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Exploration and Evaluation of the Australian Geothermal Resource

by

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A thesis submitted for the degree of
Doctor of Philosophy of
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STATEMENT

This thesis is a description of research conducted during the period February 2001 to February, 2005 while I was a full time student in the Department of Earth and Marine Sciences at the Australian National University.

The mapping work described in Chapter 2 of this thesis was conducted in collaboration with Dr Prame Chopra. Otherwise, all work described in this thesis is entirely my own unless stated otherwise in the text or the acknowledgements. No part of this thesis has been submitted to any other University or similar institution.

F. L. Holgate
February, 2005
This work is for Minnie Holgate

1922 – 2004

wish you could have seen it done, Grandma
ACKNOWLEDGEMENTS

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ABSTRACT

A database of 5722 borehole temperatures, AUSTHERM03, has been assembled building upon the existing work of Somerville et al. (1994) through addition of newly available commercial open-file data. The application of more rigorous GIS techniques, including the use of new depth-to-basement and mean annual surface temperature coverages, has resulted in a more reliable extrapolation of this data to 5km depth. A new Australia-wide map of estimated temperature at 5km was created from the extrapolated data by interpolation using geostatistical kriging. The combination of new data and more sophisticated GIS processing has produced a more realistic map image that is characterised in areas of good data density by rounded, well constrained temperature anomalies. In most cases, thermal highs were found to be associated with areas of sedimentary basin cover. Geothermal resource analysis of this image indicates three major regions of prospectivity beneath the Cooper, McArthur and Carnarvon Basins.

The use of commercial borehole temperature data in the current AUSTHERM03 temperature map image means that it is affected by temperature suppression caused by the drilling thermal anomaly. Data available in AUSTHERM03 from 330 wells in the Cooper Basin of South Australia provided a unique opportunity to test the reliability of several published models for bottom of hole temperature (BHT) correction. Incorporated into a new database, the Cooper Basin Static Temperature or CBST, 61 of these wells proved suitable for use in thermal modelling. Included within these data were consecutive BHT measurements taken shortly after drilling was completed. Also available were BHT from cement bond logs (CBL) recorded a significant time after drilling which provided a good estimate of true formation temperature and a basis for comparison with model predictions. Four commonly used models of borehole thermal re-equilibration were tested: the Horner plot derived from Bullard (1947), the theoretical dual-media, zero-circulation cylindrical model of Cooper & Jones (1959), the empirical semi-log plot of Pitt (1986) and the exponential model of Nakaya (1953). On average, most models were found to under-estimate the true formation temperature. The magnitude of this bias was dependent upon assumptions implicit in each model. In most cases model prediction accuracy was improved to within around 5% of the CBL when at least one perturbed BHT was recorded >20 hours after the end of drilling. Of the models tested, the theoretical Horner plot was found to have the best combination of accuracy, utility and predictability. Applying this knowledge to perturbed BHT recorded in AUSTHERM03 enabled correction of a subset of 307 Cooper Basin wells using the Horner Plot. Two images of temperature distribution at 5km depth were constructed for these wells,
one using the perturbed AUSTHERM03 data, the other the corrected values. While the effects of the drilling temperature suppression were evident on the uncorrected image the overall anomaly structure was found to be largely undisturbed, confirming the utility of the AUSTHERM03 image for geothermal exploration.

Located within the Cooper Basin is a strong temperature anomaly that is currently the focus of Australia’s first geothermal resource development, Habanero. A geological and geochemical study of drill cuttings derived from Habanero 1, the first deep geothermal well drilled on this site, revealed the presence of a fractured, fractionated I-type granite body at depth. Similar in composition to many better known granite bodies around Australia, this data provides the basis for a geological model of an Australian-style geothermal resource that compliments the use of temperature mapping as a means of geothermal target generation. Prospective regions identified using this model include the Murray Basin area of NSW/Victoria.
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NOMENCLATURE

r  radial distance from the well axis
a  radius of the well
t  time
t_L  lag time, elapsed time since drilling ceased
t_C  total circulation time at depth z, t_C = t_D + t_{CO}
t_D  circulation time arising from drilling between depth z and EOH
t_{CO}  circulation time arising from post-drilling conditioning
T_{eq}  equilibrium temperature
T_0  initial mud temperature
ΔT(r, t)  change in temperature at time t, radius r
BHT(r, t)  bottom hole temperature at time t, radius r
T(r, t)_m  temperature at time t, radius r < a
T(r, t)_f  temperature at time t, radius r > a
k_f, k_m  thermal conductivity of the formation, well contents
c_f, c_m  heat capacity of the formation, well contents
κ_f, κ_m  thermal diffusivity of the formation, well contents
ρ_f, ρ_m  density of formation, well contents
Q  heat flow rate (constant)
σ_1  maximum principle stress
σ_2  intermediate principle stress
σ_3  minimum principle stress
σ_H  maximum horizontal stress
σ_n  minimum horizontal stress
σ_y  vertical stress
CHAPTER 1
INTRODUCTION AND BACKGROUND

1.1 Introduction
The continental crust of the Australian mainland is old and stable. Characterised by relatively low seismicity it hosts no active plate margins, no active volcanoes and no geyser fields. An absence of high-temperature conventional geothermal resources near surface has meant that the continent has been largely overlooked as a target for geothermal exploration and only limited work has been conducted to characterise the distribution of thermal energy in the crust. The recent shift in definition of an exploitable geothermal resource that has accompanied the rise of alternative technologies such as Hot Dry Rock (HDR) implies that many crustal areas previously considered barren may now contain potential for exploitable geothermal resources. For a landmass the size of Australia this presents a considerable problem as vast tracks of land can now be considered prospective. The challenge then is to find methods for discriminating local geothermal targets that are simple, effective, available and able to be applied at very large scale. To do this well it will also be necessary to recognise, and understand, the style of resource in question.

Exploration for dry geothermal resources is unique in that the commodity in question is not matter but energy. This distinction is small but crucial as it sets dry geothermal apart, even from conventional geothermal fields where the commodity is not simply heat but rather hot water. For dry geothermal exploration it is necessary to directly evaluate the distribution of heat energy within the crust. To this end, temperature and heat flow mapping techniques developed for Australia by Cull (1982), Cull & Conley (1983) and Somerville et al. (1994) have already proven useful. Temperature maps, based largely upon data derived from commercial boreholes, provide a more detailed coverage than that which is currently available from heat flow data. The techniques used to create these maps were relatively primitive however and much room exists for improvement in the resulting images. One aim of the current work is to examine the potential for producing an enhanced version of the Somerville et al. crustal temperature map by addition of new borehole data combined with application of more
sophisticated image processing techniques. The results of this work are detailed in Chapter 2.

One of the problems affecting the accuracy of crustal temperature maps produced from borehole data is that of the drilling induced thermal anomaly. Fully described in Chapter 3 the drilling induced thermal anomaly is caused by the action of circulating fluids used to cool and lubricate the bit. Thermal suppression caused by this process may reduce bottom of hole temperatures recorded shortly after drilling by amounts greater than 50°C. Whilst it is possible in some cases to apply models for the correction of perturbed borehole temperature data, to date relatively little work has been conducted to assess the accuracy of these techniques. Chapter 4 describes data currently available from the central Australian Cooper Basin which provides a unique opportunity to rectify this situation. Equilibrium temperature prediction of four models for bottom of hole thermal recovery, the Horner plot of Bullard (1947), the Cooper & Jones (1956) model, the semi-log plot of Pitt (1986) and Exponential model of Nakaya (1951) are tested for accuracy using this data in Chapters 5 – 8. Choosing the best performing of these models, raw Cooper Basin temperature data is then temperature corrected and the effects of using this data in mapping and resource analysis assessed in Chapter 9.

When seeking to locate any natural resource it is useful to have models or case studies for reference or comparison. In Australia the lack of volcanism and major tectonic activity implies geological models appropriate for foreign HDR sites are generally not applicable. Nevertheless Australia does have high temperature geothermal regions. These typically occur in areas where sedimentary basin overlies and insulates the basement strata. The type example of this style of resource is found within the Cooper Basin of South Australia where radiogenic granite lies beneath thick coal-bearing sedimentary sequences. Commercial development of this resource is currently underway at the Habanero project near Innamincka. A case study of the regional Cooper Basin is undertaken in Chapter 10 as the part of a detailed resource analysis. More specific geological investigations into the Habanero HDR resource are included in Chapter 11. It is hoped that this work will provide a basis for the ongoing construction of a resource model that will ultimately benefit future
geothermal exploration in Australia. The final chapter of this thesis provides a summary of all generated results and includes suggestions for future work.

1.2 Background to HDR

To successfully explore for any commodity it is first necessary to define the proposed target. Like most natural resources, Hot Dry Rock resources are anomalies within a larger system, in this case that of the global energy budget. The location, size and intensity of these anomalies are closely tied to larger processes within the Earth. HDR itself has arisen as a result of both scientific and technological advances. The definition of that which constitutes a viable HDR resource is intimately linked to a specific set of engineering requirements. Past work conducted on HDR projects provides a blueprint of the requisites for successful resource development. Combined, this data gives a set of key parameters that form an essential guide for exploration.

1.2.1 Geothermal Energy

The energy contained within a Hot Dry Rock resource is geothermal energy, otherwise known as the heat of the Earth. A small percentage of this energy is relic primordial heat, left over from the accretion of the planet and now retained largely in the core (Fowler 1990). The majority however, is a product of the ongoing natural decay of radioactive isotopes $^{238}$U, $^{235}$U, $^{40}$K and $^{232}$Th in the mantle and crust. The constant production of heat at depth within the Earth is balanced by a continuous loss from the surface of the planet. Heat flows from core to mantle to crust and in doing so drives planetary evolution in the form of plate tectonics. The size of the global energy flux is vast, average surface heat flow estimated to be 87mW.m$^{-2}$, a value which corresponds to a total loss of some $44 \times 10^{12}$W (Pollack, 1993).

The primary mode of heat transfer within the mantle is convection, a highly efficient mechanism which results in near adiabatic mantle temperature gradients and an excellent dispersion of heat (Fowler, 1990). By contrast heat flow into and within the crust is dominantly conductive and is relatively inefficient, the low thermal conductivity of most rock compositions impeding the rapid diffusion of heat. This in turn leads to the formation of crustal geotherms where temperature increases with
depth. The rate of mantle heat flux into the base of the lithosphere is variable, inclining to highest values within localised zones subject to advection from rising magma. As a consequence, heat loss at the surface of the crust is typically found to be greater within oceanic regions (101 mW.m\(^{-2}\)) than continental (65 mW.m\(^{-2}\)), an observation largely accounted for by the creation and subsequent cooling of new crust at oceanic spreading centres (Pollack, 1993).

A relative concentration of radioactive elements within crustal rocks implies that they are also capable of generating their own internal heat to augment the mantle flux. Whilst this is true of both oceanic and continental crust, it is within the more evolved continental crust that this property becomes most significant. Internal heat generation within the continental crust is far greater than that within the oceanic crust and accounts for up to 17% of the total global heat flux (Fowler, 1990). As a general rule, heat flow within the continental crust is subject to a wider range of potential influences, and is thus of a more complicated nature, than that observed in oceanic regions. Heterogeneities in density, porosity and permeability, structure, composition, thickness, tectonic setting and age of the continental crust may all influence local heat flow. Combined with the natural deviations in thermal conductivity that accompany compositional changes, local variations in crustal heat flow result in site-dependent geotherms and the formation of regions of higher and lower temperature. Larger continental masses are commonly subdivided into numerous ‘heat flow provinces’, subsections of crust which appear to share common thermal characteristics (Fowler, 1990). It is within those areas of relatively high crustal heat flow that natural geothermal systems may form and where exploitable geothermal resources are to be found.

