1. Objectives

The distribution of heat producing elements (HPE) exerts a first order control on the thermal structure of the crust. Understanding this distribution and the way it changes with time is therefore of paramount importance to understanding the long-term evolution of the continents. Changes in the distribution of HPE in, and therefore the thermal structure of, the crust are effected by primary tectonic processes such as magmatism, deformation and erosion, with each process resulting in the redistribution (or "fluxing") of HPE with characteristic length-scales and rates. Because many of the tectonic processes are themselves temperature dependant the recognition of this link between crustal thermal regimes and primary tectonic processes naturally leads to the notion that the tectonic processes should be subject to complex feedback loops (Figure 1).

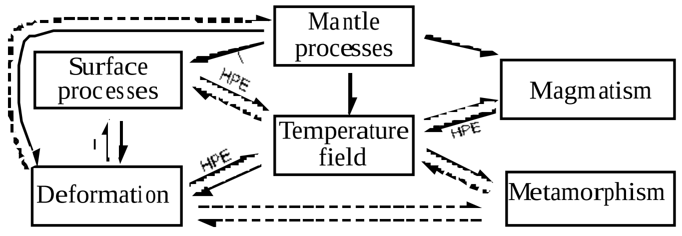

Figure 1. Some tectonic feedback loops involving the temperature field in modulating the interactions between the primary tectonic processes. Solid lines imply a first-order control, dashed lines imply a second-order control. **HPE** signifies a response that may be strongly modulated by HPE re-distribution. **I** signifies an isostatically-modulated response. Mantle processes refer to convective mantle, while surface processes refer to erosion and sedimentation consequent upon the isostatic responses of uplift & subsidence.

Investigations into this type of "tectonic feedback" have, until recently, emphasized the role played by transient processes. As just one example, Sandiford et al. (1991) showed how a feedback modulated by the temperature sensitivity of lithospheric strength provides a compelling explanation for the observed thermal evolution in metamorphic belts where there is an intimate link between granite magmatism and deformation. In contrast, there has been little understanding of the way in which redistribution of HPE during tectonism influences the long-term evolution of the continents. In a number of recent papers the applicant has demonstrated examples where "tectonic feedback" related to HPE redistribution appears to have played a central role in the development of the Australian continent. These pertain to the thermal evolution of metamorphic belts (Sandiford et al, 1999a; Sandiford & Hand, 1998a; McLaren et al., 1999); the evolution of intracratonic basins (Sandiford et al., 1998b; Sandiford & Hand, 1998b; Sandiford, 1999); the selective reactivation of pre-existing structures (lineaments) in continental interiors (Hand & Sandiford, 1999); the localization and termination of orogeny in intraplate settings (Sandiford & Hand, 1998b); and the style and distribution of basement-involved deformation in orogenic belts (Sandiford et al., 1998b; Paul et al., 1999). These examples highlight a number of specific ways in which such "tectonic feedback" may have profoundly influenced the long-term evolution of the continents; namely through the long-term thermal response to HPE "fluxes" associated with the segregation and ascent of HPE-rich granites (Figure 2a), the generation and filling of sedimentary basins (Figure 2b), and deformation and denudation in intraplate orogens (Figure 2c). The recognition this HPE-modulated "tectonic feedback" has profound consequences for our understanding of the nature and significance of (silicic) magmatism and metamorphism in continents, the nature of basin inversion and its role in localizing deformation in the continental interiors, and for the mechanics of intraplate orogeny. This project will seek to elaborate the nature and significance of such "tectonic feedback" and the role it has played in shaping the Australian continent.

"Tectonic feedback" modulated by changing HPE distributions is likely to be particularly relevant to the evolution of the Australian continent which, on the basis of both heat flow (Cull, 1982) and geochemical (AGSO Rockchem database) data, appears to be the "hottest" of all continents. For example, the average heat flow in Australia Proterozoic crust is ~83 mWm^{-2} (Cull, 1982; Table 1) reflecting a crustal compliment of HPE possibly as much as twice that inferred in equivalent-aged terranes elsewhere in the world (Table 1, Sandiford & Hand, 1998a). Such profound HPE enrichment has clearly affected the thermal evolution of the Australian crust, with attendant implications for the nature of tectonic processes. Indeed, many unique aspects of Australian crustal evolution, particularly in the Proterozoic (eg, Etheridge et al., 1987), may simply reflect extreme differentiation necessitated by this extraordinary HPE enrichment (McLaren & Sandiford, SGTSG Halls Gap conference, February, 1999). This project will use constraints on HPE distributions in each of the main tectonic provinces in

