Variations in continental heat production from 4 Ga to the present: Evidence from geochemical data

Article *in* Lithos · June 2019

DOI: 10.1016/j.lithos.2019.05.034

4 authors, including:

Matthew Gard
Geoscience Australia

Derrick Hasterok
University of Adelaide

Variations in continental heat production from 4 Ga to the present: Evidence from geochemical data

M. Gard[a,*], D. Hasterok[a,b], M. Hand[a,b], G. Cox[a]

[a] *Department of Earth Sciences, University of Adelaide, North Terrace, SA, 5005, Australia*
[b] *Mawson Geoscience Centre, University of Adelaide, North Terrace, SA, 5005, Australia*

Abstract

Crustal heat production accounts for 30 to 40% of continental heat loss and enhances thermally controlled processes such as melting and metamorphism, yet is in general poorly constrained. We present a new model for continental igneous heat production from ∼4 Ga to the present using a global geochemical database of 75,800 whole-rock analyses providing the highest resolution record to date. Hypotheses advanced to explain past heat production–age variations include erosion of the enriched felsic upper crust, decay of the radioactive elements, geodynamic processes such as the supercontinent cycle, secular cooling, lithological controls, and/or a major shift in the bulk composition in the crust during the late Archean. However, previous heat production–age models are often coarsely resolved, poorly sampled, and/or spatially biased. To test these hypotheses and refine secular trends in crustal heat production, we construct a model by correcting for radioactive decay and normalizing by SiO_2 content to remove the gross influence of lithology. The variations through time are highly correlated among both plutonic and volcanic samples, as well as mafic and felsic distributions. Unsurprisingly, compositional normalization indicates lithological control is the dominant factor on heat production after the influence of decay is removed. Following these adjustments, we find heat production has been relatively constant from ∼2.8 Ga to the present, with an increase from ∼3.4 Ga to ∼2.8 Ga. We suggest the heat production–age pattern does not significantly reflect the influences of erosion, secular cooling, depletion, or the supercontinent cycle as suggested by some previous studies. Heat producing element distributions might be expected to be similar regardless of the age of melt generation, once compositionally normalised and adjusted for the decay of the various isotopes. Compared to this reference model, we observe a heat production and heat producing element enrichment deficit, particularly for the Archean and Paleoproterozoic. This deficit is accounted for by a rapid increase in heat producing element concentrations associated with a

*Corresponding author
Email addresses: `matthew.gard@adelaide.edu.au` (M. Gard), `dhasterok@gmail.com` (D. Hasterok), `martin.hand@adelaide.edu.au` (M. Hand), `grant.cox@adelaide.edu.au` (G. Cox)

shift in the bulk composition of the crust from the early Archean to ∼2.7 Ga. Additionally, we suggest that the heat production record may also represent a biased sample set, perhaps as a result of selective preservation due to thermal stability. This new model will lead to better crustal heat production and global heat loss estimates both at present and within Earth's past.
Keywords: radiogenic heat generation, continental crust, crustal composition, secular crustal evolution

1. Introduction

Processes contributing to continental crust generation are suggested to have changed significantly throughout Earth's history (Belousova et al., 2010; Hawkesworth et al., 2016; Campbell, 2003). Fundamental changes such as the shift from vertical to horizontal tectonics and the supercontinent cycle are largely driven by the thermal evolution of the mantle (Condie et al., 2016). Factors such as the decay of radioactive isotopes through time, and depletion of the upper mantle in heat producing elements (HPEs) due to crustal formation have drastically changed the energy partitioning of heat between the crust and mantle through time. However, the temporal variations in heat production in the crust and mantle are poorly constrained.

Nearly 99% of radiogenic heat production is due to the decay of ^{40}K, ^{235}U, ^{238}U and ^{232}Th (Rybach, 1988; Wasserburg et al., 1964). Within the continental crust, heat production typically accounts for 30 to 40% of the heat loss (Pollack and Chapman, 1977; Artemieva and Mooney, 2001), but could in some cases account for 75% or more (Hasterok and Gard, 2016). As such, the distribution of HPEs affects the geotherm and influences thermally-controlled processes such as melting and metamorphism, as well as physical properties such as density, seismic velocity and viscosity (Sandiford and McLaren, 2006; Kelsey and Hand, 2015; McKenzie and Priestley, 2016). Heat production variations have the largest influence on heat loss in regions that are near thermal equilibrium (Cooper et al., 2004). Since stable regions account for nearly 85% of the continental crust by area (Gordon, 1998), understanding temporal variations in crustal heat production is important.

Past models for temporal variations in global HP are based on observations of heat production and/or surface heat flow (Vitorello and Pollack, 1980; Jaupart and Mareschal, 2014; Jaupart et al., 2016; Artemieva et al., 2017). These models are typically low in temporal resolution and/or contain geographic and lithological bias, generally a result of low sample numbers.

A few studies address regional variations of heat production with time, though these models are limited to the types and timing of magmatism of the area, making it difficult to draw direct inferences about globally extensive trends (Kukkonen and Lahtinen, 2001; Slagstad, 2008).

Despite variations in interpretations, nearly all models agree that present-day crustal heat production is systematically lower in Archean terranes relative to modern ones. Several hypotheses have been advanced to account for the variations through time, and can be explained broadly in two categories;

1. the rock record preserves a representative distribution of the heat production of the crust, with the variations in response to physical or geodynamic processes operating at the time, and/or
2. the rock record is biased or modified to preserve only selected samples.

We consider the following hypotheses from the literature in this manuscript:

1. decay of the radioactive elements through time leads to a first order monotonic decrease in heat production with increasing age (Jaupart and Mareschal, 2014; Jaupart et al., 2016);
2. lithological variations are the primary control on heat production, and may mask any temporal signals attributed to other secular or cyclical Earth processes (Kukkonen and Lahtinen, 2001; Slagstad, 2008);
3. heat producing element enrichment increased at the Archean-Proterozoic boundary, associated with a significant episodic shift towards more felsic compositions in the crust (McLennan et al., 1980);
4. heat production through time exhibits a non-monotonic trend with an approximate first order correlation with plate velocity, the supercontinent cycle and/or geodynamic setting (Artemieva et al., 2017);
5. erosion of an enriched radioactive upper crust leads to a decrease in heat production in older terranes as deeper, less enriched crust is exhumed (Vitorello and Pollack, 1980); and
6. selective preservation due to thermal stability has shifted older terranes to lower heat production distributions (Morgan, 1985).

In this study, we have estimated the heat production from an expanded compilation of igneous rock geochemistry with associated crystallization ages and heat production estimates.

We evaluate the contributions of the aforementioned hypotheses to the temporal heat production record. By improving our understanding of the temporal variations in heat production, it will be possible to develop more accurate estimates of heat production and heat loss with few direct measurements. Furthermore, the understanding of heat production variations through time yields important constraints on the physical and chemical processes operating over the past 4 Ga.

2. Review of Previous Models

2.1. Radioactive Decay

The radioactive isotope abundance in a rock at present-day does not equate to its abundance at formation. Heat production is the result of the decay of the unstable radioactive isotopes, whereby a fraction of the original mass is converted to energy. Jaupart and Mareschal (2014) showed such a systematic decrease in average heat production with increasing age, albeit in conjunction with large scatter on account of lithology variations. By fitting an average composition decay curve to the heat production trend, Jaupart and Mareschal (2014) proposed that there is little difference in the heat production distribution for any age interval at formation (Figure 1b). This model suggests the average heat production of newly formed crust is initially the same throughout geologic time, which implies the thermal conditions for crustal stabilization have remained largely unchanged since the Archean. In contrast, some regional studies do not necessarily observe such a defined trend (e.g. Kukkonen and Lahtinen, 2001; Slagstad, 2008), likely due to unique tectonic histories and varying lithologies.

2.2. Lithological controls

It is well documented that a rough first-order correlation exists between heat production and relative silica enrichment (Wollenberg and Smith, 1987; Kukkonen and Lahtinen, 2001; Hasterok and Webb, 2017). Felsic rocks are typically more enriched in heat producing elements; with enrichment generally decreasing with increasing maficity. For instance, median heat production declines from granite (3.54 μW m^{-3}), to diorite (1.20 μW m^{-3}), to gabbro (0.46 μW m^{-3}) (Hasterok and Webb, 2017). However, this trend is weak as natural variability is high (standard deviations of 0.74, 0.74 and 1.23 $\log_{10}$-units for granite, diorite, and gabbro, respectively). This lithological control hinders identification of any other temporal heat production signal. Regional studies in Norway and Finland do not produce clear relationships between heat production and age (Kukkonen and Lahtinen, 2001; Slagstad, 2008). Heat production of the Fennoscandian shield, Paleoproterozoic Transscandinavian Igneous Belt, and the Permian Oslo Rift, for example, overlap significantly in median heat production values regardless of age, tectonic environment and lithology. As HPEs are mostly concentrated in trace minerals, vast differences in concentrations between similar rock types can result from different alteration and enrichment histories (Kukkonen and Lahtinen, 2001). While Kukkonen and Lahtinen (2001) found a weak increase in heat production from Archean to Proterozoic-aged metasedimentary samples, both studies ultimately concluded that the lithologic controls on heat production make it difficult to assess temporal variations in heat production on a regional data set.

2.3. Shift in the bulk composition of the crust

While not specifically calculating past heat generation, McLennan et al. (1980) did investigate the temporal record for thorium and uranium enrichment for relatively uniform composition sedimentary and metasedimentary samples. They found that Th (and U) enrichment showed a monotonic increase in enrichment within samples at, and leading up to, the Archean-Proterozoic boundary, and then remained relatively constant moving towards the present. It was proposed that these observations were consistent with previous studies; that there was a significant episodic shift in the composition of the exposed crust, associated with an influx of granitic intrusions at the end of the Archean (e.g. Taylor and McLennan, 1985; Condie, 1993; Dhuime et al., 2015; Tang et al., 2016, and references therein). These intrusions would have contained much higher concentrations of Th and U than existing crustal material, and marked a step change in the average composition of the crust (from mafic to felsic), evidenced by no significant changes in element enrichments from $\sim$2.5 Ga to present.

2.4. Geodynamic Controls and Crustal Reworking

Since the difference in median heat production between felsic and mafic rocks is approximately an order of magnitude, shifts in average rock compositions may dominate the temporal record. These variations in composition may potentially reflect periodic or secular changes in dominant geodynamic and crustal reworking processes, e.g. the change from vertical to horizontal tectonics, or correlations to supercontinent formation and breakup. A recent study of heat production analyzed the temporal record of a restricted rock database (granites only); Artemieva et al. (2017).

Artemieva et al. (2017) utilized 445 globally distributed heat production estimates from gamma-ray spectrometry and found a highly variable, rather than monotonically decreasing heat production–age relationship, in contrast to some previous studies on a larger range of compositions (e.g. Vitorello and Pollack, 1980; Jaupart et al., 2016). They suggest a rapid increase, followed by a slow decline in heat production from the Mesoproterozoic to the present is correlated to similar variations in plate velocities, possibly associated with the assembly of the supercontinent Nuna (Figure 1c). However, their interpretations are tenuous given the significant spatial biases within their dataset; a point recognized by the authors themselves.

2.5. Erosion of Enriched Upper Crust

Early studies of heat flow suggested that surface heat flow and heat production were linearly related, leading to the concept of reduced heat flow (Roy et al., 1968; Birch et al., 1968). Under a reduced heat flow model, the crust is conceptualized as a high upper crustal heat producing layer (intercept) with a characteristic thickness (slope). This model only survives under erosion if heat production exponentially decreases with depth (Lachenbruch, 1970). Surface heat production observations in some obliquely exposed crustal sections, such as the Idaho and Closepet batholiths, appear to support the exponential model, either as a result of pluton emplacement or through the redistribution from fluid flow (Gosnold, 1987; Kumar and Reddy, 2004).

However, more recent evidence does not support a clear relationship between depth and heat production. In contrast, variations in heat production with depth in deep drill cores and along exposed crustal cross-sections exhibit more complex patterns of heat production with depth, rarely suggestive of an exponential decrease (Hasterok and Chapman, 2011). Even in some obliquely exposed crustal sections such as the Sierra Nevada Batholith, the apparent heat production depth relationship appears somewhat inconsistent with the generalized exponential distribution function (Sawka and Chappell, 1988; Brady et al., 2006). Lateral variations in heat production can alter the slope of the reduced heat flow–heat production relationship, further complicating the connection to depth dependence on heat production (Jaupart, 1983). Furthermore, indiscriminate studies of reduced heat flow lack a trend between heat flow and heat production (Sandiford and McLaren, 2002). More recently, Alessio et al. (2018) also showed that in metasedimentary crust, increasing depth as recorded by increasing metamorphic grade did not result in reduced heat production.

Vitorello and Pollack (1980) had this concept of reduced heat flow and differential erosion in mind when proposing an erosional control on the average heat production through time. They assumed older terranes have generally undergone greater exhumation, and thus exhibit lower heat production at the surface today (Figure 1a). Although this concept of reduced heat flow tailored their models, the erosional hypothesis is not necessarily negated by the complications discussed. The original reduced heat flow studies applied this method only to cogenetic plutons (Roy et al., 1968; Birch et al., 1968). Heat production decreases almost exponentially with SiO_2 content, on average, for igneous rocks (Hasterok and Webb, 2017), which could explain why the Idaho and Closepet batholiths are the exceptions that validate the exponentially decreasing heat production with depth and the differential erosion hypothesis. Inconsistencies arise when the dominant lithology in the vertical structure is not co-genetic, for example the metasediments atop the Sierra section, or as a result of their natural variability when considering individual point departures. In a perfectly co-genetic system, an exponential decrease with depth may be a reasonable model, but these idealised zones are few and far between and variance is high.

Furthermore, there is good observational evidence from holistic studies of continental crust composition that suggests heat production should decrease with depth from upper to lower crust because of a general increase in mafic compositions at depth (Rudnick and Gao, 2003, and references therein). Although recent studies challenge the assumption that mafic proportions general increase with depth (e.g. Hacker et al., 2011, 2015; Williams et al., 2014), heat production must decrease with depth, otherwise surface heat flow would be higher than observed (Taylor and McLennan, 1985).

2.6. Selective Preservation due to Thermal Stability

From observations on Precambrian cratons, there is qualitative evidence to suggest that terranes with relatively low radiogenic heat production may be less susceptible to reworking by orogenesis than regions with high heat production (and thus higher geotherm). Such cratons have generally remained relatively stable while surrounding provinces have often undergone rigorous deformation and magmatism (e.g. Clifford, 1970). High heat-producing terranes can be thermally weak as a result of the increased geotherm and susceptible to deformation, particularly when these HPEs are distributed at depth (Hand and Sandiford, 1999; Sandiford et al., 2002).

