Western Australian
Geothermal
CENTRE OF EXCELLENCE

Perth Basin Assessment Program

Project 2:
GEOMODEL

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October 2012

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ISBN 978-0-643-10905-6

Report 3

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EXECUTIVE SUMMARY

The Western Australian Geothermal Centre of Excellence (WAGCoE) conducted scientific and engineering research into WA's geothermal resources, principally Hot Sedimentary Aquifer (HSA) resources in the Perth Basin. Project 2 of the Perth Basin Assessment Program focused on the development of a geological model of the Perth Basin. Knowledge of the structural architecture and stratigraphic geometry of the Perth Basin is a vital prerequisite for understanding subsurface fluid and heat flow. This understanding is fundamental to the identification of geothermal prospects and to effective aquifer management in the Perth Basin. The present report provides new approaches, data sets and analyses for characterising the structural and sedimentary geology of the Perth Basin. Results are presented in eight sections:

Section 1. The most up-to-date publically available aeromagnetic, gravity, bathymetry and digital terrain data are reprocessed to develop the first three-dimensional model of the entire Perth Basin. This model incorporates newly identified faults and fault segment extensions.

Section 2. A new high-resolution, three-dimensional model of the Perth Metropolitan Area (PMA) is presented. The PMA model incorporates a dense network of faults of several orientations which account for depth and thickness changes in subsurface geology, and horizontal compartmentalisation of the subsurface geology is indicated on a scale of 1.5-2 km.

Section 3. A new sedimentological model is developed for key geothermal target formations in the central Perth Basin via a lithofacies analysis of core from existing deep petroleum exploration wells. Complex stacking arrangement of lithofacies on the order of 10 cm to approximately 2 m vertical scale is observed in all formations and wells, which indicates complex switching of different sedimentary depositional environments in time and space.

Section 4. New data is presented on petrography, detrital and diagenetic mineralogy, and laboratory-measured petrophysical data (porosity, permeability, thermal conductivity) from core from key geothermal target formations in the central Perth Basin. These data provide vital new fundamental parameters for geothermal exploration of the Perth Basin.

Section 5. Wireline logs from Cockburn-1 well were used to estimate porosity and permeability traces, providing insight into the variation of these parameters with depth for a continuous vertical profile.

Section 6. A stratigraphic forward model of the Yarragadee aquifer (using Sedsim) provides an insight into the three-dimensional stratigraphic architecture of a key geothermal target of the Perth Basin.

Section 7. The effects of faulting on fluid flow properties are assessed via a multi-scale analysis of core of a potential geothermal target formation from the damage zone of a regional fault in the North Perth Basin. Subvertical fault-related fractures have been sealed by brecciation, quartz and siderite cementation; sub-horizontal stylolites are common and contain halos of quartz cementation. These studies indicate that most, if not all of the faults in the northern Perth Basin would be sealing at depths relevant to geothermal exploration.

Section 8. The contribution of radiogenic heat from the basement to the Perth Basin is characterised using existing and newly acquired data from the Leeuwin complex, SW Australia, and existing data from proposed analogues to the Perth Basin basement in Antarctica. Estimates of the total heat flow due to radioactive decay in the basement are of the order of 25 to 56 mW m^{-2}, and geothermal gradients calculated for plausible thermal conductivity values are 17 to 35 °C km^{-1}.

The data in this report provides new fundamental constraints from which geothermal potential can be assessed and geothermal resources can be defined in the Perth Basin.

PREFACE

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

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

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

The Perth Basin Assessments Program contained the following four research Projects:

- WAGCoE Data Catalog (Project 1)
- Perth Basin Geomodel (Project 2)
- Hydrothermal Simulations (Project 3)
- Reservoir Productivity and Sustainability (Project 4)

This document is the final research report of Project 2 within Program 1 of WAGCoE. The format of the document is that of a summary report; detailed tabulations of technical data and results are to be found in the supporting research reports, papers and theses cited herein.

ACKNOWLEDGEMENTS

WAGCoE was funded by the Western Australian government and the partners of CSIRO, the University of Western Australia, and Curtin University. We also received financial support from our industry associates, Green Rock Energy Ltd and GT Power Pty Ltd. We acknowledge the use of regional geophysical datasets from Geoscience Australia and Geological Survey of Western Australia in Section 1. We gratefully acknowledge the guidance and assistance provided by GT Power Pty Ltd and Green Rock Energy Ltd for financial support and help with securing permissions from Councils and Department of Mines and Petroleum, and for various exploration activities in their geothermal lease holdings. We particularly thank Atlas Geophysics for their professionalism and collaboration in acquiring new high resolution gravity data in the Perth metropolitan area in 2009 and 2010, presented in Section 2. Two University of Western Australia students - Thomas Hoskin and John Mitchell – are also thanked for their assistance with gravity data acquisition. We thank Curtin Department of Exploration Geophysics staff for collaboration in the Vertical Seismic Profiling (VSP) surveys carried out at St Hilda’s School, Mosman Park and in Kensington. Rockwater Pty Ltd kindly provided assistance in accessing the new geothermal borehole at St Hilda’s School. Maxam Australia Pty Ltd is acknowledged for the provision of explosives and expertise in the conduct of the VSP surveys. Dariush Nadri of CSIRO provided processing expertise in reprocessing the VSP data. We thank the Western Australia Core Library facility for their assistance with access to the core and sampling. C. Delle Piane, L. Esteban and S. Israni acknowledge receipt of funding through a CSIRO ISF project “Rock Physics for geothermal applications”. Sandra McLaren (University of Melbourne) is thanked for assistance during acquisition of thermal conductivity data. The Institute of Geoscience Research (TIGeR) at Curtin University is thanked for provision of some of the equipment used in this study. Susanne Schmidt (CSIRO) is thanked for her assistance with the Zeiss Axio Imager II system. H. Olierook thanks ARC Energy Ltd for use of their porosity and permeability data from Apium-1 (Section 7). We thank Elaine Miller and Rob Hart (Curtin University) for support with electron microscopy. Cameron Huddlestone-Holmes, Susanne Schmidt, June Hill, Domenik Wolf-Boenisch and Mike Trefry are acknowledged for their careful reviews of earlier versions. We thank Angelo Vartesi for his draftsmanship and assistance with compilation of the report. We acknowledge support from the Western Australian Geothermal Centre of Excellence.

8. QUANTIFICATION OF MAGNITUDE AND LENGTH SCALE VARIATION OF HEAT PRODUCTION FROM THE BASEMENT ROCKS OF THE PERTH BASIN

8.1 Introduction

The Perth Basin covers an area of around 4000 km^2, and is comprised of up to 12 km thickness of Phanerozoic sedimentary rocks. A significant proportion of these units have relatively high permeabilities and form good aquifers (Davidson, 1995). There is, therefore, significant potential for HSA (Hot Sedimentary Aquifer) geothermal energy extraction in the Perth Basin.

Successful prediction of the geothermal potential of the Perth Basin requires knowledge of a wide variety of parameters; the parameter of interest for this study is the heat production potential of the crystalline basement to the Perth Basin. If the basement is rich in heat-producing elements such as U, Th and K then the basement will provide enhanced heat flow to the overlying sediments, which will increase the viability of geothermal energy applications.

In addition to the magnitude of the heat producing capacity, it is necessary to determine the spatial variation of this parameter. Natural variations occur as a function of changes in rock type, both laterally and vertically, and the magnitude and typical length scale of these variations will determine if the geothermal potential of the Perth Basin is evenly distributed, or varies only on short length scales (less than tens of metres). If this is the case then locations for drilling are likely to be determined by factors such as site accessibility and the geology of the Perth Basin sediments. If, on the other hand, heat production varies significantly on length scales large enough to influence fluid temperature (tens of kilometers upwards), then it is worth focusing effort into location of hot spots, and further investigation of the Perth Basin geology.

Unfortunately, the basement to the Perth Basin is largely inaccessible because of the thick sedimentary cover, and there have been relatively few measurements of the heat production of the basement. The purpose of this study is to combine new and existing measurements of heat production from the Perth Basin, and from rocks deemed to be equivalent that are exposed elsewhere. The data compilation is then used to investigate the likely distribution of heat production in the Perth Basin basement, and to estimate the probable dominant length scale and magnitude of variation. This information can then be used to develop stochastic models of heat production that can be used to constrain models of heat flow in the Perth Basin.

8.2 Geological Background

The Perth Basin sedimentary sequence overlies crystalline basement that is thought to form part of the Pinjarra orogen (Fitzsimons, 2002). The Pinjarra orogen lies at the current western margin of the Yilgarn Craton, and is at least 1500 km long. The orogen, in Australia, is bounded by the Darling Fault to the east, and by the ocean to the west, and is thought to extend along the whole length of the western continental margin (Fig. 8.1).