Province	qs	q*	qc	hr
Central Australia	83±21	27±6	**56**	11
Eastern USA	57±17	33±4	24	7.5
Brazilian Shield	56±15	28±7	28	13.1
Indian Shield	71±11	38±2	33	14.8
Zambia	67±7	40±6	27	7.5

Table 1: Heat flow data (mWm^{-2}) from various Proterozoic provinces (from Table 5.5, Taylor & McLennan, 1985). **qs** is the average measured surface heat flow, **q*** is the estimated reduced heat flow, **qc** is estimated contribution of crustal HPE, and **hr** is the estimated characteristic length scale of HPE distribution. While such data are subject to large uncertainties (eg, Jaupart, 1983), they do suggest extraordinary enrichment in HPE in the Australian Proterozoic.

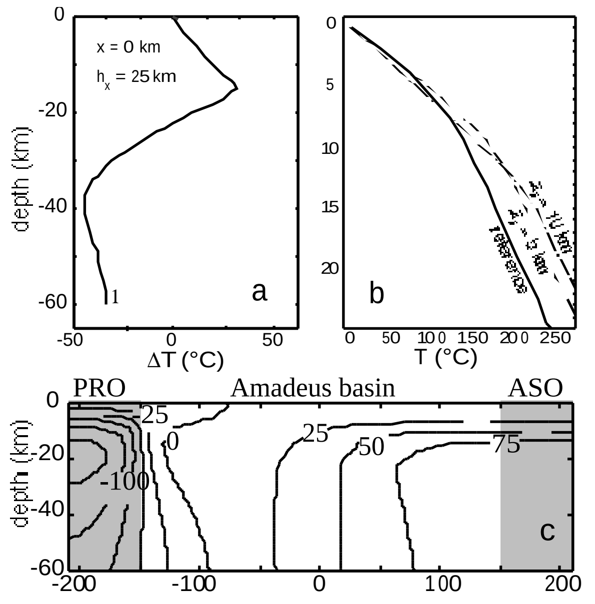

Figure 2 : Tectonic processes with profound long-term thermal consequences. **(a) Segregation and emplacement of HPE rich granites** : predicted temperature changes following emplacement of a granite batholith with HPE concentrations like the Sybella Granite, Mount Isa. Calculations assume granite is sourced from 40 km depth and is intruded at 15 km, and are with reference to the geotherm prior to granite segregation (McLaren et al., 1999)**. (b) Generation and filling of sedimentary basins :** temperature changes due to rift basin development with thermal parameters appropriate to the Amadeus basin. Reference curve : geotherm prior to basin development (Sandiford, 1999). zs = 5 km is appropriate to long-term effects of basin with 5 kilometers of fill, while zs = 10 km is appropriate to long-term effects of basin with 10 kilometers of fill. **(c) Denudation of intraplate orogens** : Predicted long-term temperature changes following erosion of the Petermann Ranges Orogeny (PRO), and associated syn-orogenic sedimentation in central Australia. The figure shows a crustal scale profile across the Amadeus basin from the Petermann Ranges in the south (left) to the Arunta Block (right) in the north (Sandiford & Hand, 1998a).

Australia to document the magnitude and rates of HPE fluxes during the tectonic processes that have shaped the continent. The impact of these HPE fluxes on the long-term evolution of the continent, and their role in facilitating "tectonic feedback" will be quantified with newly developed numerical models which couple thermal, mechanical and geochemical aspects of crustal differentiation. Particular focus will be awarded to Proterozoic Australia, because of its unusual HPE enrichment.

2. The significance, impact and outcomes of the project

This study will have broad implications for our understanding of the nature of metamorphism, magmatism and deformation in shaping the continental lithosphere. It will be particularly significant in understanding factors controlling deformation in continental interiors (intraplate orogeny), and will contribute valuable new insights into the factors that control lithospheric strength. Because understanding thermal regimes is central to all lithospheric processes, this project will have important consequences for understanding the origin and distribution of mineral deposits within the Australian continent.

