Western Australian
Geothermal
CENTRE OF EXCELLENCE

Perth Basin Assessment Program

Final Report: INVESTIGATING SEDIMENTARY GEOTHERMAL RESOURCES IN WESTERN AUSTRALIA

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Report 1

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EXECUTIVE SUMMARY

Western Australia is endowed with vast areas of deep sedimentary basins, which contain and transmit correspondingly vast amounts of natural geothermal energy. This energy is a valuable resource which, if tapped, could transform the urban and industrial energy landscape of the state.

The Western Australian Geothermal Centre of Excellence was established in 2009 with a three-year grant from the Western Australian government, with the mission to provide scientific excellence in geothermal research and to assist public and private sectors benefit from the state's geothermal resources, especially in the Perth Basin. Program 1 of WAGCoE, entitled "Perth Basin Assessments" and incorporating nearly two-thirds of the WAGCoE research effort, was charged with characterizing and investigating hydrothermal processes in the Perth Basin, and developing new methods to tap the geothermal resources.

Over its three years of operation, Program 1 attracted the energies of approximately 6.5 FTE of professional research staff per annum (from the three research partner organizations), trained 33 students and interns (including 7 PhD level students with 3 completed theses), produced over 60 international scientific journal publications and one international patent application, and made over 70 presentations at scientific and industry conferences in Australia and overseas.

Key advances of Program 1 include:

New Geological Understandings

- A detailed lithofacies classification and analysis of sediments in the upper 3 km of the Perth Basin, as represented in cores taken from the Cockburn-1, Pinjarra-1 and Gingin-1 core sets.
- A new fault network interpretation for the Perth Basin, integrating new geophysical, topographic and structural assessments, and showing the potential for significant reservoir compartmentalization.
- The first three-dimensional geological structural model of the entire Perth Basin, to a depth of 30 km below sea level, and incorporating prior structural models of the northern Perth Basin and the Perth metropolitan area together with newly collected and interpreted structural and basement data.

New Hydrothermal Understandings

- A revised and extended temperature profile data set for the Perth metropolitan area, leading to enhanced estimates of vertical heat flow, and to the identification of widespread non-conductive thermal anomalies in shallow formations.
- The first three-dimensional conductive heat flow model for the entire Perth Basin, calibrated against temperature profile data, and highlighting the prospectivity of the northern Perth Basin for high-temperature geothermal applications.
- The first three-dimensional, high-resolution convective heat flow model for the upper 3 km of sediments within the Perth metropolitan area, showing the potential for significant convective cells within the Yarragadee aquifer and the key controlling influences of the fault structures identified in the geological investigation.

New Reservoirs and New Management Approaches

- A state-wide permeability and heat flow assessment of geothermal resources potential in the major Western Australian sedimentary basins, including the Canning, Carnarvon, Officer and Perth basins.
- Identification and characterization of a convenient low-temperature resource, the Mullaloo aquifer in the Perth metropolitan area, suitable for long-term heat rejection schemes.
- Subsurface stirring: an exciting new technology application for subsurface reservoir management, capable of boosting subsurface heat exchange performance

New Tools for Geothermics

- GeoTemp™: a public domain software tool for analysis of subsurface temperature profile data
- An automated and integrated model development workflow for building complex structural and hydrothermal models, with uncertainty quantification
- A web-based, searchable geothermal data catalogue for Western Australia

As useful as these items are for defining geothermal resources in Western Australia, and for designing and engineering productive geothermal applications, there is much still to learn before the deep geothermal potential of Western Australia can be unlocked. Important knowledge gaps and engineering challenges are discussed in later sections of this report, including the need to maintain and build Western Australia' geothermal science capability, and the imperative to advance subsurface resource definition activities, including drilling and geophysical measurement.

PREFACE

The Western Australian Geothermal Centre of Excellence (WAGCoE) was established in 2009 for an initial three-year term with a $2.3M grant from the Western Australian Department of Commerce. WAGCoE operated as an unincorporated joint venture between CSIRO, the University of Western Australia, and Curtin University of Technology, with CSIRO as the Centre agent. The remit of WAGCoE was to assist the Western Australian Government to provide a foundation for a sustainable geothermal industry by conducting advanced scientific and engineering research into Western Australia's geothermal resources, principally hot sedimentary aquifer resources in the Perth Basin, and to develop and transfer to industry innovative new technologies for direct heat use.

In order to deliver on this task, WAGCoE was structured into three mutually supportive research Programs:

- Perth Basin Assessments (Program 1)
- Above-Ground Engineering (Program 2)
- Deep Heat and Future Resources (Program 3)

The Perth Basin Assessments Program contained four research Projects which have reported separately as follows:

- WAGCoE Data Catalogue (Project 1)
  Poulet and Corbel (2012) WAGCoE Data Catalogue. Final report of Project 1, Perth Basin Assessments Program, WAGCoE Report EP118209, January 2012, 32pp.
- Perth Basin Geomodel (Project 2)
  Timms et al. (2012) Perth Basin Geomodel. Final report of Project 2, Perth Basin Assessments Program, WAGCoE Report EP122443, April 2012, 202pp.
- Hydrothermal Simulations (Project 3)
  Reid et al. (2012) Hydrothermal modelling in the Perth Basin, Western Australia. Final report of Project 3, Perth Basin Assessments Program, WAGCoE Report EP121504, April 2012, 202pp.
- Reservoir Productivity and Sustainability (Project 4)
  Ricard et al. (2012) Productivity and sustainability of low-temperature geothermal resources. Final report of Project 4, Perth Basin Assessments Program, WAGCoE Report EP122629, April 2012, 158pp.

This document is the final report of Program 1 of WAGCoE. The format of the document is of a summary and highlights report; detailed tabulations of technical data and results are to be found in the four supporting Project reports, and the various papers and theses cited therein.

ACKNOWLEDGEMENTS

This work was supported by the Western Australian Geothermal Centre of Excellence (WAGCoE) and CSIRO. WAGCoE was funded by the Western Australian government, through the Department of Commerce, and the three research partners: CSIRO, The University of Western Australia and Curtin University of Technology. This document is an output from the CSIRO Petroleum & Geothermal Portfolio.

The author is grateful to many WAGCoE colleagues, students and collaborators for assistance and advice during the three year lifetime of Program 1 of WAGCoE. Particular thanks are expressed to Margaret Pryor, Melina Ielati, Tim Wong and Chitra Viswanathan for able and cheerful support with administration and finance issues.

Program 1 was fortunate to have been able to work closely with a range of geothermal companies and consultants, including Green Rock Energy Pty Ltd (Adrian Larking, Garry Meyer), GT Power Pty Ltd (Jenny Archibald, Shelly Robertson), Newcrest Mining Ltd (Dean Collett, Cam Mackey), New World Energy Ltd (John Libby) and Rockwater Pty Ltd (Grant Bolton, Martin Pujol). Each of these companies provided valuable opportunities for Program 1 researchers to test their approaches in practical geothermal contexts.

The WA Department of Mines & Petroleum and Department of Water, together with Water Corporation of Western Australia, have been generous with their assistance and collaboration with Program 1. Special thanks are given to Mike Middleton and Ahmeed Ghori from DMP, Yvonne Thompson, Jean-Philippe Pigois and Alex Kern from DoW, and Mike Martin from Water Corporation for their support and expert input.

Program 1 also benefited from involvement in the Pawsey/SESKA capital projects through CSIRO, which generated a global range of research and engineering contacts for Program 1 staff. Thanks are due to Steve Harvey and Jacqui Cook for inviting Program 1 to contribute to these projects.

I wish to recognize the energy and positive efforts of all the scientists who took on project leadership roles within Program 1: Frank Horowitz, Thomas Poulet, Steve Reddy, Lynn Reid, Ludovic Ricard, Nick Timms, and Paul Wilkes, who also deputized ably as Program 1 Leader during my absences. The four projects of Program 1 were the research units primarily responsible for scientific innovation and advance in the Program. Key scientific contributions were also made by Soazig Corbel, Martin Danišik, Claudio Delle Piane, Grant Douglas, Lionel Esteban, Katy Evans, Brendan Florio, Cedric Griffiths, Anna Kaksonen, Dariush Nadri, Hugo Olierook, Joel Sarout, Heather Sheldon, Florian Wellmann and Moyra Wilson.

Finally, I am indebted to the WAGCoE leadership team, Klaus Regenauer-Lieb, Hui-Tong Chua, Steve Reddy and Sean Webb, for their friendly support and advice as we together pursued geothermics in the Western Australian context over the past three years.

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1. INTRODUCTION

Sustainable and low-emissions energy sources are key technologies for modern energy economies. As the only renewable energy source capable of supporting large-scale base load energy demands, regardless of climate, weather and solar cycles, geothermal energy ranks highly in terms of its potential contribution to world energy supply. Around the globe there are many long-standing, robust and profitable examples of geothermal systems and applications. Nevertheless, the world's geothermal resources are vastly underutilized, a situation which seems incongruous for an energy resource with such positive potential and widespread availability.

The mismatch between geothermal potential and reality is driven by the risk-return profile of the geothermal industry. At the most fundamental level, the technical risks associated with any geothermal project increase rapidly with the depth of the geothermal resource, simply due to the complex and unexplored nature of the subsurface environment and to the difficulty of engineering sustainable heat extraction systems at depth. Where technical risks escalate, industry must provide a sound risk management plan in order to attract the investment necessary to proceed with geothermal applications.

Geothermal systems that bring significant heat close to the ground surface are well studied and have been exploited successfully for centuries. Examples include magmatic/volcanic zones that circulate boiling water to the ground, e.g. hot springs, geysers. Apart from the beneficial health uses of such natural hydrothermal expressions, the earliest geothermal power station, Lardarello in Italy, has tapped a volcanic resource to generate electrical power reliably for over a century. The technical risks associated with these surface/shallow geothermal resources are low and easily managed.

This is not the case for deep geothermal resources. Though potentially able to supply similar or even greater amounts of heat as do the shallow volcanic plays, deeper geothermal resources are often poorly understood and are rarely brought into production due to the capital expense of subsurface characterization. This represents a significant impasse for the geothermal sector: what is the minimum knowledge required to unlock a geothermal resource, and how do we gain such knowledge with minimum expense?

These questions can readily be answered for many shallow geothermal contexts, where the groundwater and petroleum exploration provide ready-made data sets for geothermal exploration, and where costs associated with drilling and sampling the geothermal resource are manageable. However, apart from magmatic/volcanic systems which are absent in mainland Australia, the energy benefits of such resources are relatively small and can support only low-capacity heat exchangers, e.g. for swimming pool heat, building climate regulation, ground source heat pumps etc. For deeper contexts, where temperatures exceed 100 °C and the potential for large-scale electrical power generation arises, much less is known about the geothermal reservoir itself and the knowledge scarcity issue escalates risk.