Morgan (1985) suggested that the early Earth rock record may not be a representative sample of the original heat production distribution, owing largely to these qualitative observations of Precambrian cratons and reduced standard deviations in Archean heat flow globally. Crust with low heat production, and thus lower geotherms, may have a much higher probability of stabilization and survival. Due to relatively high mantle temperatures, and higher average concentrations of heat producing isotopes globally than present-day (due to radioactive decay), average geotherms in the Archean crust were likely of higher temperature and greater variability than geotherms today. However higher mantle temperatures do not automatically imply higher mantle heat flow and vice versa, for instance, higher temperatures below a thick lithosphere can have lower heat flow than lower temperatures beneath a thin lithosphere. In the Archean, low heat production crust was far more likely to stabilize, according to Morgan (1985), while higher heat production terranes (even values that would be considered normal today) were more likely to be reworked and effectively removed from the record. Morgan (1985) observed an Archean–Proterozoic transition in the heat production record, where Archean samples seemed systematically lower than Proterozoic samples even when considering decay. He proposed that this may have indicated the last remobilisation of the high heat producing Archean crust, and the onset of a mantle thermal regime in which the range in crustal heat production typical of Proterozoic and younger crust would no longer be a major factor in localizing crustal remobilisation.

3. Geochemical data set

To examine the heat production–age record, we utilise a large whole-rock geochemical database, comprised of existing databases, and supplemented with geological survey compilations and individual data sets we have collated from the literature. The existing databases utilised include first and foremost EarthChem (`https://www.earthchem.org/`), which consists of many federated databases such as The Petrological Database of the Ocean Floor (PetDB) (`https://www.earthchem.org/petdb`), The North American Volcanic and Intrusive Rock Database (NAVDAT) (Walker et al., 2006), the USGS National Geochemical Database (`https://mrdata.usgs.gov/ngdb/rock/`) and Geochemistry of Rocks of the Oceans and Continents (GEOROC) (`http://georoc.mpch-mainz.gwdg.de`), as well as individually submitted publications. Additional databases utilised include the Newfoundland and Labrador Geoscience Atlas (Newfoundland and Labrador Geological Survey, 2010), Australia's national whole-rock geochemical database (OZCHEM) (Champion et al., 2016) and the Finnish lithogeochemical rock geochemistry database (RGDB) (Rasilainen et al., 2007). A complete list of references and link to the database are included in the supplementary material. These samples are sourced from a variety of locations and depths including drill cores, xenoliths etc., however the vast majority are surface samples from outcrop. The full database is available online at Zenodo (1,023,491 samples) (Gard et al., 2019) (`https://zenodo.org/record/2592823`), and the subset utilised in this manuscript is provided as supplementary data (75,800 samples).

For our analyses, we chose to focus on igneous and meta-igneous samples only, as these rocks make up the bulk of the continental crust. Furthermore, sedimentary and meta-sedimentary samples are excluded because these rocks generally represent an integration of material from a variety of sources that may have radically different ages, thus convoluting any potential heat production–age variations. SiO_2 is also restricted to between 40 and 85 wt.% and normalized to anhydrous conditions. This restriction only excludes $\sim$1.7% of samples. Extreme silica concentrations outside this range generally represent insignificant fractions of crustal samples, and statistically very little is lost due to their removal.

Rather than relying on highly variable and inconsistent rock naming schemes supplied by the various authors and sources, we chose to classify rock types using a total alkali–silica (TAS) naming scheme, modified from Middlemost (1994), to additionally classify high-Mg volcanics, as recommended by Le Bas and Streckeisen (1991). An advantage of such a scheme is that it is based on major element chemistry and can be used to directly compare plutonic and volcanic rocks of similar compositions.

We chose to only utilize samples with a reported/estimated age with an uncertainty of $\leq$200 Ma. Dating of rocks can be complicated as the radiometric dates of samples can be influenced by crystallization, metamorphism and/or inheritance. We use crystallization ages associated with the samples as that most likely represent the time at which heat production is set.

After the above filtering, the number of samples available for analysis is 75,800 (Table 1). The database represents measurements spanning a significant fraction of the continental area

Table 1: Data distribution - ages

Age range (Ma)	No. Data
0 – 200	34,034
200 – 400	4,787
400 – 600	6,741
600 – 800	2,187
800 – 1000	1,528
1000 – 1200	1,770
1200 – 1400	934
1400 – 1600	1,644
1600 – 1800	3,314
1800 – 2000	6,099
2000 – 2200	1,783
2200 – 2400	501
2400 – 2600	2,005
2600 – 2800	4,336
2800 – 3000	1,748
3000 – 3200	841
3200 – 3400	413
3400 – 3600	696
3600 – 3800	312
3800 – 4000	127
Total	75,800

(Figure 2a). While some large gaps persist, the sampling is sufficient to characterize many common rock types for most age intervals. The lowest populated age bins are mostly concentrated in the oldest age intervals, with the lowest containing 127 samples (3.8 to 4 Ga), and the largest hosting >34,000 (0 to 0.2 Ga) (Figure 2b, Table 1). The majority of age bins hold >500 samples, with 13 of the 20 bins containing 1000 samples or more. This constitutes a respectable increase in sample numbers over past studies.

Our data set significantly expands on the current compilations, particularly for those with associated ages and heat producing element concentrations. As EarthChem is biased towards young and volcanic rocks, the improvement is most apparent among age bins >200 Ma and plutonic samples.

4. Methods

4.1. Estimating Heat Production

Heat production can be estimated from the concentration of HPEs. We use the formulation and coefficients by Rybach (1988),

$$A(\mu\text{W m}^{-3}) = 10^{-5}\rho(9.52[C_{\text{U}}] + 2.56[C_{\text{Th}}] + 2.89[C_{\text{K}_2\text{O}}]), \tag{1}$$

where C_{U} and C_{Th} are the concentrations of uranium and thorium in parts per million (ppm) respectively, $C_{\text{K}_2\text{O}}$ is the concentration of K_2O in wt.%, and ρ is the density in kg m^{-3}.

4.2. Estimating Density

Since heat production requires density, and few samples within the global database include density measurements, we need a way to estimate density for the geochemical samples. Many studies simply assume densities but lack compositional information to develop more accurate estimates. To estimate density, we use major element compositions following the method of Hasterok et al. (2018). Compositions are first normalized on an anhydrous basis and then density is calculated for silicate-dominated igneous samples using

$$\rho = 2506 + 205\,\text{Fe}^* + 793\,\text{maficity} - 4.5\,\text{MALI}, \tag{2}$$

where

$$\begin{aligned} \text{Fe}^* \text{ (iron number)} &= C_{\text{FeO}_\text{T}}(C_{\text{FeO}_\text{T}} + C_{\text{MgO}})^{-1} \\ \text{MALI (modified alkali-lime index)} &= C_{\text{Na}_2\text{O}} + C_{\text{K}_2\text{O}} - C_{\text{CaO}} \\ \text{maficity} &= n_{\text{Fe}} + n_{\text{Mg}} + n_{\text{Ti}}, \end{aligned}$$

and n is the molar fraction (Frost et al., 2001; Clemens et al., 2011). Estimated average uncertainty in density is ± 97 kg $\text{m}^{-3}(1\sigma)$, translating to a heat production uncertainty for each sample of ($\sim$4%).

This density relationship is calibrated to igneous samples with density estimates (Haus and Pauk, 2010; Bédard et al., 2016; Barette et al., 2016; Slagstad, 2008, 2017). We consider these uncertainties acceptable and superior to assuming a constant density for all samples, as is often the case. This method will likely overpredict densities for any volcanic samples that have porosity, since porosity is not included as a parameter. However, since porosity estimates are not included in the database, it would be impossible to correct for it in this current iteration. For the majority of other samples however, the predicted densities fall very close to typical assumed values e.g. $\sim$2.75 g/cm^3 for granite samples. For further discussion on this density model fit, refer to Hasterok et al. (2018).

4.3. Correcting for radioactive decay

Heat production of bulk Earth decreases with time due to the radioactive decay of the heat producing isotopes. If we wish to observe any variations in heat production separate from this long-period decay influence, we must adjust each sample to its estimated heat production at formation.

Samples inherently host lower heat production at present than at the time of formation. We can estimate the heat production at the point of crystallization by applying a decay correction. By utilizing present-day abundances of the isotopes, in conjunction with their measured decay constants, we can recompute each sample's individual isotope concentrations (^{40}K, ^{235}U, ^{238}U and ^{232}Th) at the time of formation, and then recompute the heat production estimate using Equation 1.

Radioactive decay follows the following relationship:

$$A_t = A_0 \mathrm{e}^{-\lambda t}, \tag{3}$$

where A_t is the concentration of the HPE isotope at some time in the past at time t, A_0 is the HPE isotope concentration at present-day, λ is the decay constant for the HPE isotope, and t is the time to project back to. The decay constant it given by,

$$\lambda = \frac{ln(2)}{t_{1/2}}, \tag{4}$$

where λ is the decay constant, and $t_{1/2}$ is the half-life of the isotope.

We recompute the ^{40}K, ^{252}Th, ^{238}U and ^{235}U isotopes in this manner for each individual sample. The present-day concentrations of each isotope are estimated from the given concen-

Table 2: Caption

Isotope	Half-life (Ga)	Abundance
^{238}U	4.510	0.9928
^{235}U	0.713	0.00711
^{232}Th	13.90	1
^{40}K	1.230	0.000117

trations of the elements, multiplied by the average abundances of the isotopes.

This adjustment assumes other influences such as disequilibrium, or post-formation processes have not significantly altered the isotope ratios or concentrations since creation of the samples, at least on average for the bin distributions.

5. Temporal analysis of Heat Production

5.1. Unprocessed temporal trend

Previous studies, often for local regions, tend to plot different rock types, ages, and tectonic environments together on the same plot and ordered temporally to examine if there are any apparent trends with heat production and age. We have done similar in Figure 3 in 200 Ma age bins. Compared with previous models, our temporal sampling is at a much higher resolution. In past heat production–age studies, most authors utilize very coarse age resolutions (Jaupart and Mareschal, 2014; Artemieva et al., 2017), or ordered time-period data (Kukkonen and Lahtinen, 2001; Slagstad, 2008). This higher resolution may increase our ability to determine whether variations are smoothly varying or step changes. While Jaupart and Mareschal (2014) discussed heavily the variability of samples within any age group, such extended age intervals can give the impression either heat production varies simply over coarse temporal resolutions or that there are step changes corresponding to divisions in the geologic timescale instead of gradients (Morgan, 1985). This delineation of step changes or smooth variations are important to help identify processes which may affect continental evolution. Our results using 200 Ma bins suggest the changes are generally smooth (also suggesting relatively low bias), but that there are variations that are not captured by the coarse resolutions of previous studies (Figure 1 and 2b). We observe significant variations in the global median heat production over the past 4 Ga. The median heat production varies between a max of ∼2.52 in the 1600 to 1800 Ma interval, and minimum of ∼0.15 in the 3000–3200 Ma interval.

While it can be seen that older samples on average have less heat production (likely due to decay, but not quantified or validated in this figure), not much more information can be drawn from this. Spatial bias, lithology bias, and other influences are likely buried in this trend. In this study we work towards processing this information to decipher as much information as possible from these temporal trends.

5.2. Decay correction and silica distributions

Removing the influence of decay is the first step in deciphering heat production variations at formation. Figure 4a depicts the decay adjusted temporal trend for heat production based on the method in section 4.3. The oldest Archean data increase ∼0.5 log-units in heat production on average (Figure 3 vs. Figure 4a).

For the purposes of this study, 'felsic' and 'mafic' samples are taken to be greater and less than 60 wt.% SiO_2 respectively. Besides being commonly divided in this way, we also note a minimum in SiO_2 composition histograms at ∼60 wt.% (Figure 4b), an observation often referred to as the 'Daly gap' (Daly, 1925). After decay adjustment, we observe the heat production at formation to be relatively flat through time at the longest wavelength, albeit with significant shorter temporal variations persisting. Median felsic heat production is 2.53 μW m^{-3}, and median mafic heat production is 0.61 μW m^{-3}. Figure 4b and c depict how silica distributions vary for each age bin, and there appears to be a correlation between relative mafic/felsic proportions and the observed heat production medians in the bins. This correlation is expected; there is a propensity for felsic material to be more enriched in heat producing elements than mafic material (Rybach and Buntebarth, 1984; Fountain, 1987; Hasterok and Webb, 2017). The exact magnitudes do not necessarily correlate; for example the lowest median silica bin does not correlate to the lowest heat production age interval, however the step-wise pattern of increasing and decreasing heat production compared to adjacent intervals does appear correlated.

The types of magmatism occurring within the continental crust are generally related to the tectonic processes operating at any given time. Some tectonic settings are more common during particular intervals of Earth's history. For example, mafic dike swarms are common during periods of supercontinent breakup, felsic magmatism is dominant during continent-continent collisions and arc magmatism during intervening periods (e.g. Hawkesworth et al., 2009, and references therein). Periods with varying dominant tectonic environments may perhaps lead to coarse variations in heat production signal, potentially as a product of a mafic/felsic bias in the preserved global rock record, or as varying enrichments of trace elements for similar major element composition samples. Felsic (intermediate) magmas are far more abundant in continental arcs than in island arcs (Lee and Bachmann, 2014), and these environments are more common during intervals of supercontinent amalgamation. Conversely during supercontinent breakup, extensive rift environments and associated mafic dike swarms become more prevalent in the rock record (e.g. Worsley et al., 1984). Extensive flood basalts, increased mafic magmatic activity and continental dike swarms for example have also been utilised as potential evidence for one or more Late Archean supercontinents (Heaman, 1997; French et al., 2004).

While we do observe heat production variations that appear to correlate with shifts in felsic to mafic dominance (Figure 4 a,b and c), there appears to be little to no correlation with the supercontinent cycle and orogenic activity from Condie and Aster (2013). This correlation is not observed in either the heat production–age temporal record, contrary to the suggestions made by Artemieva et al. (2017), or the relative concentrations of felsic/mafic samples (Figure 4d). While it is possible such high frequency variations in composition related to orogenic cycles are aliased by the 200 Ma interval size, this issue is even more likely present in previous lower resolution studies (e.g. Artemieva et al., 2017).

The observed trends in the decay adjusted plot are still subject to significant sampling (lithologic) and spatial biases. As discussed previously, for example, incompatible heat producing elements are more likely to be concentrated in felsic lithologies than mafic samples, so merging all samples together will be heavily influenced by relative proportions of these rock types. Known spatial bias from previous literature may also obfuscate the temporal trends e.g. Proterozoic Australian rocks are known to be highly enriched in heat producing elements, which can be observed in the record at least from 1400–1800 Ma. We return to this in Section 5.4.