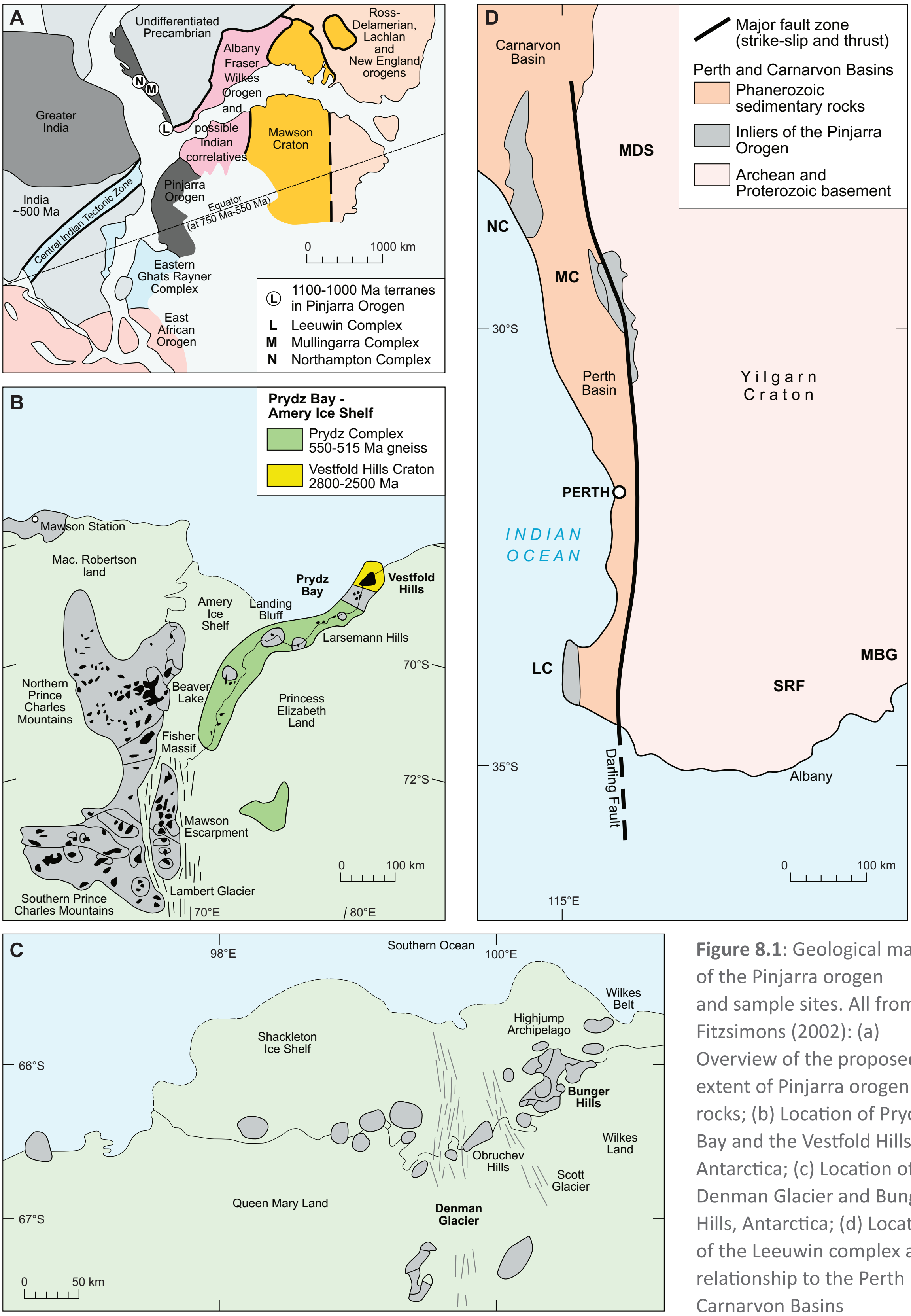


Figure 8.1: Geological map of the Pinjarra orogen and sample sites. All from Fitzsimons (2002): (a) Overview of the proposed extent of Pinjarra orogen rocks; (b) Location of Prydz Bay and the Vestfold Hills, Antarctica; (c) Location of the Denman Glacier and Bunger Hills, Antarctica; (d) Location of the Leeuwin complex and relationship to the Perth and Carnarvon Basins

The Pinjarra orogen is a N-S-trending tectonic boundary that records deformation, magmatism at 1080 and 750 to 500 Ma (Fitzsimons, 2002; Myers, 1990). The Darling Fault, at the western margin is, most recently, a Phanerozoic structure with a record of normal displacement during Gondwana breakup.

Exposure of the orogen is poor, however, and outcrops are found only in the Northampton and Mullingara complexes. The Leeuwin complex has rocks that have been produced and metamorphosed at similar ages to those included in the Pinjarra orogen, but the precise relationship of this block to the Pinjarra orogen is controversial (e.g. Wilde, 1999).

It has been proposed that the Pinjarra orogen extends into Antarctica (Fig. 8.1; Fitzsimons, 2002; Boger, 2011), and is exposed in the region of the Denman Glacier. It has also been proposed that rocks in the Prydz Bay area, the Vestfold Hills and the Bunger Hills may form part of the orogen (Fitzsimons, 2002; Boger, 2011), but poor exposure of the regions between these areas of outcrop preclude definitive attribution of areas such as the Vestfold and Bunger Hills to the Pinjarra orogen. Antarctic evidence suggests that the Pinjarra orogen was a major orogen that divides East Gondwana in two, and may record either Mesoproterozoic collision (1080 Ma) followed by intracratonic reactivation in the Neoproterozoic, or a major Neoproterozoic suture that incorporates Mesoproterozoic terranes.

The Northampton and Mullingara complexes are mostly composed of psammitic paragneisses, with subordinate conformable lenses of pelite, quartzitic and mafic gneisses (Myers, 1990). The Leeuwin complex is different in that the most common rock type is felsic orthogneiss, with mafic, intermediate, and anorthositic units (Fig 8.2; Myers, 1990; Wilde and Murphy, 1990; Collins, 2009).

Variably deformed felsic plutonic rocks are the most common rock type in the Denman Glacier area. These are associated with lesser quantities of hornblende-biotite orthogneisses, and psammitic and pelitic gneisses. The Prydz bay region comprises interleaved ortho- and paragneisses which have been metamorphosed at granulite facies and intruded by Neoproterozic granites. The Vestfold Hills, which lie within the greater Prydz Bay region, contain much older Archean cratonic rocks (2800 – 2500 Ma), and include tonalitic and monzonitic gneisses, plus younger basic intrusions. The Bunger Hills contains Archean – Palaeoproterozoic crust that was reworked by both the Albany-Fraser and Pinjarra orogens. The basement in this area is granulite-facies tonalitic to granitic orthogneisses, plus layered psammitic and pelitic paragneisses. This basement has been intruded by gabbroic to granitic plutons (Fitzsimons, 2002).

Only a small number of rocks from the basement to the Perth region have been described (HDR, 2008). The rock types noted are garnet- and sillimanite-bearing paragneisses, granites, and quartzites (Fletcher and Libby, 1993).

The variety of rocks exposed in known and proposed areas of the Pinjarra orogen suggest that the heat production of this basement is highly variable. Archean and Palaeoproterozoic fragments in the Bunger and Vestfold Hills would have relatively low heat producing capacity, while regions of felsic paragneisses, such as those in the Northampton and Leeuwin complexes would be expected to have heat production similar to that of the upper crust today.