The Western Australian Geothermal Centre of Excellence (WAGCoE) was established in 2009 by the Western Australian government with a three-year remit to pursue research on Western

Australia's geothermal resources. WAGCoE was run as an unincorporated joint venture between CSIRO, University of Western Australia (UWA) and Curtin University of Technology (Curtin), with CSIRO operating as centre agent. An appreciation of the practical difficulties involved in moving from shallow, low-temperature geothermal resources to deep, high temperature resources was embodied in the research plan of WAGCoE. Essentially WAGCoE sought to provide a "knowledge link" between shallow and deep geothermal engineering, so that government and industry had a rational and demonstrated scientific and engineering protocol to follow in identifying, characterizing and developing deep geothermal resources into the future.

WAGCoE's research plan was to investigate the medium-temperature, medium-depth resources of Western Australia as a means of completing the science and technology path from shallow to deep geothermal systems. Western Australia is ideally placed to support such research, since the state has several extensive and deep sedimentary basins which contain vast volumes of heated water held within porous rocks and sediments that are reasonably accessible to modern drilling techniques. This kind of geological system, known as a hot sedimentary aquifer (HSA), represents a perfect natural laboratory for medium-temperature geothermal investigation. HSA systems are well suited to direct-use geothermal applications, i.e. applications where heat energy is used directly without conversion to electrical power as an intermediate step. Common direct-use applications include space heating, water heating/chilling, industrial processing/drying etc.

1.1 WAGCoE Structure

In order to capitalise on the geothermal research opportunity discussed above, WAGCoE was organized into three research programs:

- Perth Basin Assessments (Program 1)
- Above-Ground Engineering (Program 2)
- Deep Heat and Future Resources (Program 3)

The WAGCoE Board agreed that each of the three partners would contribute one Program Leader to WAGCoE, and that Prof. Klaus Regenauer-Lieb would act as Centre Director, with Mr Sean Webb (UWA) as Centre Business Manager. The three Program Leaders were Dr Mike Trefry (CSIRO), Prof. Hui-Tong Chua (UWA) and Prof. Steve Reddy (Curtin) for Programs 1, 2 and 3, respectively. Program 1 accounted for the majority, approximately 60%, of the professional research effort of WAGCoE.

The first two programs were complementary, in that Program 1 investigated below-ground geothermal resources in Western Australia and means for tapping these resources to produce hot water at the ground surface, and Program 2 considered novel above-ground designs for using hot water flows for societal and industrial benefit. Program 3 was a forward-looking research effort focused on understanding the physics and mechanics of deep-heat resources.

Whilst there was significant research and business overlap between the three programs, and a full appreciation of the research impact of WAGCoE would require assessment of the outputs and outcomes of all three programs, for the remainder of this document the activities of Program 1 will be the sole focus.

In terms of research effort, Program 1 included four full-time CSIRO staff plus fractions of other staff contributed by CSIRO, UWA and Curtin. The total research effort of Program 1 totalled approximately 20 FTE over the three year term of WAGCoE. In addition, Program 1 benefited from collaboration with CSIRO researchers employed on relevant projects independently through the Geothermal Stream of the CSIRO Petroleum & Geothermal Portfolio. The combined research efforts of WAGCoE Program 1 and related projects within Petroleum & Geothermal Portfolio represented, during 2009-2012, the world's largest dedicated research group in hot sedimentary aquifer geothermics.

1.2 Perth Basin Assessments – Program 1 Role and Structure

The role of Program 1 was, simply, to perform research to improve the understanding of Western Australia's sedimentary geothermal resources, principally in the Perth Basin. This role could be fulfilled in many different ways. After some discussion it was decided that, in light of the diversity of data sources and the range of potential stakeholders, the tasks of Program 1 would best be divided into four mutually supporting Projects, as described in the following subsections.

1.2.1 Project 1 - Data Catalogue

The aim of Project 1 was to establish a modern data catalogue for geothermal data assembled, collated or produced by WAGCoE and its collaborators. Apart from the normal benefits of good data stewardship, this project provided training for junior geoscientists and interns, and also performed valuable scrutiny of legacy data sets and records from industry and government sources. Once brought into the catalogue and its supporting storage space, data could be accessed directly by WAGCoE researchers and collaborators using a modern standards-based interface with open and extensible metadata formats. Although the scientific output of this project was necessarily low, it was an essential part of the WAGCoE science infrastructure.

The Project Leader of this project was Dr Thomas Poulet (CSIRO), with deputy Ms Soazig Corbel (CSIRO). Primary external research links were with AusScope, and with Western Australian government agencies, including Department of Mines and Petroleum, and Department of Water. There was also significant involvement with the geothermal industry, including Green Rock Energy Limited and GT Power Pty Ltd, through a joint research contract. This project employed casual personnel to perform data quality assurance and data entry.

1.2.2 Project 2 - Perth Basin Geomodel

Upon commencement of WAGCoE, it was immediately apparent that very little was known about the geothermal resources of Western Australia, or indeed the deeper geological structure of the state's sedimentary basins. Project 2 focused on developing a geomodel for the Perth Basin. This project was critically important to the Program in that its mission was to expand and refine the state of knowledge about sedimentary sequences in the Perth Basin and elsewhere in Western Australia. Only by investigating and defining these systems could the Program move towards analysis of hydrothermal characteristics and reservoir productivity that is so important for the geothermal industry. Developing a sedimentary geological model suitable for transfer to quantitative physics and engineering specialists requires a multidisciplinary approach; developing such a model in the face of data scarcity is a task requiring substantial creativity and skill.

Due to the demands of this project it was decided that Prof. Frank Horowitz (UWA) and Prof. Steve Reddy (Curtin) would co-lead the Project. However, due to staff re-assignments and departures this arrangement had to be revisited and Dr Nick Timms (Curtin) assumed full responsibility for the Project Leader role in early 2011. Other key scientific staff included Ms Soazig Corbel, Mr Paul Wilkes (CSIRO), Dr Katy Evans (Curtin), Dr Moyra Wilson (Curtin), Dr Cedric Griffiths (CSIRO) and Dr Dariush Nadri (CSIRO). The project trained a series of students and interns (4 Honours, 2 Masters, 2 PhD and several interns), and marshalled research contributions from CSIRO, UWA and Curtin. The Geomodel Project worked very closely with Project 1 to ensure that the best use was made of government agency and industry data where appropriate. This project engaged with staff of Department of Mines and Petroleum and Department of Water, and delivered research outputs to geothermal companies and through many scientific and industry conference presentations.

1.2.3 Project 3 - Hydrothermal Simulations

The basis of Project 3 was the development of quantitative understandings of temperature distributions and heat flows within sedimentary basins of Western Australia. These understandings are critical to resource estimation and geothermal prospecting, and thus underpin the viability of the geothermal industry in the state. This project used geological models developed in Project 2 as the basis for subsequent hydrothermal simulations, which predicted subsurface temperatures and flows both at basin scale and at district scale.

The Project Leader of this project was Dr Lynn Reid (CSIRO). Other key scientific staff included Dr Heather Sheldon, Dr Thomas Poulet, Dr Ludovic Ricard and Ms Soazig Corbel, all of CSIRO. This project trained a group of students and interns (7 Honours, 2 Masters and 6 PhD), and engaged with staff of Department of Mines and Petroleum and Department of Water. This project delivered many scientific and industry conference presentations and several training courses.

1.2.4 Project 4 - Reservoir Productivity and Sustainability

Project 4 dealt broadly with identification of prospective geothermal reservoirs and their sustainable management. The project worked closely with geothermal companies to facilitate learnings from the drilling and commissioning of new geothermal applications in the Perth metropolitan area, to assess the performance of existing applications, and to assist in the design of new geothermal applications, e.g. the SESKA Geothermal Project. The project also considered improvements to standard workflows in reservoir characterization and assessment.

The Project Leader was Dr Ludovic Ricard (CSIRO). Other key scientific staff included Ms Soazig Corbel (CSIRO), Dr Lynn Reid (CSIRO), Mr Paul Wilkes (CSIRO) and Prof. Frank Horowitz (UWA). The project established wide research links and collaborations within CSIRO, in government agencies including Geoscience Australia, and with geothermal companies. Many students and interns were trained (5 Honours and 8 Masters) and a range of scientific and industry presentations were made.

1.3 Summary of Outreach

Program 1 researchers engaged strongly with state, national and international geothermal research and educational communities. A summary of conference participation and educational training activities attended or provided by WAGCoE Program 1 researchers pertaining to geothermics and the geosciences is provided in Table 1. More details are provided in the individual project reports referred to above.

Conferences and Workshops Attended	**30**
Short Courses Given	**4**
Lectures, Seminars and Presentations	**70**
Journal Publications	**65**

Table 1.1: : Program 1 Outreach Summary, 2009-2012.

2. KEY SCIENTIFIC AND ENGINEERING ADVANCES

Researchers in Program 1 have generated a range of scientific and engineering advances for the geothermal sector in Western Australia. These advances are also pertinent to the investigation of hot sedimentary aquifer systems worldwide. Summaries of the research outputs of the four projects are reported separately (Poulet and Corbel, 2012; Timms et al., 2012; Reid et al., 2012; Ricard et al., 2012). Here we discuss the key advances of Program 1 and place them in context for the Western Australian geothermal sector.

2.1 New Geological Understandings of the Perth Basin

WAGCoE researchers re-evaluated existing geological data for the Perth Basin, and collected new data. This data collection, integration and analysis campaign has resulted in advances in the state of geological knowledge of the Perth Basin sediments, particularly for the deeper formations (Yarragadee and below) for which there is significant prospect of geothermal reservoirs. The following subsections list three considerable geological innovations arising from this research effort, reported in Timms et al. (2012).