1.2.2 Geothermal Resources

Whilst the Earth as a whole emits a large amount of thermal energy every second, the heterogenous global distribution of heat flow implies that, on a local scale, the flux is often too low for it to be considered as a cost-effective energy source. The economic exploitation of Earth heat is instead dependent upon the existence of natural thermal anomalies within the crust where heat flow and temperature are higher than average. Practicality currently requires that these anomalies be situated upon dry land. Geological settings capable of hosting such resources include active volcanic regions,
areas adjacent to young plutonic intrusions, zones of crustal extension and deep sedimentary basins. By far the most likely places to find these anomalies are those tectonically active zones located at the margins of major lithospheric plates, a fact clearly illustrated on global geothermal maps (Figure 1.1).

Figure 1.1: Global distribution of high temperature natural geothermal fields (stippled areas). The pattern of these resources closely follows that of the major tectonic plate boundaries.

Geothermal resources exist in a variety of forms. Geological setting, temperature and the physical nature and tertiary usage of systems can all provide criteria for schemes of resource classification (Jessop, 1990). The presence or absence of natural groundwater flows in association with a geothermal area provides a key point of distinction between different resource styles. Geothermal energy can only be extracted from the Earth via a heat transporting medium. Rock itself is such a medium but the poor conductivity of most rock types enables only a relatively slow rate of heat transportation. For the commercial extraction of heat energy a more efficient carrier is required, and is available, in the form of water. The simplest and most universal form of classification for geothermal resources is thus one which is based upon the presence or absence of an in-situ fluid.

Classifying geothermal resources on the basis of their water content effectively encapsulates the conditions of permeability and porosity within the host geology. In
areas where these parameters permit, circulating groundwater may form geothermal fields whose surface expression can produce classic geothermal features such as hot springs, fumaroles and geysers (Figure 1.2). Exploitation of water-rich geothermal resources comes down to a relatively simple matter of accessing the naturally heated fluids via bore holes or surface springs. Human interaction with the surface expressions of water-rich geothermal fields may be traced into prehistory (Smith, 1982). Active engineering of geothermal systems to better suit human needs, such as bathing and cooking, has also been known since ancient times (Smith, 1982). More sophisticated uses for geothermal energy were devised in the early twentieth century with the development of the world’s first geothermal power generator in Larderello, Italy, in 1904. Ongoing technological advances have since seen geothermal energy ‘become a proven resource for both heat and power generation’ (www.worldbank.org). In nearly 60 countries worldwide geothermal resources now provide a cumulative direct heat capacity in excess of 15,000MW and an electric power generation capacity of around 8,000MW (http://iga.igg.cnr.it).

![Image of a geyser in Yellowstone National Park, USA. Geyser, Geysers, hot springs and bubbling mud are classic surface expressions of shallow wet geothermal systems or fields.](image)

**Figure 1.2:** Geyser, Yellowstone National Park, USA. Geysers, hot springs and bubbling mud are classic surface expressions of shallow wet geothermal systems or fields.

The establishment of a significant technology for the development of geothermal fields, coupled with their long history of exploitation, implies water-bearing systems
are the ‘type’ or ‘conventional’ style of geothermal resource. At the other end of the scale are systems where rock permeability and porosity are very low and which, as a consequence, are not host to significant natural fluid flow. These areas may still have anomalously high temperatures however and may rightly be considered as geothermal resources. The technology which enables this form of resource to be counted as exploitable is a relatively recent innovation and consequently is less well understood than that employed in conventional fields.

Between the two extrema of ‘wet’ conventional and ‘dry’ non-conventional lies a continuous spectrum of geothermal resource styles. Some are water bearing but deeply buried, perhaps bounded by impermeable layers preventing surface expression. Others have reasonable porosity but low permeability, inhibiting the free circulation and escape of heated water, whilst others may simply be water-poor. This diversity of forms has led to a proliferation of names to describe individual non-conventional resources. Terms such as ‘hot fractured rock’, ‘hot wet rock’, ‘deep heat mining’ and ‘engineered’ or ‘enhanced’ geothermal systems are all currently in use, each referring to slightly different positions on the wet/dry spectra. For the purposes of this work all non-conventional resources will be referred to by the blanket term applied to the initial experimental work in the development of dry geothermal resources, that is, Hot Dry Rock or HDR.

1.2.3 Hot Dry Rock

The theory behind the exploitation of dry or non-conventional geothermal resources is a remarkably simple one. Nature itself provides a blueprint for the efficient extraction of geothermal energy in the form of conventional geothermal fields. Logically, areas of crust which are anomalously hot but which do not support natural fluid flow should be able to be exploited by creating an artificial version of the natural system, that is, by engineering a permeability at depth into which a forced circulation may be introduced. Such a system may be created between deep boreholes using techniques of hydraulic fracturing and reservoir engineering similar to those already in use in the oil industry (Figure 1.3). Circulation of fluids at depth in an artificial fracture system linking two or more boreholes should mimic the plumbing of a natural system, allowing the efficient extraction of heat to surface. Empirical investigations into this theory of energy extraction from hot dry rock have now been conducted for over
thirty years at more than eleven different test sites in seven countries. Detailed case histories of work conducted at these sites are included in Appendix 1. Lessons learnt during these projects have resulted in significant technological advances and led to the evolution of a mature, practicable HDR concept.

![Diagram of HDR geothermal system](image)

**Figure 1.3:** Schematic illustrating the fundamental concept of an HDR geothermal heat exchanger. Cold water is pumped to depth via an injection well (blue) where it is forced out into a fracture network hosted within crystalline basement. Moving through this network the fluid absorbs heat from the surrounding rock mass. Eventually the heated water returns to surface via production wells (red). Once at surface hot fluids are passed through a heat exchanger, cooled and ultimately recycled back into the injection well.

The theory of energy extraction from HDR was first proposed in 1970 at the Los Alamos National Laboratories in New Mexico, USA (Smith, 1975). In a deceptively straightforward plan it was proposed that a pair of boreholes be drilled within a region of hot, homogenous and effectively impermeable rock. These wells would be hydraulically connected at depth by application of downhole pressure, forcing fluid into the rock mass and creating a single large ‘penny-shaped’ hydraulic fracture (Figure 1.4). Following establishment of this connection one of the well pair could be used to inject pressurised water into the rock at depth. Theoretically, this water would
enter the artificial fracture and circulate through the rock mass becoming hot and buoyant before eventually returning to surface via the second well. High temperature water produced at surface in this way could be passed through a heat exchanger, cooled, and returned back to the subterranean system to form a continuous cyclical loop. Assuming the temperature of the produced water was sufficient, heat liberated in the heat exchanger would enable generation of geothermal power.

![Diagram](image)

**Figure 1.4:** The original Los Alamos concept for HDR energy extraction illustrating the simple single penny-shaped hydro-fracture theory. Modified after Smith (1975).

The ingredients necessary for the implementation of the original Los Alamos vision were fairly straightforward: an area of anomalously high temperature at relatively shallow depth, accessible by drilling, and a homogenous, impermeable medium. For the Los Alamos workers both of these requirements were satisfied by a site located nearby at Fenton Hill in the Jemez Mountains of northern New Mexico. Here, high temperature gradients related to young Tertiary volcanism were observed in crust with a relatively shallow depth to crystalline basement (<1km) (Smith, 1975). Physically,
the crystalline rock was considered an ideal medium for fracturing, the matrix being brittle, relatively homogenous and of very low permeability.

Results from initial experimental testing of the HDR concept at Fenton Hill were highly encouraging (Appendix 1). Application of high fluid pressure successfully created an artificial fracture system connecting two separate wells at around 2km depth (Murphy, 1981). By 1977 circulation of fluid between the two wells was achieved and high temperature water was produced at surface (Cremer, 1982). Unfortunately, progress at Fenton Hill very shortly hit a major snag. Reassured by the initial results, the development of a deeper, hotter reservoir system was commenced in 1979 with the drilling of a new pair of wells (Cremer, 1982). The geometry of this new well system had been carefully designed on the assumption that the orientation of the hydraulic fractures to be created would be identical to those already observed in the shallow reservoir (Cremer, 1982). Subsequent attempts to hydraulically connect the two wells proved that this was not to be the case however, the application of downhole pressure instead resulting in the formation of fractures misaligned with the well plane (Brown & Duchane 1999). By 1984, after an extended series of fracturing experiments, it was clear that no amount of applied downhole pressure was capable of creating a fracture that would match the pre-determined well geometry (Brown & Duchane 1999).

By this time hints as to the nature of the problem plaguing the deep Fenton Hill system were already available from the second HDR test site located in the Cornubian Granite at Rosemanowes in the UK. Commencing in 1975 work at the Rosemanowes site had specifically set out to investigate engineering techniques necessary for the development of a fractured HDR resource (Batchelor, 1984). Unlike the ‘single-fracture’ vision of the American project at Fenton Hill, the early British concept of HDR imagined formation of a subterranean ‘reservoir’ comprising an extended and interconnected fracture network (Smith, 1987). Of particular interest at this site was the question of natural fractures and their potential contribution to the creation of permeability at depth. The key question asked by the Rosemanowes workers was whether the application of downhole pressure could be used to open or ‘stimulate’ existing weakness in the rock and, if so, whether this would preclude the build-up of pressure necessary to create new hydraulic fractures.
Fracturing experiments conducted at Rosemanowes were accompanied by an important innovation, namely the use of a microseismic network to monitor and record acoustic emissions generated during the forced injection of water (Batchelor, 1984). Results from microseismic monitoring were able to accurately locate the movement of water into the rock mass, enabling construction of a three-dimensional map of the induced zone of permeability (Batchelor, 1984). What these results showed at Rosemanowes was the development of a complex network of flow paths, a field of 'stimulated' natural fractures and joints which opened at relatively low injection pressures to accept fluid from the well (Batchelor, 1984). Contrary to the Fenton Hill theory, it seemed pre-existing fractures were controlling the rock behaviour, even at depths where no natural voids remained (Kerr, 1987).

The results of the work at Rosemanowes led to a significant shift in thinking regarding the creation of fractured HDR heat exchangers. Instead of the original concept of an artificial fracture linking two wells, injection of fluid into open bore holes led to a build up of pressure only until the minimum principle stress was reached. Around this point favourably oriented natural fractures were stimulated, opening to accept water and reducing the pressure in the well. The control exerted by the natural fracture system, in combination with the in-situ stress regime, thus dictated both the size and shape of the artificial permeable zone. This in turn meant that predicting the orientation of a deep fractured reservoir was an involved task. Relying on knowledge of the geometry of natural joints was not enough. Wells drilled at Rosemanowes to intersect natural joint planes, for example, were later found to be misaligned with the local stress field, resulting in weak hydraulic connectivity (Batchelor, 1984). Fortunately, the continued success of microseismic methods provided an alternative to the blind drilling of wells. Rather than drilling two holes at once and then attempting to link them, the use of microseismic event location enabled a dual well HDR system to be created by targeted drilling of a permeable zone previously engineered around a single injection well.