5.3. Sampling bias (lithological)

It is clear that lithological variability appears to dominate the temporal trends in heat production after decay adjustment, corroborating previous studies (e.g. Slagstad, 2008; Kukkonen and Lahtinen, 2001). To account for this variability, one may choose to analyse individual rock types separately to significantly reduce the variability due to lithology (e.g. Artemieva et al., 2017). Figure 5 presents the temporal trends of decay-corrected heat production for the four most prevalent rock types in our database.

From 3.2 to 0 Ga, nearly all rock types have similar long period heat production–age variations. From the Archean to Paleoproterozoic, heat production appears (relatively) constant, and there may be a minor step increase in heat production at ∼2 Ga to ∼1.2 Ga (Figure 5), and then decreasing again to a similar median to the rest of the set. One may suggest the timing of this increase is consistent with the formation of the supercontinent Nuna, however this is unclear since there is no apparent correlation to other supercontinent cycles. Other than these gross observations, it is difficult to interpret finer scale variations in these individual rock-type plots due to the many fewer samples in individual age bins (expanded here to 400 Ma). Archean bins in particular suffer from poor sampling and strong spatial bias when observing any one rock type.

While observing individual rock types may be a reasonably valid method for damping the lithological influence, this restricts the data available analysis and as a result lowers temporal resolution of the data set. It is clear that there may be consistent long period trends across mafic and felsic ranges of rocks, albeit at different magnitudes. We seek a simple adjustment that allows all rocks (or at least the largest percentile rocks) to be compared on an equivalent scale for interpretation. One possible method removes gross lithological variations by adjusting compositions to a common silica content, removing the dominant effect of fractionation.

5.3.1. Silica normalization

Correlation between heat production and silica is generally considered weak because of large natural variability (Fountain, 1987; Kukkonen and Lahtinen, 2001; Artemieva et al., 2017). For example, Kukkonen and Lahtinen (2001) applied a linear fit between silica content and heat production and resolved a correlation coefficient (r-value) of 0.44 and 0.69 for plutonic and metavolcanic rocks, respectively. We calculate an r-value between SiO_2 and the log of heat production of 0.62 (r^2 value of 0.38) on this global data set, confirming the suggestion that this is a weak relationship. This weakness is due to the high natural variability within narrow silica bands. Heat production can vary by an order of magnitude or more within any silica interval. Values that sit above the median tend to be more alkali-rich (especially potassium), whereas lower values tend to be alkali-poor (Hasterok and Webb, 2017).

Despite the natural variability, there is a well resolved trend in median heat production and silica content (Figure 6a). Calculating the median log heat production in 2 wt.% SiO_2 bins resolves an r^2-value that is much higher than for the individual samples (weighted linear fit - r^2 = 0.91), suggesting the two are quite well correlated, on average, but that natural variability is high. There is some non-linear behaviour the tails i.e., for mafic samples with SiO_2 <46 wt.%, as well as highly felsic samples with SiO_2 >78 wt.%. If these tails are ignored, r^2 is as large as 0.96. Thus, for the majority of rocks, a silica adjustment works very well as a means to directly compare heat production.

To remove the dominant lithological influence on the temporal heat production record, we produce a linear fit to the median heat production that is weighted by the number of samples per silica-bin. This weighting reduces the influence of the tails on the overall fit at the expense of a slightly lower r^2 value (0.91), but should fit the bulk of the data much more reasonably. The weighted fit is given by,

$$\log_{10} A = 0.0349\, C_{\mathrm{SiO_2}} - 2.0565, \tag{5}$$

where A is heat production in μW m^{-3} and $C_{\mathrm{SiO_2}}$ is the median SiO_2 concentration in wt.%. The RMSE (root mean square error) is 0.09 log-units.

Heat production estimates for individual samples with varying SiO_2 can now be normalized to a common SiO_2 by simply shifting the data up or down-slope using the relationship,

$$\log_{10} \bar{A}_i = \log_{10} A_i + 0.0349(\bar{C}_{\mathrm{SiO_2}} - C_{\mathrm{SiO_2,\,i}}), \tag{6}$$

where $\bar{A}_i$ is the heat production normalized to a reference SiO_2 concentration of $\bar{C}_{\mathrm{SiO_2}}$.

The exact value of SiO_2 normalization is unimportant since it simply represents a shift of the data. This adjustment maintains the natural variability within each silica bin but shifts the distributions to comparable magnitudes. For example, a mafic sample that sits 0.5 log-units below the median at an SiO_2 of 50 wt.% will retain a similar position in the normalized distribution, ∼0.5 log-units below the median heat production. We chose a value of 75 wt.% SiO_2 as the reference value.

5.3.2. *Temporal plutonic and volcanic trends*

Though some of our estimates are derived from drill cores and xenoliths, the vast majority of samples originate at the surface and therefore represent an estimate of the average surface heat production. However, in the analysis that follows, one must be careful equating samples collected at the surface with information about the surface alone. While volcanic rocks are surface samples, plutonic rocks originate from below the surface thus providing a vertical dimension, even if we are not certain at what depths they are derived from. In our analysis, we must examine the differences between plutonic and volcanic samples to potentially identify any coarse depth influence on heat production.

There is a dichotomy between plutonic and volcanic rocks (Figure 6b and Figure 7a) that presents the potential for both a compositional bias and difference in magnitude. There are some age bins for which the heat production of plutonic and volcanic rocks are similar, but for bins that differ, the plutonic heat production tends to be greater than the volcanic heat production (Figure 7b).

After normalizing for SiO_2, both sets have similar median values and variance, and are approximately log-normal (Figure 7c). The similarity in heat production for the majority of ages (Figure 7d) suggests that the raw plutonic and volcanic differences are dominated by the bias associated with SiO_2 content from each respective set. Furthermore, the similarity of the adjusted trends indicates that both plutonic and volcanic data can be analyzed together to produce a more robust temporal model. However, since both plutonic and volcanic data include mafic and felsic samples, the two sets are not compositionally independent.

5.3.3. *Temporal mafic and felsic trends*

Decay-adjusted felsic and mafic temporal trends appear to be correlated, separated by a relatively constant magnitude (Figure 8a and b). After silica normalization, the median heat production values for felsic and mafic samples are essentially coincident. A wider distribution among mafic samples persists after normalization (Figure 8c). Examination of the normalized heat production–age curves shows similar temporal trends between the two (Figure 8d). The correlation appears to break down within some intervals e.g. between 1.6-1.8, 3.2-3.4, and 3.8-4 Ga where sample numbers are lowest. As the two records are largely coincident post-SiO_2 adjustment, we choose to merge the two sets for the subsequent analyses. With the ability to adjust heat production to a common SiO_2 magnitude, it is now possible to examine global temporal variations free from the largest compositional influence resulting from fractionation.

5.4. Sampling bias (spatial)

Silica normalisation removes the first-order component of spatial bias due to differences in lithology, though it will not remove biases related to trace element enrichment and/or depletion that may be attributed to the source or crustal contamination. The remaining spatial variations are, in general, relatively small (Table 3).

However there are some exceptions, including the oldest age intervals of $\sim\geq3$ Ga, where the amount of preserved crust is small, and the number of regions are limited. A peak also persists in heat production in the Mesoproterozoic to the late Paleoproterozoic (from $\sim$1.4 to 2 Ga). This peak is attributed almost exclusively to the dominance of the high heat-producing felsic samples of the Australian data set. While Artemieva et al. (2017) attribute this peak to potential supercontinent cycle and plate velocities, it is clear from our analysis that this is just an artifact of spatial bias.

This irregularity is unsurprising, as the anomalous nature of the Australian Proterozoic samples is well documented in studies of heat flow, heat production and thermal isostasy (Morgan, 1985; Neumann et al., 2000; McLaren et al., 2003; Hasterok and Gard, 2016; Hasterok and Webb, 2017). While this region is generally considered anomalous, the Proterozoic terranes of Australia are spatially extensive and make up a significant fraction of the preserved crust from that time. Our data set contains $\sim$2,000 Australian samples in the age range from 1.4-2 Ga, accounting for around half the samples in this interval. Removing the Australian Proterozoic samples in this interval brings the median heat production down to similar magnitudes of neighbouring ages (Figure 9a and b). We chose to remove the Australian Proterozoic samples, as they represent the largest deviation from the global means.

6. Discussion

Temporal variations in decay-corrected mafic and felsic heat production are very similar for the majority of Earth history, for both lithologically normalized and un-normalized distributions (Figure 8b and d), with the exception of some of the oldest intervals ($\geq$3 Ga). This similarity is remarkable considering the diversity of sources and processes that create or alter the chemistry

Table 3: Analysis of spatial bias among decay and SiO_2 normalized HP distributions by age interval [a]

Age bin (Ga)	Country	Country % of age bin	Median HP (Country) (μW m^{-3})	HP Quantiles (Elsewhere) (μW m^{-3})		
				0.25	0.5	0.75
0-0.2	US	47.51%	1.038	0.559	1.166	2.525
0.2-0.4	CN	16.61%	1.050	0.692	1.097	1.599
	AU	18.05%	1.273	0.612	1.013	1.614
	CA	21.47%	1.077	0.632	1.101	1.701
0.4-0.6	CA	51.92%	1.047	0.637	1.102	1.797
0.6-0.8	CN	21.54%	0.927	0.495	0.937	1.637
	EG	23.59%	0.783	0.484	1.040	1.739
0.8-1.0	CN	63.29%	0.815	0.611	1.074	1.574
1.0-1.2	AU	18.98%	1.670	0.848	1.375	2.356
	CA	19.83%	1.731	0.856	1.380	2.205
1.2-1.4	AU	19.59%	0.796	0.805	1.346	2.666
	CA	24.30%	1.042	0.769	1.348	3.067
1.4-1.6	CA	20.32%	1.001	1.074	1.822	3.051
	AU	39.78%	2.607	0.755	1.183	1.827
1.6-1.8	AU	66.66%	2.582	1.021	1.532	2.295
1.8-2.0	AU	27.58%	2.151	0.667	1.196	1.902
	FI	38.10%	1.190	0.892	1.663	2.480
2.2-2.4	CA	17.37%	1.175	0.955	1.501	2.228
	CN	27.54%	1.506	0.850	1.390	2.039
	IN	30.54%	1.520	0.884	1.389	2.071
2.4-2.6	FI	15.41%	1.364	0.572	1.095	2.005
	CN	46.33%	0.894	0.748	1.471	2.283
2.6-2.8	CA	35.77%	0.792	0.626	1.261	2.284
2.8-3.0	AU	16.59%	2.005	0.444	0.753	1.268
	GL	21.51%	0.654	0.543	0.998	1.855
	CA	39.65%	0.817	0.533	0.938	1.840
3.0-3.2	AU	16.88%	0.838	0.390	0.618	1.103
	GL	58.38%	0.551	0.507	0.906	1.584
3.2-3.4	AU	15.74%	1.049	0.254	0.551	0.972
	ZA	16.71%	0.455	0.292	0.715	1.179
	IN	39.23%	0.314	0.440	0.780	1.255
3.4-3.6	SZ	31.90%	0.442	0.747	1.428	2.084
	AU	45.83%	1.597	0.237	0.582	1.379
3.6-3.8	TF	16.99%	0.857	0.585	1.105	2.276
	GL	58.01%	0.972	0.685	1.184	2.738
3.8-4.0	CA	41.73%	2.557	0.603	0.797	2.373
	GL	54.33%	0.804	1.530	2.489	3.776

[a]Deviations of country median beyond the 0.25 or 0.75 quantiles of the "elsewhere" set highlighted in grey

of a melt. Mafic melts are typically extracted from the mantle, whereas felsic melts are more complex, originating from fractionation of mafic melts or melting of the crust, both of which may incorporate variable amounts of metasedimentary material. The absence of a temporal lag between the mafic and felsic records implies that whatever process has led to this shared relationship must occur with a separation of no more than 200 Ma (the width of our age bins).

After the decay correction, silica adjustment, and removal of the Australian Proterozoic terranes, the distribution of heat production through time exhibits shallow long-period variations (Figure 9b). These changes are similar or shallower in magnitude to the width of the interquartile range of natural variability, with the exception of a potential decrease from 4-3.2 Ga and a subsequent increase from 3.2-2.8 Ga. The downwards trend from 4-3.2 Ga is likely due to the divergence in felsic and mafic correlation discussed previously, where merging of the sets may not be valid (Figure 8d). These trends are only observed in the mafic samples, whereas the felsic samples appear relatively flat for the entire period from 4.0-2.8 Ga. Plutonic and volcanic rocks do not share this breakdown in correlation but are also are not compositionally independent.

6.1. Observed and expected Heat Production

Jaupart et al. (2016) discussed that crustal heat production appeared to show a clear trend of decrease with increasing age, and was able to be accounted for almost exclusively by decay. While we agree this flattens this first order variability of the heat production record, there is still more to this result that needs to be discussed, even after the lithological influence is normalised. In the Archean, heat production of the bulk silicate Earth was 3 to 4 times higher than the present-day due to decay alone. In a simplified sense, ignoring other known processes that may influence HPE distributions temporarily, one might expect samples from the Archean to contain 3 to 4 times as much heat production at formation as a result. If we project the present-day heat production distribution back into the past using the inverse of Equation 1, we expect an exponential decrease in heat production at formation from the Archean to present-day (Figure 10). The adjusted heat production record falls below this prediction, which we refer to as a deficit in old terranes (Figure 10). This deficit is as large as 0.5 log-units in the Early Archean. The comparison to this deficit is simply to acknowledge a decrease in heat production enrichment compared to present day conditions extrapolated to the past. Either the rock record is biased towards lower HP distributions and/or the HP distributions for similar lithologies have varied through time as a result of differing conditions in the past. Below we discuss the relevance of the aforementioned hypotheses that may contribute to variations in the temporal heat-production record to produce the observed deficit.

6.1.1. Shift in bulk crustal composition

There is clear evidence for a temporal shift in HPE concentrations for approximately uniform major element composition sedimentary and metasedimentary samples (McLennan et al., 1980). This shift is attributed to a shift in the composition of exposed crust from more mafic (lower Th and U) in the Archean, to more felsic (higher Th and U) towards the end of the Archean. Though we normalize for SiO_2, granites derived from more mafic sources are likely to have lower heat production than those with greater contributions from felsic and intermediate crust. Hence, the composition of the crust being reworked will have an influence on newly formed melts, raising the heat production by differing amounts depending upon the SiO_2 content of the crust. With time, the enrichment of U and Th may then indicate a shift from more mafic crust in the Archean, to more felsic crust in the late Archean, and maintained to present day.