2.1.1 Sedimentary lithofacies classification

Through detailed mapping and analysis of extant deep cores (Cockburn-1, Pinjarra-1 and Gingin-1) a new lithofacies classification and analysis was developed for the sediments in the upper 3 km of the Perth Basin. A fluvial-dominated lithofacies scheme, as shown in Figure 2.1, has been developed and applied to the Yarragadee Formation, Cadda Formation, Cattamarra Coal Measures, Eneabba

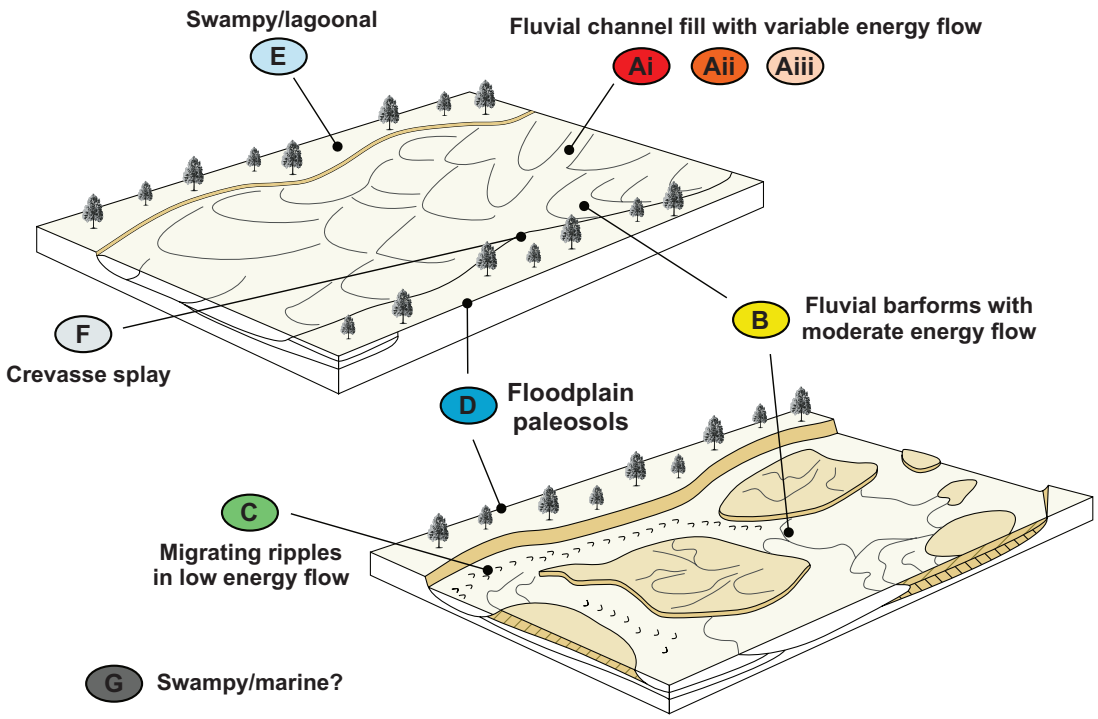

Figure 2.1: Fluvial lithofacies for the upper Perth Basin (Timms et al., 2012, Figure 3.03)

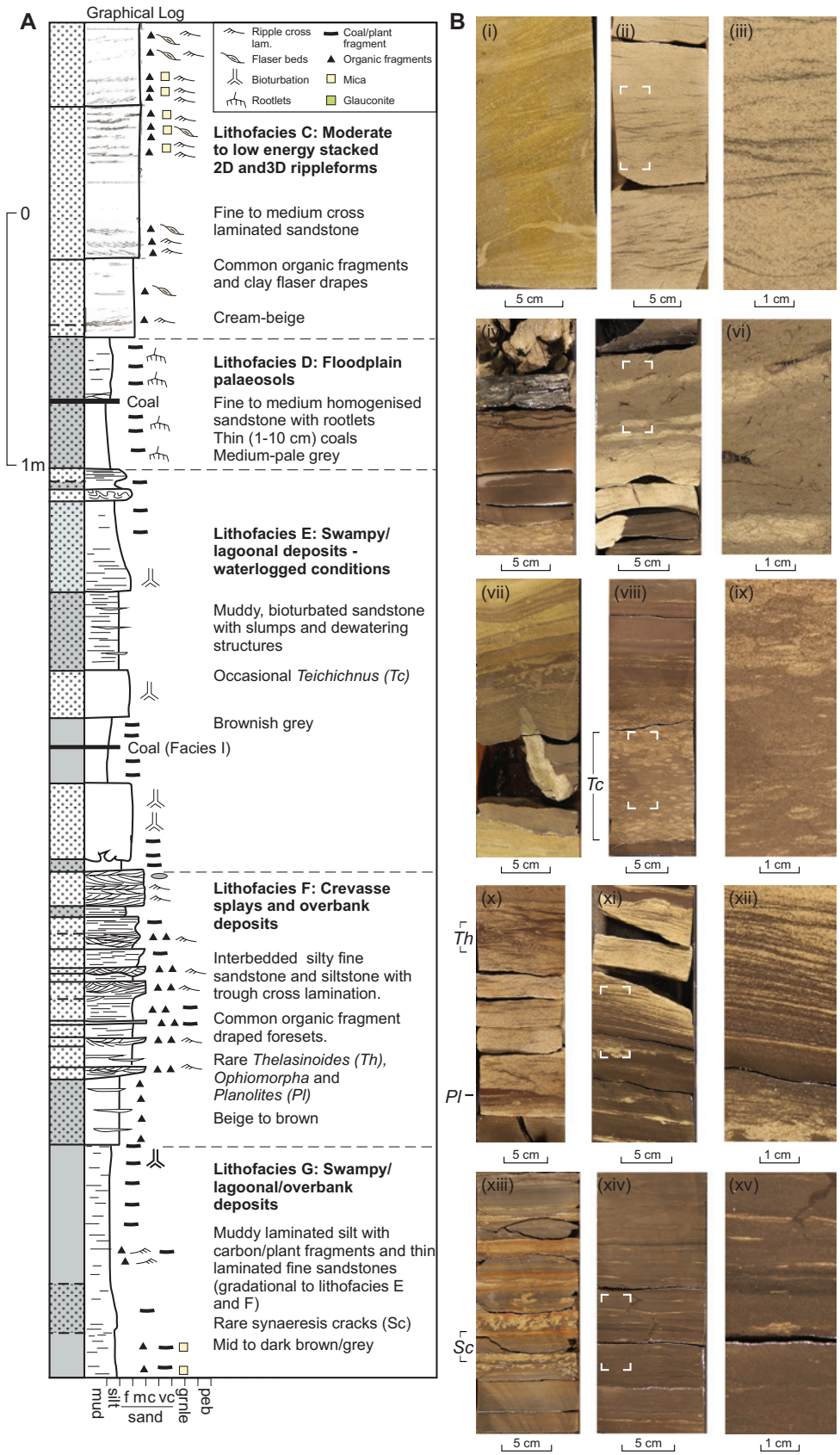

Figure 2.2: Detail of lithofacies identification from Cockburn-1 core (Timms et al., 2012, Figure 3.02b).

Formation and Lesueur Sandstone. The results show that the Yarragadee, Cadda and Cattamarra Coal Measures have a wide variety of lithofacies types in very similar proportions. The Lesueur Sandstone is dominated by coarse-grained high energy fluvial deposits. Complex switching of lithofacies on the order of 10 cm to approximately 2 m vertical scale is observed in all formations and wells, as shown in Figure 2.2. This finely structured vertical lithofacies sequence combined with the proposed fluvial depositional (interbedded) environment suggests an intricate three-dimensional sedimentary architecture characterised by length scales at the 10 cm scale and higher. This provides valuable information on the potential nature of deep reservoirs, and their permeability structures. When compared with the forward stratigraphic modelling predictions, showing formation of meanders and reaches in the water courses, a hierarchy of structural scales emerges.

2.1.2 Fault network interpretation

Knowledge of the structural architecture and stratigraphic geometry of the Perth Basin is a vital prerequisite for understanding subsurface fluid flow. By re-processing regional geophysical data a much higher density of faults was identified in the Perth Basin than previously mapped, particularly within the area from Bunbury to Lancelin. Analysis of the regional data shows that sets of NW-SE trending faults are much more prevalent across the whole Perth Basin than previously recognised, and that these faults significantly influence the structural architecture of the Perth Basin and the adjacent Yilgarn Craton. A completely new fault network has been identified in the Perth Metropolitan Area. Part of this network is presented in Figure 2.3, drawn with prior fault networks proposed by other authors. Depth penetration of the new fault network remains to be established by field observations (e.g. through drilling), however this fault analysis has raised the prospect of compartmentalization in the upper 3 km of sediments at least. In shallow formations where permeabilities are high and fault sealing seems uncommon, compartmentalization may not be problematic for water supply. However, in deeper formations that are likely to display lower permeabilities and greater potential for fault-fracture diagenesis, compartmentalization may potentially become important for geothermal heat extraction activities.

2.1.3 Entire Perth Basin three dimensional structural model

By integrating the lithofacies model with new and re-processed gravity and aeromagnetic data at basin scale, the WAGCoE team has constructed the first three-dimensional geological structural model of the entire Perth Basin, to a depth of 30 km below sea level. This model incorporates prior structural models of the northern Perth Basin and the Perth Metropolitan Area together with newly collected and interpreted structural and basement data. Figure 2.4 shows the workflows involved in constructing the three-dimensional structural models. Modelling of the new gravity data in the Perth area shows that bedrock is shallower near the coast than it is inland and this is consistent with previous offshore gravity studies.