The significance of the proposed work can be appreciated in the light of our current understanding of the role played by tectonic processes in shaping the continents. In the last 30 years, since the formulation of plate tectonics, the processes of crustal growth and differentiation have been framed almost exclusively in terms of plate boundary interactions. Implicitly, geologists now view primary tectonic process (eg., deformation, metamorphism and magmatism) as responses to *tectonic forcing* at plate boundaries, where the principal control is the rate and obliquity of relative plate margin motion. While this approach has been tremendously successful, it has obscured the role played by the evolving internal configuration in understanding feedback between ongoing tectonic processes. One of the main contemporary challenges is to distinguish the *tectonic signals* that reflect the *boundary conditions* from those that reflect the changes in the *internal configuration* of orogenic belts. By exploring the hypothesis that the intrinsic properties of the continental interiors (specifically HPE distributions) exert a profound influence on their long-term evolution this project directly tackles this challenge. Furthermore, as the strength of the lithosphere is closely allied to its thermal regime (Brace & Kholsetdt, 1980; Sonder & England, 1987), the results of this project should have considerable impact on our understanding of its long-term mechanical behaviour.

Recent years have seen a tremendous resurgence of interest in the causes and consequences of tectonic activity in continental interiors, and there is now a growing awareness that that continents have been significantly shaped by intraplate processes (eg. 1997 Penrose Conference entitled "Tectonics of Continental Interiors"). This is nowhere better illustrated than in central Australia where major tectonic activity in the Phanerozoic lead to widespread deformation and metamorphism of the crust in settings remote from active plate boundaries (eg. Tessyier, 1985). Dramatic testimony to the significance of these central Australian "intraplate" orogens is evident in their extraordinary gravity anomalies (Lambeck, 1983), which are amongst the largest known on the continents. Understanding the controls on, and links between, the tectonic processes affecting continental interiors will have a major impact on the way geologists view the evolution of the continents and will provide a major focus of this project.

The distribution of HPE has played a profound role in the metallogenic evolution of the Australian continent, with some of our largest ore-bodies located in or near HPE-rich granites (eg Mount Isa, Olympic Dam). This project, which focuses on the nature and consequences of HPE distributions in the Australian crust, will therefore have significant impact on our understanding of the crustal environments conducive to such mineralisation, with all its attendant economic implications.

The applicant has a strong record of publishing new conceptual work in high profile international journals (see attached references), and the results of this project will continue to be presented in these journals, as well as at international conferences. In addition, the applicant is committed to use of the world-wide-web as a venue for distributing the results of research, especially in the fields of computational geology where both animations and interactive computations allow much greater insight into complex physical processes than the more traditional "static" modes of publishing provided by printed media. To this end the applicant is currently involved in the implementation of new web-based techniques that will be used to further enhance the impact of the proposed research (examples can be seen on the applicants website *htttp://jaeger.geology.adelaide.edu.au/ msandifo.html*).

3. Preliminary studies

This proposal represents the culmination of a major, on-going research effort by the applicant into the causes and consequences of anomalous heat production distributions in the crust (Sandiford & Hand, 1998a&b; Sandiford et al 1998a & b; Sandiford, 1999; Hand & Sandiford, 1999, McLaren et al., 1999). These publications provide the foundation for the notion that "tectonic feedback" has played a paramount role in shaping the Australian continent.

