A crustal profile of the heat production of the Harts Range Group, Northern Territory

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SUMMARY

Medium pressure-high temperature (MP-HT) metamorphism is generally accepted to be driven by crustal thickening within compressional tectonic regimes. Despite this consensus, the Harts Range Group located in central Australia provides evidence for MP-HT metamorphism occurring as a result of burial in a deep intracontinental rift. Detrital zircon studies of metasediments within the Harts Range and surrounding sedimentary sequences indicate that the Harts Range Group represent the metamorphosed equivalents of the sedimentary successions located in the neighbouring Late Neoproterozoic to Cambrian Amadeus and Georgina Basins. Whilst the metamorphic character of this region has been studied, the thermal character of each of the individual sequences that infilled the rift are yet to be examined. The exhumation and preservation of all metamorphosed components of the Harts Range rift basin, along with the proximity of these metasediments to their protolith equivalents, provide a unique opportunity to examine the heat production of components that infilled the rift throughout the Cambrian.

We undertake a field study to measure heat production across three lithological units that comprise the Harts Range Group. We also apply heat production calculations to calibrated airborne radiometric datasets in order to calculate the approximate heat production of these sedimentary sequences when buried to ~30 km depth. We use the ground-sourced measurements as a tool to validate our derivation of heat production from airborne radiometrics. If statistically sound, we are then able to use the airborne radiometric dataset to calculate average heat production and relative heat flow of each succession contained within the rift. This can provide insights into the thermal drivers of medium pressure-high temperature metamorphism in an extensional intracratonic tectonic setting.

Key words: heat production, airborne radiometrics, gamma ray spectrometry, Harts Range

INTRODUCTION

Crustal thickening is thought to be the common driver of medium pressure-high temperature (MP-HT) metamorphism in intracontinental settings. Metasediments of the Harts Range Group (HRG), located in central Australia (Figure 1), have shown evidence for MP-HT metamorphism occurring as a consequence of intracontinental rifting (Maidment et al. 2013; Tucker et al., 2015); mafic magmatism and infill of sediment providing the heat and pressures necessary to metamorphose the sediments deposited at the base of the rift. This region represents a unique field location which comprises deep rift successions that have been exhumed and have retained their stratigraphic order and structural thickness. Importantly, the neighbouring Georgina and Amadeus Basins (Figure 1a) preserve the unmetamorphosed protoliths to the HRG metasediments. This allows the opportunity to examine the entire depth slice of a Cambrian deep intracontinental rift to determine past thermal conditions through the analysis of the thermal characteristics of the rift successions in their present form.

Previous studies indicate that the HRG were buried to a depth of ~25-30 km and experienced peak upper amphibolite to granulite facies metamorphism at *c.* 480-460 Ma (Tucker et al., 2015). The deep rift basin is characterised by mafic magmatism and resultant high heat flows. The basin was subsequently inverted during the c. 450-300 Ma Alice Springs Orogeny (Raimondo et al., 2014) and is believed to have remained in the same stratigraphic order as the time of burial. Whilst a number of studies exist regarding the metamorphic conditions experienced in the Harts Range intracontinental rift (Buick et al., 2005; Maidment et al., 2013; Tucker et al., 2015), none are yet to focus on the thermal character of each of the components of the rift succession, including the sediments that would have buried the HRG to depth.

Cooling in a post-rift setting is slowed when blanketed by sediment and this may allow for heat flow to remain higher for much longer periods (Beardsmore and Cull, 2001). Sedimentary successions with high concentrations of potassium, uranium and thorium will commonly exhibit high heat production (Mareschal and Jaupart, 2013) and contribute more significantly to crustal heat flow (if of sufficient structural thickness). Their corresponding thermal conductivity (also dependent on mineral composition (Liu et al., 2011)) will determine the efficiency with which these packages allow for the flow of heat through the crust. These characteristics are important, particularly in rift settings, to understand not only the magmatic thermal drivers of metamorphism occurring within the rift, but also of the way the sediments packaged above contribute to the metamorphic process.