A reduced portion of the basin geological model corresponding to the upper 3 km of the Perth Metropolitan Area was extracted and refined in detail using existing well logs from water and petroleum drilling investigations, together with new geophysical survey data. The Perth Regional

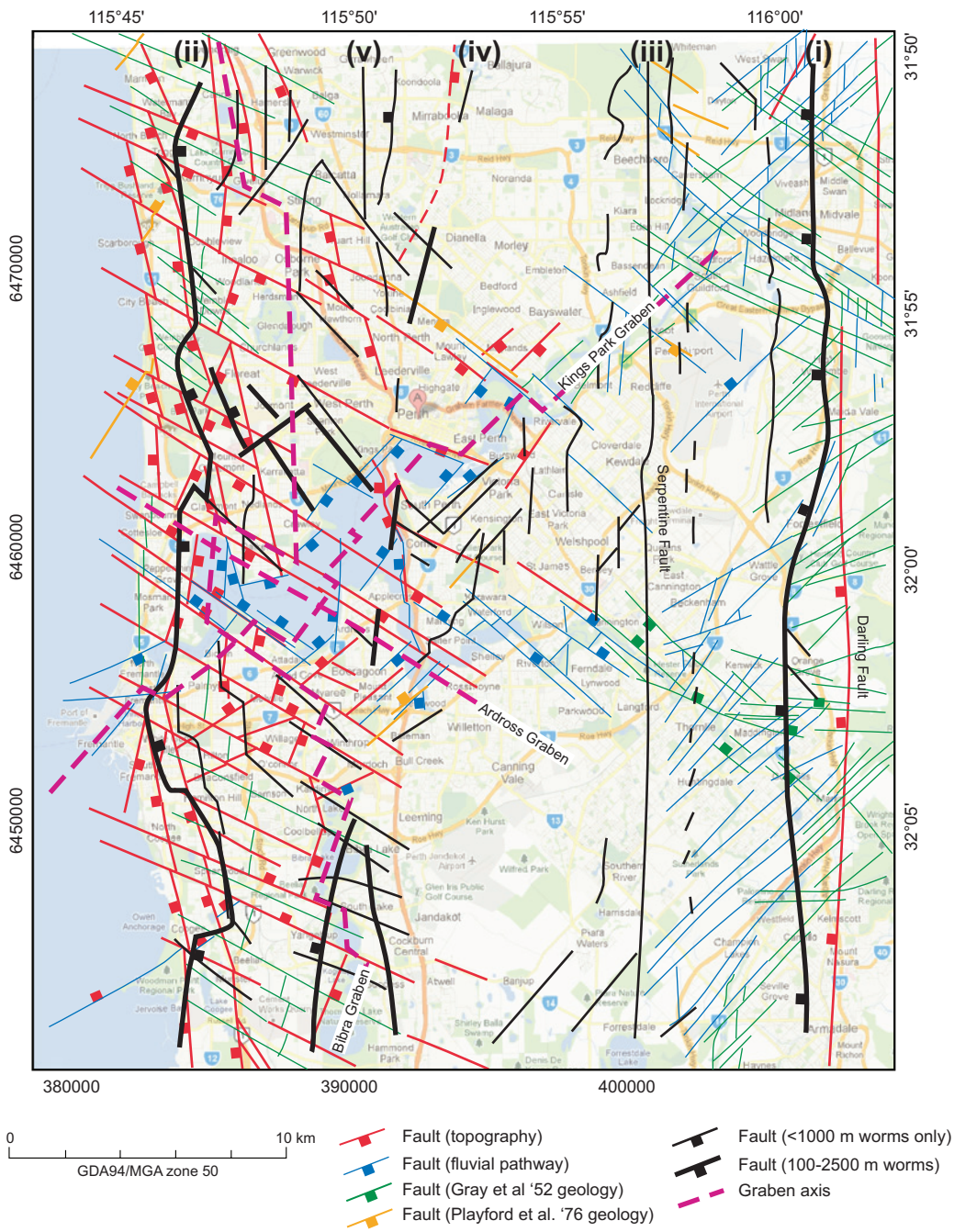

Figure 2.3: Fault network proposed for the Perth Metropolitan Area (Timms et al., 2012, Figure 2.18).

Aquifer Model (Davidson and Yu, 2006) was used as a geometric basis for the formations above the Yarragadee Formation. The detailed stratigraphic information was cross-correlated with fault interpretations and geophysical data to produce a high-resolution geological model of the Perth Metropolitan Area down to the base of the Yarragadee Formation, with depositional processes studied via stratigraphic forward modelling (Figure 2.5). Although data for the deeper formations is scarce, some of the newly identified faults strongly influence the geometry of confined aquifers in the

Perth Basin, and specifically the Perth metropolitan area and, therefore, could be highly significant in controlling the palaeo- and modern day fluid flow in areas relevant to geothermal exploration. The new 3D model provides an entirely new insight into the tectonics and stratigraphic architecture of the subsurface geology in the Perth Metropolitan Area.

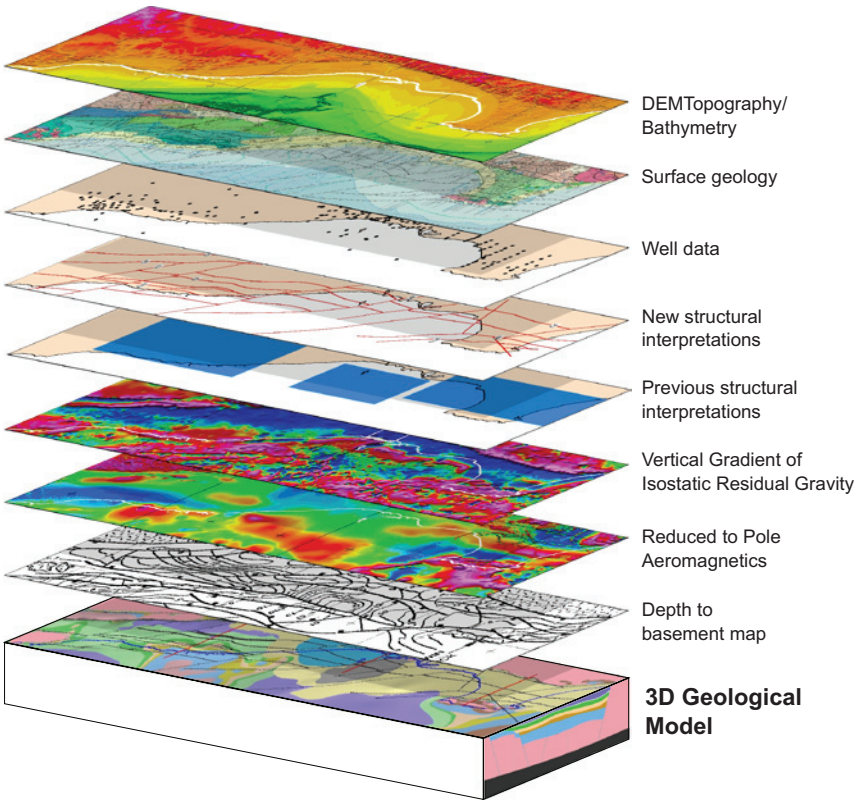

Figure 2.4: Entire Perth Basin geomodel (Timms et al., 2012, Figure 1.09)

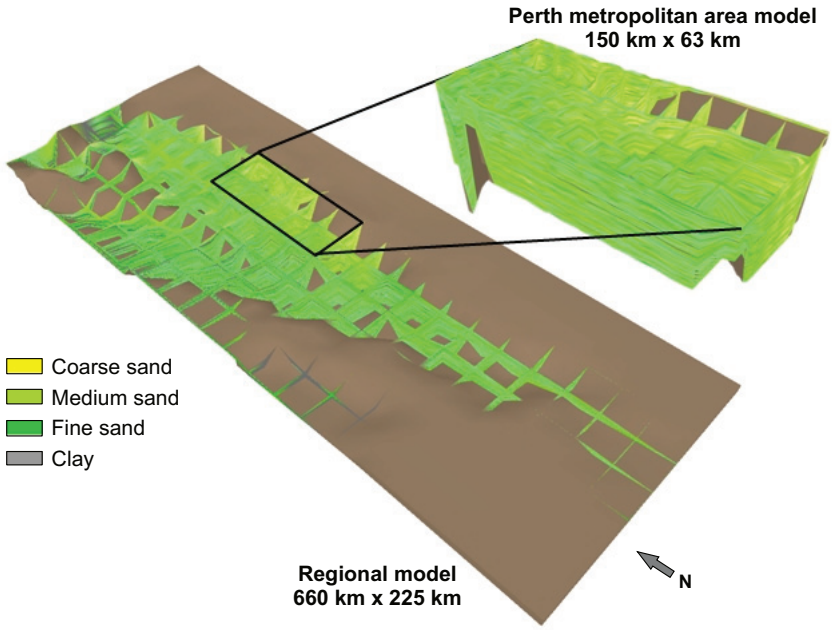

Figure 2.5: Stratigraphic forward modelling of the Yarragadee Formation (Timms et al, 2012, Figure 6.05).

2.2 New Hydrothermal Understandings

Based on the new data and new geological interpretations developed above, WAGCoE researchers were able to produce new theoretical and calibrated computational models of heat flow and fluid migration within the Perth Basin. These three-dimensional hydrothermal models provide information that establishes dominant heat flow regimes in the Basin, and define the inter-relationship of groundwater flow and temperature distributions. This inter-relationship is fundamental to all geothermal prospecting in the Perth Basin. The following subsections list three significant hydrothermal innovations arising from this research effort, reported in Reid et al. (2012).

2.2.1 Temperature profile data set

A comprehensive shallow temperature profile data set was assembled by WAGCoE researchers, by compiling results from existing logs and supplementing these results with two separate field logging programs utilising Department of Water artesian monitoring (AM) bores throughout the Perth Metropolitan Area. The resulting combined data set provided two key outcomes. The first outcome was a robust estimate of the variation of the shallow temperature gradient across metropolitan Perth which showed significant horizontal anomalies which are thought to reflect structural heterogeneity in the underlying sedimentary sequences. The second outcome was the identification of strongly non-conductive signatures in the vertical temperature profiles at a number of locations. Figure 2.6 shows measured (red) and modelled conductive (blue) profiles for location AM33A, exhibiting a non-conductive anomaly in the Wanneroo Member. Non-conductive signatures were found to be depth-correlated with major Perth aquifers, leading to the interpretation that advective groundwater flows

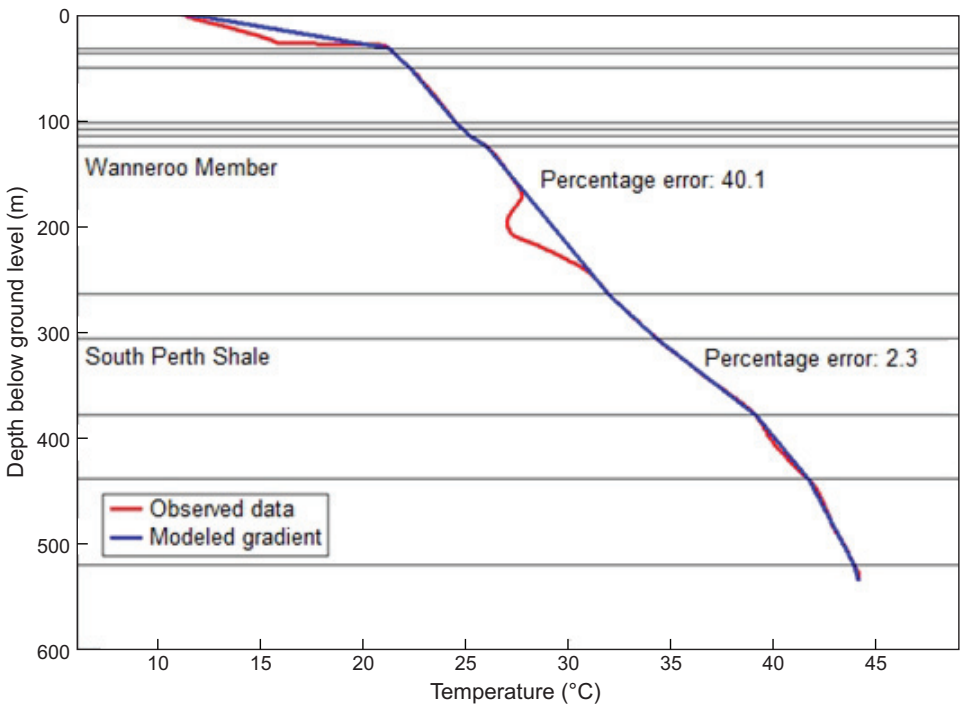

Figure 2.6: A thermal profile in the Perth Metropolitan Area showing a non-conductive signature within the Wanneroo Member (Reid et al., 2012, Figure 3.17).

were responsible for the non-conductive phenomena. Taken together, these outcomes demonstrate the potential for structural heterogeneity and advective groundwater flows to influence or control three-dimensional temperature distributions in sedimentary geothermal formations. This profound finding is based on detailed field observations, and indicates the need for new industry approaches in assessing geothermal resources in sedimentary systems.