The importance of the interaction between the local stress field and fracture network to the development of a deep reservoir extends to the ability of the newly formed system to preserve its induced permeability (Willis-Richards et al., 1995). Rock
mechanical work undertaken at Falkenberg in Germany demonstrated the potential for creating a permanently enhanced permeability during fracture stimulation (Kappelmeyer and Jung, 1987). Shear failure, induced by fluid injection is sufficient to cause misalignment and/or deformation of asperities on fracture surfaces, generating an irreversible increase in permeability (Kappelmeyer and Jung, 1987). Sites such as Fenton Hill and Bad Urach in Germany, at which shear stress is thought to be comparatively small, are characterised by fractured reservoirs which, whilst capable of being ‘jacked’ open to accept fluid will, upon the release of pressure, simply close again, expelling much of the injected water (Willis-Richards et al., 1995). Overall, the history of HDR development is littered with examples emphasising the significance of the stress/fracture relationship to the successful engineering of a deep reservoir. At Rosemanowes high horizontal stress anisotropy resulted in a system almost too easily stimulated, the downward shearing of natural sub-vertical fractures, even at relatively low pressure, causing high water losses during circulation (Parker, 1989a). At Ogachi in Japan attempts to develop two separate vertically stacked reservoirs, rather surprisingly, produced two structures that extended perpendicular to each other. Differences between the E-W trending upper reservoir and N-S trending lower reservoir (separated by less than 300m vertically) appear to have arisen solely from variations in the local fracture network (Kiho and Mambo, 1995).

In almost all HDR developments to date stimulated fractures have been dominated by sub-vertical dips, producing reservoirs which are in turn primarily vertical (Appendix 1). This apparent preference reflects the tectonic setting of most sites, which are typically strike-slip or extensional, characterised by a horizontal minimum principle stress. Choosing to locate an HDR site in an area where the minimum stress is vertical, however, can in turn lead to the formation of a horizontal reservoir, as demonstrated at the Swedish site, Fjällbacka (Eliasson et al., 1987). The importance of tectonic setting to the successful engineering of an HDR reservoir is also manifest in a number of other ways. Operating in young volcanic environments Japanese sites at Hijiori and Ogachi suffered from systems which, whilst developed in crystalline rock, were highly fractured and, hydraulically, very open. Despite innovative designs that used multiple production wells to encircle a single injection point, water loss from these dry systems was consistently high (Kuriyagawa and Tenma, 1999; Kitano
et al., 1999). By contrast, researchers at the European HDR site at Soultz-sous-Forêts in France were able to take advantage of the open nature of their system to actually reduce water losses. Located in an extensional environment on the western rim of the extensive Rhine Graben, subcropping granite at Soultz supports a deep circulation system connected to overlying sedimentary aquifers (Baria et al., 1999). This natural system was exploited to the benefit of the HDR development by use of downhole pumps which manipulated the in-situ hydraulic head, causing fluid inflow into the production well and reducing water loss during circulation to zero (Baria et al., 1999).

These experiences, derived from the decades of work expended at HDR test sites around the world, provide important clues to the parameters necessary for the development of non-conventional resources. High temperature, relatively shallow depth, fractured crystalline basement and favourable local stress conditions are the essential ingredients of an exploitable HDR resource. Each of these factors are linked to the broader tectonic setting which may also play a significant role in the success or failure of a project. Collectively these parameters provide the basis of a resource description which is vital for the process of HDR exploration.

1.2.4 Geothermal Exploration

For a non-conventional geothermal resource, temperature is the key parameter that defines both its existence and its grade. Studies of existing HDR developments define additional parameters, such as geology and tectonic setting, depth and stress regime which together impact upon how exploitable a given resource may be. Conditions of exploitability hinge not only upon engineering considerations however but also upon economics. That which is cost-effective will vary depending upon both time and place. Currently, for an Australian HDR resource to be economically exploitable for electrical power generation, the basic conditions are:

1. Temperature >165°C

Economic analyses of geothermal power generation indicate a minimum rock temperature of 165°C, necessary to ensure water temperature at surface of at least 150°C (Somerville et al., 1994).
2. Depth <5km

Analysis of the costs of drilling indicate an economically exploitable resource should be located less than 5km beneath surface (Somerville et al., 1994).

3. Geology

Successful engineering of an HDR reservoir requires the presence of a large volume of relatively impermeable homogenous crystalline rock.

Dry geothermal exploration, like any other form of natural resource identification, is a process of progressive target definition. Techniques suitable for this process will vary depending upon the scale at which they are to be applied. The scale of a given exploration project is itself dependent upon the amount of previous work conducted and the degree to which an area is believed to be understood. For a continent like Australia, where relatively little work has been undertaken, most of the landmass should probably be considered as a potential target. Exploring an area the size of a continent is a daunting task. What is needed is a cost-effective regional-scale technique capable of reliably delineating target from non-target zones. The higher the resolution that can be gained from this technique, the better.

Techniques suitable for use in identifying HDR resources are limited to those which may provide information on temperature at depth. Many techniques currently used in conventional geothermal exploration translate well to the non-conventional case. Geophysical survey methods used to detect temperature variations in the crust, including electrical resistivity and magnetotelluric surveys, may be of use. The pool of available survey data is likely to be quite small however, cost and logistical restrictions implying that regional applications of these techniques are usually not practical. More suited to regional target identification are techniques that can draw upon large existing databases. In this regard indirect indicators of temperature such as seismic velocity and depth to curie temperature (interpreted from magnetic data) may be of more use, although their resolution is likely to be relatively poor. Complicating the search for dry geothermal resources is the depth of the exploitable resource base which, whilst only 5km, is sufficient to reduce the effectiveness of many geophysical survey systems. For these reasons, measurements of temperature and heat flow, which may be used to directly predict thermal conditions at depth and which are often
readily available from borehole data, are likely to be the most useful and accurate techniques for identifying regions of deep hot rock.

Supplementary to geophysical surveys are geological models which may also be of assistance in the identification of HDR resources. The need for a crystalline substrate must necessarily play a role in target delineation in areas characterised by regional thermal anomalies. Likewise, knowledge of local or regional stress regimes may influence resource location. Unfortunately, Australia is devoid of many of the geological settings usually associated with high crustal geotherms, such as volcanoes and young tectonic zones. The presence of the known high temperature HDR resource in the Cooper Basin of central Australia provides a starting point for the construction of a new resource model however. Although not yet well defined, studies of this resource should provide a blueprint for application to future target areas.

Ultimately, the only true test of any geothermal prospect is to drill and directly evaluate the *in-situ* crustal conditions. This process represents the final stage of the exploration project, that of resource delineation. For most commodities delineation represents a vital stage in commercial development where engineering appraisals are made and results are reported to market. The novelty of HDR technology implies that there are, as yet, no criteria for the full definition of a commercial resource. Information derived from past HDR developments, combined with knowledge of economics and the exploration process, imply that four main parameters are necessary to begin describing a resource: temperature, depth, geology and local stress conditions. Knowledge of these parameters should provide a starting point to judge the prospectivity of the resource, as well as forming the basis for comparison with future discoveries.
CHAPTER 2
THE AUSTRALIAN CRUSTAL TEMPERATURE MAP

2.1 Introduction
The scientifically preferred method for regional geothermal exploration is that of the heat flow survey. Reliable heat flow measurements provide an indication of the thermal flux at a given point in the crust and may be used in conjunction with knowledge of crustal composition to calculate temperature at depth. The calculation of heat flow requires knowledge of both temperature and thermal conductivity of the crust however and most heat flow measurements are derived from specific purpose-drilled wells from which rock samples are also collected. As a consequence, the determination of reliable heat flow data is a costly and involved task. For a continent like Australia, in which commercial geothermal exploration has been virtually non-existent, relatively few of these data are available. The most recent published compilation of this data, Cull (1982) concluded that there were less than 200 reliable heat flow points for onshore Australia. Whilst this data density is sufficient to define broad scale heat-flow provinces across the continent, it does not allow for the generation of specific localised exploration targets. Although there are additions to the Australian heat flow database from time to time there is little likelihood of significant short term redress to the overall data shortage. To generate a more detailed map of heat energy within the Australian crust then it is necessary to seek an alternative source of data. Fortunately, an alternative, if imperfect, source is available in the form of commercial temperature data derived from both on and offshore petroleum wells.

2.2 Regional Heat Flow Patterns
Much of the available Australian heat flow data were recorded in the 1960’s and 1970’s by researchers working at the then Department of Geophysics and Geochemistry at the Australian National University (ANU) (Lilley et al., 1977). Compilations of this early heat flow data, along with more recent additions including work by the then Australian Bureau of Mineral Resources (BMR), are contained
within Lilley et al. (1977), Cull & Denham (1979) and Cull (1982). From the late 1970's onwards over one hundred onshore data points were available, sufficient to allow for the assemblage of contoured continental heat flow maps (Figure 2.1). Although relatively broad in scale these images were able to identify a number of geothermal anomalies and established the existence of several heat flow provinces across the continent (Figure 2.2). Regional trends evident in heat flow included a general increase from west to east ‘into regions of greater surface radioactivity and more recent tectonism’ (Cull & Denham, 1979). Of particular interest is the anomalously high flux associated with the Central Australian heat flow province, which averages 83mWm$^{-2}$ (Sass & Lachenbruch, 1979). More localised anomalies included lows and highs associated with recharge and discharge of the Great Artesian Basin respectively and general highs associated with recent vulcanism in Queensland and western Victoria (Cull & Denham, 1979). A general correlation was also observed between heat flow, crustal age and upper mantle seismic velocity (Beardsmore & Cull, 2001).

![Figure 2.1: Contoured heat flow map of Australia showing the distribution of available heat flow data points. Contour interval is 10mW.m$^{-2}$. Image reproduced after Cull (1982).](image-url)
Figure 2.2: Australian heat flow provinces as defined by Sass & Lachenbruch (1979). A = Western Shield Province, B = Central Shield Province, C = Eastern Province.

Despite the success of the regional heat flow maps there still remained large gaps within the available data coverage. Most noticeable was a lack of data from regions where basement lithology is obscured by sedimentary basins. Given the large extent of Phanerozoic cover across much of central Australia, the absence of data from these regions presented a significant problem. Cull & Conley (1983) attempted to address this issue by creating a new heat flow image based on a composite dataset, this time containing around 1200 points and including both existing heat flow measurements and new heat flow estimations (Figure 2.3). Here, new estimates of heat flow were calculated by combining temperature data derived from selected water bores and commercial petroleum wells with thermal conductivities estimated from sediment compaction models. Despite the large potential for systematic error in the data, including issues of vertical fluid migration, heat refraction associated with basement topography and drilling induced thermal disturbances, the produced image was found to compare favourably with the earlier heat flow maps (Cull & Conley, 1983). Moreover, the introduction of data into sedimentary regions allowed for development
of a more detailed image, most noticeably around the Great Artesian Basin of central Australia. The presence of a number of previously undetected bulls-eye anomalies within this latter region provided clear evidence of the advantages to be gained through the use of the larger dataset.

Figure 2.3: Contoured heat flow map of Australia produced using both heat flow holes and commercial borehole temperature data. Reproduced after Cull and Conley (1983). Contour interval is 10mW.m$^2$.