Despite relatively constant heat production discussed in this manuscript, we also show a rapid increase in Th and U content from early Archean to ∼2.7 Ga, and then a relatively constant Th value to present day (Figure 11). At first glance this may appear contradictory, as one might expect that an increase in heat producing element enrichment would be associated with an increase in heat production. However, this is easily resolved when analysing the decay adjustment. In the early earth, the proportion of the isotope ^{235}U to ^{238}U was significantly higher than today due to the much shorter half life of ^{238}U (see Table 2). The decay of ^{235}U (∼575 μW kg^{-1}) produces just over six times as much energy as that of the decay of ^{238}U (∼91.7 μW kg^{-1}), and ∼20 times that of ^{232}Th and ^{40}K (∼25.6 and ∼29.7 μW kg^{-1}, respectively) (Rybach, 1988). Thus, while total heat producing element enrichment was lower in the Archean, this was counterpoised by increased ^{235}U proportions. Thus, the heat production deficit identified in Figure 10 is the result of a shift in HPE enrichment, independent of lithology, and likely due at least in part to the shift in bulk crustal composition (McLennan and Taylor, 1980). However, other hypotheses must also be considered that might attribute to this alteration of HPE enrichment.

6.1.2. Crustal Reworking

In a simplified global crustal reworking model, it is assumed an increase in heat production in younger rocks should be observed. HPEs preferentially partition into melts during partial melting due to their incompatibility (e.g. Workman and Hart, 2005), so during consecutive events of crustal accretion, orogenesis and tectonic reworking one may expect differentiation of the continental crust to progressively increase. Nd and Hf isotopes both suggest that crustal and mantle reworking is an important process for crustal evolution and may account for a significant fraction of the present volume of the crust (Hawkesworth et al., 2019). Such processes could be assumed to increase on average during periods of supercontinent formation and breakup. As a result, in a simplified model, one may expect a general first order increase in heat production through time due to progressive reworking, with a second order variation correlated with periods of supercontinent formation and breakup (Figure 12).

The average heat production of igneous rocks appears to change on multiple temporal scales in our analyses. Most of the short period variations were removed through the compositional normalization. What remains are smoothly varying and long-period temporal differences that could potentially be considered within natural variability. Artemieva et al. (2017) suggested the pattern of heat production through time for a small set of granites was correlated with estimated plate velocities from Korenaga (2013). However, we find no correlation to the decay-corrected, nor silica normalized temporal heat production models (Figure 4a and 9b, respectively). Similarly, we do not observe a correlation with these estimated plate velocities for the unprocessed granite data or even similar temporal trends of heat production as Artemieva et al. (2017) (Figure 5a).

Within our silica and decay adjusted temporal signal, we observe no apparent periodic correlation to supercontinent formation or break up, and no systematic increase through time in heat production. Interestingly, mafic and felsic temporal trends track each other almost coincidentally (Figure 8d). If partial melting and assimilation of older heat production into younger rocks was occurring on a global scale in the crust, and if the sources of mafic melts have remained relatively constant through time, we might expect a divergence in the mafic and felsic samples temporally, increasing towards the present. Additionally, modern felsic samples, in particular, are expected to be more enriched in HPEs relative to the oldest Archean samples after decay adjustment. While we observe greater enrichment in the present, the long term trend does not fit the expected response of reworking. It is possible enrichment due to this reworking argument may have limited potential to redistribute HPEs. With each instance of successive partial melting, the ability to redistribute meaningful amounts of trace elements plummets rapidly. In general, there may be only one or two instances of HPE redistribution associated with partial melting, but even melting may not redistribute HPEs in any meaningful way unless significant amounts of water are reintroduced (Alessio et al., 2018).

Surprisingly, our results suggest that global variations in dominance of geodynamic processes have little influence on relative heat production enrichment for similar rock types. Instead, it is likely that these processes impart a quasi-periodic signal on the median volumes of different compositions of melts through time, rather than the heat production of the individual compositions themselves e.g. periods of more intense and voluminous mafic magmatism may be associated with certain temporally dominant geodynamic environments. However, such an influence could only be observed prior to SiO_2 normalization and would then, in turn, likely be heavily masked by compositional sampling bias. Prior to the adjustment for SiO_2 there could potentially be a weak correlation to troughs and peaks of heat production to supercontinent cycle, but there is large uncertainty as a result of the compositional influences. Deciding how to differentiate whether a certain rock type was more pervasive during a time interval, or if it's merely the result of oversampling of a particular rock type in that time period is difficult to distinguish from the database alone.

6.1.3. Secular Cooling and Melt Fractions

Earth's internal temperatures have reduced through time, a function of secular cooling with primordial heat loss and the decrease of HPE due to radioactive decay. Evidence of this cooling has been observed in the decline in relative abundance of komatiites (Nisbet et al., 1993), studies of mantle potential temperatures from MORB's (Abbott et al., 1994), xenon isotope data (Coltice et al., 2009), and continental basaltic geochemistry (Keller and Schoene, 2012). These studies suggest that Archean mantle temperatures were on the order of 100-200°C hotter than present-day. Processes such as crustal diapirism, formed by the process of sagduction (Goodwin and Smith, 1980), a unique feature of the Archean, also suggests a hotter and more ductile crust (Mareschal and West, 1980). Similarly, high and intermediate thermal gradients in the continental crust were also perhaps more common in the past (Brown and Johnson, 2018).

Existing thermal evolution models suggest an increase in temperatures in the first 1-1.5 Ga of Earth history, and then cooling towards present at an increasing exponential rate (Labrosse and Jaupart, 2007; Herzberg et al., 2010; Condie et al., 2016). Greater temperatures in the mantle and crust in the past might suggest that higher degrees of partial melting were present, and thus one may hypothesize a signal in the heat production record as a result. As previously discussed, HPEs preferentially partition into the melt phase during partial melting (e.g. Workman and Hart, 2005), and thus higher melt fractions on average may produce lower heat producing melt products. Thus, if there exists a partial melting signal associated with cooling rates, we may expect a general increase in heat production towards the present, with most rapid variation closest to present-day due to more rapid cooling (Labrosse and Jaupart, 2007; Condie et al., 2016; Herzberg et al., 2010) (Figure 12).

While there may be a slight decrease in heat production from 1 Ga to present-day (Figure 10), the trend appears to be within the natural variability of the distribution and is hard to distinguish with any certainty. It is also expected that if this was a temperature/partial melting influence, the median at 1 Ga should persist further into the past, however the period from 1-2 Ga has much the same median as the present-day age interval. It appears unlikely that secular cooling has exerted a significant influence on the heat production–age record from these results.

6.1.4. Mantle Depletion

The formation of the continental crust has depleted the mantle of incompatible elements. While the rate of continental growth and rates of recycling are still debated (Belousova et al., 2010; Condie and Aster, 2010; Armstrong et al., 1981; Goodwin, 1996; Pujol et al., 2013), mantle depletion should result in a decrease in heat production of progressively younger rocks extracted from the products of mantle melting (Figure 12), assuming other influences such as degree of mantle melting were constant. Thus, we may expect depletion should cause a surplus of heat production in the early Earth rather than the deficit observed. Among the better constrained portion of the temporal heat production curve (<3.4 Ga), we observe no surplus pattern in heat production (Figure 9b). It is possible most of the continental crustal growth occurs >3.4 Ga, where there appears to be a rapid decrease in heat production of mafic samples (Figure 8d), divergent to the relatively flat trend in the felsic samples. For example, Campbell (2003) suggests that at ∼3 Ga, ∼75% of the present-day continental mass already existed. However, the relatively few sites from which these data are drawn makes it difficult to interpret these changes with great confidence (Figure 8d). It is also possible such a signal might be offset or altered by subduction enrichment, especially at continental margins with high erosion rates (e.g. Scholl and von Huene, 2007).

6.1.5. Erosional Influence

Modern orogens may be eroded with time, exposing deeper and presumably more intermediate to mafic rocks (e.g. Christensen and Mooney, 1995; Rudnick and Gao, 2003). Thus, it is reasonable to assume there is also a compositional influence on the vertical heat production distribution. Vitorello and Pollack (1980) suggested an impact on the heat production record may be observed due to this erosional influence; subsequent to formation and mountain building, surface heat production may approach an equilibrium at an exponential rate after a few hundred million years.

The global signal expected from erosion is, at least on a global scale, an increase in the proportion of felsic rocks exposed towards the present with an associated increase in median heat production (Figure 12). Such variations may be hard to distinguish when observing a global data set; as the largest component of this influence is likely compositionally entwined (increasing maficity with depth), we may have effectively removed its impact with the silica normalization. Thus, we do not preclude the existence of an erosional influence for local regions, but there appears to be no systematic decrease in silica or heat production in the global data set within the first 200-500 My in the pre-silica correction data sets (Figure 4a,b).

For most stable continental regions, the upper crustal rocks (∼10 km) are responsible for the majority of the bulk crustal radiogenic component of surface heat flow (McLennan and Taylor, 1996). As HPEs are highly incompatible, they will be preferentially enriched during partial melting and crustal growth. The exact nature of the vertical distribution is unique to any location and sometimes highly variable, dependent on complex histories of crustal growth, accretion, deformation and tectonic reworking (e.g. Brady et al., 2006; He et al., 2008; Ketcham, 2006). The lack of an erosional signal in the globally averaged rock record may also be attributed in part to this complexity. As volcanic and plutonic samples are so similar after silica adjustment (Figure 7), this suggests that depth of emplacement has a minor influence on HPE concentrations once lithology is accounted for, at least on a globally averaged scale.

6.1.6. *Thermal Stability and Selective Preservation*

Morgan (1985) suggested that the early earth heat production record may not represent the true global distribution of the time due to a selective preservation bias (discussed in more detail in Section 2.6). Lithosphere with lower heat production will house lower geotherms and will be internally cooler than regions with higher heat production and similar mantle heat flow contributions. As a result, these low heat producing regions are less susceptible to orogenic reworking and have a higher probability of stabilization and survival in the Archean record (see also Sandiford et al., 2002). This influence does not preclude higher heat producing rocks existing in these older time intervals or being preserved in some locations. Instead, Morgan (1985) hypothesizes that, in general, high heat producing regions will be statistically less likely to survive in the geologic record resulting in a decrease in the average preserved heat relative to the true heat production distribution. Delineating a quantifiable thermal stability derived preservation model from the other processes discussed however is almost impossible.

Although heat production appears to be relatively constant through time for similar major element compositions, the concentrations of HPE's were lower in the Archean. This result seems well described by the bulk composition shift in exposed terrains, as discussed previously. The oldest sediments should also preserve a record of the samples at the surface at this time, even if the sources themselves have disappeared through thermally driven tectonism or reworking. The sedimentary record from McLennan and Taylor (1980) presents similar results compared to the trends in the igneous/metaigneous sample set here (Figure 11), suggesting that our data set may not be biased towards lower heat production compared to the true distribution of the time. However, the sedimentary record utilised within their study is not entirely immune from this hypothesis either. Samples from these oldest time periods are metamorphosed, carried to various depths within the crustal column, and thus also vulnerable to thermal instability. Thus, we do not believe that the sedimentary result entirely precludes an existence of a thermal preservation influence on the record either. Is the more mafic Archean crust we observe today a natural consequence of growth of the crust and continental crust, or is it at least in part a consequence of being more thermally stable than more felsic crust? If it is the later, what is the degree to which felsic crust has been destroyed, and was there a time in Earth's history where mafic crust was also largely unstable due to high radioactivity, i.e., in the earliest Archean or Hadean?

6.2. Implications for the continental crust

There are three major implications one can draw from the heat production analysis performed in this study: (1) a shift in the crustal composition appears to have enhanced enrichment in heat producing elements for similar major element composition samples up to to the Archean-Proterozoic boundary; (2) Thermal stability may perhaps provide a complimentary chemical bias in the rock record; and (3) a correlation between mafic/felsic and plutonic/volcanic heat production allows us to draw inferences about the vertical distribution of HPEs in the crust.

Changes in thermal stability through time has the potential not only to affect the heat production distribution preserved in the geologic record, but also the chemical nature of the crust that is correlated with these low heat producing regions. This selective preservation of crust has the potential to bias towards more mafic and less alkali (especially K) compositions than likely existed at the time. If valid, our models of chemical evolution of the Earth would need to be modified to take into account the potential for thermally influenced selective-preservation. The deficit in HPE enrichment is quite large in the early Earth with respect to the present, however, this model assumes that the present-day distribution is the appropriate metric from which to judge this deficit. It is likely the majority of this deficit may be accounted for by the shift in crustal composition from mafic to more felsic and intermediate compositions up to $\sim$2.7 Ga, but thermal preservation may also play an additional role.

Average heat production has been shown to follow an exponential relationship with respect to estimated P-wave velocities (Hasterok and Webb, 2017), which suggests that there is a relationship between mafic and felsic heat production in individual terranes. Although our model is global, the correlation between mafic and felsic temporal records implies that such a connection may occur for many time periods as well. Therefore, regions with high upper crustal heat production may be expected to also have high lower crustal heat production. Many general crustal heat production models often assume a common lower crustal heat production while allowing upper crustal heat production to vary (Chapman, 1986; Artemieva and Mooney, 2001; Hasterok and Chapman, 2011). As a result, these generalized geotherm models may over- or under-estimate temperatures in the lithosphere. The result may not be very large within the crust due to relatively low heat production of mafic rocks, but it could still have a significant effect on mantle temperatures and thermal estimates of lithospheric thickness. Therefore, when modelling the thermal state of the lithosphere it is advisable to take into account the age distribution of the lithosphere as well as the correlative nature of heat production.

While we have not delved into discussions about heat flow, our model undoubtedly has implications for such variations. Archean terrains are old and often more predominantly mafic, which accounts largely for their lower heat flow. However, Archean samples have been shown to have particularly low enrichments of heat producing elements even once adjusted for decay, compared to modern samples (Figure 11). While their heat production at formation would have been similar to present day samples, over the course of time their heat production dropped more rapidly than present day samples due to lower enrichments of HPEs and the decreasing proportion of ^{235}U to ^{238}U. Thus, due to extensive decay, lower average silica concentrations, and particularly low enrichment of HPEs compared to modern day equivalents, present day heat flow in these regions is uncharacteristically low.

We are not attempting to explain the decrease in surface heat flow in the past, although our model undoubtedly has implications for such variations, but must be combined with knowledge of dominant lithology and depth distribution of heat production as well.