Lithospheric thermal regimes are extremely sensitive to heat source distributions, which are classically constrained by regression of heat flow-heat production data. Such regression suggests that approximately 50% of the global average surface heat flow in the continents (~62 mWm^{-2}) is contributed by lithospheric HPE that are largely confined to the upper half of the crust. Generally lower heat flow in Precambrian terranes is attributed to significantly lower crustal HPE (Jaupart et al., 1993). Existing heat flow measurements from Australia show that it is unusually hot: for example, the 25 heat flow determinations from Australian Proterozoic terranes yield an average of 83 mWm^{-2} (Cull, 1983, Houseman, 1989) more than 25 mWm^{-2} higher than global Proterozoic average. Australian Proterozoic terranes are characterised by extraordinary enrichment in HPE, usually found in Palaeo- and Mesoproterozoic granites. For example, McLaren et al (1999) estimated that the Sybella Batholith, at Mount Isa, contributes ~ 20 mWm^{-2} to the surface heat flow, while Sandiford et al (1998a) have identified granite gneisses in the Mt Painter Inlier in South Australia with heat production rate of ~ 50 μWm^{-3}. These data suggest that Proterozoic of Australia is enriched in HPE possibly by as much as a factor of 2 compared with other equivalent aged terranes elsewhere in the world (Table 1), with the HPE largely concentrated in relatively discrete upper crustal levels in granitic sills (Sandiford & Hand, 1998a). One profound implication of such HPE enrichments in thin sill like layers is that crustal thermal regimes are extremely sensitive to small changes in the depth of these layers. Sandiford et al (1998b) have shown that for parameters typical of Proterozoic Australia, Moho temperatures will change by 20 - 30°C for every kilometer change in depth of the HPE anomaly. The potential significance of this can be evaluated in light of contemporary models for lithospheric strength, which show extraordinary temperature dependence. One such model that has been has been widely used in numerical studies of continental tectonic assumes the lithosphere deforms by a combination of frictional sliding and temperature dependent creep processes (Brace & Kholstedt, 1980). This model shows that changes in depth to such a radiogenic layer by as little as 5 kilometers can lead to changes in the vertical averaged lithospheric strain rate due to an imposed tectonic force by as much as 4 orders of magnitude (Sandiford et al., 1998b)! The implication is that subtle changes in HPE distributions in the lithosphere during tectonic activity can lead to profound changes in its subsequent "tectonic response".

An international focus on these studies is evident by invitations for the applicant to present key-note addresses on HPE distributions and the thermal and tectonic evolution of the crustat three recent international conferences (see attached C.V.), and by invitations to present the work in thematic volumes ("Tectonics of the Continental Interiors" edited by Marshak, van der Pluijm & Hamburger; " "Evolution and Differentiation of the Continental Crust" edited by Brown & Rushmer)

4. Research program and timetable

The proposed work program will encompass several distinct "phases", each designed to characterise or test a different aspect of HPE-modulated "tectonic feedback" in the Australian context. The research will involve a combination of empirical field-based observations, thermo-chronological analysis and numerical modeling and will involve extensive collaboration with research groups from various parts of the country. (With due recognition of the 6-page application limit) brief synopses of the main phases of the research program (along with the approximate timing) are presented below:

- *HPE distributions in the Australian crust (years 2000-2001).* From the point of view of understanding long-term thermal evolution of the crust it is essential to understand the gross distribution of HPE within the lithosphere. Surface heat flow provides an important constraint. While there are relatively few heat flow measurements in Australia, the available measurements are sufficient to characterize most major tectonic provinces (Sass & Lachenburch, 1978; Cull, 1983). The gross form of HPE distributions within the lithosphere can been estimated by regressing heat flow measurements against surface HPE data. However, such regression is subject to considerable error (eg. Jaupart,1983) especially in regions with significant lateral variations in HPE concentrations. Consequently this approach is best when augmented with additional geochemical and/or geophysical constraints. Regional geochemical datasets and deep seismic profiles in combination with surface heat flow measurements allow construction of relatively refined lithospheric-scale heat production models (eg. Fountain & Salisbury, 1981), and is especially suited to regions such as central Australia where surface exposures provide access to material from an array of different crustal levels. In the Australian context there has been little attempt to augment our understanding of HPE distributions responsible for the observed heat flow with the use of additional datasets, and a significant aim of this project will be to characterize HPE distributions in the Australian crust. For regions where heat flow data and/or deep seismic data spectral methods can be used to infer thermal regimes (eg, Burov et al. 1998). This approach relies on the assumption that the elastic thickness of the lithosphere, obtained from the coherence between gravity and topography, is defined by the depth to a specific is isotherm. Application of this technique, which has been developed using coherence between topography and bouguer gravity, has been hampered because of the very low signal to noise ratio for most continental regions. However recent advances which employ free-air gravity offer considerable prospects (McKenzie & Fairchild 1998), and warrant evaluation in regions where heat flow data and HPE distributions are well constrained before application to less well characterized regions.
- *HPE fluxes during granite segregation (years 2000-2003).* Granite magmatism is a key to understanding crustal differentiation. Because granites host a large proportion of the total lithospheric HPE complement, transport of granitic melt from source to emplacement levels may result in profound changes in HPE distribution in the lithosphere. This study will document the role granite magmatism in the long-term thermal evolution of the Australian lithosphere, by calculating the associated fluxes in HPE for each of the major tectonic provinces in the Australian lithosphere, from the Archaean through to the Phanerozoic. As noted earlier, many Australian Proterozoic granites are unusually enriched in HPE, with the redistribution of HPE associated with granite