2.3 The Australian Crustal Temperature Map (1994)
In the early 1990’s the database created by Cull & Conley (1983) was taken up by workers at the Australian Geological Survey Organisation (AGSO) as the basis for a new compilation of Australian geothermal data. Conducted as part of an Energy Research and Development Corporation (ERDC) project grant, this work was specifically designed to produce an assessment of the Australian ‘hot dry rock geothermal energy resource’ and the ‘technical and economic factors’ involved in its development (Somerville et al., 1994). Included within the scope of the project was a
continent-wide HDR resource analysis, undertaken by consolidation of existing borehole temperature data into a new database of geothermal gradient information. Unlike previous work, this database, known as GEOTHERM, was specifically designed to produce a coverage of crustal temperature distribution rather than crustal heat flow. By using temperature data alone and not attempting to calculate heat flow, the number of available data points were increased nearly fourfold over previous work. When completed the GEOTHERM database contained just under 4300 temperature data points. This density of available temperature data allowed the creation of a continuous colour image of estimated crustal temperature at 5km depth, now known as the Australian Crustal Temperature Map.

2.3.1 GEOTHERM (1993)

The GEOTHERM database was created as a single table ORACLE database by manual addition of new open-file petroleum well data to the existing geothermal database of Cull & Conley (1983) (Somerville et al., 1994). The basic data structure of GEOTHERM is shown in Table 2.1. Unfortunately, a detailed data key does not exist for this database and much of the original coded information is now lost. In particular, information relating to the status of the recorded temperature measurements included within the ‘Method’ field and a number of fields related to the calculation of temperature at 5km are now unable to be interpreted (Table 2.1).

In all, GEOTHERM contained records for some 4292 downhole temperatures and/or temperature gradients recorded in both on- and offshore wells across and around Australia (Figure 2.4). Most of the data included within the database is primary, that is, derived directly from an empirical source (Somerville et al., 1994). A summary of data incorporated into GEOTHERM is provided in Table 2.2.

Temperature data contained within GEOTHERM were derived from a variety of sources and as such the reliability varied significantly from point to point. All temperatures were recorded downhole within a drilled well implying all were subject to the effects of the drilling induced thermal anomaly. This disturbance, produced by the circulation of fluids during drilling, results in a suppression of the natural formation temperature within the vicinity of the well. As discussed in detail in Chapter 3, only those downhole temperatures recorded significant periods of time
<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOLENUM</td>
<td>Sequential well number including datasource</td>
<td></td>
</tr>
<tr>
<td>NAME</td>
<td>Name of well</td>
<td></td>
</tr>
<tr>
<td>BASIN</td>
<td>Basin through which well has been drilled</td>
<td></td>
</tr>
<tr>
<td>DLAT</td>
<td>Latitude in decimal degrees</td>
<td>Australian Geodetic Datum (AGD)</td>
</tr>
<tr>
<td>DLONG</td>
<td>Longitude in decimal degrees</td>
<td>AGD</td>
</tr>
<tr>
<td>ZONE</td>
<td>Australian Metric Grid Zone</td>
<td></td>
</tr>
<tr>
<td>EASTING</td>
<td>AMG casting</td>
<td></td>
</tr>
<tr>
<td>NORTHING</td>
<td>AMG northing</td>
<td></td>
</tr>
<tr>
<td>TDDRILL</td>
<td>Total depth (m)</td>
<td></td>
</tr>
<tr>
<td>TDSIZE</td>
<td>Diameter at total depth (cm)</td>
<td></td>
</tr>
<tr>
<td>TEMPD</td>
<td>Bottom hole temperature (°C)</td>
<td></td>
</tr>
<tr>
<td>DEPTH</td>
<td>Depth of temperature (metres)</td>
<td></td>
</tr>
<tr>
<td>METHOD</td>
<td>Status of temperature measurement</td>
<td>Coded data. Designed to indicate whether individual BHT measurements are equilibrium, perturbed by the drilling thermal anomaly, perturbed but corrected, extrapolated or of unknown status. No data key exists for this column.</td>
</tr>
<tr>
<td>ACCURACY</td>
<td>Accuracy of temperature measurement</td>
<td></td>
</tr>
<tr>
<td>GRADIENT</td>
<td>Geothermal gradient (°C/km)</td>
<td></td>
</tr>
<tr>
<td>STATUS</td>
<td>Current status of well</td>
<td></td>
</tr>
<tr>
<td>BHLITH</td>
<td>Bottom of hole lithology</td>
<td></td>
</tr>
<tr>
<td>TYPE</td>
<td>Purpose of well</td>
<td></td>
</tr>
<tr>
<td>DRILLDATE</td>
<td>Well completion date</td>
<td></td>
</tr>
<tr>
<td>CASING</td>
<td>Description of casing</td>
<td></td>
</tr>
<tr>
<td>OWNER</td>
<td>Owner of well</td>
<td></td>
</tr>
<tr>
<td>CONFIDENTIALITY</td>
<td>Date of confidentiality expiration</td>
<td></td>
</tr>
<tr>
<td>OTHERINFO</td>
<td>Any other data</td>
<td></td>
</tr>
<tr>
<td>AIRTEMP</td>
<td>Surface temperature (°C)</td>
<td>Assigned parameter (see text)</td>
</tr>
<tr>
<td>ELEVATION</td>
<td>Elevation in metres</td>
<td></td>
</tr>
<tr>
<td>RECN0</td>
<td>AGSO database number</td>
<td></td>
</tr>
<tr>
<td>BASEMENTTD</td>
<td>Depth to basement in metres</td>
<td></td>
</tr>
<tr>
<td>ESTBASEMENTD</td>
<td>Estimated depth to basement</td>
<td>Assigned parameter (see text)</td>
</tr>
<tr>
<td>CALCGRAD</td>
<td>Calculated geothermal gradient (°C/km)</td>
<td></td>
</tr>
<tr>
<td>ONOFF</td>
<td>Location ON or OFFshore</td>
<td></td>
</tr>
<tr>
<td>TEMP AT 5K</td>
<td>Calculated temperature at 5km depth</td>
<td>See text</td>
</tr>
</tbody>
</table>

Table 2.1: Structure of GEOTHERM (1993) database showing all interpretable data fields. Modified after Somerville et al. (1994).  

after drilling are likely to be effectively unperturbed by this phenomenon. Unfortunately, for the majority of data in GEOTHERM no information were available regarding the quality or reliability of the temperature measurements (Figure 2.5) (Somerville et al., 1994). In these cases, and also for wells where the temperature was
known to be both perturbed and uncorrected by any temperature model, Somerville et al. (1994) applied an arbitrary correction of +10%.

![Spatial distribution of borehole temperature data from the 1993 GEOTHERM database.](image)

**Figure 2.4:** Spatial distribution of borehole temperature data from the 1993 GEOTHERM database.

<table>
<thead>
<tr>
<th>Source</th>
<th>Coverage</th>
<th>No. Points</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>State and Federal Mines</td>
<td>National (PEDIN database), NSW, SA, QLD, TAS, VIC, PNG</td>
<td>3094</td>
<td>On- and offshore petroleum well data. Heat flow measurements (Tas).</td>
</tr>
<tr>
<td>Departments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industry</td>
<td>NT, NSW, WA</td>
<td>45</td>
<td>Onshore petroleum well data</td>
</tr>
<tr>
<td>Middleton (1979)</td>
<td>SA</td>
<td>12</td>
<td>Onshore petroleum well data</td>
</tr>
</tbody>
</table>

**Table 2.2:** Primary data sources for GEOTHERM (1993) database. Modified after Somerville et al., (1994).
Figure 2.5: Breakdown of GEOTHERM borehole temperature data quality. ‘Equilibrium’ temperatures are highly reliable measurements recorded a significant period of time after drilling. ‘Corrected’ and ‘Uncorrected’ temperature measurements are affected by drilling induced thermal suppression, the former having been compensated by some form of correction (see Chapter 3). Unreliable temperature measurements are obviously spurious and are excluded from use. DST temperatures are derived from downhole formation tests (see Chapter 4). Temperatures of unknown status are of uncertain reliability and are typically assumed to be both suppressed and uncorrected.

2.3.2 Temperature Modelling
As temperature varies with depth in the crust it was necessary to set a level at which the mapped image would be created. A depth of 5km was chosen based upon the economics of HDR drilling (Somerville et al., 1994). All temperature data were normalised to this depth by extrapolation of calculated or documented geothermal gradients (Somerville et al., 1994). Values of Mean Annual Surface Temperature (MAST) and depth to basement were manually assigned to each well on the basis of two separate 1° geographic grids (Somerville et al., 1994). An empirical correction of +3°C was applied to all assigned values of MAST, following the method of Cull & Conley (1983). Using these data, vertical temperature profiles, comprising linear segments for basin and basement respectively, were constructed as necessary for each well (Somerville et al., 1994). In the absence of specific data, basement gradients were calculated using the condition of heat flow continuity combined with representative thermal conductivities of 2.5Wm⁻¹°C⁻¹ (basin) and 3.5Wm⁻¹°C⁻¹ (basement) (Somerville et al., 1994). Calculated values of gradient and temperature at 5km depth for each well were incorporated into the GEOTHERM database.
2.3.3 Image Processing

Temperature data calculated for 5km depth were used to create a continuous colour image or surface using a technique known as Delaunay Triangulation (Figure 2.6). Interpolation between known data points was undertaken using a constructed triangular irregular network or TIN (Somerville et al., 1994).

Figure 2.6: Australian crustal temperature at 5km depth, map circa 1993 as created by Somerville et al. (1994) from the GEOTHERM database. Image is clipped to the continent boundary, temperature scale as shown.

2.3.4 Image Interpretation

Quantitative analysis of the 1994 crustal temperature image was focussed upon identification of potential HDR resources, singling out crustal regions for which estimated temperature at 5km is greater than or equal to 225°C (Somerville et al., 1994). The lower temperature limit of 225°C was based on an assumed minimum 60°C drawdown prior to reaching the minimum temperature required for economic...
electrical generation (165°C). In all, nine separate localities were found to satisfy the
criteria, virtually all of which were associated with sedimentary basin cover (Table
2.3; Figure 2.7). By far the largest anomaly was that associated with the central
Australian Eromanga Basin. This vast area was broken down into basin-related sub-
anomalies, included within which was the Cooper Basin region where estimated
crustal temperatures at 5km were found to be in excess of 300°C.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Surface Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eromanga Basin</td>
<td>191400</td>
</tr>
<tr>
<td>(Cooper Basin)</td>
<td>(79000)</td>
</tr>
<tr>
<td>(Galilee Basin)</td>
<td>(63000)</td>
</tr>
<tr>
<td>McArthur Basin</td>
<td>29000</td>
</tr>
<tr>
<td>Otway Basin</td>
<td>5000</td>
</tr>
<tr>
<td>Canarvon Basin</td>
<td>2000</td>
</tr>
<tr>
<td>Murray Basin</td>
<td>1200</td>
</tr>
<tr>
<td>Perth Basin</td>
<td>500</td>
</tr>
<tr>
<td>Canning Basin</td>
<td>290</td>
</tr>
<tr>
<td>East Queensland</td>
<td>80</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>229,470</strong></td>
</tr>
</tbody>
</table>

Table 2.3: Areal extent of geothermal anomalies where temperature at 5km is ≥225°C
according to the Australian Crustal Temperature Map (1993). Brackets indicate sub-
localities within the Eromanga Basin. Modified after Somerville et al., 1994.