2.2.2 Conductive heat flow model for the entire Perth Basin

Notwithstanding the results discussed in the previous subsection, geothermal resource assessment at basin scale still represents a significant technical and computational challenge. WAGCoE researchers have taken the first step towards the goal of a basin scale geothermal resource model by constructing a three-dimensional geological model for the entire Perth Basin, and calibrating a thermal conduction model against all available temperature profile data in the Perth Basin. The calibration process identified the primary parameters controlling the temperature distribution in the Basin sediments. These primary parameters are the basal heat flow, which supplies heat to the sediments from the granitic rocks below the Basin and bounding the Basin to the east, and the radiogenic heat production rate in the upper crust. The results of the calibration process emphasized the prospectivity of the northern Perth Basin for high-temperature geothermal applications. The computational challenge involved in generating this basin-scale thermal conduction model was large, but the task would be considerably larger still to incorporate hydrothermal flow processes that are so critical in sedimentary systems. Nevertheless, a basin-scale hydrothermal model is an achievable goal for Western Australia and would provide geothermal resource managers and explorers with a significant quantitative asset.

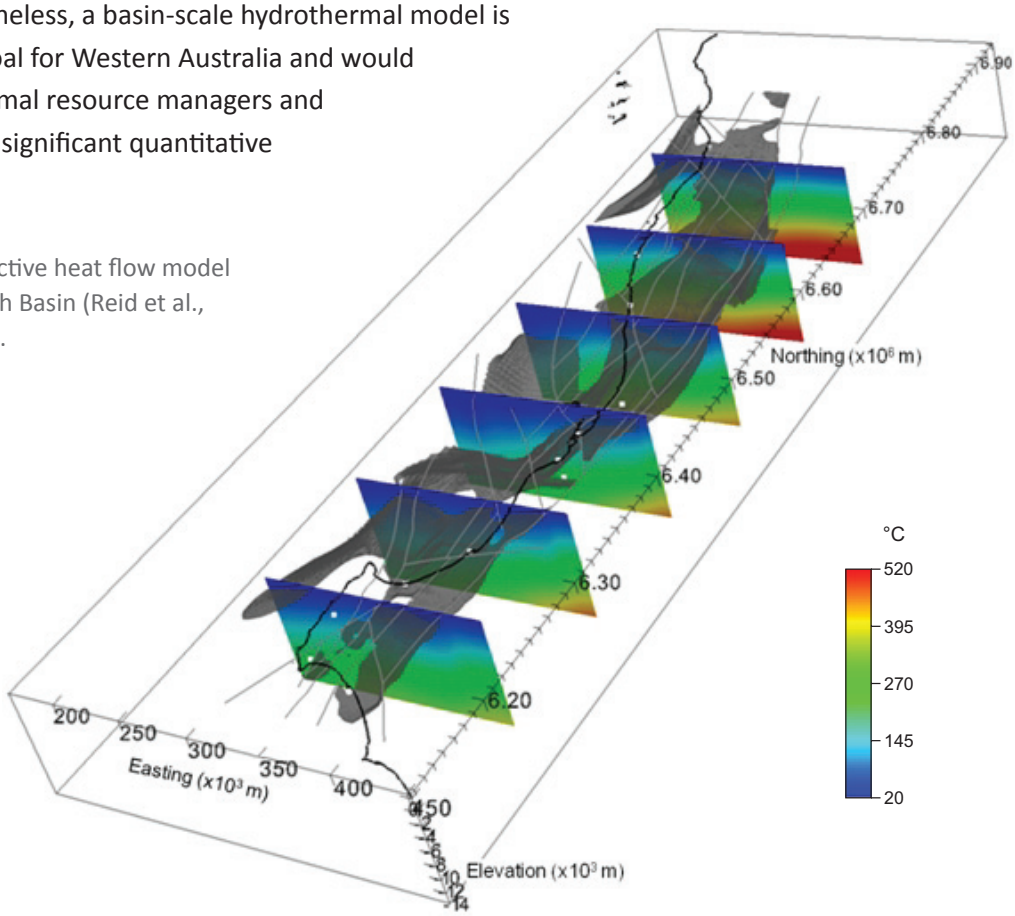

Figure 2.7: Conductive heat flow model for the entire Perth Basin (Reid et al., 2012, Figure 4.12).

2.2.3 High-resolution convective simulations

In order to explore the effects of hydrothermal processes, WAGCoE researchers constructed and refined a detailed three-dimensional hydrothermal model of the Perth Metropolitan Area, to a depth of 3 km below ground surface. High resolution hydrothermal simulations were then computed to predict temperature distributions under Perth within a range of scenarios for fault behaviour (Schilling et al., 2012). Whilst the hydrogeological data sets are still too scarce to expect that these simulations will reflect the actual thermal distributions in detail, the scenario results indicate potential for convective processes to be established by the thermal gradients, even in the presence of known saline fluids. The Yarragadee formation in particular is likely to support convective cells, with horizontal dimensions of the order of 1-5 km and circulation timescales of the order of approximately 300,000 years or less (Sheldon et al., 2012). The location and transmissivity of faults in the subsurface controls the topology of the convective cells, as is depicted in Figure 2.9, and the effective permeability of the key aquifers controls the onset of convection. Through this work, and for the first time, the geothermal industry can see the potential complexity of the geothermal resource beneath the Perth Metropolitan Area and, by extension, elsewhere within the Perth Basin. This represents a significant conceptual advance for the direct-use geothermal industry, in Western Australia, and elsewhere in Australia and overseas.

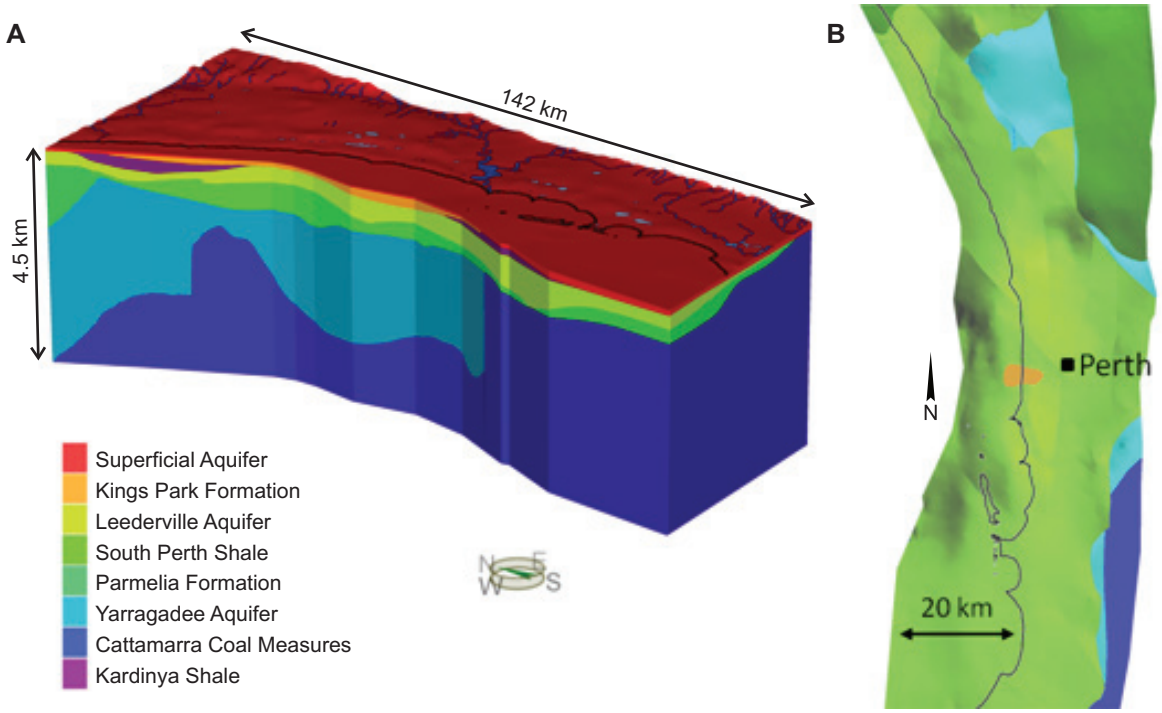

Figure 2.8: Three-dimensional model of the Perth Metropolitan Area (Reid et al., 2012, Figure 4.21).

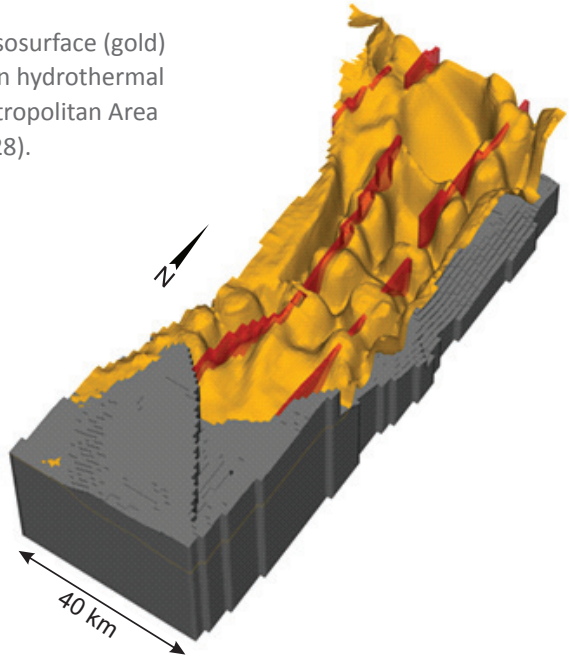

Figure 2.9: A temperature isosurface (gold) shows fault (red) controls on hydrothermal convection in the Perth Metropolitan Area (Reid et al., 2012, Figure 4.28).