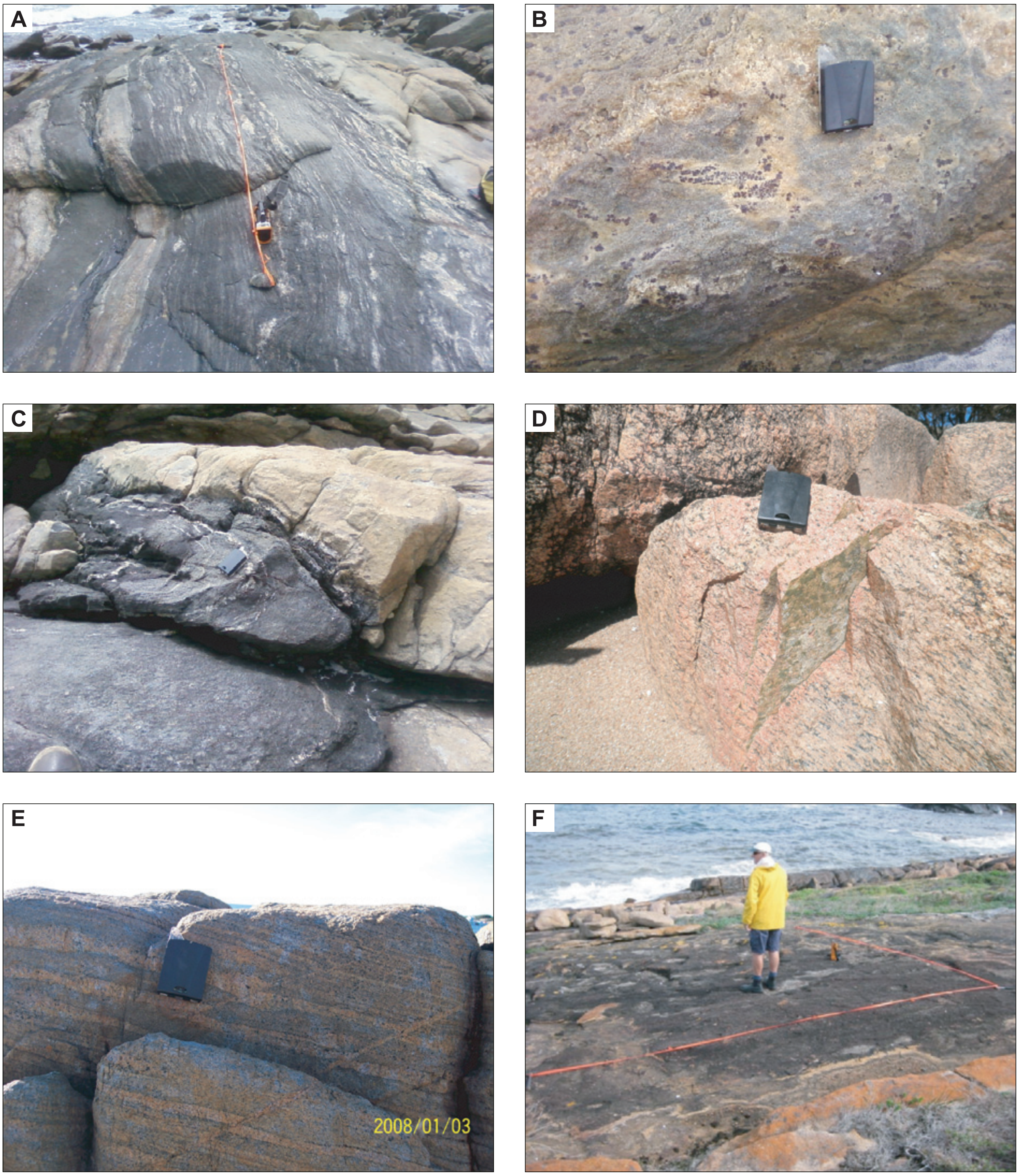


Figure 8.2: Rocks of the Leeuwin complex: (a) interlayered mafic and intermediate rocks at Skippy Rock, SW Australia; (b) garnet-bearing felsic gneiss at Skippy Rock, SW Australia; (c) folded mafic and felsic gneisses at Skippy Rock, SW Australia; (d) ksp-porphyritic granite, Bunker Bay, SW Australia; (e) layered ksp-rich and dioritic gneisses at Sugarloaf rock, SW Australia; (f) typical sample layout for GRS analysis on the Leeuwin anorthosite complex near Augusta, SW Australia.

8.3 Methods

Literature data was collected, where available, for the Mullingara, Northampton, Leeuwin complexes, the Perth region, and the proposed areas of Pinjarra orogen in Antarctica. Data is relatively sparse for these areas, particularly the Northampton and Mullingara complexes. Data for the Antarctic exposures was obtained from the Geoscience Australia database, filtered by latitude, longitude and locality.

New data was collected from the Leeuwin complex. Fieldwork was undertaken using a RS-125 super spec gamma ray spectrometer (GRS) from Radiation Solutions INC (Fig. 8.2f). This device uses a 6.3 cubic inch sodium iodine detector and a 1024 channel spectrometer to detect gamma ray emitting elements and gives their abundance in a sample. It has a detection range of 3 foot (~92 cm) radially from the detector (Radiation Solutions, 2009). The detector was normalized to the background at each new location before the actual measurements to remove the effects of background radiation.

Measurements were taken on outcrops of Proterozoic basement. Nine measurements were taken at each locality to ensure a representative result was obtained at each location. This strategy was employed in order to gain information on spatial variability of heat production at relatively short length scales; the heat-producing elements U and Th are expected to be heterogeneously distributed because they generally occur in accessory minerals which may not be spread homogenously throughout the outcrop.

The criteria used to select measurement localities were that the top surface of the outcrop should be relatively flat, and big enough to accommodate 9 measurements including the ~1 metre buffers to account for the measurement volume. Care was also taken to ensure that there were no holes underneath the outcrops or that they were at least ~1 metre thick.

The nine measurements were arranged, where possible, in an L configuration with five and four measurements taken on each arm. The GPS position was taken at the ends of each line segment (Fig. 8.2f). The average and standard deviation of the concentrations of the three main heat producing elements, K, U and Th, were calculated for each outcrop, and these data were used to calculate the heat production in $\mu W\ m^{-3}$, assuming a density of 2800 kg m^{-3}.

Rock samples were also gathered at selected localities but, due to the flat nature of the outcrops suitable for measurement, it was often necessary to travel up to 30 m from the GRS site to find an in-situ site where a sample could be taken. Twenty rock samples were collected, and these were subjected to bulk composition analysis. The crushed sample was fused with lithium tetraborate to form glass discs, which were then analysed by a combination of ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry), for the major elements and ICP-MS (Inductively Coupled Plasma Mass Spectrometry) for rare earth elements and for trace elements such as U and Th. Analysis was undertaken by Intertek-Genalysis commercial laboratories in Perth. Repeat analysis of selected samples and of known secondary standards indicated that accuracy and precision of the analysis was satisfactory.

The mineral hosts for U, Th and K in the Leeuwin sample rocks were determined using a combination of optical microscopy and scanning electron microscopy. Data was collected using the Zeiss Evo scanning electron microscope at the Centre for Materials Research at Curtin University. The analysis was completed with an accelerating voltage of 20 kV, a working distance of between 8 and 9 mm. The contrast was increased and brightness decreased to reveal likely minerals containing heat-producing elements, as U and Th have a high atomic number and thus appear bright in the SEM image with these settings. Element-specific mapping using the EDS system was also used to locate mineral phases that contain uranium and thorium.

Analyses by GRS and ICP were compared to allow validation of the GRS technique. Hand-held field equipment provides a valuable means to obtain large amounts of information quickly in the field, but it is necessary to evaluate the accuracy and precision of this data if it is to be combined with data obtained using other sources. The spatial variability of the distribution of heat producing elements was determined on the outcrop scale, by examination of the standard deviation of the nine measurements taken for each outcrop. Histograms were used to assess variability on the 10 – 100 km, and orogen length scales, and to examine the differences in distribution of heat producing elements as a function of rock type. Heat production was plotted as a function of longitude and latitude to determine any systematic spatial variation in its distribution, and probability plots were constructed to allow the best estimate of heat production for the areas examined to be determined.

8.4 Results

8.4.1 Leeuwin Complex: Comparison of laboratory analyses with GRS results

GRS results correlate well with laboratory analyses for K, but the data is more scattered for U and Th (Fig. 8.3). Some degree of scatter is expected, because the samples are not taken from sites identical to those sampled with the GRS, so it is useful to compare the extent of scatter with the standard deviation for measurements from single outcrops (Fig. 8.4). The mode of the standard deviation for K is about 10%, relatively, while standard deviations for U and Th are around 50 and 20% relative, respectively. The larger scatters for U and Th are expected given the low concentrations of these elements and the likely heterogeneous distribution of these elements within the rock.

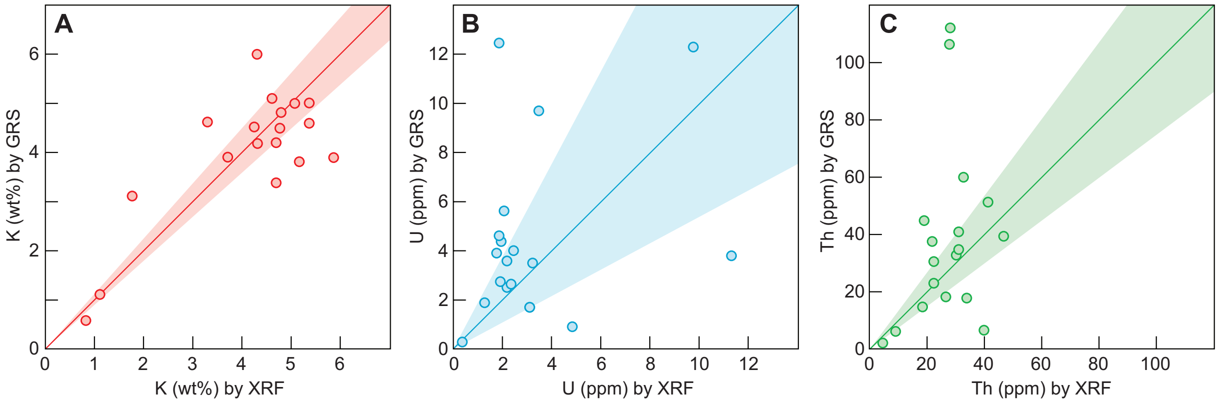


Figure 8.3: Comparison of element concentrations measured by hand held gamma ray spectrometer and by ICP-MS. Shaded region indicates estimate of spatial variation (1 sd) at each outcrop based on 9 measurements: (a) potassium; (b) uranium; (c) thorium.

If variation within an outcrop is taken to account then the bulk of measurements lie within the expected region. However, the GRS may systematically overestimate U and Th contents, since more samples lie above the line of GRS = ICP-MS than below it for both these elements, although the number of samples that lies outside the expected envelope above and below the line is similar. In the case of U, there are two cases where the GRS appears to significantly overestimate the Th concentration but it is difficult to determine if this is due to real heterogeneity or a systematic analytical issue with the GRS.