The strong coincidence of thermal anomalies with basement cover lead Somerville et
al., (1994) to conclude that there was likely a significant thermal blanketing effect of
basin over basement. A model for Australian style geothermal resources was
constructed where crystalline basement, preferably granite, was present beneath
sedimentary sections. Knowledge derived from existing drill intersections, combined
with interpretation of gravity data, enabled identification of number of actual and
potential basement granites in the hot Eromanga Basin region. In some cases, such as
the Cooper Basin, these rocks were known to be characterised by relatively high
proportions of heat producing (radiogenic) elements. In these situations the presence
of the granite at depth was considered likely to be contributing significantly to the
geothermal resource. Areas such as the Cooper Basin were thus reasoned to be at the
high grade end of a continuous resource scale.
2.4 The Australian Crustal Temperature Map (2003)

Work conducted as part of the ERDC project successfully demonstrated the utility of temperature data in the production of a continental scale geothermal map. Somerville et al., (1994) also clearly established the utility of such an image as a starting point for the identification of prospective geothermal resources. The temperature map created under the auspices of the ERDC project was not ideal however, a fact acknowledged by Somerville et al., (1994). The use of a TIN processing technique resulted in the generation of many image artefacts, most noticeably distinctly triangular shaped anomalies and sharp linear breaks (Figure 2.8). It follows from the diffusive nature of
heat that such features are physically unrealistic, implying that the map is failing to properly depict the distribution of temperature in the crust.

![Image: Australian Crustal Temperature Map]

**Figure 2.8:** Details of the Australian Crustal Temperature Map at 5km depth as generated by Somerville *et al.*, (1994). Sharp linear breaks and triangular shaped anomalies are characteristic image artefacts brought about as a result of the TIN image processing technique.

The underlying cause of image artefacts in the 1994 temperature map is the GEOTHERM data distribution which is highly heterogeneous, reflecting the uneven distribution of its major source, petroleum wells (Figure 2.4). Ironically, the problem of no data in sedimentary basins, encountered by the original heat flow maps, has now reversed to become an issue of data shortages in basement terrains. A new temperature mapping project, commenced in 2001, undertook to resolve some of these issues. The aim of this work was to investigate the potential for improvement of the existing crustal temperature image by both updating and augmenting the GEOTHERM database and reapproaching the image processing by using more sophisticated and rigorous GIS techniques. Results generated by this project included a new crustal temperature database, AUSTHERM03 and an improved, more realistic, temperature map.

### 2.4.1 AUSTHERM (2003)

The AUSTHERM03 database is a 30 mega-byte multi-table relational database produced in this study and managed in Microsoft Access 1997. AUSTHERM03 was
created by amalgamating the existing single-table Oracle database GEOTHERM with newly released open-file data from five states. A total of 1430 new points have been added to the database increasing the number of available temperature measurements by around 33% to 5722 (Table 2.4). A complete data key for AUSTHERM03 is included in Appendix 2.

<table>
<thead>
<tr>
<th>Source</th>
<th>Coverage</th>
<th>No. Points</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEOTHERM (1993)</td>
<td>National</td>
<td>4292</td>
<td>Onshore heat flow data, water bore data, on- and offshore petroleum well data.</td>
</tr>
<tr>
<td>PIRSA</td>
<td>SA</td>
<td>494</td>
<td>Onshore petroleum wells</td>
</tr>
<tr>
<td>DME</td>
<td>QLD</td>
<td>335</td>
<td>Onshore petroleum wells</td>
</tr>
<tr>
<td>WADME</td>
<td>WA</td>
<td>594</td>
<td>On and offshore petroleum wells</td>
</tr>
<tr>
<td>MRT</td>
<td>TAS</td>
<td>4</td>
<td>Offshore petroleum wells.</td>
</tr>
<tr>
<td>DMR</td>
<td>NSW</td>
<td>3</td>
<td>Offshore petroleum wells.</td>
</tr>
</tbody>
</table>

Table 2.4: Primary data sources for AUSTHERM (2003) database. PIRSA = Department of Primary Industry and Resources, South Australia; DME = Department of Mines and Energy, Queensland (now Natural Resources and Mines, Queensland); WADME = West Australian Department of Mines and Energy (now Department of Minerals and Petroleum Resources); MRT = Mineral Resources Tasmania; DMR = Department of Mineral Resources, New South Wales.

New data included in AUSTHERM03 are derived from five states only. No new temperature records were collected from Victoria or the Northern Territory. Although the respective State Mines Departments were approached, in both cases no new data were found. This outcome is considered to be due more to the lack of an effective mechanism for seeking out recently drilled wells with temperature records rather than an actual deficiency of new data. In the case of Victoria a relational database was under construction at the time of enquiry but was not yet completed.

The AUSTHERM03 database structure is illustrated in Figure 2.9. The database comprises a set of eleven unrelated master data tables and four slave or relational data tables each of which is linked to an individual master. Nine of the eleven master tables contain petroleum well data, the remaining two consist of water bore data from the Great Artesian Basin (GAB WB) and continent-wide equilibrium heat flow data (Cull, 1982). Petroleum well data within both master and related data tables are divided by location into seven states, NSW, NT, WA, SA, Vic, Qld, TAS and Papua.
New Guinea (PNG). A series of miscellaneous petroleum well data, originally sourced from the BMR for the GEOTHERM database comprise the remaining master table.

<table>
<thead>
<tr>
<th>MASTER TABLE</th>
<th>BMI</th>
<th>GAEL WH</th>
<th>HEAT FLOW</th>
<th>NSW</th>
<th>NT</th>
<th>PNG</th>
<th>QLD</th>
<th>SA</th>
<th>TAS</th>
<th>VIC</th>
<th>WA</th>
</tr>
</thead>
<tbody>
<tr>
<td>MULTI TABLE</td>
<td>QLD Multi</td>
<td>SA Multi</td>
<td>Tas Multi</td>
<td>WA Multi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2.9:** Table structure of the AUSTHERM03 database. Master tables in which each well is associated with a single temperature data point are divided on the basis of (a) data provenance and (b) geographic location. Multi-tables containing wells with multiple temperature data points are linked to master tables as shown. For a full data key refer to Appendix 1.

The four relational data tables contain records for petroleum wells which have multiple downhole temperature measurements available. This data typically arises from consecutive downhole logging runs, although some drill stem test (DST) and well formation test (MDT/RFT) data are also included. Referred to as ‘Multitempdata_(state)_PW’ each of these four tables is related to their master via a one-to-many relationship. The data contained within these tables are exclusive to the AUSTHERM03 database and were not incorporated into GEOTHERM.

The overall data quality of AUSTHERM03 is greatly improved relative to GEOTHERM. The recent development of comprehensive digital borehole databases by several State Mines Departments has allowed a full update of all existing records for Queensland, Western Australia and South Australia. Both new and updated records are more comprehensive than those included in the original compilation, a fact reflected in the greater proportion of data fields. The improvement in data quality and the addition of multi-point temperature data for four states (QLD, SA, WA, TAS) is also reflected in a greater ability to distinguish temperatures affected by the drilling thermal anomaly. Whereas in GEOTHERM over 50% of data were assumed to be uncorrected in the absence of a known status, in AUSTHERM03 this category has been reduced to less than 30% of the total (Figure 2.10). Unlike GEOTHERM, no arbitrary correction has been applied to any AUSTHERM03 temperature data. At
worst, temperature suppression produced by the drilling thermal anomaly will result in under-prediction of temperature at 5km depth. A temperature map produced from this data should thus be viewed as reflecting a minimum value for temperature at 5km, the possibility of underestimation being more desirable from an exploration point of view than overestimation.

![Pie chart showing data quality breakdown](chart)

**Figure 2.10:** Breakdown of AUSTHERM03 borehole temperature data quality. Key is as for Figure 2.5.

Despite the addition of over 1400 new data points, the data distribution encompassed by the AUSTHERM03 database shows relatively little improvement over that seen with GEOTHERM (Figure 2.11). Whilst there has been some enhancement of the spatial coverage, most noticeably in Western Australia, the bulk of the new data are found to be clustered into the same provinces that dominate the original dataset. As a result, data distribution across the continent remains patchy and irregular. It appears that the relatively mature state of onshore Australian hydrocarbon exploration is inhibiting significant further improvement to the AUSTHERM03 data distribution by addition of temperature data derived from petroleum wells. Any future attempts at expanding the current dataset will thus need to seek alternative sources of sub-surface temperature data, such as water wells, deep mineral exploration holes and geothermal exploration wells.
Figure 2.11: Spatial distribution of borehole temperature data from the AUSTHERM03 database. Red stars indicate new data exclusive to this dataset; grey circles existing data incorporated from GEOTHERM.

2.4.2 Temperature Modelling

The basic technique used for the extrapolation of in-situ AUSTHERM03 temperature measurements to 5km depth closely resembles that developed for the earlier map. A simple two-layer crustal model comprising sedimentary basin overlying crystalline basement was employed (Figure 2.12). All estimated geotherms were assumed to be linear and were calculated wherever possible from well data. In cases where basement geotherms could not be calculated from actual data, a value of 25°C/km was assigned. The use of a single basement geotherm is a simplifying assumption which allowed for ease of calculation. A value of 25°C/km was chosen as it represented a reasonable continental average, compared to modelled crustal geotherms of the three known Australian heat flow provinces (Sass and Lachenbruch, 1979).

Individual determinations of MAST and depth to basement were calculated for each temperature data point by Dr Prame Chopra using a selection of GIS techniques more rigorous than those employed for the original map. All GIS work was conducted
Figure 2.12: Simple crustal model used for the extrapolation of AUSTHERM03 borehole temperature data to 5km depth. $dT/dz =$ crustal geotherm, $z =$ depth.

Figure 2.13: Mean Annual Surface Temperature across the Australian Continent. Universally kriged continuous GIS coverage created by Dr Prame Chopra from data derived from the Australian Bureau of Meteorology.
using Arc/Info software. MAST data were supplied by the Australian Bureau of Meteorology as a digital grid comprising 22,244 points spaced at 0.25°. The geostatistical technique known as Universal Kriging (see below) was applied using Arc/Info to these data to interpolate onto a regular 0.1° grid and create a smooth continuous surface (Figure 2.13). Depth to basement data were supplied by Geoscience Australia as a GIS coverage comprising linear isopachs. In this case a minimum curvature spline technique was employed to interpolate a continuous depth to basement layer (Figure 2.14). Once completed both new GIS grids were intersected with well location data from AUSTHERM03 and values of MAST and depth to basement estimated for each individual temperature point. Temperature at 5km depth in each individual well was then calculated by application of one of five different model scenarios (Figure 2.15).

![GIS coverage displaying estimated depth to basement across the Australian Continent.](image)

**Figure 2.14:** GIS coverage displaying estimated depth to basement across the Australian Continent. Image created by Dr Prane Chopra using minimum curvature spline. The image is based upon sedimentary isopach data supplied by Geoscience Australia. Lighter shades represent greater depth. White contour = 0m; yellow depths between 1999-3000m; orange 5000-8000m and red >9000m.
In the process of estimating temperature at 5km depth, four data points were identified with seemingly anomalous temperature data. Investigations revealed the majority of these data were typographical errors and all but one was able to be corrected. The lone spurious point was excluded from further consideration along with a large number of offshore wells which lay outside the depth to basement GIS coverage. A working database comprising 5306 points with estimated temperature at 5km depth was thus generated for image processing.

**Figure 2.15:** Five possible scenarios encountered during extrapolation of AUSTHERM03 borehole temperature data to 5km depth. Pink indicates basement lithology, yellow basin, solid line with t-bar indicates total depth of a well, dashed lines the direction and extent of temperature extrapolation. T5km = temperature at 5km depth; TD = total depth of well in metres. Bottom of hole temperatures (BHT) from wells which terminated in basement were extrapolated to 5km using the standard geotherm of 25°C/km. BHT recorded in sediment were used to calculate a basin gradient [dT/dz(basin)] using Mean Annual Surface Temperature (MAST). This value was then used to extrapolate temperature to depth of basement (basement z) or 5km, whichever came first.