emplacement having profound long-term thermal consequences (Figure 1a). HPE concentrations for Australian granites are well constrained by both extensive geochemical data (AGSO's Rockchem database) and by regional airborne radiometric data. The observation that granite generation results in significant redistribution of HPE in the lithosphere begs the question of how the ensuing long-term thermal changes feedback into the ongoing potential for magmatism. This problem is of profound significance for our understanding of magmatic process in the crust, and now represents a tractable computational problem because of the development of (1) new thermodynamic models for melting in crustal systems (Powell et al.,1998) and (2) new conceptual framework for understanding the migration of fluids within the crust (Conolly & Podladchikov, 1998). During this phase of the project numerical models incorporating the thermal/geochemical causes for, and consequences of, grnaite melting and migration will be combined with these new developments to provide new insights into the nature of magmatic events in the crust.

- *High geothermal gradient metamorphism and thermal subsidence (years 2000-2001).* High geothermal gradient metamorphism has played a critical role in the differentiation, stabilization and reactivation of the Australia continent. It is therefore crucial to understand the factors that contribute to such metamorphism. This project will test the hypothesis that high geothermal gradient metamorphism can be produced by burial of a radioactive basement beneath a thick sedimentary blanket during thermal subsidence using the Mount Painter region in northern Flinders Ranges. A detailed discussion of this models and its applicability to the Mt Painter region is given in Sandiford et al. (1998a). The methodology involves a combination of field-based empirical studies and application of Ar-Ar chronology (to be carried out in collaboration with Prof. Ian McDougall at ANU RSES). This phase of the project has already commenced in 1999 under the auspices of an ARC large grant (A39943129) to the Applicant.
- *Mechanics of basin inversion (years 2002-2003).* The generation and filling of sedimentary basins results in long-term changes to the thermal structure of the lithosphere which can impact on the way its responds to subsequent tectonic events (Figure 2b). In a number of papers the applicant has shown how such thermal changes can lead to localization of intraplate deformation, as evident by the common phenomena of basin inversion (Sandiford & Hand, 1998a; Sandiford et al., 1998b; Sandiford, 1999). This hypothesis contrasts with previous work in this field which suggest that such localization is related exclusively to weaknesses developed in the initial structuring of basins. These contrasting models have important implications for our knowledge of the factors controlling the strength of the lithosphere, and consequently there is now a need to test their relative roles in controlling basin inversion. Few numerical studies have yet to be concerned with details of inversion geometries, partly because they require numerical methods that allow for material strain localization phenomena in addition with thermal localization. The FLAC (Cundall, 1989) algorithm is ideally suited to such phenomena because of its ability to handle non-associated plasticity typical of many geological phenomena (Hobbs et al, 1989), and will be used in this phase of the project to model the interaction of thermal and material-controlled localization phenomena in sedimentary basins.
- *Process rates and mechanics of intraplate orogens (years 2002-2004).* The ongoing thermal evolution of orogenic belts is critically dependent on the rates of convergence and denudation. For typical plate margin orogens there is little potential for lithospheric scale cooling, because either mass fluxes entail significant orogenic thickening, or strongly focussed localized denudation serves to remove material from the orogens at rates to fast to allow significant cooling at depth. In contrast with plate margin orogens, rates of convergence associated with intraplate orogens are poorly constrained. Available data from the Alice Springs Orogen (as presented by Haines, Hand & Sandiford at the SGTSG conference, Halls Gap, Feb, 1999) imply that it evolved at very much slower rates that typical of plate margin orogens. However, these data are poorly constrained because the available bio-stratigraphic data pertaining to the onset orogen is subject to significant uncertainty. During this phase of the project, low-temperature thermo-chronometers will be used to constrain the thermal evolution of clasts in syn-orogenic sediments, and so constrain the rates of process attendant with the early stages of intraplate deformation in Central Australia. Ultimately, this phase of the project is designed at testing the notion that intraplate orogens may be self-locking, as proposed by Sandiford & Hand (1998b). This will be achieved by the use of numerical models of lithospheric deformation based on finite element algorithms (preliminary results illustrating the