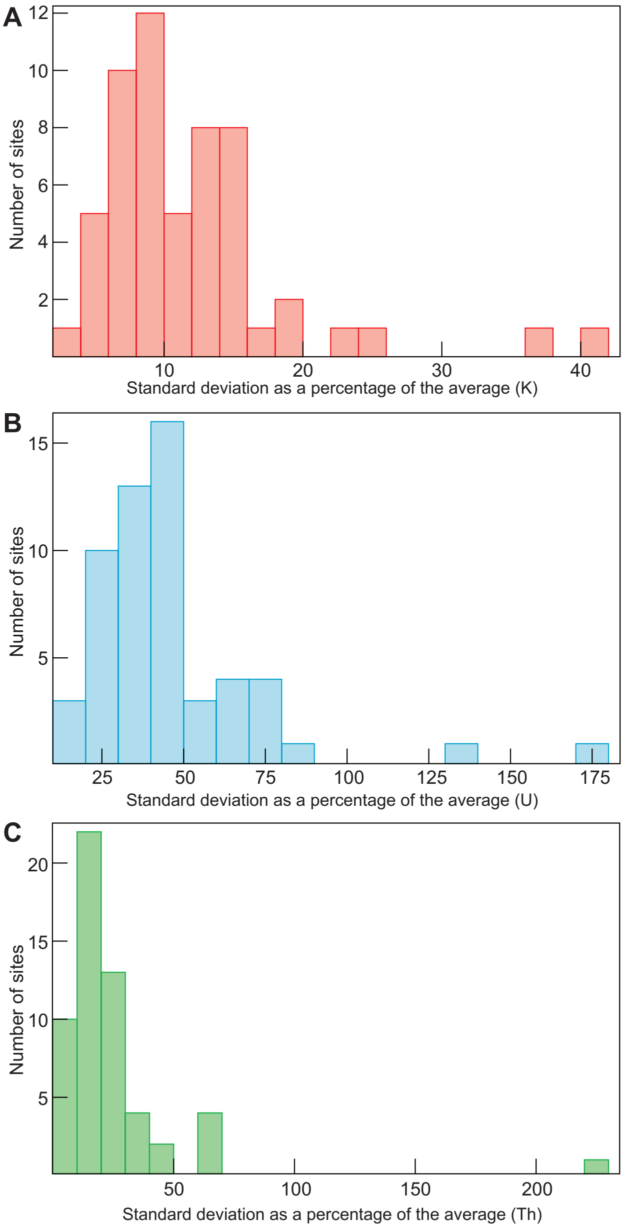


Figure 8.4: Histograms of the variation in GRS measurements from the 9 data points taken at each outcrop: (a) potassium; (b) uranium; (c) thorium.

8.4.2 All samples: heat production

The mean heat production for all 678 samples is 1.7 ± 2.56 μW m^{-3} (1 standard deviation), which is somewhat lower than an estimate of the crustal average of 1.9 ± 1.4 μW m^{-3} (Beardsmore and Cull, 2001), or the average for granitic rocks of 2.82 ± 1.03 μW m^{-3} (Beardsmore and Cull, 2001). These low values are heavily influenced by large numbers of samples from the Archean Bunger Hills and Vestfold Hills areas, with values of 1.3 ± 2.75 μW m^{-3} (246 samples) and 0.69 ± 0.77 μW m^{-3} (277 samples) respectively (Fig. 8.5). Samples from the Perth region are most similar to those from the Prydz Bay area; the 13 samples from the Perth region have a value of 2.38 ± 3.04 μW m^{-3}, while the Prydz Bay samples give 2.56 ± 2.55 μW m^{-3} (30 samples). This does not imply that the two regions come from the same original terrain, though this is not impossible. However, it is more likely that the similar values arise from common genetic processes that occurred at different times and in different places,

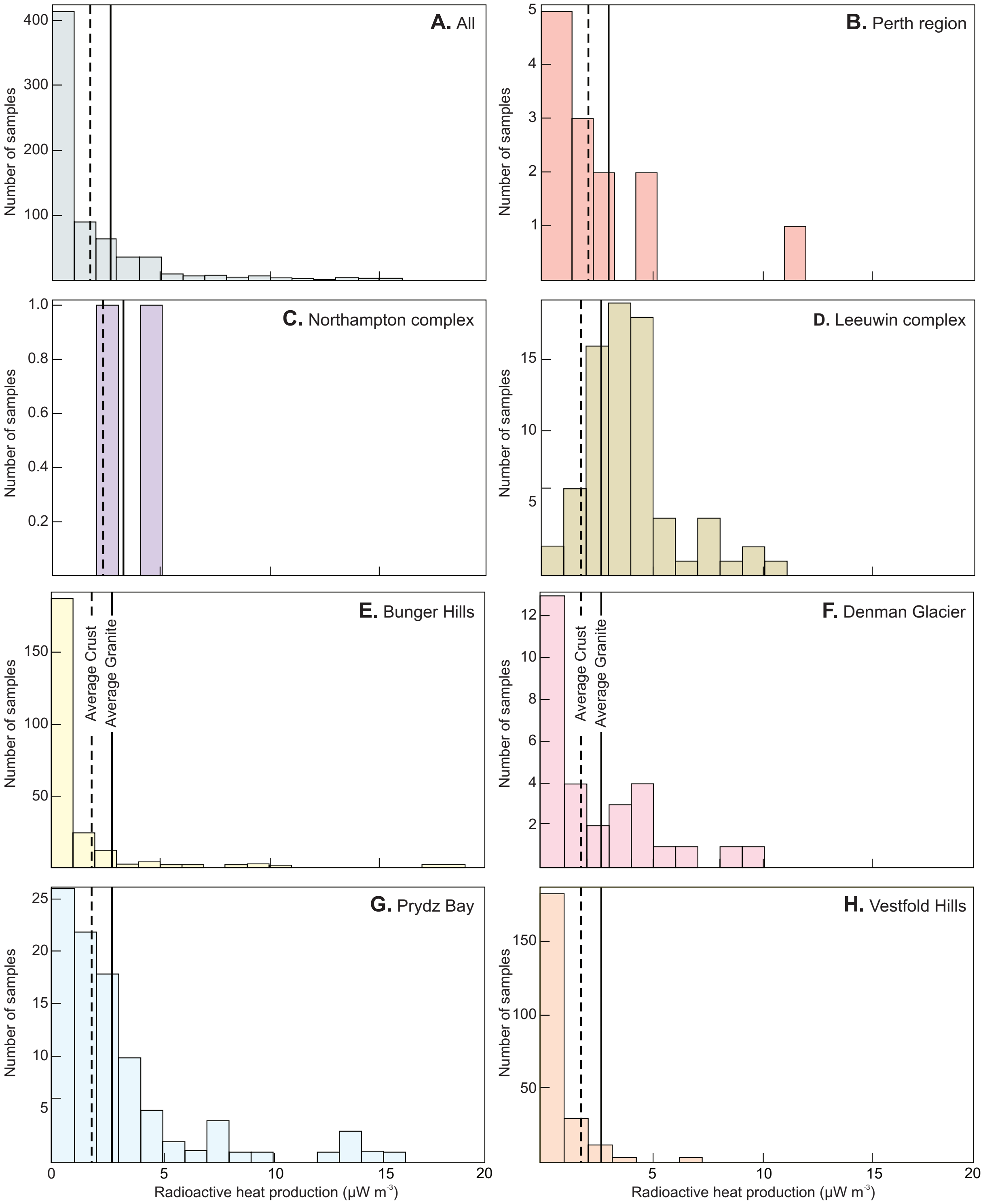


Figure 8.5: Histograms of the calculated heat production for the seven regions studied and for the whole sample set: (a) all samples; (b) Perth region; (c) Northampton complex; (d) Leeuwin complex; (e) Bunger Hills; (f) Denman Glacier; (g) Prydz Bay; (h) Vestfold Hills. Average crust and average granite values are from Beardsmore and Cull (2001).

rather than a close spatial relationship at some point in time. Heat production in the Perth basin basement and Prydz Bay fall between those for the crustal average and the average for granitic rocks. Samples from the Denman Glacier, the Northampton complex and the Leeuwin complex all have heat production values that are higher than the granite average, although the low number of samples (2) for the Northampton complex precludes any reliable determination of the average heat production.

If the analyses are divided into mafic and felsic rock types (Fig. 8.6) then it can be seen that the felsic rocks have distinctly higher heat production than the mafic rocks, and that the number of mafic rocks sampled is much greater than the number of felsic rocks sampled, in spite of descriptions of the various areas which suggest that felsic rocks are more common.

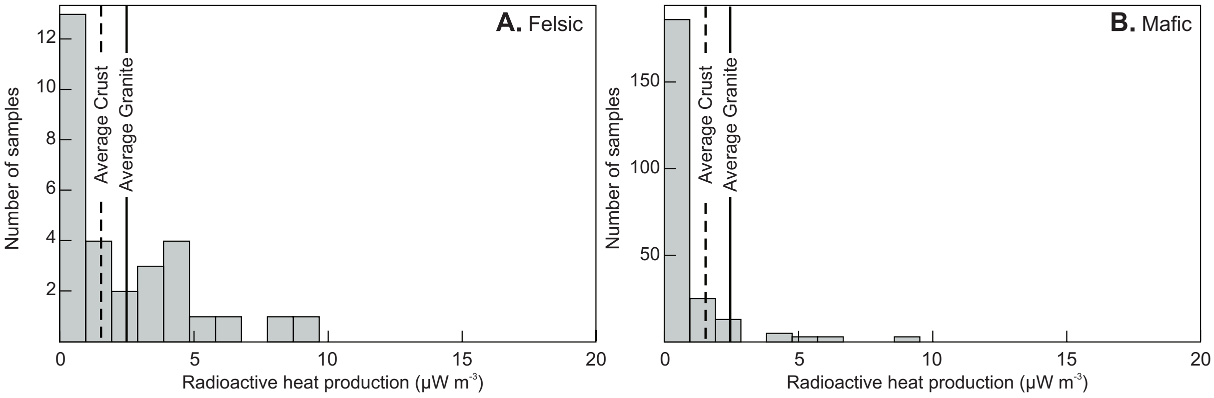


Figure 8.6: Histograms of calculated heat production split by rock type: (a) felsic; (b) mafic.