### 2.4.3 Image Processing

The artefact problems introduced by the TIN interpolation technique of Somerville *et al.* (1994) led to a search for a more rigorous method of image processing better suited to the strongly heterogenous AUSTHERM03 data distribution. A geostatistical
technique, Ordinary Kriging was eventually chosen. The kriging technique interpolates by using regionalised variable theory (RVT) to model the degree of spatial correlation between individual points based on their separation (Burrough and McDonnell, 1998). Points located within a finite distance of one another share a spatial correlation that increases with their proximity. Conversely, as point separation increases, spatial correlation decreases and eventually becomes statistically independent. The degree of spatial correlation of an attribute \( z \) between nearby pairs of points \( (x_i, x_{i+h}) \) separated by a given distance, \( h \), is given by its semi-variance \( \gamma(h) \) where,

\[
\gamma(h) = \frac{1}{2n} \sum_{i=1}^{n} (z_{x_i} - (z_{x_i} + h))^2
\]  

(1)

The pattern of spatial correlation for a given population may be illustrated using a semivariogram, a plot of semivariance versus distance, \( h \). Using the semivariogram, spatial variance present in the population can be modelled to enable a kriged interpolation which best fits the data. Application of a given model of spatial variance (e.g. spherical, circular, exponential, gaussian etc.) to data in which no systematic trends are present is called Ordinary Kriging. In cases where underlying trends are present within a population (e.g. the MAST data) an alternative process known as Universal Kriging, is used (Burrough and McDonnell, 1998).

![Figure 2.16: Semivariogram of AUSTHERM03 temperature data produced by ordinary kriging. The red line indicates the pattern of actual temperature data, blue the exponential spatial model fit.](image)

35
Ordinary Kriging of the estimated temperature at 5km depth data derived from AUSTHERM03 was conducted by Dr Prame Chopra in the Arc/Info GIS. A semivariogram of the temperature data is given in Figure 2.16. Despite some unevenness, including strong variance at large distances, an exponential spatial variance model appeared to be a reasonable approximation to the data. The exponential distribution is particularly appropriate in this instance as it reflects the theoretical conductive distribution of temperature with distance from a heat source or sink. Ordinary Kriging using the exponential model was then applied to the data to interpolate a regular 0.02° grid and create a smooth continuous surface (Figure 2.17).

**Figure 2.17:** Australian crustal temperature at 5km depth map version II (2003) created from the AUSTHERM03 database. Image is clipped to the continent boundary. Temperature scale as shown.
2.4.4 Image Interpretation

Like its predecessor the newly developed crustal temperature image (Figure 2.17) clearly delineates between regions of hot and cold continental crust. For the most part these regions are seen to be similar in location to those identified in the original map. Large disparities are evident in both the size and shape of the anomalies, however. These are clearly demonstrated by comparing the potential HDR resource surface areas calculated for the new and old images (Table 2.5; Figure 2.18). Using this standard, the new map image reduces the predicted HDR resource by nearly half compared to the 1993 map.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Surface Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>McArthur Basin</td>
<td>97140</td>
</tr>
<tr>
<td>Eromanga Basin</td>
<td>7660</td>
</tr>
<tr>
<td>(Cooper Basin)</td>
<td>(5030)</td>
</tr>
<tr>
<td>Canarvon Basin</td>
<td>9440</td>
</tr>
<tr>
<td>Canning Basin</td>
<td>1080</td>
</tr>
<tr>
<td>Perth Basin</td>
<td>390</td>
</tr>
<tr>
<td>Otway Basin</td>
<td>320</td>
</tr>
<tr>
<td>Surat Basin</td>
<td>260</td>
</tr>
<tr>
<td>Bass Basin</td>
<td>170</td>
</tr>
<tr>
<td>Gippsland Basin</td>
<td>50</td>
</tr>
<tr>
<td>Officer Basin</td>
<td>30</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>116540</strong></td>
</tr>
</tbody>
</table>

Table 2.5: Location and extent of geothermal anomalies where temperature at 5km is ≥225°C according to the Australian Crustal Temperature Map (2003). Brackets indicate sub-localities within the Eromanga Basin.

The marked differences in the size and shape of temperature anomalies described by the two maps are likely due to a number of factors. The use of Ordinary Kriging in the new image has clearly produced a better, more realistic interpolation. Temperature anomalies in areas of high data density on the new image appear as smooth, rounded features and contrast strongly with the sharp angular shapes of the original (Figure 2.19). Changes in image processing may also be partly responsible for variations in the size and location of specific anomalies. The increase in size of the McArthur Basin anomaly, for instance, cannot be attributed to differences in data distribution as no new points have been added to this area. Of particular interest with this anomaly is a lateral (EW) shift evident between the new and old images. Unlike
the TIN image, where the thermal high was located in an area of little or no data, the kriged image has placed the anomaly directly atop data.

Figure 2.18: Location and extent of geothermal anomalies (red) where temperature at 5km is \( \geq 225^\circ C \) according to the Australian Crustal Temperature Map (2003).

On the whole, structures present within the new image appear better constrained than those of the old map. Greater resolution in the surface temperature and depth to basement coverages is almost certainly contributing to this success. In the case of the McArthur Basin, which is characterised by relatively shallow wells, improvements to MAST may be contributing to the overall increase in the size of the anomaly. Also of significance (in areas outside Victoria and the Northern Territory) are the effects produced by the addition of new data points. These are most noticeable in Western
Australia, where the proportion of new data was highest, and are almost certainly responsible for changes such as the increase in size of the Carnarvon and Canning Basin anomalies.

Figure 2.19: Details of the new Australian Crustal Temperature Map at 5km depth as generated using geostatistical kriging of data contained in the AUSTHERM03 database. Areas shown are as for Figure 2.8, datapoint localities are indicated by black crosses. Comparing the new and old maps it is clear that the use of kriging has produced a smoother, more realistic image. Image artefacts remain apparent however, most noticeably in areas of sparse data coverage.

Although the overall patterns of relative temperature distribution appear broadly similar between both new and old images, there are some significant differences in absolute temperature predicted by the two maps. Generally speaking, high temperature zones within the central and eastern regions appear to be cooler in the new map than the old. Also different is the temperature of the western Archaean cratonic regions which are estimated to be warmer in the new image than in the old. Several factors are likely contributing to these discrepancies. Some temperature variations may be related to the application, in the new map, of the standard basement geotherm of 25°C/km. Heat flow models produced by Sass and Lachenbruch et al. (1979) predict theoretical steady state crustal gradients of between 10-18°C/km, 10-38°C/km and 20-40°C/km for the Western, Central and Eastern Australian Heat Flow Provinces respectively. Corresponding to average geotherms of around 14, 24 and 32°C/km it is clear that the use of the standard 25°C/km geotherm may result in both
temperature over-prediction in the West and under-prediction in the East. Any bias so introduced by the assumed basement geotherm could be reduced by using different standard values for each of the recognised Australian heat flow provinces. Technically this would not be difficult to achieve as it would merely involve dividing data into spatially associated groups prior to undertaking crustal modelling. Unfortunately time constraints on the current project did not allow for the testing of this possibility, hopefully it will be explored in future work.

The use of a standard basement geotherm is probably not the sole cause of absolute temperature variation between the two maps. Also likely to be contributing to these variations is the addition of greater control via new data and the removal of the automatic +10% temperature correction applied by Somerville et al. (1994) to all data of unknown status. In the latter case, by not using the Somerville correction a large proportion of the temperatures used in the new map are guaranteed to be lower than those employed in the GEOTHERM-derived image. It is not surprising then that much of the new image sees a general lowering of temperatures, particularly in regions such as the Cooper Basin where most records are derived from deep commercial wells that were likely to have been corrected in this way. Of course, by abandoning the use of the Somerville correction the new map is left open to the possibility that its temperatures are too low on account of the drilling induced thermal perturbation. An attempt to quantify the possible impact of this temperature suppression on the mapping process is included in Chapter 9 following an investigation into the performance of models for the correction of perturbed bottom of hole temperatures in Chapters 3 - 8.

Overall, areas identified by the new image as thermally prospective share much in common with that of the 1993 map. Whilst quantitative analysis (using the 225°C contour) sees the shuffling of some small anomalies (e.g. the loss of the Murray Basin anomaly and the gain of the Bass Basin one) in both cases areas of highest temperature are found to be exclusively associated with sedimentary basins. The three largest thermal anomalies, the Eromanga, McArthur and Carnarvon Basins are the same on both maps, although their relative magnitudes do differ. In each of these cases the temperature anomalies are established by data from multiple wells, decreasing the possibility that they could be the result of error. Outside of these areas
anomalies are generally supported by one or two wells only, implying their reliability may be reduced. In the case of the McArthur, Carnarvon and most Western Australian anomalies additional caution must also be exercised as the available temperature data were often sourced from relatively shallow wells (>1000m) and the extrapolation of temperature to 5km is large.

Most of the thermal anomaly attributed to the Eromanga Basin is in fact located within the region of the obscured Cooper Basin. As mentioned, high temperatures within the Cooper region were attributed by Somerville et al., (1994) to buried radiogenic granites. Two main anomalies are visible in this area. The first is a strong peanut-shaped feature (1882km$^2$) based upon multiple well data and located to the south. The second, a large round anomaly (3005km$^2$) located to the north is based solely upon one well, Whanto 1 [26°31’13.44” S, 142°11’40.92” E]. Of the two anomalies, only the southern is known to be spatially associated with basement granite. More detailed discussion on the size, shape and causes of these features are included in Chapters 9 and 10.

Outside of the Cooper, the Eromanga is host to only a relatively few, isolated, single-well anomalies. Somewhat ironically the largest of these is centred upon the geothermal bore at Birdsville which taps into the high temperature Jurassic aquifers of the Great Artesian Basin, specifically for the purposes of power generation. The detection of this anomaly, which is attributable to advection of heat by migrating groundwater, indicates the potential of the map image for the identification of both wet and dry geothermal resources. Similar ‘wet’ geothermal resources may account for other thermal anomalies in the Eromanga as well as in the Carnarvon and Otway basins where advective fluid effects have also been documented (Swift, 1988; Somerville et al., 1994).

Of more interest to dry geothermal exploration are anomalies contained within areas which may be associated with buried crystalline rock. Aside from the Cooper these include some areas in the Eromanga and McArthur Basins. Of particular note in the Eromanga is an isolated anomaly associated with well Mulkarra West 1 [27°51’35.576”S, 138°39’58.385”E]. Previously observed by Somerville et al. (1994) this anomaly is one of few to reappear on the new mapped image and is located above
a gravity low which Somerville *et al.* considers to be a granite body. Proterozoic granite intrusions are also observed within the McArthur Basin and may be of relevance to HDR exploration (Rawlings & Page, 1999). Structures such as the Wilton Dome in the Mt Marumba area of south-central Arnhem Land, interpreted by Rawlings & Page (1999) as a buried microgranitic laccolith, may also prove to be a suitable target for exploratory drilling. This structure is believed to be analogous to a number of other features identified across the exposed basin (Rawlings & Page, 1999). Of particular interest is the possibility that such features may also exist within the buried McArthur sequence beneath the Phanerozoic Georgina Basin to the south.