2.3 New Reservoirs and New Management Approaches

With the conceptual advances outlined in the previous subsections, based on field data and advanced computational simulation, the nature of geothermal resources in the Perth Basin has become more apparent. The proposed fault network has defined a spatial scale for reservoir compartmentalization, and the analysis of impacts of advection and convection on thermal profiles has indicated the key hydrothermal processes influencing reservoir temperature. In this context, new approaches to resource assessment and management are required. The following subsections list three significant resource management innovations arising from this research effort, reported in Reid et al. (2012) and in Ricard et al. (2012).

2.3.1 State-wide geothermal resource assessment

The Western Australian government is responsible for overseeing the development of a viable geothermal industry. Apart from regulatory reforms required to establish the operational basis for this industry, government planning for future geothermal activities requires summary overviews of the resource potential. WAGCoE researchers developed a simple approach for calculating and summarising geothermal resource potential across Western Australia. This approach combines aquifer productivity with temperature, producing a surrogate estimate for extractive heat production. Using reservoir data (to determine aquifer productivity) and thermal measurements (to estimate aquifer temperatures) together, a map of geothermal resource potential was constructed for Western Australia, including the Canning, Carnarvon, Officer and Perth Basins. Significant high-temperature potential is seen in the Canning and Carnarvon Basins, whilst the large urban population of the Perth Basin ensures that ready markets are available for local direct-use applications, as shown in Figure 2.10. The northern Perth Basin also has potential for electricity generation.

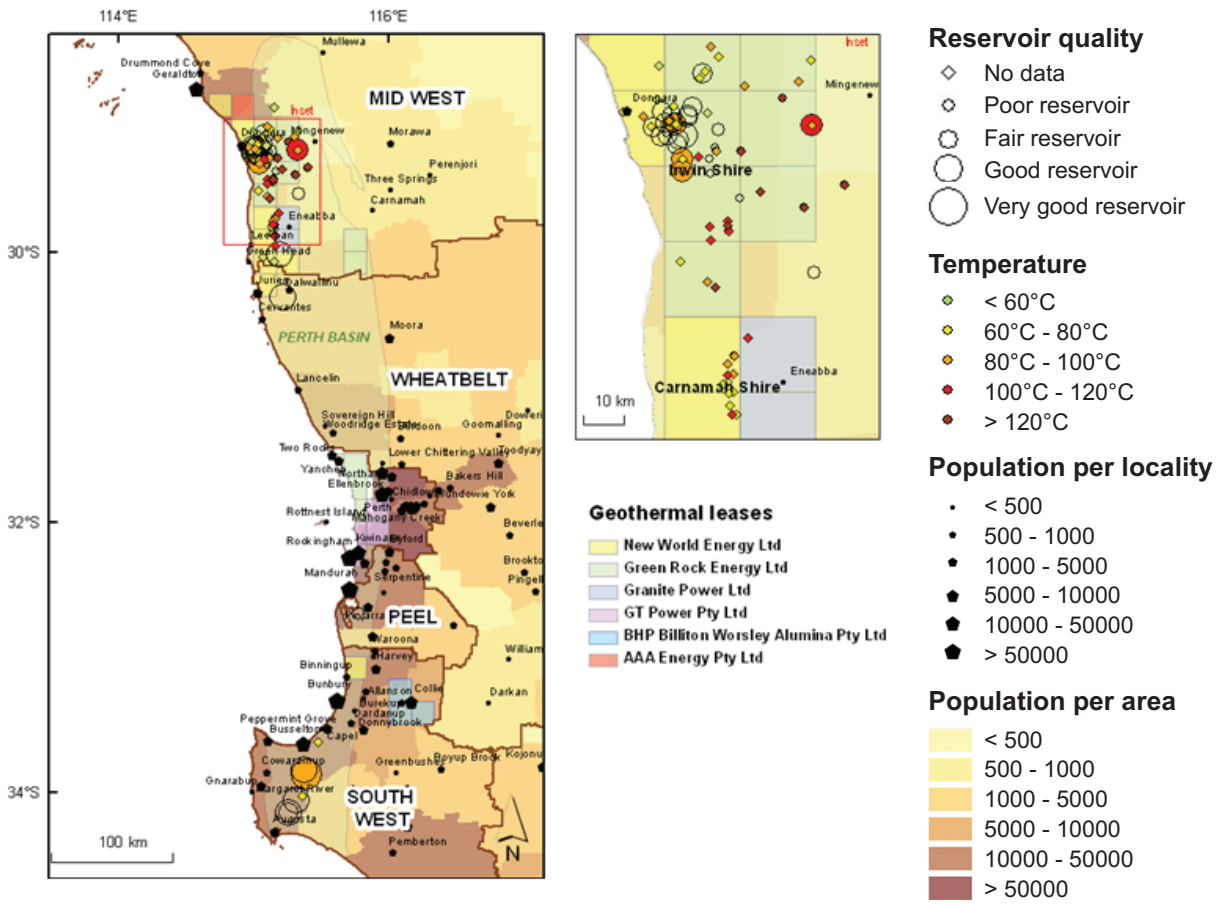

Figure 2.10: Geothermal resource potential in the Perth Basin (Reid et al., 2012, Figure 3.04).

2.3.2 Mullaloo Aquifer: a new resource for heat rejection in metropolitan Perth

Geothermal resources need not have high temperatures in order to present economically feasible energy management options. Urban centres produce large waste heat fluxes which can be viewed as energy resources themselves. By rejecting waste heat to the subsurface, it is possible to avoid above ground cooling solutions which can often consume valuable commodities, e.g. water and power. Through investigating geothermal technologies for the Pawsey Supercomputer Centre, WAGCoE researchers have identified a shallow, highly transmissive formation which has properties conducive for rejecting or storing heat. This formation is the Mullaloo Aquifer, a little-studied and under-utilised high-quality freshwater resource 50-150 m below the ground surface. Biogeochemical analysis performed by WAGCoE has indicated that the aquifer is likely to be geochemically stable to thermal perturbations associated with heat rejection/storage operations (Douglas et al., 2012; see Figure 2.11). The Mullaloo aquifer is not widely exploited for water supply and is not extensive beneath Perth, but where it is present it is likely to afford a valuable resource for a range of low-temperature geothermal applications.

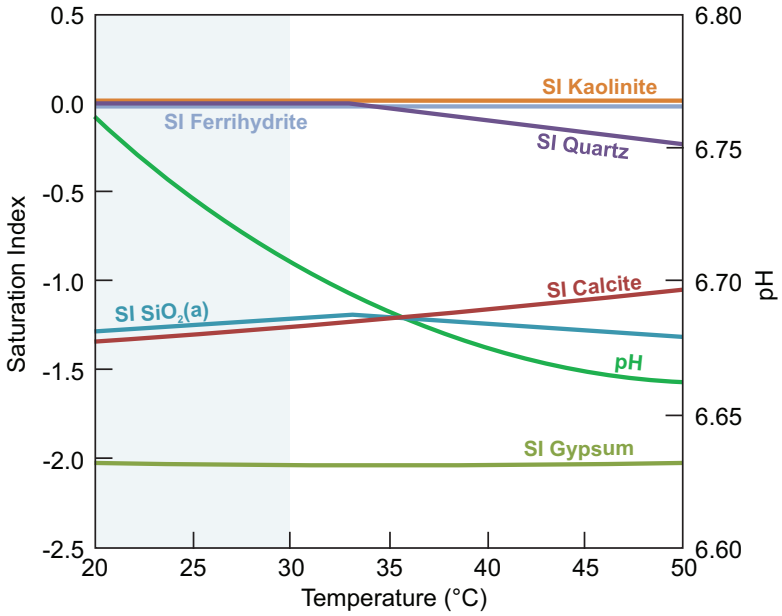

Figure 2.11: Predictions of thermally induced geochemical alterations (variations of pH and mineral saturation index) in the Mullaloo aquifer (Douglas et al., 2012; Ricard et al., 2012, Figure 6.20).

2.3.3 Subsurface Stirring: innovation in reservoir sustainability

Both heat rejection and heat harvesting require the use of fluid pumping techniques in the subsurface. Conventional techniques of subsurface heat exchange relay on dipole arrangements of injection and extraction wells, which have modest heat exchange efficiencies. WAGCoE researchers have adapted to the geothermal context a new CSIRO technology, Subsurface Stirring, which was designed for boosting heat and chemical exchange efficiencies in subsurface systems and has been shown to be robust in the presence of moderate permeability heterogeneity (Figure 2.12). The WAGCoE concept is to apply the chaotic dynamical model inherent in Subsurface Stirring to provide large efficiency gains in the exchange of heat in the subsurface, e.g. for facilities management applications where waste heat from air conditioning etc must be managed. Efficiency gains can be realized in terms of increased operational lifetime for heat exchange infrastructure, or in terms of reduced pumping costs, or combinations of both.

