, 1994; King et al, 2008). The inferred present-day stress regime in the Perth Basin is transitional reverse fault to strike-slip (King et al, 2008), which controlled the formation and reactivation of faults and fractures.

For the Perth Basin, Van Ruth (2006) reported maximum horizontal stress (~26.1 MPa/km) was greater than vertical stress (~21 MPa/km), which in turn exceeded minimum horizontal stress (~15.3 MP/km). Pore pressure is ~10.2 MPa/km. The regional maximum horizontal stress determined by the Australia Stress Map Project is approximately east–west (087ºN). These data were compiled for the geomechanical analysis of the offshore southern Perth Basin for CO_2 storage for Greenhouse Gas Technology (CO2CRC).

The Carnarvon Basin is also characterised by broadly east–west maximum horizontal stress but rotates north-east–southwest in the Canning and Bonaparte basins.

POTENTIAL GEOTHERMAL RESOURCES

The Southern Carnarvon and Canning basins are classified as Palaeozoic, Perth Basin as Palaeozoic–Mesozoic, and the Northern Carnarvon Basin as Mesozoic–Cenozoic, based on the age of their dominant sedimentary fill and tectonic activity (Hocking et al, 1994). The stratigraphic succession and geographic extent of the Carnarvon, Canning and Perth basins are sufficiently large (Figs 1 and 9) that they may have high potential for geothermal resources that are not associated with volcanic activity, as noted by Eggle and Sametinger (2008). The temperature of thermal water in these basins depends on the geothermal gradients and aquifer depths, which in turn depend on heat flow, geological development, structure, and sediment distribution. Available oil and gas exploration and production data indicate both thick high porosity and permeability intervals (fluid reservoirs) and impermeable strata (traps for reservoired fluids and heat contained in rocks).

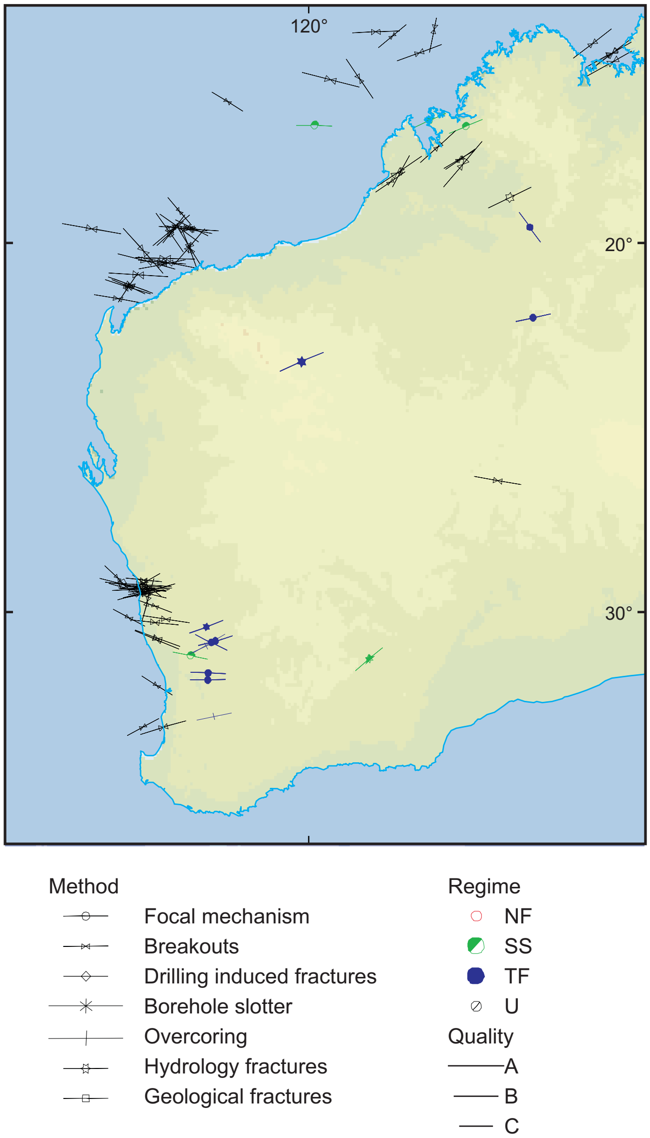

Figure 8. Map showing method, regime and quality of stresses in Western Australia, compiled from release 2008 of the World Stress Map (Heidbach et al, 2008).