There was no systematic variation of heat production with longitude or latitude (Fig. 8.7), either within Australia, Antarctica, or where data for the two continents was combined, although the Australian samples cluster at slightly higher heat production values, because of the lack of low heat production Archean craton material. There is no significant difference between heat production in the Perth region, the Northampton complex and the Leeuwin complex.

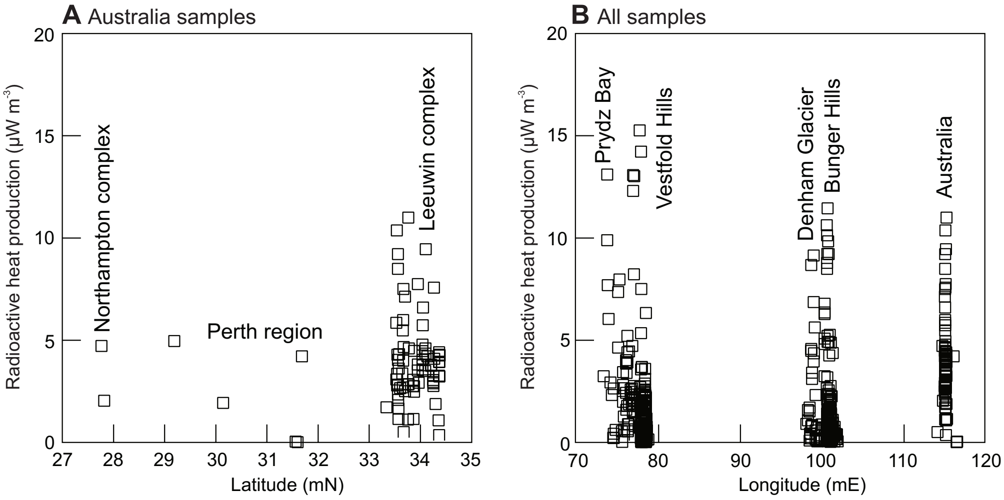


Figure 8.7: Calculated heat production plotted against longitude and latitude: (a) Australian samples only; (b) all samples.

Cumulative frequency plots (Fig. 8.8) reveal that the Perth region and Prydz Bay regions have a similar distribution of heat production, with a steep climb in heat production above the 50th percentile, although the Perth region plot is less well defined because of the low number of samples. The Leeuwin complex samples have a distinctly different frequency plot, with a much more consistent gradient, and less of an “S” shape to the frequency plot, as does the Denman Glacier. This grouping reflects that of the overall heat production, with the Perth region and Prydz Bay regions having similar heat production, and the Leeuwin complex and Denman Glacier region having higher heat production (>3 µW m^{-3}).

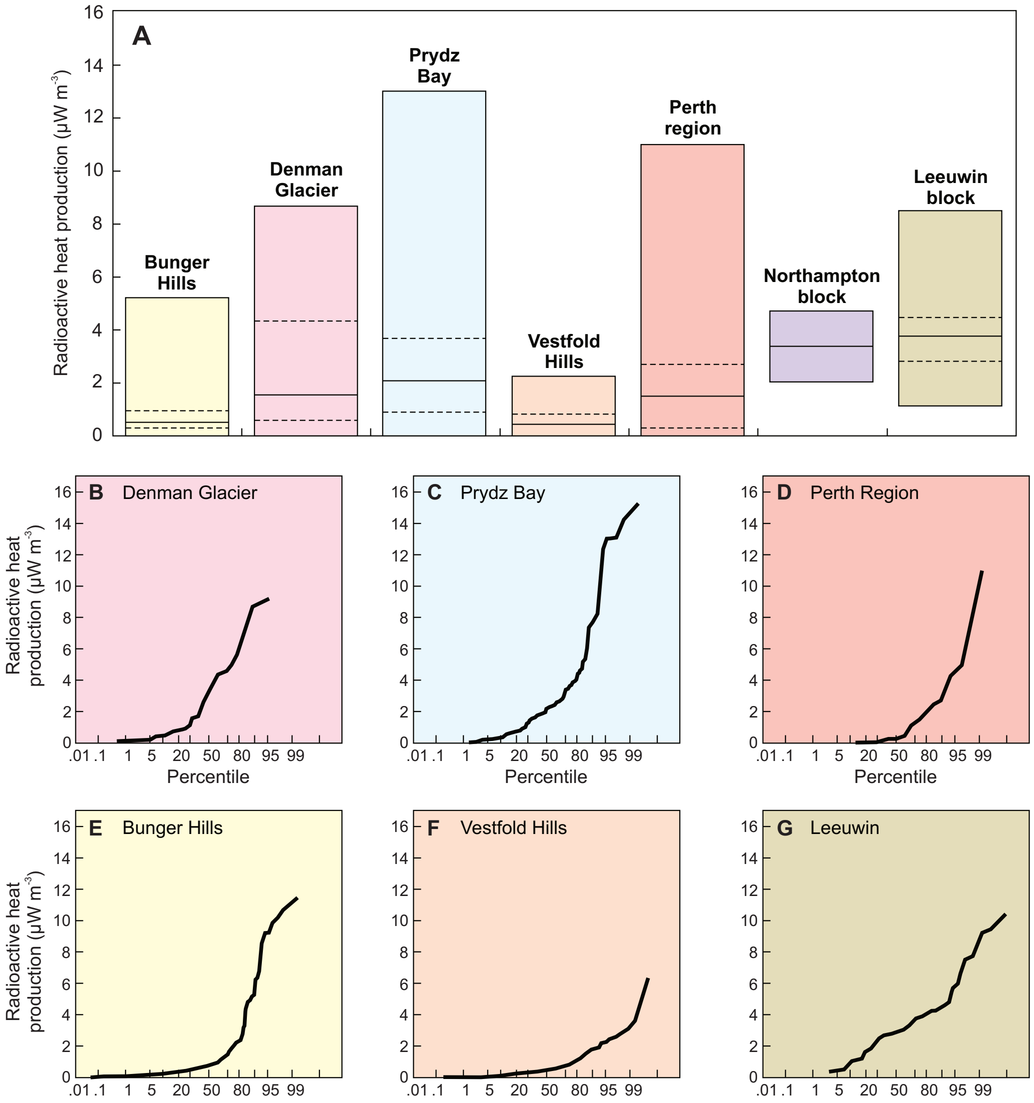


Figure 8.8: Box plots and frequency plots of heat production from the different regions considered. (a) Box plot comparing all regions; the thick line in each box is the median value, the dashed lines are the 1st and 3rd quartiles, and the end of the boxes are the 5th and 95th percentiles. Cumulative frequency plots for (b) the Denman Glacier; (c) the Prydz Bay region; (d) the Perth region; (e) the Bunger Hills; (f) the Vestfold Hills; (g) the Leeuwin complex.