This study aims to produce the first thermal characterisation of the lithological packages contained within the Harts Range intracontinental rift through the use of calibrated airborne and ground-sourced radiometric data. Our initial work undertakes statistical analysis of ground-sourced heat production data in comparison to heat production derived through airborne radiometrics, in order to determine the validity of this method. This part of the study focuses on the Upper and Lower Brady Gneiss and Irindina Gneiss (Figure 1b), which are representative of a large portion of the HRG metasediments. We will then apply heat production calculations to airborne radiometric data from a wider portion of Harts Range and the surrounding Amadeus and Georgina basins. We aim to produce a crustal profile of thermal characteristics of the packages contained within the deep rift that buried and subsequently metamorphosed the HRG sediments to upper amphibolite to granulite facies during the Cambrian.

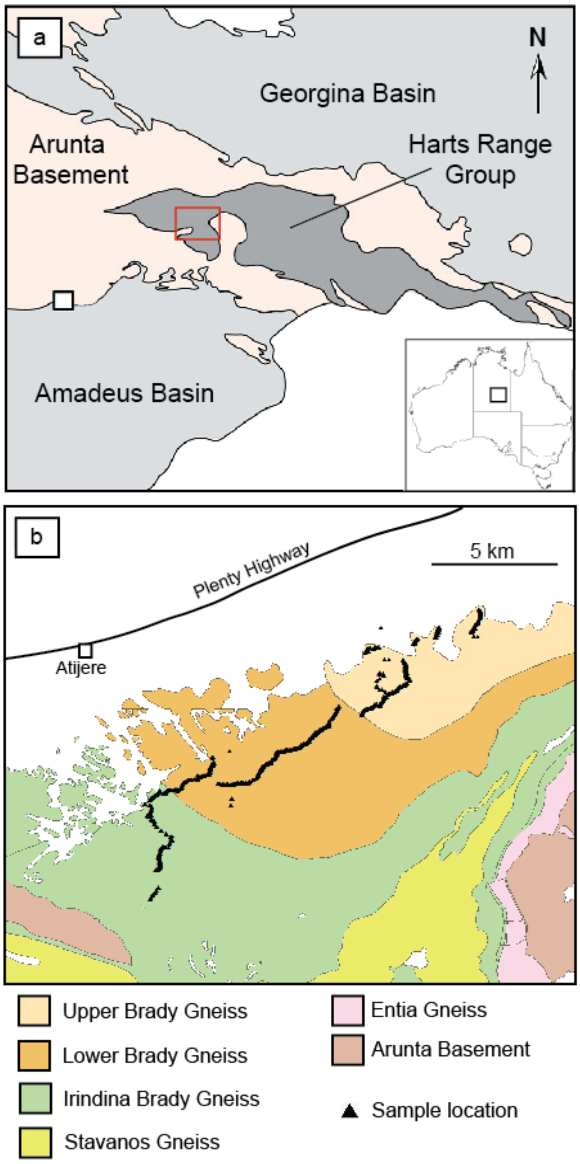

Figure 1. (a) Simplified regional geology map showing the relationship of Harts Range with the surrounding Late-Neoproterozoic to Cambrian basins and Proterozoic Arunta Basement; (b) Geological map of the study area for ground sourced heat production measurements. Black triangles represent the location of >700 measurements taken across the three lithologies of interest.

METHOD

This study involved manipulation of the 2009 Radiometric Map of Australia dataset (Minty et al., 2009) to estimate heat production over a large scale, along with the collection of detailed ground-sourced radiometric data using hand-held gamma ray spectrometers. The ground-sourced data was collected to determine the validity of heat production estimated from airborne radiometrics.

Heat production

The concentrations of uranium (C_U), thorium (C_{Th}) and potassium (C_K) are used to determine the heat production at each location using the following equation:

$$H = \rho\,(C_U H_U + C_{Th} H_{Th} + C_K H_K) \qquad (1)$$

where ρ denotes the rock density (average $\rho = 2700$ kg m^{-3} after Carmichael (1989)), C represents the individual concentrations of U, Th and K, and the rate of heat release of U ($H_U = 9.81 \times 10^{-5}$ W kg^{-1}), Th ($H_{Th} = 2.64 \times 10^{-5}$ W kg^{-1}) and K ($H_K = 3.48 \times 10^{-5}$ W kg^{-1}) are known quantities (Turcotte and Schubert 2002).