Carnarvon Basin

The Carnarvon Basin extends over 1,000 km along the western and northwestern coastline between Geraldton and Karratha (Fig. 1), covers 650,000 km^2 including a 115,000 km^2 onshore part (Hocking et al, 1987), and contains up to 15 km of Palaeozoic to Recent sedimentary fill. The Southern Carnarvon Basin is mostly onshore and the Northern Carnarvon Basin mostly offshore. In the Southern Carnarvon Basin, the three major periods of subsidence and fill occurred in the Ordovician–Silurian, Devonian, and Late Carboniferous–Permian. The Northern Carnarvon Basin was active during the Mesozoic fragmentation of Gondwana, and contains seawards-thickening wedges of Cenozoic sedimentary rocks overlying a thick Mesozoic succession (Hocking and Preston, 1998).

Table 1. Locality and quality of stresses in selected petroleum wells of Western Australia, compiled from release 2008 of the World Stress Map (Heidbach et al, 2008).

Locality	Latitude	Longitude	Azimuth	Type	Depth	Quality	Regime	Basin	Position
Cambridge-1	-14.29	128.433	53	BO	1.30	B	U	Bonaparte	Offshore
Barcoo-1	-15.344	120.637	105	BO	4.78	A	U	Browse	Onshore
Caswell-2	-14.075	122.468	50	BO	0.00	C	U	Browse	Offshore
Echuca Shoal-1	-13.758	123.717	11	BO	3.99	B	U	Browse	Offshore
Yampi-2	-14.559	123.276	70	BO	0.00	B	U	Browse	Offshore
Blina-1	-17.624	124.501	55	BO	0.32	C	U	Canning	Onshore
Boronia-1	-17.758	124.572	40	BOC	2.80	A	U	Canning	Onshore
Cow Bore-1	-17.969	122.724	28	BOC	1.59	C	U	Canning	Onshore
East Crab Creek-1	-18.017	122.608	56	BOC	1.91	A	U	Canning	Onshore
Hakea-1	-17.626	124.463	60	BOC	1.10	C	U	Canning	Onshore
Hedonia-1	-18.277	122.401	55	BOC	1.03	C	U	Canning	Onshore
Kora-1	-17.26	123.829	48	BOC	2.24	B	U	Canning	Onshore
Bambra-1	-20.533	115.633	94	BO	2.23	B	U	Carnarvon	Offshore
Brigadier-1	-19.097	116.136	140	BO	3.03	C	U	Carnarvon	Offshore
Campbell-2	-20.417	115.717	92	BO	1.97	A	U	Carnarvon	Offshore
Chinook-2	-21.167	114.683	110	BO	2.56	B	U	Carnarvon	Offshore
Cossack-1	-19.567	116.5	116	BO	2.93	C	U	Carnarvon	Offshore
Emma-1	-20.533	115.783	101	BO	1.96	A	U	Carnarvon	Offshore
Goodwyn-3A	-19.733	115.867	48	BO	0.70	C	U	Carnarvon	Offshore
Goodwyn-4	-19.694	115.848	145	BOC	2.50	B	U	Carnarvon	Offshore
Goodwyn-8B	-19.633	115.9	50	BO	2.90	B	U	Carnarvon	Offshore
Goodwyn-9A	-19.6	115.967	39	BO	3.02	C	U	Carnarvon	Offshore
Griffin-1	-21.233	114.617	107	BO	2.94	B	U	Carnarvon	Offshore
Griffin-3	-21.233	114.617	33	BO	2.63	C	U	Carnarvon	Offshore
Griffin-4	-21.217	114.633	113	BO	2.05	C	U	Carnarvon	Offshore
Jupiter-1	-19.582	113.533	100	BO	0.00	A	U	Carnarvon	Offshore
Maitland-1	-20.5	115.167	105	BO	1.09	A	U	Carnarvon	Offshore
Marra-1	-20.6	115.633	80	BO	1.70	B	U	Carnarvon	Offshore
North Rankin-5	-19.572	116.137	126	BOC	2.88	B	U	Carnarvon	Offshore
Santo-1	-21.55	114.317	100	BO	1.38	B	U	Carnarvon	Offshore
Scindian-1A	-21.183	114.7	110	BO	2.73	C	U	Carnarvon	Offshore
Tingle-1	-20.167	116.467	149	BO	0.69	B	U	Carnarvon	Offshore
Wanaea-1	-19.583	116.433	94	BO	3.04	A	U	Carnarvon	Offshore
Wanaea-2	-19.617	116.417	99	BO	2.94	B	U	Carnarvon	Offshore