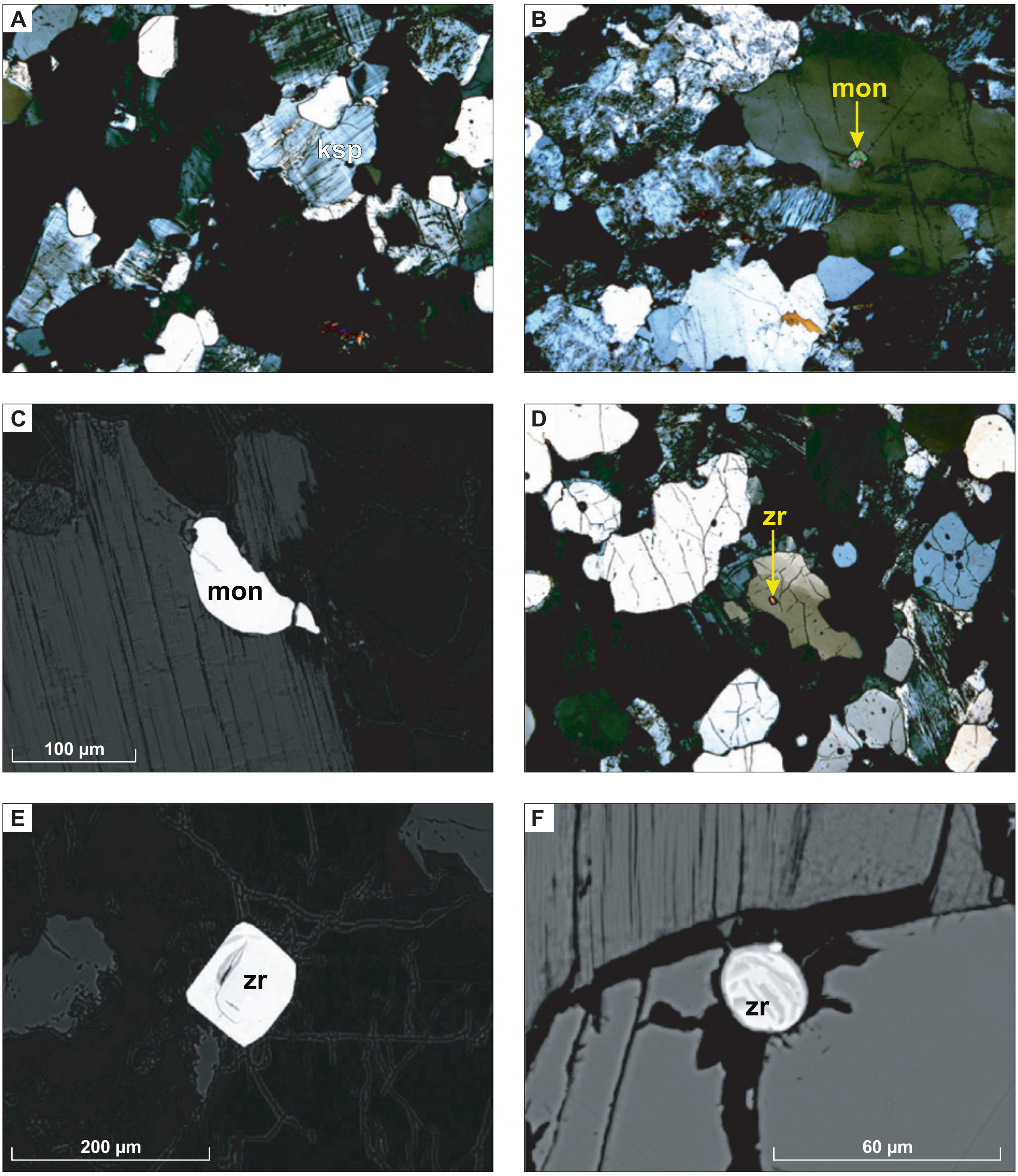


Figure 8.9: Mineral hosts for heat producing elements in Leeuwin complex samples. (a) photomicrograph of perthitic, alkali feldspar and microcline in sample CNCL-1205-09, FOV is 23mm, XP; (b) photomicrograph of monazite hosted in quartz in sample CNCL-1905-20, FOV is 23mm, XP; (c) Back scattered SEM image of monazite on margin of a mica grain in sample CNCL-1305-11; (d) photomicrograph of equant zircon included in quartz in sample CNCL-1105-07, FOV is 23mm, XP; (e) Back scattered SEM image of equant zircon in sample CNCL-1305-11; (f) Back scattered SEM image of rounded zircon with magmatic zoning in sample CNCL-1005-05.

8.4.3 Mineral Hosts

Mineral hosts to the heat producing elements are typical of those in high grade gneissic terranes (Fig. 8.9). K is hosted by k-feldspar (Fig. 8.9a), biotite and muscovite. U is hosted by zircon, and Th is hosted by monazite (Fig. 8.9b, c) and xenotime. There is considerable variation in zircon morphology; equant, cubic grains (Fig. 8.9d, e) and rounded magmatically zoned grains (Fig. 8.9f) were observed.

8.5 Discussion

8.5.1 Comparability of GRS and ICP data

K concentrations compare well between GRS and ICP methods. The means of the two datasets are well within error of each other, the t-test probability that the means of the two sample sets are the same is 88%, and the correlation coefficient is 0.83, which is significant at the $P<0.0005$ level.

U and Th correlations compare less well. The mean of the GRS dataset is higher for both U and Th than for the ICP dataset, although the values are within a single standard deviation of each other for both elements so the overestimation is not necessarily systematic. The t-test for U and Th is 24 and 19% respectively, which is too low to state convincingly that the two data sets are the same, but also too high to reject the hypothesis that they are different. The correlation coefficient for both U and Th is 0.36, which is slightly lower than that required for a $P<0.05$ probability of correlation, which requires a correlation coefficient of 0.39. These data suggest that either the GRS does not measure U and Th very accurately, or that the spatial variation within an outcrop is sufficiently large to destroy the correlation and provide difficulties with representative sampling.

To distinguish between these possibilities, the average standard deviation of the 9 GRS analyses for each outcrop was used to place uncertainty bounds on Fig. 8.3. If the variation observed is due only to the natural variability rather than to a systematic error then we would expect to see about a third of the samples plotting outside the shaded area, and indeed the proportion plotting outside is about a third, so the GRS method is likely to be acceptable. However, the small number of very high Th values is a concern so further work may be necessary to test the comparability of the two methods.

8.5.2 An analogue for the Perth Basin Basement?

Determination of the probable heat production of the Perth Basin basement requires assessment of the degree to which the various datasets utilized here are likely to represent that below the Perth Basin.

Datasets from the low heat production Archean craton material in the Bunger and Vestfold Hills seem unlikely to represent the Perth Basin basement, as the small existing dataset (13 samples) from the Perth basin basement has quite different rock types, in that there is a lack of monzonitic and tonalitic material, and the average heat production is much higher than that from the Bunger and Vestfold hills.

The dataset from the Leeuwin, which has relatively high heat production is on average higher, the central 50% of its data distribution does not overlap with that of the Perth basin basement (Fig. 8.8a), and it has quite a different distribution to that of the small dataset for the Perth region on a cumulative probability plot (compare Figs 8.8b and c). The high heat production samples in the Leeuwin come from outcrops dated as Neoproterozoic (~650 – 750 Ma; Collins, 2009). These rocks have the geochemical signature of A-type granites (Fitzsimons, 2000), and may be related to accretion of the Northampton and Mullingarra complexes to the Yilgarn craton, and, in this case, may not be spatially as widespread as older Mesoproterozoic rocks which may underlie the Perth Basin. It may, therefore, be unwise to use the Leeuwin complex as a model for the Perth Basin basement.

The Northampton complex dataset is too small to assess in any meaningful way. The Denman Glacier and Prydz Bay datasets, show similar averages to the small Perth Basin dataset and the Prydz Bay dataset shows a similar cumulative frequency curve. It therefore seems likely that these datasets are the most likely to provide a plausible analogue for the Perth Basin basement. This proposal is consistent with the similarity of T_{DM} Nd model ages for the Denman Glacier to those from granitic Perth Basin basement (2200 Ma – 2000 Ma; Fletcher et al., 1985; Fletcher and Libby 1993).

8.5.3 Typical Length Scale of Variation

A simple exercise was undertaken to investigate the typical length scale of variation. For the dataset of interest, a list of all pairwise permutations of sample numbers was generated. For each pair of samples, the distance between the samples, and the difference in heat production (ΔHP) between the samples was calculated to produce a dataset in which each data point was a pair of {distance, ΔHP} values. This dataset was then sorted and averaged to give an estimate of the distribution of heat production variation for length scales of 10 m to 10 000 km (Fig. 8.10).

With this type of plot, low values of ΔHP are expected if the area under investigation is homogenous on that length scale considered, whereas high values would be expected if the area is highly heterogeneous on the length scale of interest. Low values may result due to large continuous areas with similar heat production or to repetition on the length scale of interest.

Results indicate that ΔHP generally increases with length scale, with two exceptions, which will be discussed below. Significant jumps in ΔHP are observed on length scales of 1 – 100 km for most datasets investigated (Fig. 8.10a, c, d), which suggests that variation in ΔHP, like geological variation is on this length scale. Under these circumstances it is probably worth seeking high heat producing areas of basement, if calculations show that the additional heat influx could provide higher temperature geological fluids.

Drops in ΔHP with increasing length scale are observed for the Prydz Bay and Denman Glacier datasets. The reason for this is not fully understood, but could reflect either: (1) an anomalous increase at the length scale immediately preceding the drop. This could reflect short scale variation due to features such as dykes; or (2) a decrease in variation due to repetition of features at the length scale of interest. Explanation (1) seems most likely given the heterogeneity and natural variability of geological datasets.