7. Concluding remarks

Correcting for the decay removes a long-term trend that described the first-order decrease in heat production with age as suggested by (Jaupart and Mareschal, 2014). The decay-corrected pattern suggests a quasi-periodic variation in heat production that can be linked to lithology. This lithological influence is the largest source of variability and can be removed by in large by normalizing for SiO_2.

After correcting for gross lithological changes and radioactive decay, a deficit in heat production remains compared to modern day sample projections. A number of hypotheses have been proposed to account for heat production variations through time:

1. A shift in the bulk composition of the crust, evidenced by various studies (e.g. Taylor and McLennan, 1985; Condie, 1993; Dhuime et al., 2015; Tang et al., 2016, and references

therein), and discussed with respect to heat producing element enrichment in sediments by McLennan and Taylor (1980). Our results seem closely aligned with the sedimentary record, and appears to provide further evidence for a shift in bulk composition of the crust rapidly altering heat producing element enrichments for similar major element composition samples. The total heat generated by uranium drops drastically due to a significant drop in the proportion of ^{235}U compared to ^{238}U, which leads to the heat production record not appearing to correlate with this HPE increase, and instead remaining relatively constant. We consider this hypothesis to be the best explanation for the observed, relatively constant temporal heat production signal at formation after correction for gross lithology and decay.

2. We do not find a clear correlation with the super-continent cycle or modelled plate velocities as suggested by Artemieva et al. (2017), either before or after SiO_2 normalization and decay adjustment. Secular cooling and mantle depletion are also not clearly expressed in the SiO_2 normalized heat production model.

3. Contrary to the heat flow based model by Vitorello and Pollack (1980), we do not observe a clear decrease in heat production with time due to any evident erosional influences in either the distribution of samples in silica space or heat production as deeper rocks are exhumed. Our model does not rule out the potential for local erosional influences on heat production, only that erosion is not a significant influence on secular variations in global heat production.

4. Selective preservation due to thermal stability, as discussed by Morgan (1985), may impart an additional heat production deficit (greatest in the Archean and increasing to a steady-state as Earth cools). Regions with high heat production may not have been stable in the early Earth as the crust in high heat producing regions would be hot and weak, making them susceptible to destructive plate forces. As a result, a selective bias could be created for regions with low heat producing elements. This selective bias could raise interesting questions about the chemical nature of regions that were unable to survive this period and their influence on the chemical evolution of the continental crust. Quantifying this influence is difficult however, and would contribute in conjunction, or perhaps control in part, the hypothesis of a shift in bulk composition.

This study has implications for improving heat production distribution estimates, particularly when providing initial constraints on poorly understood regions. Magmatic age, and dominant lithological type in silica space can provide two independent constraints for bounding heat production estimates of large-scale provinces. Adjusting for decay and lithological influence appears to remove the majority of the temporal heat production distribution variations. More robust constraints on crustal heat production, temperature, and heat loss are thus possible, particularly for poorly understood terranes where simply assuming continental averages is often the case. Although these correlations are weak when considering individual rock samples and geological suites, their strength lies in providing initial constraints on heat production for thermal estimates at large scales.

8. Acknowledgements

We would like to thank the following for providing datasets and/or personal compilations: D. Champion (GA), D. Claeson (SGU), T. Slagstad (NGU), and H. Furness. Peter Johnson provided a collection of papers with data for the Arabian-Nubian Shield. M. Gard is supported by an Australian Government Research Training Program Scholarship.

We would like to thank Roberta Rudnick for her thorough review which helped immensely in improving this manuscript. Additionally, thank you to the two anonymous reviewers whose comments assisted in clarifying some content.

Abbott, D., Burgess, L., Longhi, J., Smith, W. H. F., jul 1994. An empirical thermal history of the earth's upper mantle. Journal of Geophysical Research: Solid Earth 99 (B7), 13835–13850.

Alessio, K. L., Hand, M., Kelsey, D. E., Williams, M. A., Morrissey, L. J., Barovich, K., 2018. Conservation of deep crustal heat production. Geology 46 (4), 335.

Armstrong, R. L., Harmon, R. S., Moorbath, S. E., Windley, B. F., 1981. Radiogenic isotopes: The case for crustal recycling on a near-steady-state no-continental-growth earth [and discussion]. Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences 301 (1461), 443–472.
URL http://www.jstor.org/stable/37029

Artemieva, I., Mooney, W., 2001. Thermal thickness and evolution of Precambrian lithosphere: a global study. J. Geophys. Res. 106, 16387–16414.

Artemieva, I. M., Thybo, H., Jakobsen, K., Sørensen, N. K., Nielsen, L. S., 2017. Heat production in granitic rocks: Global analysis based on a new data compilation GRANITE2017. Earth-Science Reviews 172 (Supplement C), 1 – 26.
URL http://www.sciencedirect.com/science/article/pii/S001282521730199X

Barette, F., Poppe, S., Smets, B., Benbakkar, M., Kervyn, M., sep 2016. Spatial variation of volcanic rock geochemistry in the Virunga Volcanic Province: Statistical analysis of an integrated database. Journal of African Earth Sciences.

Bédard, J. H., Hayes, B., Hryciuk, M., Beard, C., Williamson, N., Dell'Oro, T. A., Rainbird, R. H., Prince, J., Baragar, W. R. A., Nabelek, P. I., Weis, D., Wing, B., Scoates, J., Naslund, H. R., Cousens, B., Williamson, M.-C., Hulbert, L. J., Montjoie, R., Girard, É., Ernst, R., Lissenberg, C. J., 2016. Geochemical database of franklin sills, natkusiak basalts and shaler supergroup rocks, victoria island, northwest territories, and correlatives from nunavut and the mainland. Open-file 8009, Geological Survey of Canada.
URL https://doi.org/10.4095%2F297842

Belousova, E., Kostitsyn, Y., Griffin, W., Begg, G., O'Reilly, S., Pearson, N., 2010. The growth of the continental crust: Constraints from zircon hf-isotope data. Lithos 119 (3), 457 – 466. URL http://www.sciencedirect.com/science/article/pii/S0024493710002008

Birch, F., Roy, R., Decker, E., 1968. Heat flow and thermal history in New England and New York. In: Zen, E., White, W., Hadley, J., Thompson, J. (Eds.), Studies of Appalachian Geology: Northern and Maritime. Interscience, New York, pp. 437–451.

Brady, R., Ducea, M., Kidder, S., Saleeby, J., 2006. The distribution of radiogenic heat production as a function of depth in the Sierra Nevada Batholith, California. Lithos 86, 229–244.

Brown, M., Johnson, T., 2018. Secular change in metamorphism and the onset of global plate tectonics. American Mineralogist 103 (2), 181–196.

Campbell, I., 2003. Constraints on continental growth models from nb/u ratios in the 3.5 ga barbarton and other archaean basalt-komatiite suites. American Journal of Science 303, 319–351.

Champion, D., Budd, A., Hazell, M., Sedgmen, A., 2016. Ozchem national whole rock geochemistry dataset. Tech. Rep. Downloaded July 2016, Geoscience Australia.

Chapman, D. S., 1986. Thermal gradients in the continental crust. Geological Society, London, Special Publications 24 (1), 63–70. URL http://sp.lyellcollection.org/content/24/1/63

Christensen, N., Mooney, W., 1995. Seismic velocity structure and composition of the continental crust: a global view. J. Geophys. Res. 100, 9761–9788.

Clemens, J., Stevens, G., Farina, F., oct 2011. The enigmatic sources of i-type granites: The peritectic connexion. Lithos 126 (3-4), 174–181.

Clifford, T., 1970. The structural framework of africa. African Magmatism and Tectonics, 1–26.

Coltice, N., Marty, B., Yokochi, R., aug 2009. Xenon isotope constraints on the thermal evolution of the early earth. Chemical Geology 266 (1-2), 4–9.

Condie, K. C., 1993. Chemical composition and evolution of the upper continental crust: Contrasting results from surface samples and shales. Chemical Geology 104 (1), 1–37. URL http://www.sciencedirect.com/science/article/pii/000925419390140E

Condie, K. C., Aster, R. C., 2010. Episodic zircon age spectra of orogenic granitoids: The supercontinent connection and continental growth. Precambrian Research 180 (3), 227 – 236. URL http://www.sciencedirect.com/science/article/pii/S0301926810001026

Condie, K. C., Aster, R. C., 2013. Refinement of the supercontinent cycle with hf, nd and sr isotopes. Geoscience Frontiers 4 (6), 667 – 680, thematic Section: Antarctica – A window to the far off land.
URL http://www.sciencedirect.com/science/article/pii/S1674987113000820

Condie, K. C., Aster, R. C., van Hunen, J., 2016. A great thermal divergence in the mantle beginning 2.5 ga: Geochemical constraints from greenstone basalts and komatiites. Geoscience Frontiers 7 (4), 543 – 553.
URL http://www.sciencedirect.com/science/article/pii/S1674987116000311

Cooper, C., Lenardic, A., Moresi, L., 2004. The thermal structure of stable continental lithosphere within a dynamic mantle. Earth and Planetary Science Letters 222 (3), 807 – 817. URL http://www.sciencedirect.com/science/article/pii/S0012821X04002444

Daly, R. A., 1925. The geology of ascension island. Proceedings of the American Academy of Arts and Sciences 60 (1), 3–80.
URL http://www.jstor.org/stable/25130043

Dhuime, B., Wuestefeld, A., Hawkesworth, C. J., 2015. Emergence of modern continental crust about 3 billion years ago. Nature Geoscience 8, 552–555.

Fountain, D., 1987. The relationship between seismic velocity and heat production—reply. Earth Planet. Sci. Lett. 83, 178–180.

French, J., Heaman, L., Chacko, T., Rivard, B., 2004. Global mafic magmatism and continental breakup at 2.2ga: evidence from the dharwar craton, india. Geological Society of America Abstracts with Programs 36 (5).

Frost, B., Barnes, C., Collins, W., Arculus, R., Ellis, D., Frost, C., 2001. A geochemical classification for granitic rocks. J. Petrol. 42, 2033–2048.

Gard, M., Hasterok, D., Halpin, J., 2019. Global whole-rock geochemical database compilation (data files).
URL https://zenodo.org/record/2592823

Goodwin, A., Smith, I., 1980. Chemical discontinuities in archean metavolcanic terrains and the development of archean crust. Precambrian Research 10 (3), 301 – 311, comparative Planetary Evolution: Implications for the Proto-Archean.
URL http://www.sciencedirect.com/science/article/pii/0301926880900169

Goodwin, A. M., 1996. Chapter 6 - evolution of the continental crust. In: Goodwin, A. M. (Ed.), Principles of Precambrian Geology. Academic Press, London, pp. 261 – 280.
URL http://www.sciencedirect.com/science/article/pii/B9780122897702500066

Gordon, R., 1998. The plate tectonic approximation: Plate nonrigidity, diffuse plate boundaries, and global plate reconstructions. Annu. Rev. Earth Planet. Sci 26, 615–642.

Gosnold, W., 1987. Redistribution of U and Th in shallow plutonic environments. Geophys. Res. Lett. 14, 291–294.

Hacker, B. R., Kelemen, P. B., Behn, M. D., 2011. Differentiation of the continental crust by relamination. Earth and Planetary Science Letters 307 (3), 501–516.
URL http://www.sciencedirect.com/science/article/pii/S0012821X11003074

Hacker, B. R., Kelemen, P. B., Behn, M. D., 2015. Continental lower crust. Annual Review of Earth and Planetary Sciences 43 (1), 167–205.

Hand, M., Sandiford, M., 1999. Intraplate deformation in central australia, the link between subsidence and fault reactivation. Tectonophysics 305 (1), 121–140.

Hasterok, D., Chapman, D., 2011. Heat production and geotherms for the continental lithosphere. Earth Planet. Sci. Lett. 307, 59–70.

Hasterok, D., Gard, M., 2016. Utilizing thermal isostasy to estimate sub-lithospheric heat flow and anomalous crustal radioactivity. Earth Planet. Sci. Lett. 450, 197–207.

Hasterok, D., Gard, M., Webb, J., 2018. On the radiogenic heat production of metamorphic, igneous, and sedimentary rocks. Geoscience Frontiers 9 (6), 1777–1794, reliability Analysis

of Geotechnical Infrastructures.
URL http://www.sciencedirect.com/science/article/pii/S1674987117301937

Hasterok, D., Webb, J., may 2017. On the radiogenic heat production of igneous rocks. Geoscience Frontiers.

Haus, M., Pauk, T., 2010. Data from the PETROCH lithogeochemical database. Miscellaneous release—data 250, Ontario Geol. Surv.

Hawkesworth, C., Cawood, P., Kemp, T., Storey, C., Dhuime, B., jan 2009. A matter of preservation. Science 323 (5910), 49–50.

Hawkesworth, C., Cawood, P. A., Dhuime, B., 2019. Rates of generation and growth of the continental crust. Geoscience Frontiers 10 (1), 165 – 173.
URL http://www.sciencedirect.com/science/article/pii/S1674987118300501

Hawkesworth, C. J., Cawood, P. A., Dhuime, B., 2016. Tectonics and crustal evolution. GSA Today 26 (9), 4 – 11.

He, L., Hu, S., Huang, S., Yang, W., Wang, J., Yuan, Y., Yang, S., 2008. Heat flow study at the Chinese Continental Scientific Drilling site: borehole temperature, thermal conductivity, and radiogenic heat production. J. Geophys. Res. 113, B02404.

Heaman, L. M., 1997. Global mafic magmatism at 2.45 Ga: Remnants of an ancient large igneous province? Geology 25 (4), 299–302.

Herzberg, C., Condie, K., Korenaga, J., 2010. Thermal history of the earth and its petrological expression. Earth and Planetary Science Letters 292 (1), 79–88.
URL http://www.sciencedirect.com/science/article/pii/S0012821X10000567

Jaupart, C., 1983. Horizontal heat transfer due to radioactivity contrasts: Causes and consequences of the linear heat flow relation. Geophys. J. R. astr. Soc. 75, 411–435.

Jaupart, C., Mareschal, J.-C., 2014. Constraints on crustal heat production from heat flow data. In: Treatise on Geochemistry. Elsevier, pp. 53–73.
URL https://doi.org/10.1016/b978-0-08-095975-7.00302-8

Jaupart, C., Mareschal, J.-C., Iarotsky, L., 2016. Radiogenic heat production in the continental crust. Lithos 262, 398–427.

Keller, C., Schoene, B., 2012. Statistical geochemistry reveals disruption in secular lithospheric evolution about 2.5 gyr ago. Nature 485, 490–493.

Kelsey, D., Hand, M., 2015. On ultrahigh temperature crustal metamorphism: Phase equilibria, trace element thermometry, bulk composition, heat sources, timescales and tectonic settings. Geosci. Frontiers 6, 311–356.