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Locality	Latitude	Longitude	Azimuth	Type	Depth	Quality	Regime	Basin	Position
Wanaea-3	-19.567	116.433	99	BO	2.89	C	U	Carnarvon	Offshore
Wandoo-3	-20.133	116.433	160	BO	0.59	B	U	Carnarvon	Offshore
Wandoo-7	-20.117	116.433	41	BO	0.69	B	U	Carnarvon	Offshore
West Barrow-1A	-20.883	114.917	94	BO	2.87	A	U	Carnarvon	Offshore
West Tryal Rocks-2	-20.215	115.066	139	BO	0.00	A	U	Carnarvon	Offshore
Kanpa-1A	-26.528	125.614	100	BOC	2.18	B	U	Officer	Onshore
Apium-1	-29.316	115.071	90	BO	2.82	C	U	Perth	Onshore
Beekeeper-1	-29.714	115.185	15	BO	2.81	B	U	Perth	Onshore
Beharra Springs North-1	-29.435	115.144	78	BO	2.95	C	U	Perth	Onshore
Beharra Springs North-1	-29.435	115.144	87	DIF	3.14	C	U	Perth	Onshore
Beharra Springs South-1	-29.505	115.151	80	BO	3.08	B	U	Perth	Onshore
Beharra Springs South-1	-29.505	115.151	80	DIF	3.21	C	U	Perth	Onshore
Cliff Head-4	-29.258	114.457	96	BO	1.34	C	U	Perth	Offshore
Cliffhead-4	-29.258	114.457	104	DIF	1.42	B	U	Perth	Offshore
Coomallo-1	-30.248	115.415	96	BO	2.88	B	U	Perth	Onshore
Dongara-20	-29.266	115.022	93	BO	1.21	A	U	Perth	Onshore
Geelvink-1A	-29.096	114.298	135	BO	2.98	C	U	Perth	Offshore
Georgina-1	-29.145	115.074	95	BO	1.35	C	U	Perth	Onshore
Hakia-1	-29.216	115.096	61	BO	7.44	C	U	Perth	Onshore
Kingia-1	-29.393	115.029	88	DIF	2.52	A	U	Perth	Onshore
Kingia-1	-29.393	115.029	94	BO	1.81	B	U	Perth	Onshore
Lake Preston-1	-32.92	115.66	74	BO	3.51	B	U	Perth	Onshore
Mentelle-1	-29.436	114.889	104	DIF	1.19	A	U	Perth	Offshore
Mullaloo-1	-31.867	115.462	122	BO	1.46	C	U	Perth	Offshore
Redback-1	-29.458	115.162	75	BO	3.18	A	U	Perth	Onshore
Redback-1	-29.458	115.162	76	DIF	3.20	B	U	Perth	Onshore
South Turtle Dove-1	-30.13	114.636	118	BO	1.22	C	U	Perth	Offshore
Sugarloaf-1	-32.915	115.052	62	BO	3.43	C	U	Perth	Offshore
Twin Lions-1	-29.37	114.886	90	DIF	1.30	C	U	Perth	Offshore
Walyering-2	-30.701	115.472	113	BO	3.51	B	U	Perth	Onshore
Walyering-3	-30.666	115.492	110	BO	2.41	B	U	Perth	Onshore
Warradong-1	-29.301	115.171	127	BO	3.45	C	U	Perth	Onshore
Warro-1	-30.168	115.736	99	BO	1.18	B	U	Perth	Onshore
Woodada-4	-29.835	115.414	110	BO	1.83	C	U	Perth	Onshore