Of course, granite plutons are not the only possible substrate for HDR development. As demonstrated by the Fenton Hill and Bad Urach projects, gneissic crystalline basement may also be employed to host the engineered reservoir (Appendix 1). The possibility of exploration targets relating to subcropping Proterozoic basement, such as the Pine Creek Inlier under the McArthur or the Musgrave or Willyama complexes under the Eromanga (Chapter 10) should not be eliminated. It must also be remembered that the 225°C contour is an arbitrary limit and does not rule out the prospectivity of other buried granites in nearby regions which are likely to be only slightly cooler. A map illustrating the distribution of potentially semi-prospective granite bodies within the Cooper Basin region is included in Chapter 10.

### 2.5 Future Work

The creation of the new Australian Crustal Temperature map has demonstrated the advantages of using more rigorous GIS techniques including interpolation by means of geostatistical techniques. The application of Ordinary Kriging to the AUSTHERM03 temperature data has resulted in the production of a temperature map characterised by more realistic smooth and rounded anomalies. Unfortunately, like the old image the new map is subject to regions of interpolation error and there remain many structures evident in the new image which are clearly spurious (Figure 2.19). For the most part these structures appear in areas where there is little or no temperature data available implying that, once again, the underlying problem is that of a strongly heterogenous data distribution.
The AUSTHERM03 database represents the most complete and up-to-date compilation of Australian crustal temperature data currently available. It is clear from work recently conducted on this database that any future addition of newly released petroleum well temperature data is unlikely to contribute to an improvement in data distribution. Unfortunately, examination of the alternative sources of crustal temperature data indicate relatively little potential for solving this problem. Mineral wells, whether deep or shallow, generally do not have downhole logs run or records of downhole temperature. Likewise, examination of temperature datasets derived from water wells reveal most are recorded from flowing water at surface. Typically, this water is derived from one or more screens accessing several different aquifer depths. In the absence of any viable alternative then, the problem of the heterogeneous data distribution appears set to persist.

This being the case the question remains as to whether any steps may be made to improve the quality of the mapped image. The possible impact of applying borehole temperature corrections will be examined in Chapter 9 although this line of enquiry will necessarily focus upon image quality in areas already populated by data and not, therefore, those host to artefacts. The key to techniques that may assist in artefact reduction may instead lie in the observation that heat flow provinces are characterised by a narrow range of basement geotherms. This result necessarily implies that areas of crust having similar histories and composition may also display similar thermal traits and raises the possibility of using geological controls to influence the image creation. Application of geological control, based upon boundaries defined by known or inferred basement provinces, could effectively isolate areas of little or no data coverage, preventing interference effects which add to image artefacts. Whilst such a concept would likely result in the creation of a map which contains white areas or data holes it, would also serve to produce a more reliable image in which coloured areas occur only where data is present. Attempts at providing basement control for the kriged temperature image using boundaries as defined in the Australian Tectonic Elements map (Shaw et al., 1996) are currently underway. Some preliminary results of this work are detailed in the paper Chopra & Holgate (2005).
2.6 Conclusions

Work completed on the production of a new Australian Crustal Temperature Map included the successful expansion and updating of an existing database of borehole temperatures created by Somerville et al., (1994) to form a new database called AUSTHERM03. A GIS coverage based upon AUSTHERM03 was created using geostatistical kriging to interpolate a new temperature image. These efforts combined resulted in the production of a map image in which many major artefacts and linear anomalies originally present have largely been eliminated. High temperature anomalies identified on the new map are generally coincident with those previously identified by Somerville et al., (1994) although there is some significant variation in the size and shape of these areas. Regions of greatest geothermal prospectivity on the new map are located in or beneath sedimentary basin sequences, the three largest anomalies being within the McArthur, Cooper and Carnarvon Basins respectively. Despite the successes of the new map there still remain a number of areas in which further improvement is possible. Image artefacts present in the updated map reflect ongoing problems of unequal data distribution and are unlikely to be further assisted by addition of new petroleum well data to AUSTHERM03. Future improvements to the temperature image are more likely to result from improved image processing techniques one of which, the introduction of geological control to the kriging process, remains under investigation.
CHAPTER 3
MODELLING BOREHOLE THERMAL RECOVERY

3.1 Introduction
The economic commodity contained within any geothermal resource is heat and the effective grade of the resource is reflected by its temperature. Accurate measurement of the static or true formation temperature is thus a critical requirement for the identification of thermally prospective regions which may contain an economically viable geothermal resource. Measurement of true formation temperature at depth within the crust requires the physical emplacement of a thermometer to depth. There are a number of methods by which this may be achieved, the most common (and economical) being to drill a borehole. Unfortunately, the process of drilling deep wells is usually dependent upon the circulation of drilling fluids or ‘mud’ for the cooling and lubrication of the drill bit. Such fluids necessarily provide an extremely efficient heat transfer mechanism and often result in the introduction of a persistent thermal anomaly into the region surrounding the well. These anomalies may be significant and, if left unaccounted for, may lead to highly erroneous estimations of true formation temperature.

Any given drilling-induced thermal disturbance is small when compared to the crust as a whole implying that the problem of anomalous borehole temperatures may be avoided altogether if sufficient time is available to allow for full thermal relaxation prior to recording a measurement. The length of time necessary for this recovery is dependent upon a number of factors and may vary widely from minutes to months or even years for a rotary drilled well. As a general rule Bullard (1947) suggests a period of between ten to twenty times the total duration of mud circulation in the well will be required for full thermal re-equilibration. Should it not be possible to wait for this length of time then some form of calculated adjustment is necessary in order to relate perturbed temperature measurements to the true formation temperature.

The range of available models describing the thermal evolution of the well-rock system is quite large and varies from simple empirical formulae to more complex
theoretically derived solutions. The most common (and the simplest) forms are those which focus solely upon the recovery of the deepest well regions where temperatures are most often recorded. To date at least twenty different mathematical and empirical models have been proposed to simulate bottom of hole well temperature relaxation (Bullard, 1947; Nakaya, 1953; Cooper & Jones, 1959; Lachenbruch & Brewer, 1959; Parasnis, 1971; Albright, 1975; Dowdle & Cobb, 1975; Fertl & Wichmann, 1977; Middleton, 1979a; Leblanc et al., 1981; Middleton, 1982; Lee 1982; Luhehi, 1983; Perrier & Raiga-Clemenceau, 1984; Pitt, 1986; Ribeiro & Hamza, 1986; Shen & Beck, 1986; Cao et al., 1988a; Cao et al., 1988b; Neilsen et al., 1990). Most of these models solve for true formation temperature by simulating the time-dependent thermal recovery of the well, usually via some form of curve-matching technique. Input data required for these solutions thus invariably includes a consecutive series of perturbed downhole temperature measurements, recorded at discrete intervals after the end of drilling. While such data, derived from successive wireline logging runs in commercial petroleum and water wells, are often readily available, far more rare is reliable information about true formation temperature. To re-enter a well long after drilling has ceased is costly and most often not commercially necessary. Similarly, the high cost of drilling combined with limited research budgets necessarily restricts the number and depth of scientific wells drilled for stratigraphic and/or heat flow measurements. For this reason most models of bottom of hole thermal recovery suffer from a distinct lack of field validation.

Several attempts to circumvent the lack of available measures of true formation temperature and test the accuracy of models for bottom of hole thermal recovery by using suitable substitute formation temperature estimates have been made (Perrier & Raiga-Clemenceau 1984; Hermanrud et. al. 1990; Förster and Merriam 1995). Drill stem or formation tests (DST), often run routinely on exploratory or appraisal petroleum wells, produce temperature results which are commonly cited as a good alternative to measured static temperature. Hermanrud et. al. 1990 provide a comparison of twelve different bottom of hole models using data from 18 North Sea oil wells. In this case temperature predictions are normalised to a depth of 2700m and rated against temperatures derived from DST. To date this paper is the only other known attempt at comparing the performance of a range of bottom of hole

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temperature models. No further large-scale studies of these models have been found and certainly none at all which use actual measured formation temperatures.

A significant feature of Australian mining and petroleum law is the inclusion of mandatory annual reporting as a condition in the granting of both mineral and petroleum licences. All on-site activity conducted by a leaseholder or its authorised agent, and the results of that activity, must necessarily be reported in full to the relevant government department upon the anniversary of the lease. These data are compiled and held confidential for a limited period before eventually being released onto an open-file system for public access. As a result large databases of down-hole temperature measurements derived from commercial wells are common and often freely available. The vast majority of these reported downhole temperatures are uncorrected values measured shortly after the cessation of drilling and thus require correction. The AUSTHERM03 database is a compilation of this kind of available open-file downhole temperature data derived from bore holes drilled across the Australian continent. Included within AUSTHERM03 are a large amount of data sourced from the South Australian Department of Primary Industries and Resources (PIRSA) and detailing wells located in the Cooper Basin region of SA.

Situated in north-east SA the Cooper Basin is host to a number of commercial gas and oil fields and has been extensively drilled over a period of 30 years. These wells are often suspended post-drilling to await future development as production points and may remain in this state for periods of several years prior to reactivation. A common practise for both newly completed and older suspended wells is the running of a sonic cement bond log (CBL) designed to evaluate the quality and integrity of the casing cement. These logs, run anywhere from days to years after the end of drilling commonly include a maximum reading thermometer (MRT) bottom hole temperature (BHT) measurement which often effectively represents the true formation temperature. These data have been captured by PIRSA alongside the standard post-drilling log BHT and are included in the AUSTHERM03 database. A total of three hundred and thirty-five (335) wells from the Cooper basin region contain records with CBL static temperatures. These wells have been extracted from AUSTHERM03 into a new dataset entitled the Cooper Basin Static Temperature database (CBST) and
provide the basis for a unique comparative study of the performance of bottom of hole temperature recovery models in real-world application.

3.2 The Drilling Induced Thermal Disturbance

The act of drilling into the crust produces a thermal disturbance at each point along the length of the borehole. The shape and strength of this disturbance is dependent upon the size and depth of the well and the style of drilling used to create it. The mechanisms for heat transfer between the rock and well are direct conduction across the borehole wall and convection from mass transfer of fluids into or out of the well. At modern drilling rates heat exchange between the borehole contents and rock begins the moment the drill bit passes through a given point and continues over time until the system regains equilibrium. This period may be divided into two separate phases, that of active disturbance during drilling and passive relaxation after drilling has ceased.

The process of drilling deep wells is dependent upon the circulation of drilling fluids throughout the hole. Drill fluid or ‘mud’ is necessary for the cooling and lubrication of the drill bit and pipe, the exhumation of cuttings from the bottom hole and assumes an important role in the maintenance of well bore stability. Fluids are generally pumped down the centre of the hollow drill pipe to the bottom hole region and are released into the hole through the bit before returning to surface via the annular region between the drill string and the well wall. Circulation volumes and rates vary considerably depending upon drilling technique and conditions but are usually much lower for diamond drill holes than rotary wells. The presence of a circulating fluid plays a pivotal role in the transfer of heat throughout the drilling process. Circulation maintains relatively low and often near constant mud temperatures within the well thereby enhancing the temperature gradient across the well wall which in turn promotes conductive heat exchange with the formation. By comparison, most other potential sources of thermal disturbance associated with drilling, such as frictional heating from the bit and rotation and deformation of the drill pipe are generally negligible and any heat generated in this way is quickly dissipated by the circulating mud (Lachenbruch & Brewer 1959). Drilling techniques which do not depend upon large volumes of circulating fluid, such as diamond coring, generally display much smaller thermal anomalies than those found associated with rotary wells (Jaeger,
1961; Wilhelm, 1990). The only other process likely to produce a substantive contribution to the thermal state of the borehole during drilling circulation is that of the advection of heat via fluid exchange between the well and formation.