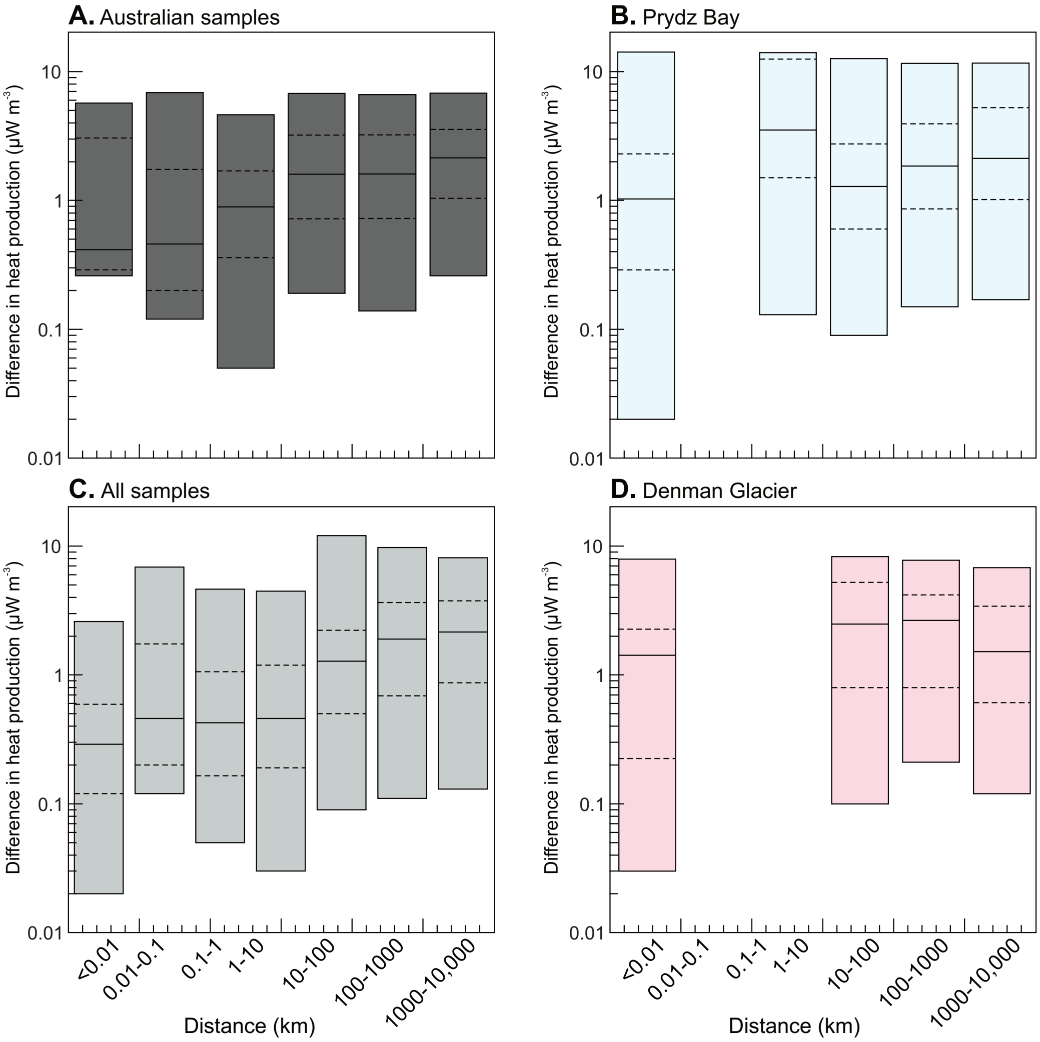


Figure 8.10: Box plots to represent variation in heat producing capacity at the different length scales studied. the thick line in each box is the median value, the dashed lines are the 1st and 3rd quartiles, and the end of the boxes are the 5th and 95th percentiles. (a) Australian samples; (b) Prydz Bay samples; (c) All samples; (d) Denman Glacier samples.

8.5.4 Stochastic models for heat distribution

A preliminary investigation of the predicted heat flow contribution from the Perth Basin basement assuming that the heat production was distributed identically to that at Prydz Bay, and decreased exponentially with depth to 0.8 μW m^{-3}, a plausible value for the lithospheric mantle. The expression for the decrease is

$$HFS = HP_s e^{\frac{1}{30000} Ln\left(\frac{0.8}{HP_s}\right) z} \qquad [1]$$

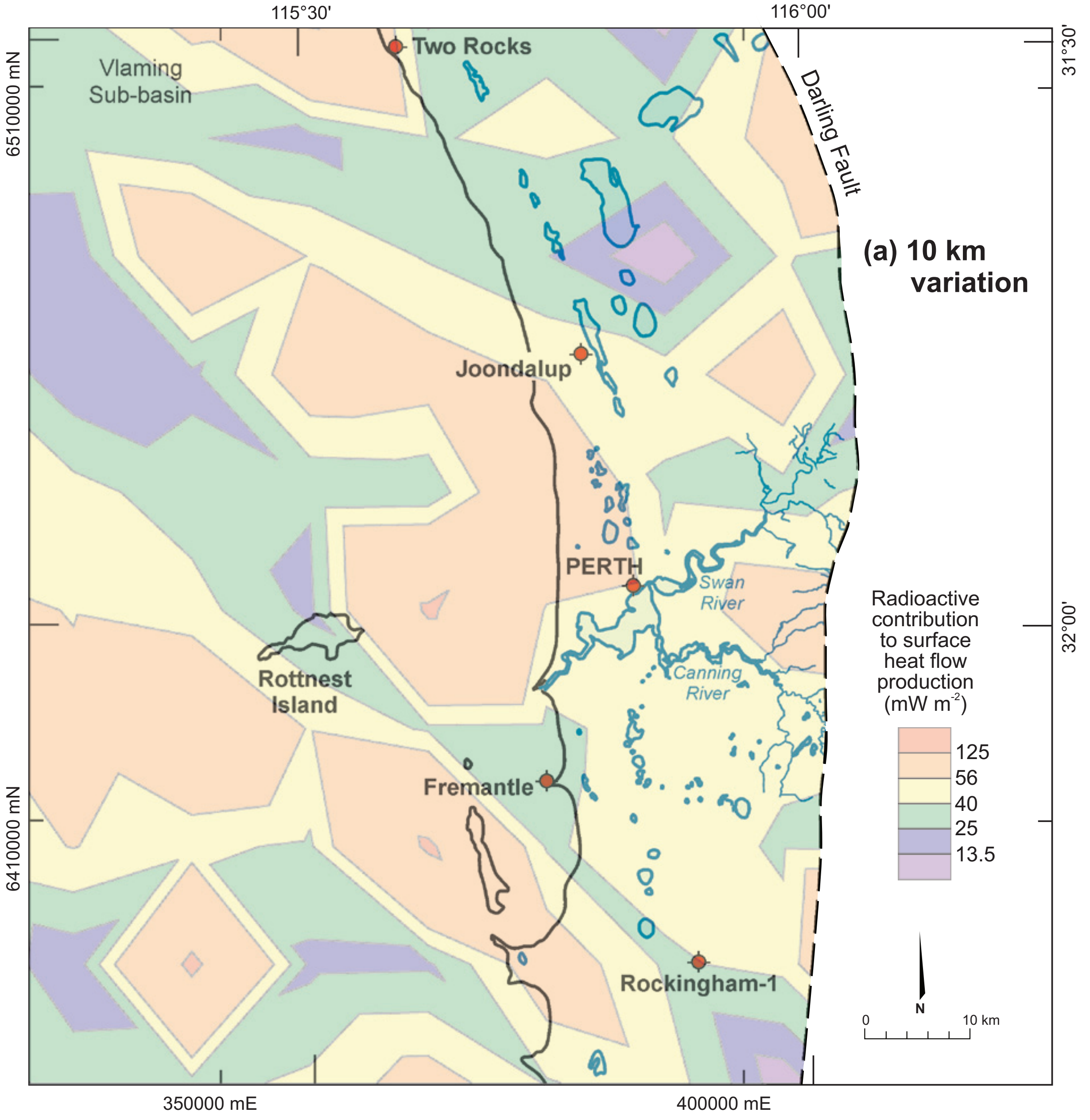
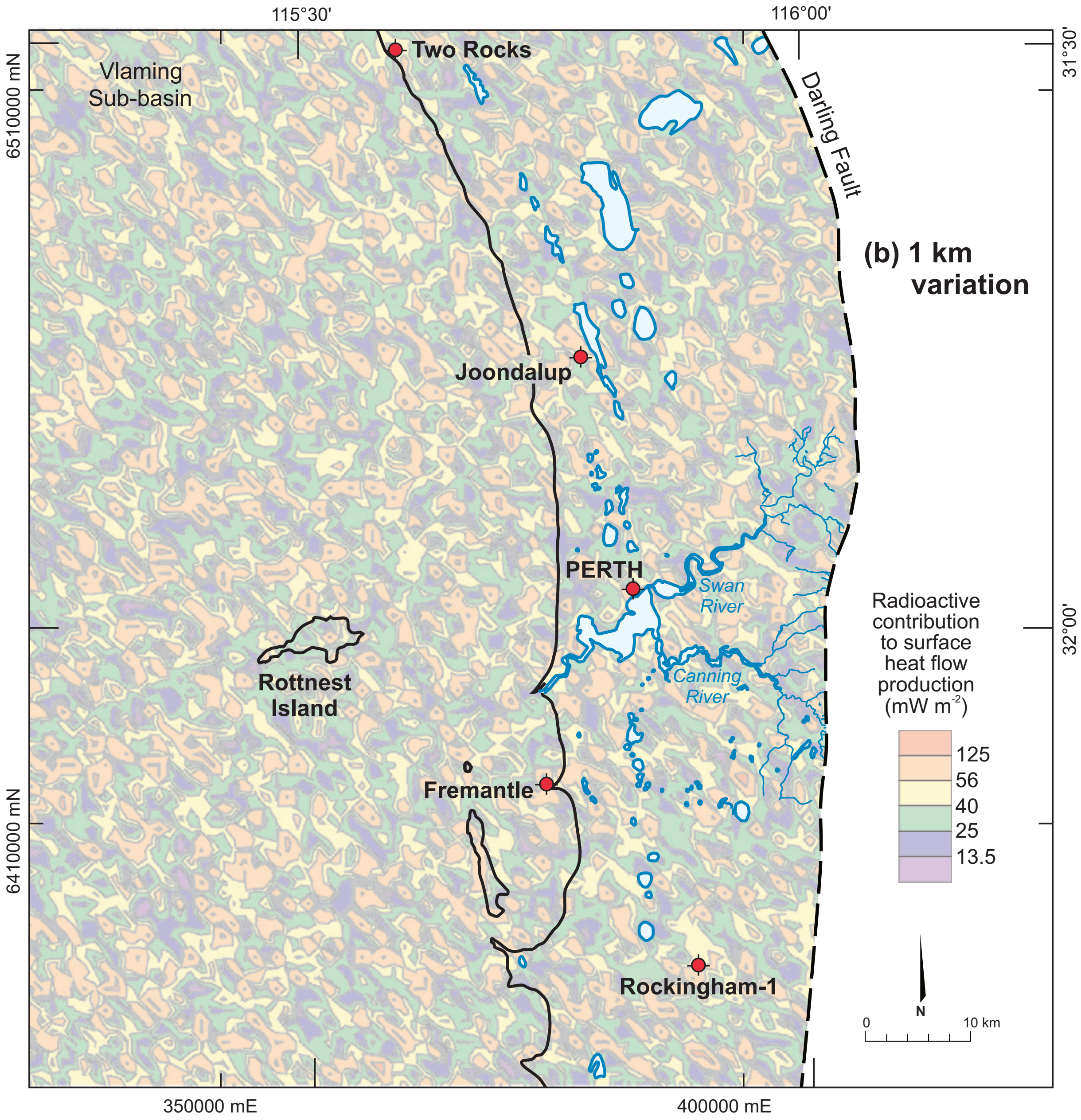


Figure 8.11: Stochastic simulations of the possible heat production from the Perth Basin basement for (a) 10 km characteristic length scale variation and (b) 1 km characteristic length scale variation.



where *HFS* is the heat flow from the basin rocks at the top of the basement and *HPs* is the heat production at the surface. Random values were generated from the Prydz Bay distribution and allocated to grid co-ordinates. Stochastic simulations with grid spacing of 10 km (Fig. 8.11a) and 1 km (Fig. 8.11b) were made. Although these simulations are unconstrained by local data, the spatial correlation scales shown indicate the potential length scales of basal heat flow variation that may persist into the sedimentary cover. For example, it can be seen that heat flow will vary significantly on the 10 km scale if the characteristic length scale of heat production variation is of the order of 10 km, whereas, heat flow might be expected to be averaged by kilometre-scale flow cells if the characteristic length scale of variation is closer to 1 km. Further work is necessary to constrain this length scale of variation and to assess the potential conductive and advective heat signatures in the saturated sedimentary sequences above the basement.