Ketcham, R., 2006. Distribution of heat-producing elements in the upper and middle crust of southern and west central Arizona: evidence from core complexes. J. Geophysical Res. 101, 13611–13632.

Korenaga, J., 2013. Archean Geodynamics and the Thermal Evolution of Earth. American Geophysical Union (AGU), pp. 7–32.
URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/164GM03

Kukkonen, I., Lahtinen, R., 2001. Variation of radiogenic heat production rate in 2.8–1.8 Ga old rocks in the central Fennoscandian Shield. Phys. Earth Planet. Int. 126, 279–294.

Kumar, P., Reddy, G., 2004. Radioelements and heat production of an exposed archaean crustal cross-section, dharwar craton, south india. Earth and Planetary Science Letters 224 (3), 309 – 324.
URL http://www.sciencedirect.com/science/article/pii/S0012821X04003528

Labrosse, S., Jaupart, C., 2007. Thermal evolution of the Earth: Secular changes and fluctuations of plate characteristics. Earth Planet. Sci. Lett. 260, 465–481.

Lachenbruch, A., 1970. Crustal temperature and heat production: implications for the linear heat flow relation. J. Geophys. Res. 75, 3291–3300.

Le Bas, M., Streckeisen, A., 1991. The IUGS systematics of igneous rocks. J. Geol. Soc., London 148, 825–833.

Lee, C.-T. A., Bachmann, O., 2014. How important is the role of crystal fractionation in making intermediate magmas? insights from zr and p systematics. Earth and Planetary

Science Letters 393, 266–274.
URL http://www.sciencedirect.com/science/article/pii/S0012821X14001319

Mareschal, J.-C., West, G., 1980. A model for archean tectonism. part 2. numerical models of vertical tectonism in greenstone belts. Canadian Journal of Earth Sciences 17, 60–71, cited By 62.

McKenzie, D., Priestley, K., feb 2016. Speculations on the formation of cratons and cratonic basins. Earth and Planetary Science Letters 435, 94–104.
URL https://doi.org/10.1016%2Fj.epsl.2015.12.010

McLaren, S., Sandiford, M., Hand, M., Neumann, N., Wyborn, L., Bastrakova, I., 2003. The hot southern continent: heat flow and heat production in australian proterozoic terranes. In: Evolution and Dynamics of the Australian Plate. Vol. 372 of Special Pub. Geological Society of Australia, pp. 151–161.

McLennan, S., Taylor, S., 1996. Heat flow and the chemical composition of continental crust. Journal of Geology 104 (4), 369.

McLennan, S. M., Nance, W., Taylor, S., 1980. Rare earth element-thorium correlations in sedimentary rocks, and the composition of the continental crust. Geochimica et Cosmochimica Acta 44 (11), 1833 – 1839.
URL http://www.sciencedirect.com/science/article/pii/001670378090232X

McLennan, S., Taylor, S., 1980. Th and U in sedimentary rocks: crustal evolution and sedimentary recycling. Nature 285, 621–624.

Middlemost, E., 1994. Naming materials in the magma/igneous rock system. Earth Sci. Rev. 37, 215–224.

Morgan, P., 1985. Crustal radiogenic heat production and the selective survival of ancient continental crust. J. Geophys. Res. 90, C561–C570.

Neumann, N., Sandiford, M., Foden, J., 2000. Regional geochemistry and continental heat flow: implications for the origin of the South Australian heat flow anomaly. Earth Planet. Sci. Lett. 183, 107–120.

Newfoundland and Labrador Geological Survey, 2010. Newfoundland and Labrador GeoScience Atlas OnLine. Tech. rep.
URL http://geoatlas.gov.nl.ca[AccesssedJune2016]

Nisbet, E., Cheadle, M., Arndt, N., Bickle, M., sep 1993. Constraining the potential temperature of the archaean mantle: A review of the evidence from komatiites. Lithos 30 (3-4), 291–307.

Pollack, H., Chapman, D., 1977. On the regional variation of heat flow, geotherms, and lithospheric thickness. Tectonophysics 38, 279–296.

Pujol, M., Marty, B., Burgess, R., Turner, G., Philippot, P., Jun 06 2013. Argon isotopic composition of archaean atmosphere probes early earth geodynamics. Nature 498 (7452), 87–90, copyright - Copyright Nature Publishing Group Jun 6, 2013; Document feature - Graphs; ; Last updated - 2017-11-20; CODEN - NATUAS.

Rasilainen, K., Lahtinen, R., Bornhorst, T., 2007. The rock geochemical database of finland manual. (online). Report of Investigation 164, Geol. Surv. Finland.

Roy, R., Blackwell, D., Birch, F., 1968. Heat generation of plutonic rocks and continental heat flow provinces. Earth Planet. Sci. Lett. 5, 1–12.

Rudnick, R., Gao, S., 2003. Composition of the continental crust. In: Rudnick, R. (Ed.), Treatise on Geochemistry: The Crust. Vol. 3. Elsevier, Ch. 1, pp. 1–64.

Rybach, L., 1988. Determination of heat production rate. In: Hänel, R., Rybach, L., Stegena, I. (Eds.), Terrestrial Handbook of Heat-Flow Density Determination. Kluwer Academic Publishers, Dordrecht, Ch. 4.2, pp. 125–142.

Rybach, L., Buntebarth, G., 1984. The variation of heat generation, density and seismic velocity with rock type in the continental lithosphere. Tectonophysics 103, 335–344.

Sandiford, M., McLaren, S., 2002. Tectonic feedback and the ordering of heat producing elements within the continental lithosphere. Earth Planet. Sci. Lett. 204, 133–150.

Sandiford, M., McLaren, S., 2006. Thermo-mechanical controls on heat production distributions and the long-term evolution of the continents. In: Brown, M., Rushmer, T. (Eds.), Evolution and Differentiation of the Continental Crust. Cambridge University Press, London, pp. 67–91.

Sandiford, M., McLaren, S., Neumann, N., 2002. Long-term thermal consequences of the re-distribution of heat-producing elements associated with large-scale granitic complexes. J. Metamorphic Geol. 20, 87–98.

Sawka, W. N., Chappell, B. W., 1988. Fractionation of uranium, thorium and rare earth elements in a vertically zoned granodiorite: Implications for heat production distributions in the sierra nevada batholith, california, u.s.a. Geochimica et Cosmochimica Acta 52 (5), 1131–1143.
URL http://www.sciencedirect.com/science/article/pii/0016703788902670

Scholl, D. W., von Huene, R., 01 2007. Crustal recycling at modern subduction zones applied to the past—Issues of growth and preservation of continental basement crust, mantle geochemistry, and supercontinent reconstruction. In: 4-D Framework of Continental Crust. Geological Society of America.
URL https://dx.doi.org/10.1130/2007.1200(02)

Slagstad, T., 2008. Radiogenic heat production of archaean to permian geological provinces in norway. Norweigan Journal of Geology 88, 149–166.

Slagstad, T., 2017. Lito database (online): Geochemical mapping of Norwegian bedrock. Tech. rep., Norges Geologiske Undersøkele (NGU).
URL http://www.ngu.no/lito

Tang, M., Chen, K., Rudnick, R. L., 2016. Archean upper crust transition from mafic to felsic marks the onset of plate tectonics. Science 351 (6271), 372–375.
URL https://science.sciencemag.org/content/351/6271/372

Taylor, S., McLennan, S., 1985. The Continental Crust: Its Composition and Evolution. Blackwell, Oxford.

Vitorello, I., Pollack, H., 1980. On the variation of continental heat flow with age and the thermal evolution of the continents. J. Geophys. Res. 85, 983–995.

Walker, J. D., Bowers, T. D., Black, R. A., Glazner, A. F., Lang Farmer, G., Carlson, R. W., 2006. A geochemical database for western North American volcanic and intrusive rocks (NAVDAT). In: Geoinformatics: Data to Knowledge. Geological Society of America.

Wasserburg, G. J., MacDonald, G. J. F., Hoyle, F., Fowler, W. A., 1964. Relative contributions of uranium, thorium, and potassium to heat production in the earth. Science 143 (3605), 465–467.
URL http://science.sciencemag.org/content/143/3605/465

Williams, M., Dumond, G., Mahan, K., Regan, S., Holland, M., 2014. Garnet-forming reactions in felsic orthogneiss: Implications for densification and strengthening of the lower continental crust. Earth and Planetary Science Letters 405, 207–219.
URL http://www.sciencedirect.com/science/article/pii/S0012821X14005366

Wollenberg, H., Smith, A., mar 1987. Radiogenic heat production of crustal rocks: an assessment based on geochemical data. Geophys. Res. Lett. 14 (3), 295–298.
URL https://doi.org/10.1029%2Fgl014i003p00295

Workman, R., Hart, S., 2005. Major and trace element composition of the depleted MORB mantle (DMM). Earth Planet. Sci. Lett 231, 53–72.

Worsley, T. R., Nance, D., Moody, J. B., 1984. Global tectonics and eustasy for the past 2 billion years. Marine Geology 58 (3), 373–400.
URL http://www.sciencedirect.com/science/article/pii/0025322784902093

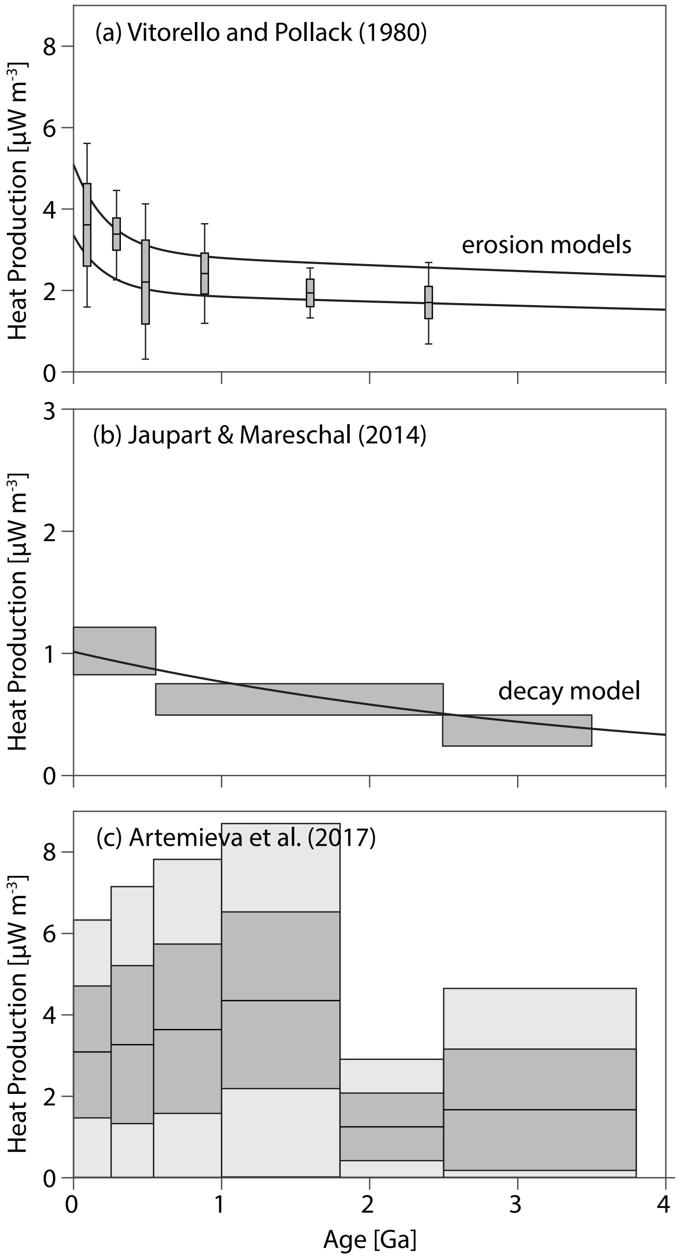

Figure 1: Previous models of heat production with age: (a) erosional model by Vitorello and Pollack (1980); (b) radioactive decay model by Jaupart and Mareschal (2014); (c) granite heat production model by Artemieva et al. (2017).

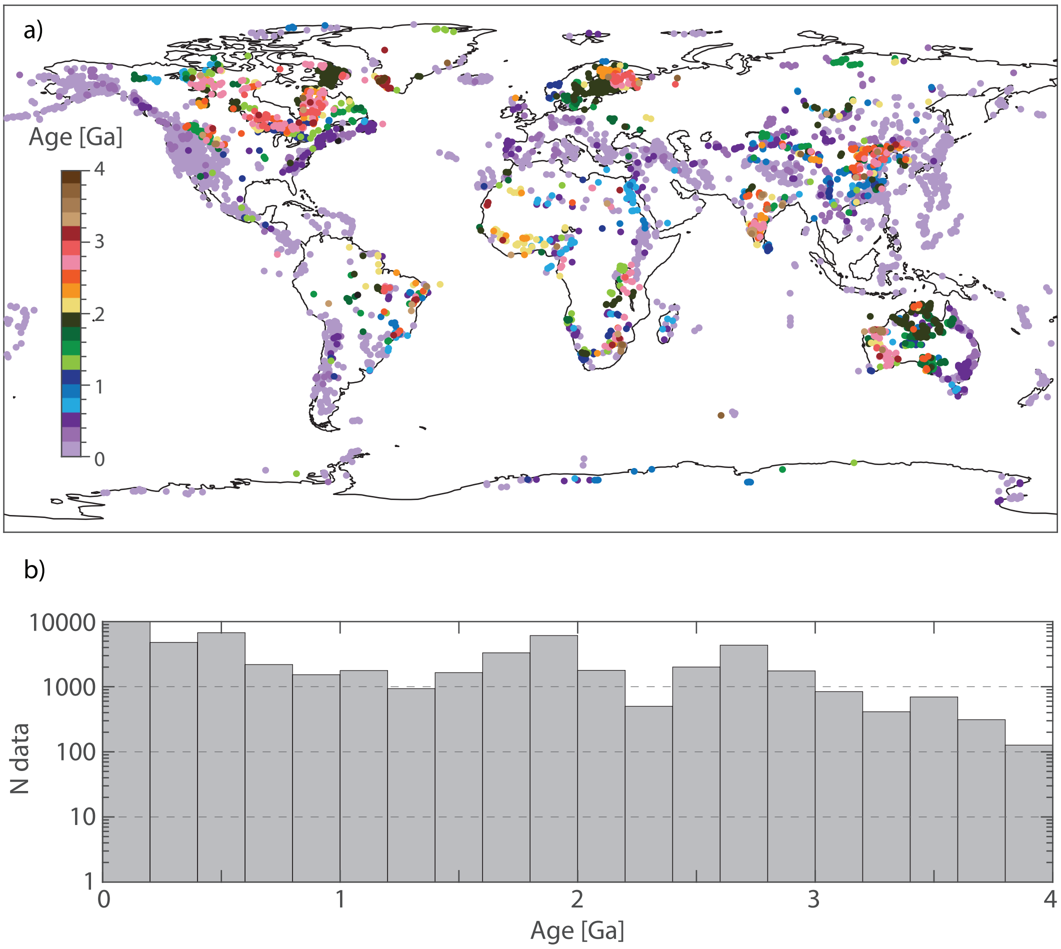

Figure 2: (a) Locations of all igneous and metamorphic heat production estimates utilized in this study. Points are coloured by age. (b) Temporal sampling of heat production data.