Ground-sourced radiometric data

Ground-sourced measurements of U, Th and K were collected using a hand-held gamma ray spectrometer (RS-330) following the method of Alessio et al. (2018). The spectrometers were placed on rock outcrops for two minutes to collect an assay of U, Th and K (parts per million, parts per million and percent, respectively). Typical uncertainties associated with the RS-330 are K: 9%, U: 28% and Th: 11%. Sampling was undertaken approximately perpendicular to strike every 25 m along the study transect.

Airborne radiometric data

The 2009 Radiometric Map of Australia (Minty et al., 2009) was imported into ArcGIS and clipped to the study region in the Harts Range, Northern Territory (Figure 1). Model building tools within the ArcGIS program were used for the conversion of the raw U, Th and K data into present-day rates of heat production using Equation 1.

Polygons of the spatial extent of the Upper and Lower Brady Gneiss and Irindina Gneiss were produced using the Alcoota, Huckitta, Alice Springs and Illogwa Creek 1:250 000 NTGS map sheets (Shaw et al., 1972; Freeman, 1978; Shaw et al., 1978; Shaw et al., 1981) which allowed for the output heat production to be binned into each lithological unit of interest. Statistical analysis of the heat production of each unit was then undertaken.

RESULTS

Figure 2 shows the output heat production derived from airborne radiometric data (Figure 2a), ground-sourced radiometric measurements (Figure 2b) and the comparison between the two (Figure 2c).

715 ground-sourced measurements of radiometric data were taken across the Upper and Lower Brady Gneiss and Irindina

Gneiss lithologies (Figure 2a). The raw U, Th and K data were converted to present-day heat production rates using Equation 1. The statistics of the ground-sourced radiometric measurements can be found in Table 1.

The ground-sourced measurements were used as a tool to examine the effectiveness of the heat production derived from airborne radiometrics. The statistics for airborne derived heat production for the Upper and Lower Brady Gneiss and the Irindina Gneiss can be found in Table 1.

The average heat production of each of the three lithological units derived from airborne radiometrics lie within one standard deviation of the average values calculated from ground-sourced measurements. Anomalously high maximum values for each of the lithologies determined from ground sourced measurements are likely due to measurements taken on outcrop with close proximity to pegmatite veins; a common feature of the Harts Range landscape known to enhance U mobility (McLennan and Taylor, 1979), which may have influenced these anomalously high results. As the airborne radiometrics are filtered and smoothed (Clifton, 2016), the effects of pegmatite veins within this dataset are reduced.