Notes: BO = borehole breakout, DIF = drilling induced fracture, BOC = cross-sectional shape of the entire well, U = unknown.

The Northern Carnarvon Basin is the main oil and gas producing basin of Western Australia, with over 984 petroleum wells providing a huge amount of subsurface data up to a drilled depth of 9 km (Fig. 2). Subsurface data for the Southern Carnarvon Basin is limited to 258 wells, mostly onshore. In the Northern Carnarvon Basin, Swift el al (1988) calculated (from 74 direct seabed measurements, and bottom hole and seabed temperatures from 23 offshore wells) that the highest present-day surface heat flow (90 mW/m^2) is near Barrow Island, and the lowest (17 $m/W/m^2$) is over the Exmouth Plateau Arch. No similar heat flow study is available for the Southern Carnarvon Basin, which contains the highest number of wells with high geothermal gradients, compared to other onshore basins. Ghori et al (2005) noted an increase in geothermal gradient from the Palaeozoic onshore to the Mesozoic–Cenozoic offshore: the average recorded geothermal gradient is 35°C/km in the Exmouth Sub-basin, 32°C/km on the Gascoyne Platform, 30°C/km in the Merlinleigh Sub-basin, and 31°C/km over the Peedamullah Shelf. These gradients indicate minimum temperature values because recorded gradients are up to 20% lower than the actual gradient based on equilibrium temperatures.

Canning Basin

The Canning Basin is the largest Western Australian basin, but has seen limited exploration and petroleum production, and lacks the infrastructure required for major geothermal resource development. The basin is west-northwesterly trending (Fig. 1), covering over 640,000 km^2, of which 530,000 km^2 is onshore. It contains up to 18 km of Ordovician to Cretaceous sedimentary rocks (Fig. 9), but mostly Palaeozoic. Subsurface temperature data are from 233 wells, of a total 274 petroleum exploration wells (Fig. 2). The recorded geothermal gradients in many petroleum wells are higher than 4°C/km (Figs 4, 5, and 6a), and the stress trend is northeast–southwest. Heat flow and subsurface temperatures from petroleum wells are presently being studied by HDRPL.

Perth Basin

The Perth Basin is a north–south elongated trough along the southwest margin of Western Australia (Fig. 1), and contains a Permian to Lower Cretaceous succession under a Cenozoic veneer (Fig. 9). The eastern boundary is the Darling Fault and the basin extends offshore to the continental-oceanic boundary. The search for petroleum, groundwater, and geothermal resources in the Perth Basin—and, in particular, the Perth region—effectively started with settlement in the 19th century. However, the right for commercial geothermal exploration and development was not formalised until 2008 under the Petroleum and Geothermal Energy Resources Act 1967 and the first geothermal acreage release in the Perth Basin (Fig. 1). For the Perth Basin, GSWA studies on petroleum resources are discussed by Crostella (1995), Mory and Iasky (1996), Crostella and Backhouse (2000), and Owad-Jones and Ellis (2000); for hydrology by Thorpe and Davidson (1991), and Davidson (1995); and for geothermal resources by Bestow (1982), Chopra and Holgate (2007), Ghori (2007, 2008a, 2008b), and Hot Dry Rocks Pty Ltd (2008).