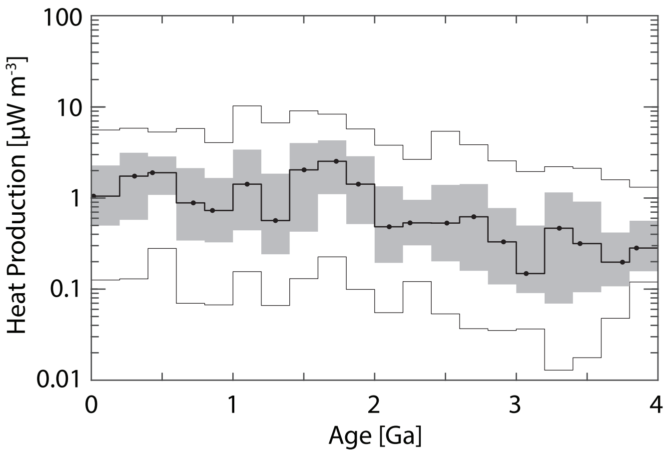

Figure 3: Raw, unprocessed heat production distributions presented in log-space. The shaded region depicts data within the 25 to 75 quartiles and the thin lines identifies the 5 and 95% quantiles. The data are divided into age intervals of 200 Ma to maintain a minimum of 100 samples within each division. Dots indicate median age and median heat production for data contained within each interval.

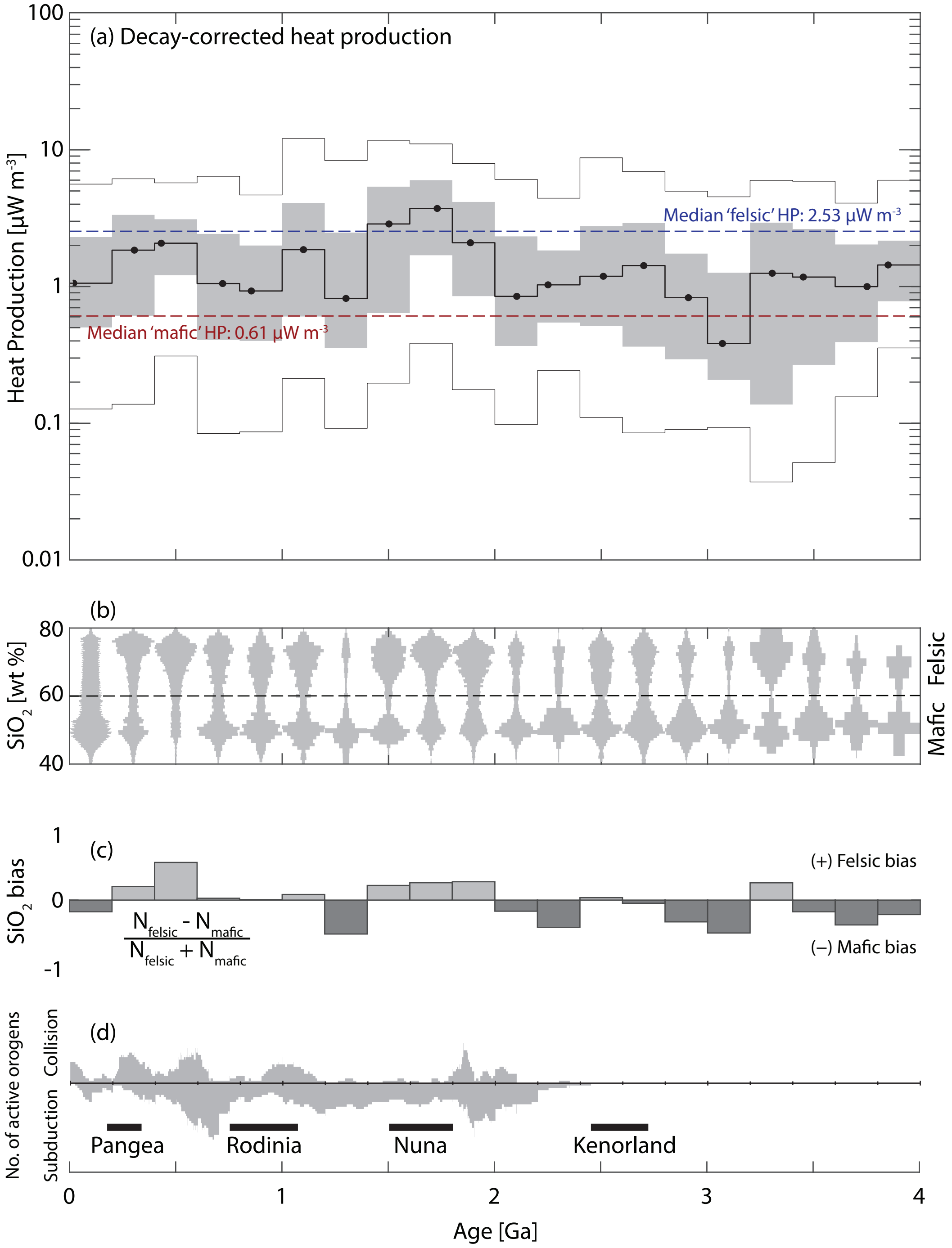

Figure 4: Heat production and composition of igneous rocks over the past 4 Ga. (a) Same as Figure 3, but the heat production has been adjusted for radioactive decay (Equation 3) (b) Variations in SiO_2 composition with age. Each 'Cloud-city' diagram is produced by constructing a histogram with respect to SiO_2 and mirroring it in order t emphasize the peaks and troughs in silica content within each age interval. (c) SiO_2 bias presented in a simple ratio bias plot for easier comparison to (b). (d) Supercontinents and orogenic activity data (Condie and Aster, 2013). The number of active collisional (above the line) and subduction orogens (below the line) active as as a function of time shaded in grey.

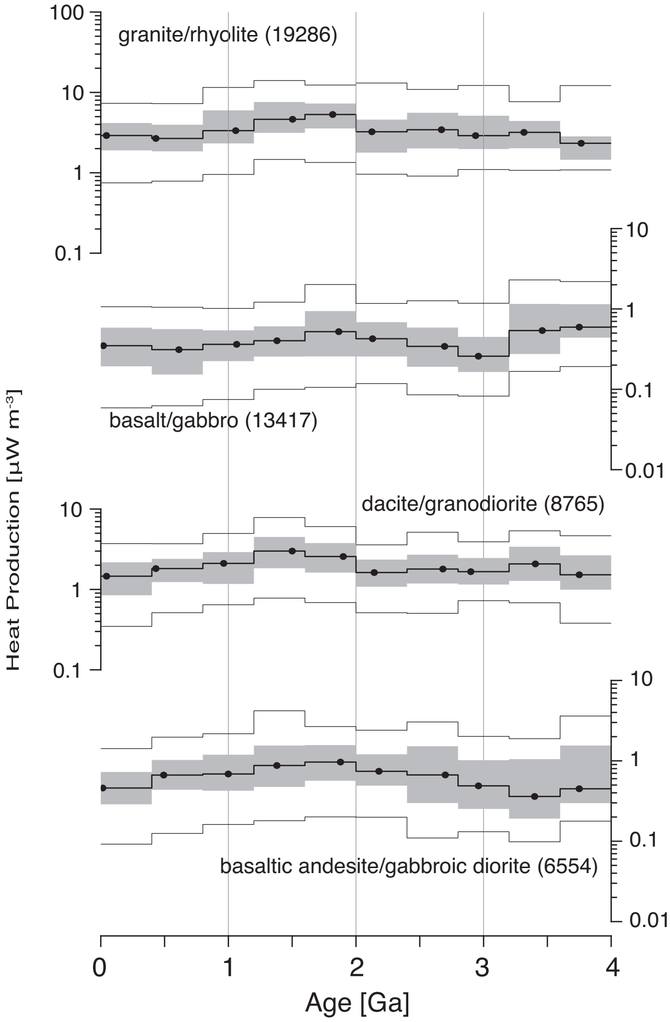

Figure 5: Heat production through time for the four most common rock types in the database. The lines and shading indicate the median and same quantiles as described in Figure 3.

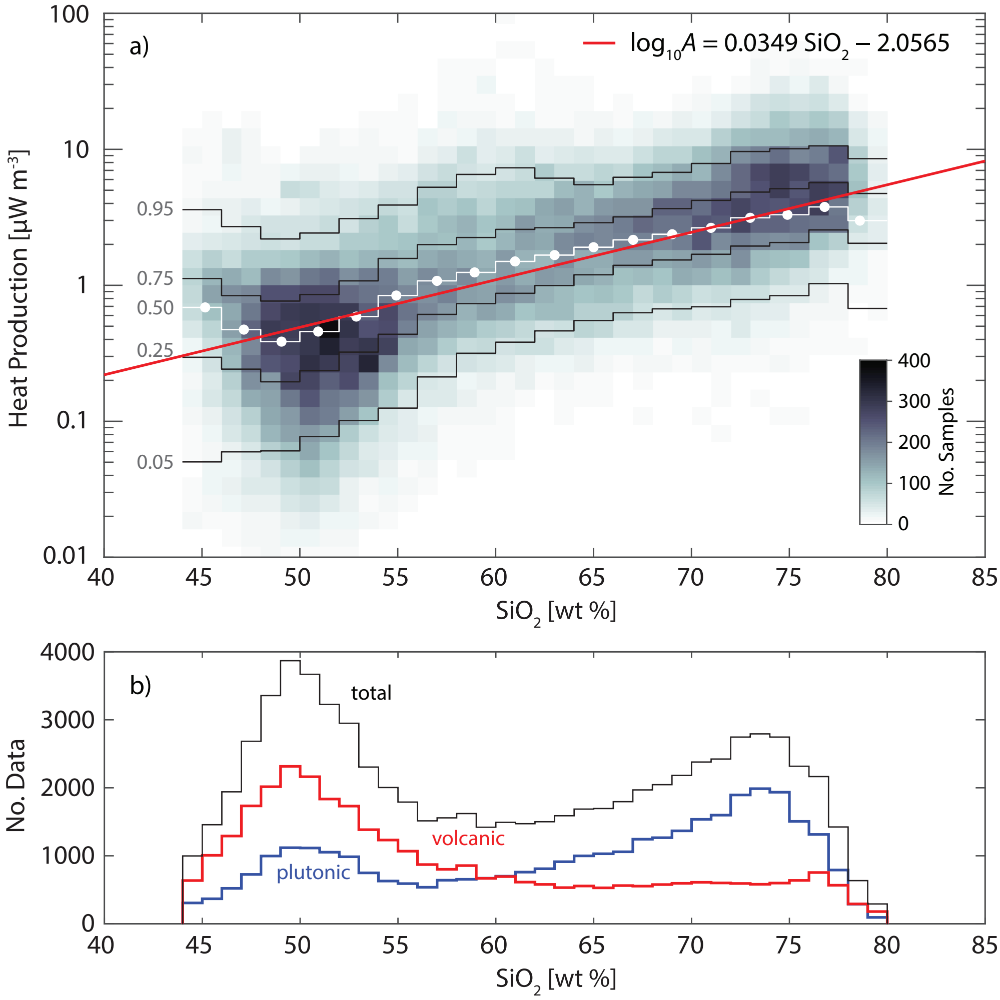

Figure 6: The relationship between SiO_2 and heat production. (a) The background 2-d histogram indicates the data frequency. The box and whisker plots identify the 0.05, 0.25, 0.75, 0.95 quantiles in SiO_2 bins of 2 wt.%. The points indicate the median SiO_2 and heat production of each respective bin. The red line is a model fit to the median SiO_2–heat production values. (b) The distribution of SiO_2 among all (black), plutonic (blue) and volcanic (red) samples.

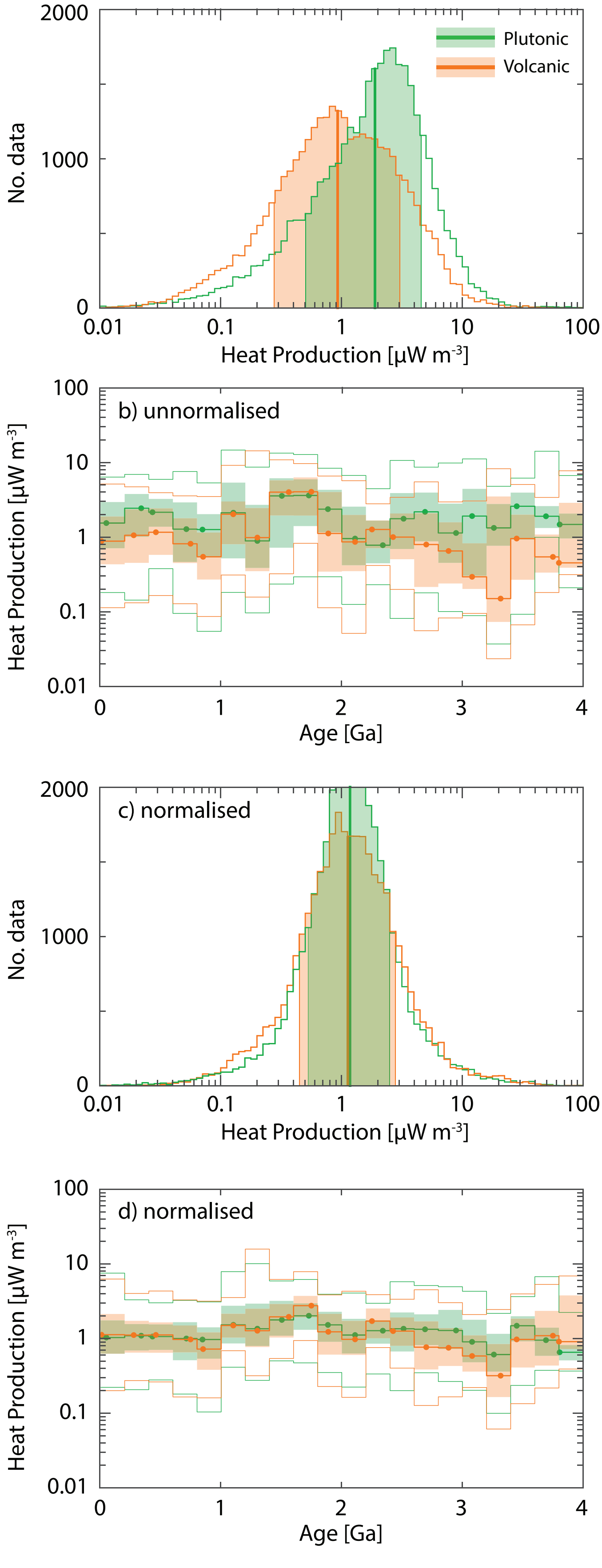

Figure 7: SiO_2 correction and its effect on plutonic and volcanic samples. (a) Plutonic (green) and volcanic (orange) heat production distributions before SiO_2 adjustment. (b) Plutonic and volcanic heat production trends through time before adjustment. (c) Heat production distributions normalized to 75 wt.% SiO_2. (d) Temporal variations in plutonic and volcanic heat production after SiO_2 normalization.