The use of drilling fluids implies that the thermal disturbance due to drilling is not instantaneous but rather begins at the time the drill bit passes through a given point and continues until the cessation of circulation at the end of drilling. Each point downhole is subject to a slightly different disturbance with points in the deepest hole regions experiencing shorter periods of circulation than those near surface. The magnitude of the thermal disturbance is therefore depth dependent, a reliance further complicated by the natural variations with depth of in-situ formation temperature and the changing physical properties of the rock strata. Thus, at any given point in time the magnitude of the drilling thermal disturbance will vary with depth down-hole.

The ongoing nature of the drilling process also implies that, in addition to this depth dependence, the intensity of the thermal disturbance at any given depth has a time dependence as the temperature of the circulating mud will vary as the bit travels deeper into the crust. In the case of deep wells in particular, points in upper hole regions which were initially cooled by the presence of circulating mud may over time in turn be heated as warmed drilling fluids continue to rise from depth. Other factors influencing the pattern of the disturbance through time include routine disruptions to the drilling process such as breaks for bit changes, logging, casing etc and unintended interruptions such as rig breakdown and hole cleaning and stabilisation. Thus, at any given depth down-hole the magnitude of the drilling thermal disturbance will vary with time.

The end of the disturbance phase coincides with the cessation of circulation at the completion of drilling. From this point on the thermal anomaly induced by the disturbance will gradually begin to fade as the system relaxes back toward equilibrium. The rate of this recovery is dependent upon the strength of the initial disturbance, the properties of the mud used and local rock types and the size of the borehole. Just as the magnitude of the initial disturbance may be influenced by advective heat exchange, so too the rate of well recovery will be enhanced or diminished by fluid transfer between the well and formation.
The drilling induced thermal disturbance is thus a time dependent, depth dependent feature which continues throughout the period of drilling circulation. Factors affecting the magnitude of the temperature disturbance include the difference in temperature between the circulating mud and rock, the length of time of fluid circulation \( t_c \), the rate of circulation, the radius of the borehole, the thermal properties of the mud and rock and the presence or absence of invading fluids. The thermal anomaly produced by the disturbance will grow throughout circulation before gradually dying away during the relaxation period after the cessation of drilling. The magnitude of the post-drilling temperature anomaly at any point downhole will depend upon the intensity of the disturbances at that point, the local thermal properties of both the mud and the formation, the amount of time elapsed since drilling ceased (post-drilling time or ‘lag’ time \( t_L \)) and the presence or absence of local invading fluids.

3.3 Models for Borehole Thermal Recovery

In commercial petroleum wells, which are almost always rotary drilled, the length of time required for full recovery of the newly drilled system is often far greater than the time elapsed prior to the running of evaluation logs. In the absence of fluid exchange with the formation the length of time required for a given well to regain thermal equilibrium is proportional to the duration of circulation although recovery times are very much longer, estimated to be of the order of ten to twenty times the total time required for drilling (Bullard, 1947). Economic pressures to complete and the generally low value placed on temperature data implies that most temperature measurements from commercial wells are collected under less than ideal conditions. Available data are usually sourced from maximum reading thermometers (MRT) which have been run attached to some other form of logging tool, often a sonic or porosity instrument. Only very rarely are there full downhole temperature logs available for commercial wells and even these are most often a by-product of logging runs primarily designed for some other purpose.

Any BHT data collected under non-equilibrium conditions will display the effects of the drilling induced thermal anomaly and can therefore be used only as a lower limit
to true formation temperature. Full downhole temperature logs taken under the same non-ideal conditions will also display artificially depressed temperatures in the bottom hole region as well as a gradual up-hole shift towards artificially enhanced temperatures (Figure 3.1). In order to relate these perturbed temperatures to the true formation temperature it is necessary to generate some form of thermal model for the well-rock system.

![Figure 3.1: Schematic diagram illustrating the effect of drilling upon true formation temperature. The stippled line (dots) represents a natural or true in situ geotherm prior to commencement of drilling. Line A (dashed) is the same geotherm measured by a wireline logging tool immediately after the end of drilling and circulation. Note the presence of an upper zone of heating caused by the rise of warm drilling fluids from depth, also the obliteration of the vertical temperature gradient in the most recently drilled EOH region. Line B (solid) represents the geotherm after a period of thermal recovery. The high rate of thermal recovery in the bottom of hole region is a product of the relatively short period of circulation experienced by this zone producing a comparatively high radial gradient.](image)

As discussed above there are a large number of mathematical models which have been created to deal with the question of the drilling induced thermal disturbance. Most commonly treated as a problem of heat conduction through a solid, models for drill hole temperature equilibration fall into two main classes: that of whole-hole and bottom of hole. Whole-hole models, as their name suggests, attempt to describe the
thermal recovery of the well-rock system along the entire length of the borehole. These models are usually complex, requiring a large number of input parameters and extensive knowledge of the drilling history, details of which are often poorly reported for commercial wells. In contrast, bottom of hole models concentrate solely on the end-of-hole region where temperatures are often recorded and may vary from relatively simple to increasingly sophisticated forms. As BHTs sourced from MRTs are the most common form of temperature measurement recorded from petroleum wells, and because of their relative simplicity, bottom of hole models are considered the method of choice for dealing with data derived from commercial sources.

3.4 Models for Bottom of Hole Thermal Recovery

Models for the thermal recovery of deep borehole regions after drilling may be broadly classified as being either empirical or theoretical in nature. Empirical models are typically based upon direct observations of thermal recovery curves and include the original Horner temperature plot (Dowdle & Cobb, 1975) the semi-log plot (Pitt 1982) and various exponential models (e.g. Nakaya, 1953; Parasnis 1971; Perrier & Raiga-Clemenceau 1984). By contrast theoretical models are based upon physical theories of heat conduction in solids and may or may not attempt to account for the added effects of advective heat transfer due to fluid transfer into and out of the well (e.g. Bullard, 1947; Middleton, 1979a; Lee, 1982; Luhehi, 1983; Shen & Beck, 1986). All bottom of hole models, irregardless of type, share the assumption of constant depth and hence need only account for changes in the temperature disturbance with time.

Hermanrud et al. (1990) provide the only known comparative study of multiple bottom of hole models. Based on petroleum well data from the North Sea Oseburg Field, the study used the results of drill stem tests (DST) as a means of estimating true formation temperature. DST data derived from 36 separate wells were normalised to a common depth of 2700m producing a single value of 107.2 ± 2.5°C. Next, twelve different BHT models were used to predict T_{eq} from logging temperature series recorded in 18 wells. The values of predicted T_{eq} were then normalised to 2700m and the mean and standard deviation of each model was calculated. In this way, assuming isothermal conditions at depth and errors due to extrapolation to be less than 2-3°C,
the accuracy and precision of the various models was able to be assessed. The results of this study are provided in Table 3.1 and will be discussed in the context of the individual models in the following sections.

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<th>Inverse</th>
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<td></td>
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Table 3.1: Results from testing of BHT models after Hermanrud et al. (1990). All temperatures are in degrees Celsius. True formation temperature is estimated to be 107.2°C. SD is standard deviation. Column “Forward” indicates results determined from forward modelling using pre-determined parameters. Column “Inverse” indicates results generated from inverse modelling where input parameters were optimised from the data.

3.4.1 Empirical BHT Models

The Horner Plot
Perhaps the most widely used technique for formation temperature estimation, the Horner plot is valued for its simplicity and easy application. Although the original Horner temperature plot was an empirical solution, the form of the equation is identical to one which may be derived mathematically from a conductive line source model of borehole axial temperature. This duplication of the equation has led to a confusing situation where the term ‘Horner plot’ is used interchangeably for both models.

The empirical Horner equation was generated out of a perceived similarity between the 1-D (radial) equations governing the pressure recovery of a well during shut-in after venting and those of conductive thermal recovery after drilling (Dowdle &
Cobb, 1975; Fertl & Wichmann, 1977). The theoretical pressure problem was solved by Horner (1951) who concluded that, for the case of constant production rate in an infinitely large reservoir, well pressure build-up could be described by the linear equation:

$$ P_{At} = P_{eq} - c \log\left(\frac{t + \Delta t}{\Delta t}\right) $$

(2)

Where $P_{At}$ is the bottom-hole shut-in pressure at time $\Delta t$ after shut-in commenced, $P_{eq}$ is the equilibrium formation pressure, $c$ is constant and $t$ is the amount of time during which the well flowed prior to shut-in. Using (2) it is possible to solve for $P_{eq}$ by straight line extrapolation on a semi-log graph of $P_{At}$ vs $(t + \Delta t)/\Delta t$, a method now referred to as the ‘Horner pressure plot’.

The problem of the thermal recovery of a well after drilling is at least superficially similar to the Horner pressure case if the thermal recovery of the well is considered to be a largely radial effect. If changes in radial temperature gradient are considered to be analogous to those in radial pressure gradient then the temperature solution may be assumed to be of identical form to the pressure:

$$ BHT(t) = T_{eq} - m \log\left(\frac{t_c + t_o}{t_c}\right) $$

(3a)

or, as it is more often written:

$$ BHT(t) = T_{eq} + m \log\left(\frac{t_c}{t_c + t_c}\right) $$

(3b)

and may be solved for $T_{eq}$ in a graphical manner analogous to the pressure problem. Dowdle and Cobb (1975) qualitatively assess the validity of this assumption by considering the respective transient processes. They find that whilst the initial and outer boundary conditions are identical for both pressure and temperature cases the internal boundary conditions are not consistent. The Horner pressure model is valid only for cases of constant production rate, a condition which implies a drop in well
pressure during venting and requires a constant radial pressure gradient. This is not consistent with the normal temperature situation where well temperature is held constant throughout circulation and radial temperature gradient decreases slowly with time. Dowdle and Cobb (1975) conclude that the Horner temperature equation is not justified mathematically by the pressure solution but is nonetheless a reasonable empirical approximation for cases where circulation time is short and radial temperature gradient may be considered approximately constant. Using several real-world examples they go on to make the point that the inherent uncertainties present in most real data are likely to justify the use of the graphical Horner solution. At short circulation times the departures of real data from the ideal straight line model are small enough that they are indistinguishable from random scatter associated with data noise.

The Semi-Log Plot

Even simpler mathematically than the empirical Horner equation, the semi-log plot is the technique most commonly used for the estimation of formation temperature in well completion reports accompanying Cooper Basin wells. The origin of the semi-log plot technique is uncertain but it is presumably an empirical model. As its name suggests, the plot solves for formation temperature by straight line extrapolation on a semi-log graph of BHT vs \( t_r \) to some arbitrarily long time. Similar in appearance to a Horner Plot, the semi-log plot is likely to be an adaptation of the Horner technique designed to estimate formation temperature where circulation time is unavailable. Pitt (1986) refers to the semi-log plot as a ‘purely mathematical construction’ for the extrapolation of temperature trends to periods of long time after drilling. He goes on to claim that formation temperatures predicted using this technique agree with Horner predictions to within two percent.

Exponential Models

The use of exponential models to describe the temperature relaxation phase of a newly drilled borehole is traced back to Nakaya (1953) who suggests a relationship of the form:

\[
BHT(t) = T_{eq} - Ae^{-\beta t}
\]  

(4)