Bestow (1982) discussed the hydro-geothermal resources and recognised low temperature reservoirs ranging from 65–85°C at depths of 2–3.5 km. The groundwater resources of the Perth region have been systematically investigated by drilling since 1961. Neogene to Jurassic aquifers up to 1,100 m deep are exploited to supplement surface supplies for the industrial and domestic water supply. The Jurassic Yarragadee aquifer is a major multi-layered confined aquifer up to 2 km thick underlying the entire Perth region, and extends almost the entire length of the basin. The salinity of groundwater ranges from 140 to more than 10,000 mg/L TDS (total dissolved solids), with temperatures from 28–45°C and averaging about 39°C. The mean geothermal gradient is about 25°C/km, with the maximum depth to the base of the aquifer about 3 km, which indicates the maximum likely temperature in the aquifer is about 90°C, if a linear extrapolation is applied. The highest temperature groundwater lies beneath the Kings Park Formation in the central Perth region (Davidson 1995), which is consistent with the findings of Bestow (1982).

Figure 10 shows the distribution of geothermal gradients and the temperature versus depth. The temperatures are from temperature logs recorded in 47 of 145 artesian monitoring bores available for this study. For each of these wells, temperatures at different depths were compiled and geothermal gradients computed. The recorded gradients range 1.1–4.4°C per kilometre, based on data from less than 1 km; both the highest and lowest recorded subsurface temperatures are near Wanneroo (Fig. 10). The lower temperatures extend north, and the higher extend south of Wanneroo. These temperatures indicate low temperature resources up to 50°C at a depth of less than 1 km in areas of high geothermal gradients. Regenauer-Lieb and Horowitz (2007) discussed and encouraged the direct use of low-enthalpy hydrothermal resources of the Perth Basin. For the hot rock resources, the recorded subsurface temperatures (Fig. 4), geothermal gradients (Figs 5 and 6c), estimated heat flows (Fig. 7), and in situ stress (Fig. 8) all suggest favourable conditions in the northern Perth Basin.

Conceptual models for petroleum and geothermal resources were developed for the Beagle Ridge (Fig. 11a) and the Cadda Terrace (Fig. 11b) of the Perth Basin, because high geothermal gradients were observed in Jurien–1 (55°C/km) on the Beagle Ridge and Woodada–2 (40°C/km) in the Cadda Terrace. Jurien–1, drilled to a total depth of 1,026 m, intersected granitic basement at 967 m and extrapolation from recorded temperatures indicates that the 200°C isotherm lies between 2.5 km and 3 km (Fig. 11c). This is an economic depth for developing geothermal resources if other EGS factors are favourable. Figure 11d shows the subsurface temperatures as a function of depth in 17 of the Woodada Gas Field wells. The reservoir temperature of the Woodada Gas Field is 120°C, at depths ranging from 2,125–2,496 m (Owad-Jones and Ellis, 2000). The extrapolated temperatures indicate that the 200°C