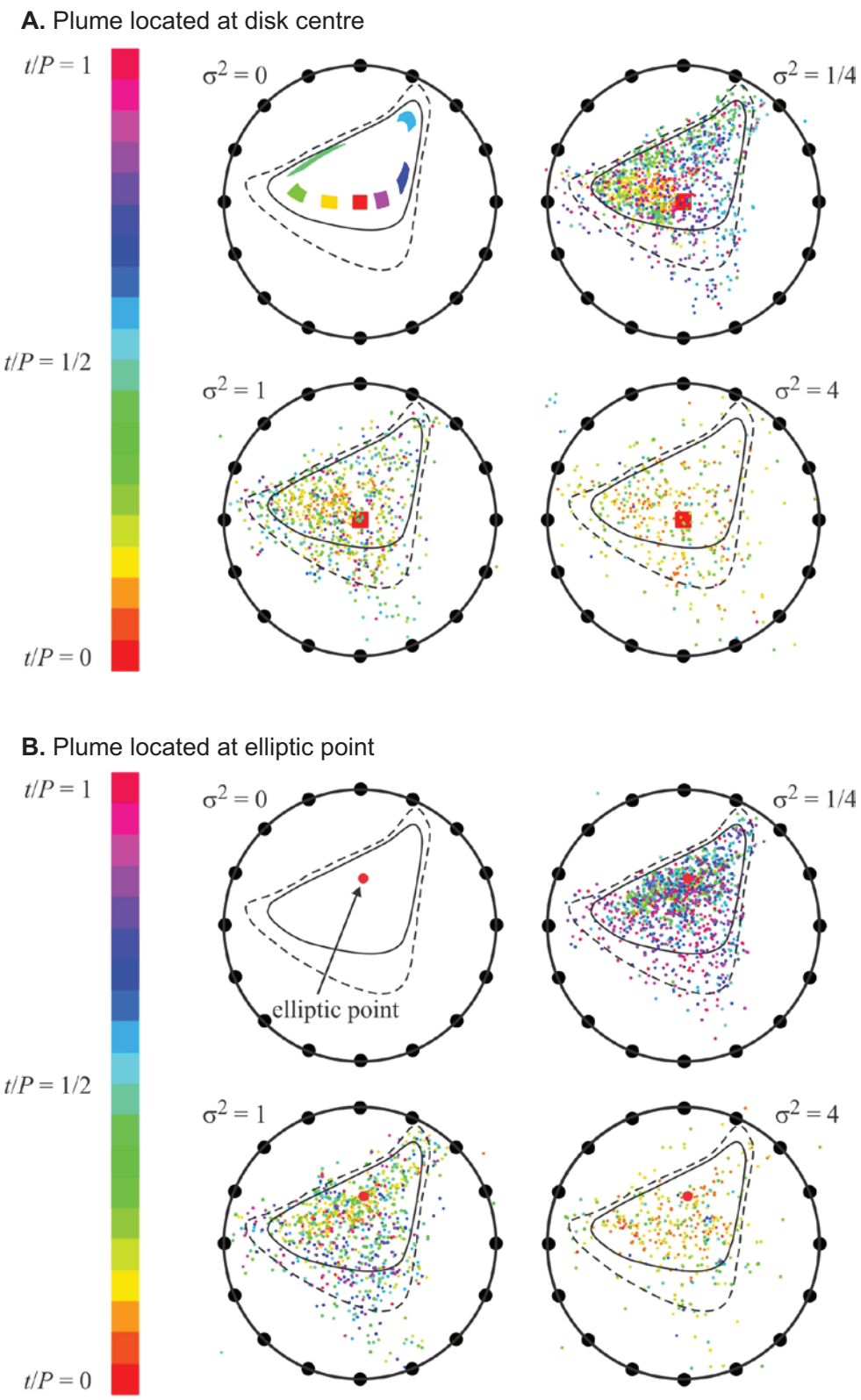

Figure 2.12: Robustness of Subsurface Stirring to aquifer heterogeneity (Trefry et al., 2012; Ricard et al., 2012, Figure 6.09)

2.4 New Tools for Geothermics

Much of the research activity involved in subsurface geothermics pertains to analysing data and generating sophisticated computational models of geological structures and fluid physics. During the research of WAGCoE, several key platforms and tools were developed to assist in the above activities, and to place them on a firmer conceptual basis. Three of these tools are discussed below; these are reported in Ricard et al. (2012), Reid et al. (2012) and Poulet and Corbel (2012), respectively.

2.4.1 GeoTemp™ for analysing temperature data

GeoTemp™ is a software tool that is freely available under license from CSIRO. The purpose of the tool is to assist geothermal engineers to assess and interpret down-hole temperature profile data with a consistent processing and interpretation workflow. The GeoTemp™ workflow includes identification of conductive and non-conductive regimes, inversion of thermal conductivities (by formation), and profile extrapolation with uncertainty. GeoTemp™ is built on a Matlab processing core and is deployable as a stand-alone menu-driven application on desktop computers (see Figure 2.13).

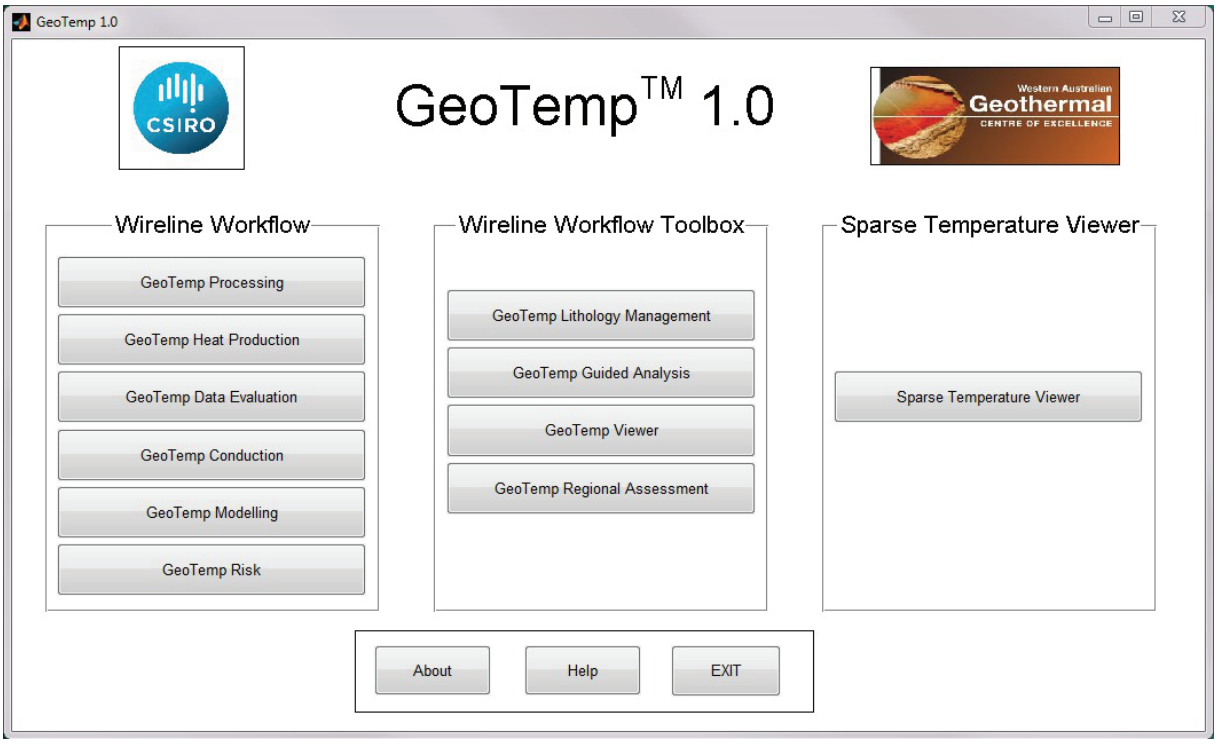

Figure 2.13: GeoTemp™ user interface (Ricard and Chanu, 2012; Ricard et al., 2012, Figure 4.01).

2.4.2 Automated workflow for geothermal modelling with uncertainty

Geothermal modelling requires the integration of diverse data sets, e.g. geophysical, geological, chemical and fluid, measured at different scales. The integration function represents a significant task that requires input from several different disciplines. Furthermore, the goal of such integration is to reduce uncertainty in geothermal resource predictions. Therefore, the concept of uncertainty needs to be considered as a fundamental driver in the integration process. WAGCoE researchers have developed an automated modelling workflow that incorporates quantitative descriptions of uncertainty right from the basic structural geology level.

The uncertainty is defined in terms of an entropic measure, which essentially summarises information content. By applying this measure to geological structural modes, it is possible to rate different structural models according to information content and then to assess quantitatively the degree to which a given structural model conforms to known and inferred structural data. This assessment then flows through to the subsequent property distributions (permeability, thermal conductivity, heat capacity etc) and hydrothermal flow simulations, yielding resource estimates that can be expressed in terms of uncertainties that are related to the choices made in the underlying structural models. Uncertainties in the overlying property distributions (from imprecise measurements and assumptions of formation heterogeneity) and in the hydrothermal flow systems (from boundary condition estimates and from fluid constitutive relations, choice of fluid processes etc) can also be introduced into the entropic uncertainty framework. This entropic assessment process is depicted in Figure 2.14.

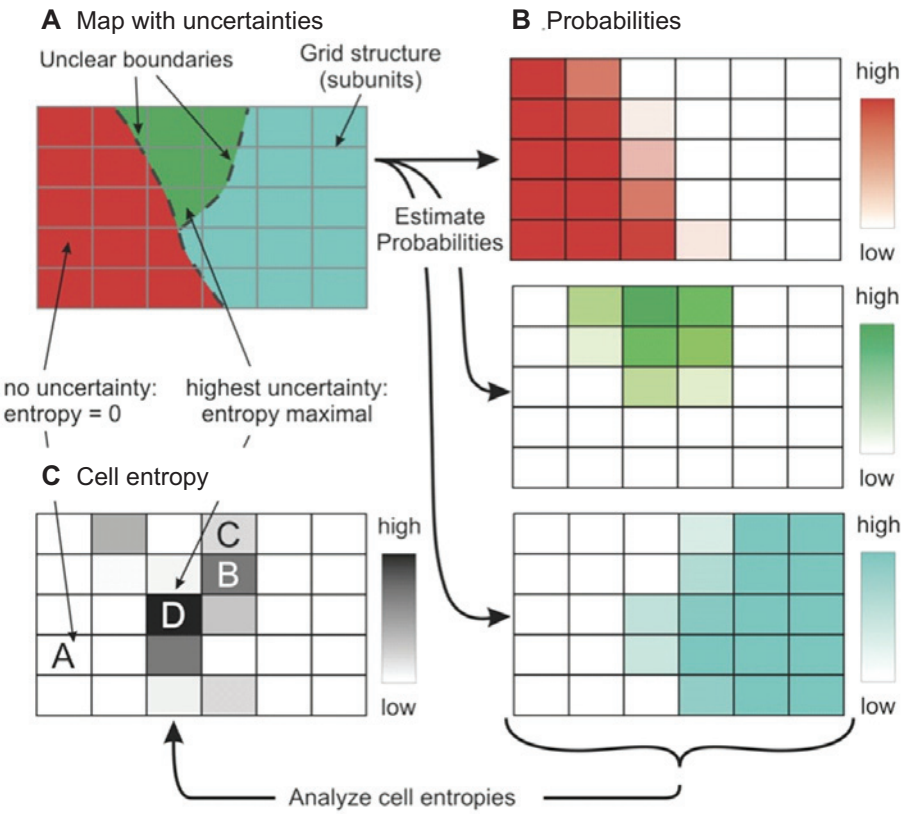

Figure 2.14: Entropic analysis of structural uncertainty (Wellmann et al. 2012; Reid et al., 2012, Figure 5.22).

This research development has the potential to change the way in which the geothermal industry (and other geological resource industries) conceptualises and model its subsurface resources. Further research is continuing on developing rigorous approaches to building complex structural and hydrothermal models with uncertainty quantification.