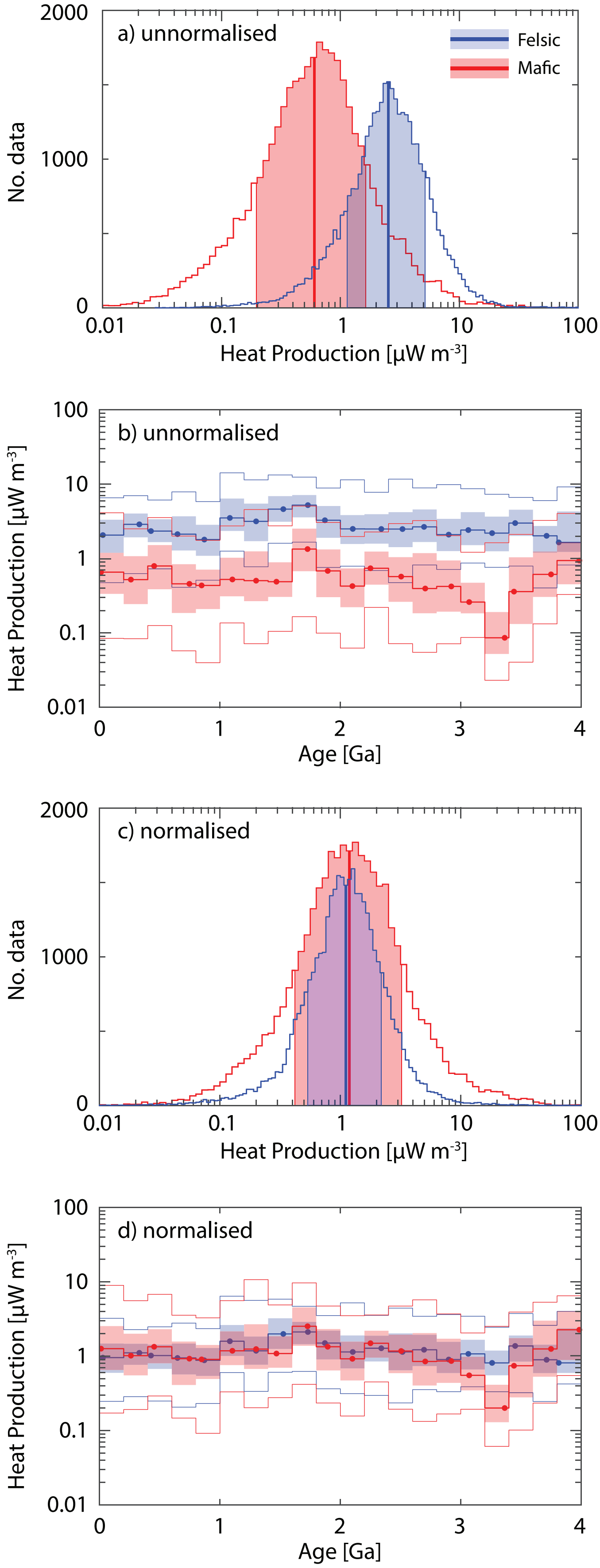

Figure 8: SiO_2 correction and effects on decay-corrected felsic and mafic samples. 'Mafic' samples are defined as those with $\leq$ 60 wt.% SiO_2 and 'felsic' samples >60 wt.% SiO_2. (a) Felsic (blue) and mafic (red) heat production distributions before SiO_2 adjustment. (b) Temporal felsic and mafic heat production (decay-corrected) before silica adjustment. (c) Heat production distributions normalized to 75 wt.% SiO_2 (d) Temporal variations in felsic and mafic heat production (decay-corrected) after SiO_2 normalization.

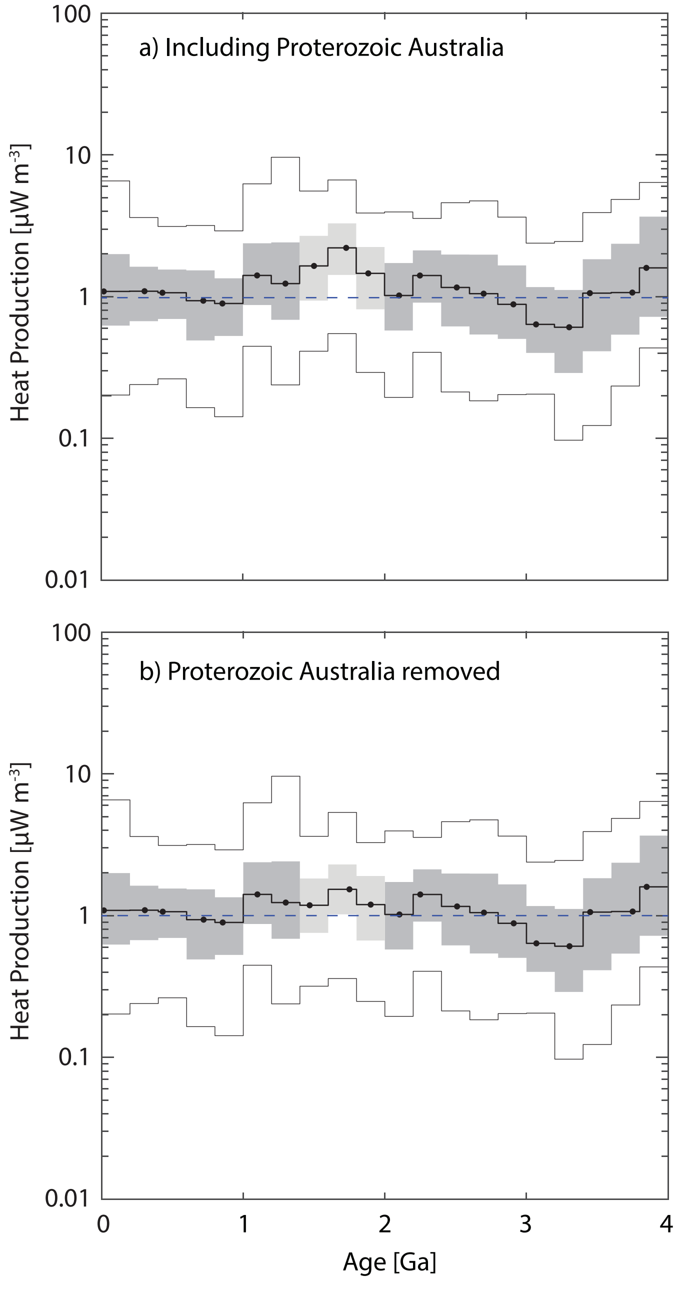

Figure 9: Decay- and SiO_2-corrected heat production through time. Dashed line denotes 1 μW m-3. a) all data, b) excluding Proterozoic Australia (1400–2000 Ma).

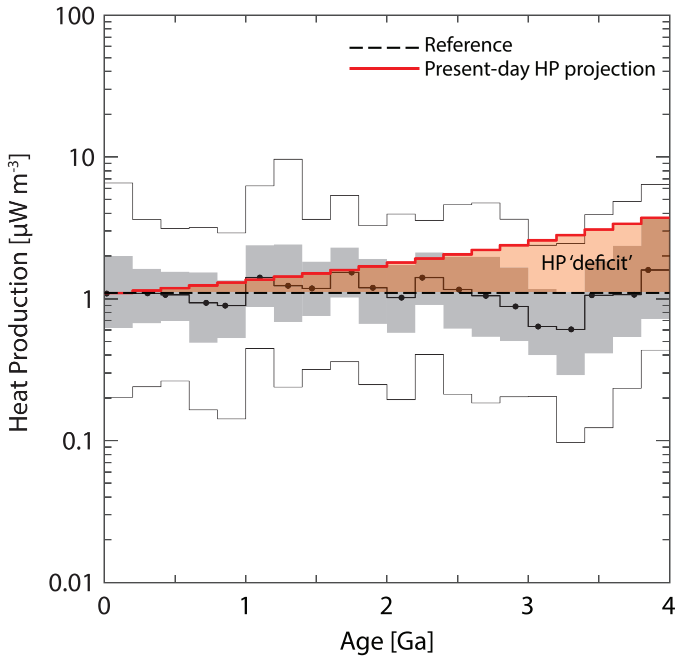

Figure 10: Present-day crystallization heat production distribution projected back into the past accounting for decay only (Density: 2.81 g/cm^3, K_2O: 2.19 wt.%, U: 1.61 ppm (99.28% ^{238}U, 0.711% ^{238}U), Th: 5.76 ppm). Assuming no other influences on HP distributions, we might expect the heat production at formation to be higher in the Archean than present-day due to the higher availability of heat producing isotopes. We do not observe this however; other influences must be responsible for the HP deficit observed in the record.

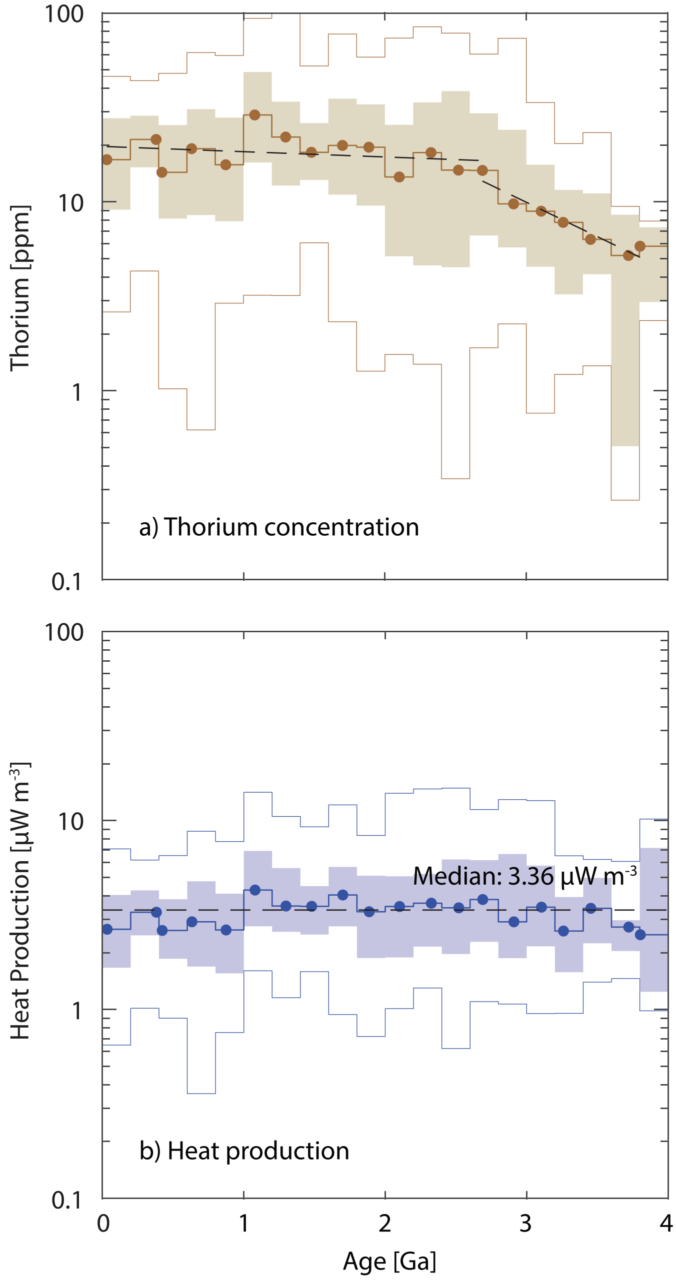

Figure 11: Temporal plots for 'granite' (TAS classification) restricted to between 72.1 and 75.97 wt.% SiO_2 (0.25 and 0.75 quantiles for SiO_2 concentration for 'granites'). a) Decay-adjusted thorium enrichment. The dashed lines represent the best fit to the median values for each bin between 0 to 2.8 Ga, and 2.8 to 4 Ga. There is a clear change in trend starting from ∼2.8 Ga. b) Decay-adjusted heat production. Thorium enrichment (as well as uranium) increases from 4 Ga to ∼2.8 Ga, and then remains relatively constant towards present day. Despite changing HPE enrichment, heat production at formation for these granites has been constant through time due to declining proportions of high heat producing ^{235}U.

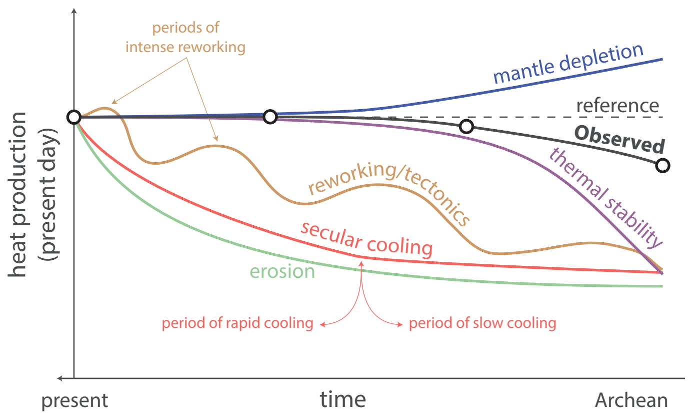

Figure 12: A conceptual diagram of expected deviations in HP observed at present-day (not decay-adjusted) for different aged rocks due to time-varying global processes. Due to decay alone, we would expect all rocks to look the same at present day (reference line) assuming all other processes and conditions are unchanged. We instead observe a roughly exponential decrease with time (solid black line). After decay correction this observed line is approximately flat (Figure 9b). This flat trend must result from other external influences lowering the 'reference' decay-only Earth curve to the observed curve.