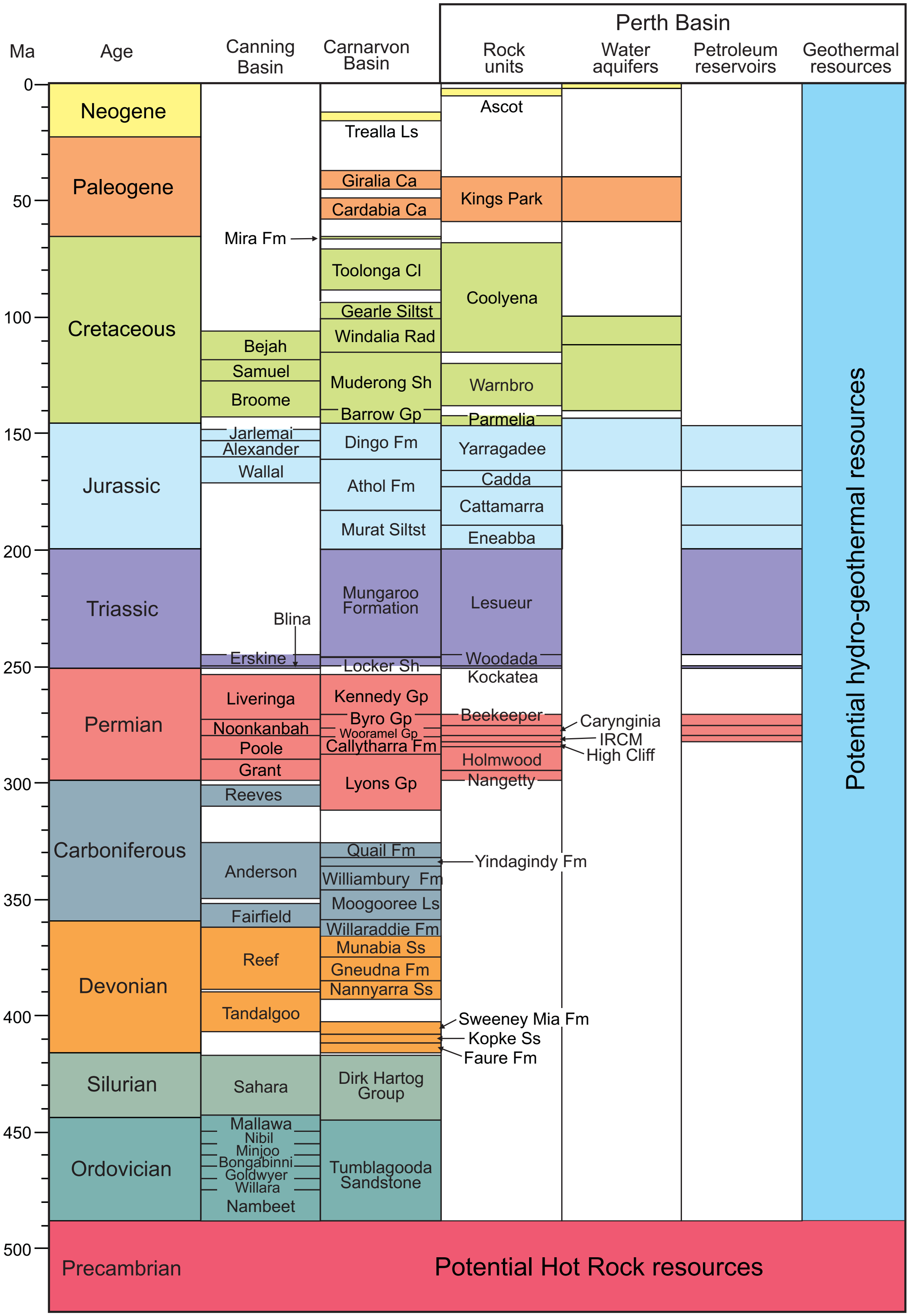

Figure 9. Generalised time-stratigraphy of the Canning, Carnarvon and Perth basins, and water, petroleum and potential geothermal resources of the Perth Basin.