8.5.5 Contribution of basement heat flow to the overall heat flow budget.

The proposed heat flow distribution contribution from the Perth Basin basement is likely to be between 25 and 56 mW m^{-2}, taken from the range between the 1st and 3rd quartiles of the Prydz Bay distribution. These data are consistent with average heat flow for Proterozoic rocks compiled by Jessop (1990). If basal heat flow from the mantle is around 25 mW m^{-2}, as suggested by Sclater et al. (1980) then the total heat flow, neglecting any contribution from overlying sediments, should be 50 to 81 mW m^{-2}. These values are similar to those proposed by Geoscience Australia for the Perth Basin (<87.5 mW m^{-2}; Beardsmore, 2009), and to those proposed by the authors of the Hot Dry Rock report, who used a small number (< 10) data samples in the Perth Basin to obtain estimates of 70 – 80 mW m^{-2} for the Perth Basin area. These values are sufficient to create temperatures gradients of 15 to 35 °C km^{-1} for plausible thermal conductivity values (HDR, 2008). These values are similar to those measured in Perth Basin boreholes.

8.6 Goals for future research

- More direct measurements from exposed regions of crystalline basement in the vicinity of the Perth Basin will help to better define the potential range and variability of basement heat flow in the Perth Basin.
- Better constraints on heat flow from borehole logs in the Perth Basin to account for surface heat flow contribution to better assess the contribution of basement heat flow.
- Test the approach documented in this study on a comparable yet better exposed orogen to develop as an exploration tool for application elsewhere.

8.7 Summary

The Perth Basin holds considerable potential for HSA (Hot Sedimentary Aquifer) geothermal energy. If this potential is to be properly assessed then it is necessary to determine the heat flow, and heat producing capacity, of the basin to the Perth Basin. However, this basement is largely covered by up to 12 km of sedimentary cover, so it is necessary to employ indirect methods for assessment.

Existing data from the Perth Basin basement, data from proposed analogues to the Perth Basin basement, and new data from the Leeuwin complex, SW Australia, has been compiled, and assessed. The small Perth Basin basement dataset shows similarities, in terms of rock types and heat producing capacity, to material from the Prydz Bay region of Antarctica. The Bunger Hills and Vestfold Hills regions have lower heat production than the proposed Perth Basin basement, most likely due to the presence of significant quantities of Archean crust in these areas. The Leeuwin complex has higher heat production than the proposed Perth Basin basement, most likely due to spatially restricted inputs of high heat production A type granites during the Neoproterozoic.

Typical heat production values are estimated to be of the order of 0.9 to 3.6 μW m^{-3}, with a median value of 2.2 μW m^{-3}. This value is greater than the average heat production of the Earth's crust, but less than the average for granites (2.8 μW m^{-3}). Estimates of the total heat flow due to radioactive decay in the basement are of the order of 25 to 56 mW m^{-2}, and are consistent with estimates from other sources. Geothermal gradients calculated for plausible thermal conductivity values are 17 to 35 °C km^{-1}.

Estimates of the length scales of variation in heat producing capacity were made to support the incorporation of basement-geology considerations into geothermal exploration. Characteristic length scales of variation are of the order of 1 to 10 km for the regions of interest; if variation is of the order of 1 km then heat flow is likely to be homogenized by fluid flow in the overlying sediments. However, if variation is of the order of 10 km then it is possible that there may be basement-induced hot and cold spots within the Perth Basin, which it may be possible to discover via exploration.

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APPENDIX A LISTING OF STUDENTS

APPENDIX B CONFERENCE AND WORKSHOP CONTRIBUTIONS

The research presented in this report has been presented in local and international conferences. In addition to publicising work performed by WAGCoE or affiliated students, conference participation provides an important forum for attendees to be exposed to related research and develop professional networks in the geothermal field. Notable conferences attended include:

WAGCoE Workshop, ARRC Building, Perth, 16 February 2011.

First International Workshop on Rock Physics, 7-12 August, 2011, Colorado School of Mines, USA.

9th Euroconference on Rock Physics and Geomechanics, 17-21 October, 2011, Trondheim, Norway.

Gas Petrophysics from Formation Evaluation Society of Australia (FESAus), 13-15 September, 2011, Perth, Australia.

Australian Geothermal Energy Conference, 2011. Melbourne, Australia.

American Association of Petroleum Geologists, 2011, Houston, Texas, USA.

Western Australian Geothermal Energy Symposium, 2011. Perth. This conference was organised in large part by members of WAGCoE.

Stanford Geothermal Reservoir Engineering Workshop, 2011 and 2012. Palo Alto, California, USA.

Structural Geology and Tectonics Specialist Group Meeting, Waratah Bay. Jan 2012.

22nd International Geophysical Conference and Exhibition, Australian Society of Exploration Geophysicists, Brisbane, February 2012.

53rd Society of Petrophysicists and Well Log Analysts Symposium, 16-20 June 2012, Cartagena, Colombia.

Presentations given at these conferences are listed in Appendix C.

APPENDIX C SCIENTIFIC PUBLICATIONS

Publications with WAGCoE authors related to geothermal characterisation and hydrothermal modelling are listed in this section, even if they have been included in the References section above. Some of these publications may also appear in reports relating to other projects with WAGCoE‘s Program 1.

Alix, R. June 2011. Reservoir characterisation of the Yarragadee Formation for geothermal exploration in the Perth Metropolitan Area, Perth Basin, Western Australia. MS, Montpellier University, France.

Corbel, S., Schilling, O., Horowitz, F.G., Reid, L.B., Sheldon, H.A., Timms, N.E., Wilkes, P., 2012, Identification and geothermal influence of faults in the Perth Metropolitan Area, Australia. PROCEEDINGS, Thirty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 30 - February 1, 2012, SGP-TR-194.

Esteban, L., Pimienta, L., Sarout, J. and Delle Piane, C., Haffen, S. and Geraud, Y., June 2012. Predicted and measured thermal conductivities in two potential geothermal fields: Soultz-sous-forets (France) and Perth Basin (Australia). 53rd Society of Petrophysicists and Well Log Analysts Symposium, 16-20 June 2012, Cartagena, Colombia.

Esteban, L., Delle Piane, C., Israni, S.R., Evans, C., Pimienta, L., Timms, N., and McLaren, S., 2012, Thermal conductivity analysis in the Perth Basin, Western Australia. CSIRO Report, February 2012.

Hamilton, J., Reddy, S.M., Olierook, H., and Timms, N.E., 2011. Stylolites; Their Origin and Impact on Reservoir Quality. In: AAPG Annual Conference and Exhibition: Making the Next Giant Leap in Geosciences. American Association of Petroleum Geologists, Houston, Texas, U.S.A.

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Israni, S.R., Delle Piane, C., 2011, Rock Physics and Petrophysical characterization of units from the Perth Basin. CSIRO Confidential Report Number EP113342, May 2011, 43 pp.

Jenner, C., 2011 Determining the geothermal properties of the Perth Basin lithology to aid geothermal energy projects. Exploration Geophysics Honours Thesis (unpublished), Curtin University, Perth.

Nadri, D., Urosevic, M, Wilkes, P.G., Asgharzadeh, M , 2012. Tube wave removal from vertical seismic profiling (VSP) surveys. 22nd International Geophysical Conference and Exhibition , Australian Society of Exploration Geophysicists, Brisbane, February 2012.

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Olierook, H., Timms, N.E., Delle Piane, C., Wilson, M., Hamilton, J., and Cope, P., 2012b, Petrography and facies analysis report on Pinjarra-1, Perth Metropolitan area, Western Australia. WA Geothermal Centre of Excellence Confidential Report, Perth, 52pp.

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Olierook, H., Timms, N.E., Delle Piane, C., and Wilson, M., 2012d, Petrography and facies analysis report on Gingin-2, Perth Metropolitan area, Western Australia. WA Geothermal Centre of Excellence Confidential Report, Perth, 32pp.

Olierook, H., Timms, N.E., Hamilton, P.J., Reddy, S.M., 2011, Characterisation of fault damage zones in the north Perth Basin, West Australian Geothermal Energy Symposium, Perth, 21-22 March 2011.

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