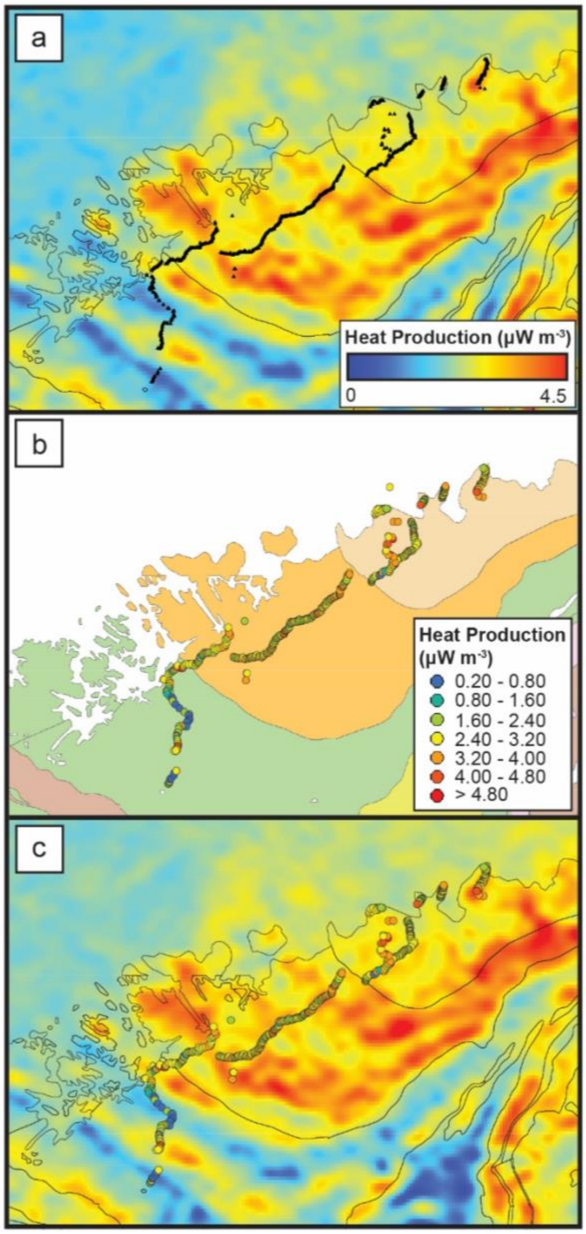

Figure 2. Results of heat production calculations from (a) calibrated airborne radiometric data (with ground-sourced measurement locations indicated by black triangles) and (b) ground-sourced measurements of U, Th and K (legend for lithological units is the same as Figure 1). (c) Comparison of heat production calculated from the separate datasets.

The current structural thicknesses of the lithological units of interest are as follows:

- Upper Brady Gneiss: ~5.5 km
- Lower Brady Gneiss: ~6 km
- Irindina Gneiss: ~5.5 km

Fortunately, the current thicknesses of these packages represent their structural thickness within the base of the rift (Hand et al., 1999); therefore, we can estimate the relative heat flow of the packages. From the data in Table 1, we can determine that the Upper Brady Gneiss is responsible for the highest heat flow of the three lithological units (16.86 mW m^{-2}), followed by similar heat flows for the Lower Brady Gneiss (16.17 mW m^{-2}) and the lowest heat flow from the Irindina Gneiss (13.09 mW m^{-2}).

These heat flows resonate with the heat production values mapped across the Harts Range (Figure 2), which also show clear distinctions between the Brady Gneiss packages and the Irindina Gneiss.

The estimation of average heat production and heat flow of the basal Harts Range Group successions has shown that the thermal character of all successions that comprised the rift can be determined. Further work will determine the thermal character of the sediments from neighbouring basins, which will provide insights into the ability of the overlying sediments to insulate the underlying successions and their contribution of heat flow into the rift system.

CONCLUSIONS

Calibrated airborne radiometric data was applied to the heat production equation to produce a map of heat production across the study area. Ground-sourced measurements of heat production data were taken from three main lithological units of the Harts Range Group metasediments to assess the accuracy of heat production derived from airborne radiometrics.

Calculations of heat production show that the average values for each lithology derived from airborne radiometric data lie within one standard deviation of the average calculated for each lithology from ground-sourced measurements. Therefore, deriving the heat production from airborne radiometrics will allow for the assessment of heat production on a much larger scale, across all components of the Cambrian Harts Range intracontinental rift without the need for extensive ground-sourced measurements.

Using this method, the heat production of all units proposed to have formed the intracontinental rift in the Harts Range can be estimated and their relative contribution of heat flow within the rift can be determined. This can provide further insights into the thermal drivers of medium-pressure, high-temperature metamorphism in an extensional intracratonic tectonic setting.

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Table 1. Comparison of heat production (HP) statistics calculated from ground-sourced radiometric measurements (G.S.) and airborne radiometric data (A.R.).

Lithological Unit:	Mean HP:		Std. Deviation:		Minimum HP:		Maximum HP:		HP Range:	
	G.S.	A.R.	G.S.	A.R.	G.S.	A.R.	G.S.	A.R.	G.S.	A.R.
Lower Brady Gneiss	2.94	2.51	0.58	0.35	0.33	1.29	5.31	3.47	4.98	2.18
Upper Brady Gneiss	2.81	2.34	0.79	0.26	0.26	1.66	5.43	3.34	5.17	1.68
Irindina Gneiss	2.38	1.67	1.20	0.53	0.29	0.30	7.35	3.11	7.07	2.81