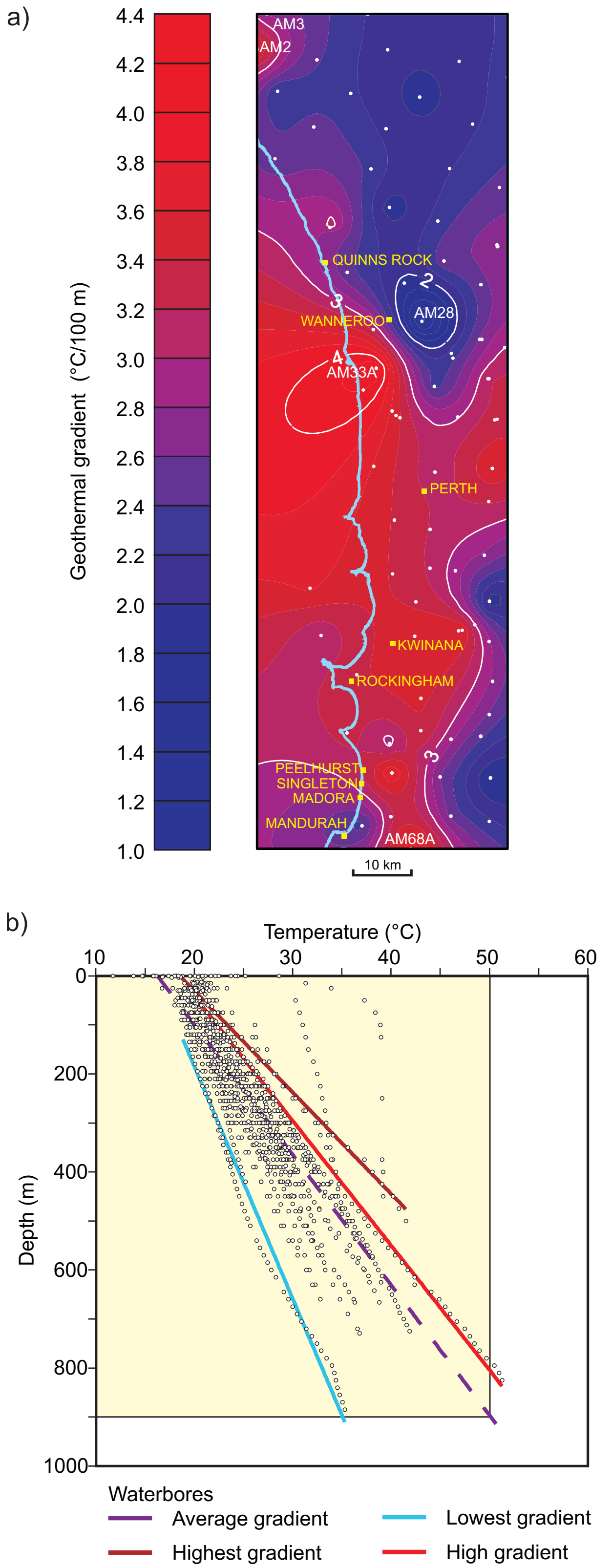

Figure 10. Average subsurface temperature gradient recorded in water bores of the Perth Region: a) geographic distribution of average geothermal gradient; b) subsurface temperature as a function of depth, modified from Ghori (2008b).

isotherm should be between 4 and 5 km; these are also suitable depths for developing geothermal resources assuming favourable EGS conditions.

CONCLUSIONS

Western Australia formalised geothermal energy exploration in January 2008 after amending the Petroleum Act 1967 to the Petroleum and Geothermal Energy Resources Act 1967, and releasing geothermal acreage for bids in the Perth Basin. The data generated from drilling since the start of modern petroleum exploration in the 1950s allows a quantitative, pre-competitive assessment of geothermal energy potential. This assessment indicates potential for low-enthalpy hydro-geothermal reservoirs with temperatures up to 85°C, within a depth of 3 km, and high-temperature hot rock resources with temperatures up to 200°C within a depth of 5 km in several regions of Western Australia's Phanerozoic sedimentary basins. The northern Perth Basin has the best conditions with favourable geology and well-developed infrastructure and commercial markets for direct and electric generation applications, but potential hot rock and hydro-geothermal resources are also present in parts of the Canning and Carnarvon basins.