2.4.3 WAGCoE Data Catalogue

In all the research of WAGCoE, large amounts of data were compiled, curated and reviewed from a range of sources, including government, research providers and private industry. WAGCoE itself measured and collected large amounts of data as well. In order to make the best use of this data, and to preserve it in a useful form, WAGCoE established a web-based data catalogue where the data could be made available to researchers and industry.

The basis of the WAGCoE Data Catalogue is a metadata-driven approach which facilitates keyword searches (see Figure 2.15), together with a programmatic management toolbox which assists Catalogue managers to regenerate catalogue entries automatically to comply with external technology changes. This flexible data searching and formatting technology makes it easy for users to discover, search and access the data. The WAGCoE Data Catalogue is a valuable tool and resource for Western Australia as it works towards establishing its own geothermal data system.

Figure 2.15: WAGCoE Data Catalogue (Poulet and Corbel, 2012, Figure 2). The Catalogue is available at https://WAGCoE.ivec.org/geonetwork/srv/en/main.home

3. OPTIONS FOR FUTURE GEOTHERMAL RESEARCH IN WESTERN AUSTRALIA

From the preceding discussion it is clear that WAGCoE has succeeded in its aim of providing research advances and new knowledge of the hot sedimentary aquifer resources of Western Australia, and particularly in the Perth Basin. Much is now known about the sedimentology and petrophysics of the Basin that was not known before. New findings about the temperature distributions and geophysical responses below Perth and the following hydrothermal scenario analyses have assisted government and industry with improved resource assessment and prospectivity predictions. Nevertheless more research still needs to be done to move the direct-use geothermal industry further forward towards commercially-viable applications in Western Australia and elsewhere. In this section several priority areas of new research pertaining to below-ground assessments and engineering are discussed. Commentary on above-ground engineering or economic and regulatory development of geothermal applications is beyond the scope of this report.

3.1 Basin Structural Research

While much is known about the geology of the shallower formations in the Perth Basin, i.e. the upper 1-2 km of sediments, the data coverage is patchy and much still remains to be measured and interpreted, e.g. structural relationships, permeability variations, aquifer leakage and connectivity, geochemistry etc. For the deeper formations, the available information is even scarcer. This means that vast volumes of the Perth Basin are only poorly characterized, if characterized at all. This situation applies for the other sedimentary basins in Western Australia as well, yet it is in these basins that the most accessible forms of geothermal energy are located.

There is a need to pursue research into these sedimentary systems in order to define the resources (water, mineral, oil/gas and geothermal) and to identify potential uses and applications. Geophysical techniques can provide information on basin dimensions and on contrasting features, e.g. faults, formation tops, saline zones etc, which can be used to constrain structural models and can be used in concert with stratigraphic forward modelling to develop basin formation models. Fault/fracture analysis combined with hydrogeological studies is important in understanding sealing processes and fluid communication pathways within and between sub-basins. Geochemical and mineralogical studies can inform models of diagenesis that are important for assessing productivity in deeper formations subject to higher temperatures and pressures.

There is much basic geology to be done in understanding the State's sedimentary geothermal resources. As engineering technology evolves subsurface characterization will become more feasible, and it is important that Western Australia develops its capability in geological research and engineering in order to maximize and sustain the benefits drawn from its sedimentary basins.

3.2 Basin Resource Demonstration

Much of the WAGCoE research involved collection of data from existing below-ground infrastructure or interpretation of third-party data, records and materials (cores, sediments etc). This mode of

research was driven by a lack of active drilling projects into the deeper hot sedimentary aquifers of the Perth Basin. Thus data collection was only possible for existing or new wells penetrating approximately to 1 km depth, associated with the drilling industry for geothermal heating of swimming pools etc using water extracted at approximately 45 °C. The lack of deeper wells under Perth that can access higher temperature water means that there is insufficient data to inform industry and government about the nature of the geothermal resources at depths greater than 1 km and to estimate the potential costs and benefits involved in accessing these resources. This is a critical hurdle for the direct-use geothermal industry in Australia; there is a range of above-ground technologies suitable for efficient direct-use applications (e.g. carbon-efficient chilling and heating) but the knowledge of the potential temperatures and flow rates achievable from the lower Yarragadee and underlying formations is simply absent. This knowledge scarcity extends to all major sedimentary basins in Western Australia, and is hampering the development of viable geothermal applications for population centres and industrial projects around the State.

CSIRO, in collaboration with WAGCoE, recognized the need for resource demonstration and was successful in obtaining a $19.8M grant from the Federal Government in 2010 to investigate the deep geothermal resources of the Perth Metropolitan Area through a drilling program at the Australian Resources Research Centre in suburban Kensington, to be conducted in 2013. This project provides the opportunity to sample and test hot sedimentary aquifer resources down to 3 km below ground surface in an urban setting, and to demonstrate direct-use geothermal technologies. The best temperature extrapolations to this depth indicate temperatures of approximately 95 °C at 3 km below Perth. If flowing geothermal resources are found at depth, this CSIRO Geothermal Project will demonstrate to the Australian community that direct-use geothermal systems are viable options for carbon-efficient energy strategies, especially in major urban centres where the market is close to the resource. Furthermore, whether the located geothermal resources are sizeable or not, the project will produce a clear assessment of the technology, regulatory and financial options for subsequent drilling and exploration activities in Australia.

The CSIRO Geothermal Project will reduce uncertainty associated with direct-use industry in Western Australia. However, as the WAGCoE research has already shown, there is significant heterogeneity in the sedimentary formations beneath Perth and elsewhere, and thus the potential demand for direct-use energy solutions within the major population and industrial centres of Western Australia is moderated by the uncertainties associated with defining appropriate geothermal resources in the subsurface. Therefore it is hoped and recommended that the CSIRO Geothermal Project be simply the forerunner of many more future resource demonstration activities in basins around Western Australia and nationally as the geothermal industry expands.

3.3 Fault-Controlled and Hard Rock Systems

The primary research focus of WAGCoE was in the area of sedimentary geothermal resources which are abundant in Western Australia. However, the State also has huge areas of cratonic shield, i.e. hard rock areas with low primary porosity and substantial fracturing and faulting. Western Australia is not highly seismically active, but there is a history of significant seismic events within the Yilgarn

Craton over the last century which indicates some continuing activity. It is not known whether these events and the associated faulting structures are associated with hydrothermal systems, e.g. fluids circulating in faults, and this deserves some further investigation. International experience has shown that fault-controlled hydrothermal systems can embody useful geothermal resources with elevated temperatures. In general the granitic rocks of the Yilgarn Craton are likely to exhibit radiogenic heat production rates significantly higher than those for the Western Australian basin sediments, therefore any deeply penetrating hydrothermal systems are likely to encounter high temperatures, potentially suitable for power generation applications. Again, as for the sedimentary basins, there is a lack of information on fault-controlled and hard rock geothermal systems in Western Australia, which limits their exploitation by the geothermal industry.

3.4 Predictive Analysis

In order to support the development of the geothermal industry, the State government charged WAGCoE with the task of bringing water and energy together, i.e. developing a hot sedimentary aquifer engineering paradigm that included the relevant aspects of hydrogeology (typically concerned with groundwater resources, supply and water quality) with deep hard-rock geothermal engineering (typically concerned with advanced drilling, geomechanics and very high temperatures). The two engineering communities focus on very different technical challenges, however for the WAGCoE context of promoting the use of medium temperature resources in flowing aquifer systems, the two communities' interests overlap. Nevertheless, there is still considerable room for tighter integration of the respective workflows and approaches to facilitate a modern direct-use industry sector.

At a fundamental level, the tools available for modelling the geothermal systems are still quite poor. The typical software packages that are used with success in the hydrogeological industry to predict flows, pressures and productivity do not incorporate the meshing and geomechanical functionality required for higher-temperature reservoirs in complex structural settings. Equally, the geomechanical and geochemical codes that can predict formation of complex structures and lithologies at elevated temperatures and stresses are not suitable for calculating reservoir properties and environmental impacts of production at short time scales and at precise shallow locations. To make matters worse, much fundamental information is lacking on how fluid, mineral and rock phases interact in these hydrothermal systems, especially in the presence of faults and compartments. With this scientific shortfall and software mismatch, geothermal companies are faced with making difficult choices about how to conceptualise and model their prospective resources.

WAGCoE and collaborators have developed a new, thermodynamically based approach for bringing fluid, geomechanical and chemical processes together into a single, rigorous and tightly coupled simulation package for the geothermal industry. This work is still at its very early stages, and the necessary research is being actively pursued. However for the geothermal industry to advance, the tools for predictive, physics-based geothermal analysis will need to take great steps forward in the coming years. In order for Western Australia to capitalize on its geothermal resources, it will need to be at the forefront in advanced geological research, including the predictive geosciences. Attracting and retaining productive researchers in these areas will require long-term investment.

4. CONCLUDING REMARKS

The research conducted by Program 1 during the three-year term of WAGCoE has resulted in a new understanding of the sedimentary geothermal resources of Western Australia, and of the Perth Basin in particular. Through the work of Program 1 researchers in CSIRO, University of Western Australia and in Curtin University, new scientific and engineering advances have accrued in topics including:

- basin evolution and depositional processes
- structural and stratigraphic parameters
- formation and aquifer characteristics
- biogeochemistry and hydrogeology
- thermal regimes and hydrothermal processes
- geothermal data analysis, curation and organization
- resource estimation with uncertainty
- geothermal energy extraction and waste heat rejection

This body of geothermal work is now being published in the international scientific literature. Simultaneous with the research effort, an active student and intern training program was run, producing many young geothermal professionals who are already working for industry and research providers.

Much research into geothermal resources and production technologies still needs to be done to assure the future of the geothermal industry in Western Australia. Some options for future research directions have been discussed in Section 3 of this report, but the key issue facing Western Australia now is how to foster and maintain a dynamic geothermal research capability in the State.

There is no doubt that geothermal energy can play an exciting and significant role in the future energy strategy for the State, and nationally as well. However, the recent scarcity of capital funds for commercial geothermal initiatives indicates that the current geothermal risk profile makes some such investments less appealing to potential investors than other investment options. It is our contention that the purpose of geothermal research is to mitigate the investment risk by

1. increasing the understanding of geothermal systems
2. identifying the most attractive geothermal resources
3. developing new engineering techniques to harness those resources efficiently and sustainably

The challenge facing geothermal stakeholders in Western Australia now is how to build on the innovations produced by WAGCoE, and how to ensure that the research capability is maintained and grown into the future for the benefit of the geothermal industry and for the wider community.

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