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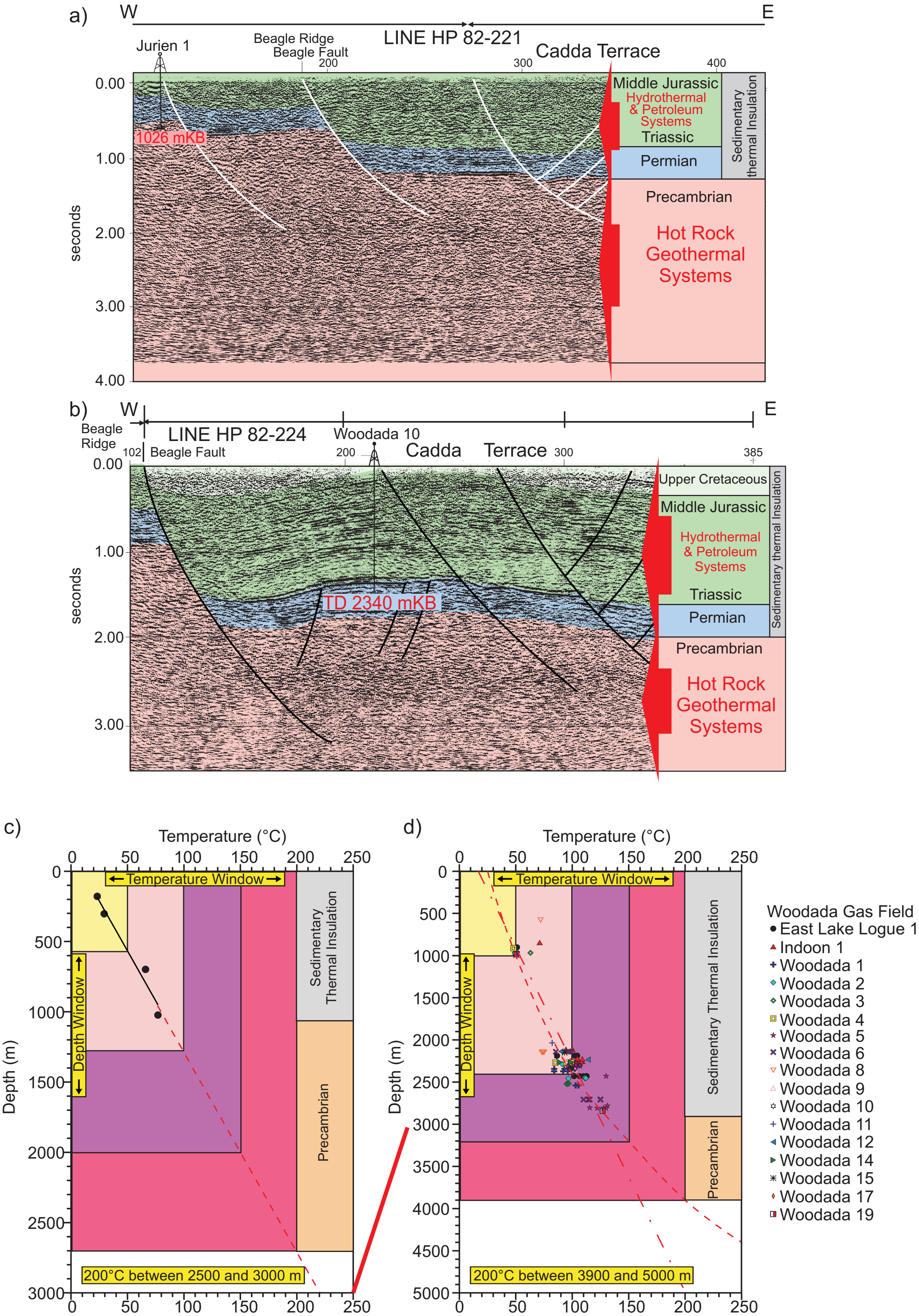

Figure 11. Conceptual model developed for Perth Basin geothermal systems, modified from Ghori (2008b).

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