methods pertinent to this modelling have been presented by Braun, Shaw, Sandiford & Gray at the SGTSG conference, Halls Gap, Feb, 1999). Of particular concern to this will be the origin of the gravity anomalies associated with the Alice Springs Orogen.

This project stems form ongoing collaboration developed between the applicant and a number of scientists in Australia and abroad, and it is envisaged that this project will see further extensive collaboration with these people. The collaborators include Dr Roger Powell and Prof Andrew Gleadow (University of Melbourne), Dr Jean Braun (RSES, ANU), Prof. Ian McDougall (RSES, ANU), Dr Martin Hand (University of Adelaide), Dr Lesley Wyborn (AGSO), Prof. Steven Marshak (University of Illinois, US),and Prof Karl Karstrom(University of Albequerque).

5. Resources

The primary funding for this project is the SRF salary. In addition, the proposed research will be supported initially under the auspices of an existing ARC-large grant (A39943129) to the applicant that terminates at the end of year 2001. The main objective of this grant relates to the first 2 years program (phases 1-3), with a specific emphasis on phase 3. A subsequent request to the ARC large grant scheme for funding in the years 2002-2004 will be submitted in 2001 to support the research involving phases 4 & 5. This application will focus on the characterization of rates and duration of intraplate orogenic processes in central Australia.

The choice of the University of Melbourne as host to this project is motivated by a number of factors. Primarily, the University of Melbourne is host to two world-leading research groups under the respective leadership of Assoc. Prof. Roger Powell and Prof. Andrew Gleadow, with whom the applicant has an established record of co-operation resulting in important publications. The move of the applicant to Melbourne would add significantly to the "dimensions" of both groups, bringing new and complimentary skills. In this regard, the choice can be counter-pointed with University of Adelaide (where the applicant is currently employed), where the "hard rock" staff profile has declined from 7 to 2 in the last 10 years (with a further 20% reduction in faculty staff projected in the next 2 years!). The challenges confronting the survival of Earth Sciences departments such as Adelaide are immense and should not be under-estimated, but are not necessarily conducive to achieving outstanding research outcomes. In order to maintain world-class research profiles in the current "Higher Education climate" there is a desperate need to concentrate critical mass. It is anticipated that the proposed move of the applicant to the University of Melbourne would help generate such critical-mass. As an indication of the applicant's commitment to this process, it is worth noting that he will be forgoing a tenured position.

6. References cited (see attached publication list for a listing of relevant publications by the applicant)

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Applicant Short C.V.

Personal Details

1978	B.Sc. (Hons) Melbourne University
1980-1984	Ph.D. Melbourne University
1984-85	Postdoctoral Fellow, Melbourne University
1986-87	CSIRO Postdoctoral Fellow, Cambridge University
1988-91	Lecturer, Adelaide University
1991-95	Senior Lecturer, Adelaide University
1996-	Reader, Adelaide University

Research

My research focuses on the interactions between metamorphism and deformation in the crust. It involves a combination of field based empirical observations and numerical modelling. The results of this research have been published in over 70 articles in international research journals and books. The research has attracted ~$1,900,000 funding in the last decade, and which has supported 8 postdoctoral fellows in this period of time. This research has attracted invitations to present keynote addresses at "Metamorphism and structure of the deep crust" (Finland 1992), "What drives metamorphism and metamorphic reactions" (U.K, 1996), "Penrose conference: Processes of crustal differentiation" (Italy, 1998) and "Orogenesis in the outback" (Alice Springs, 1999).

Teaching and Student Supervision (1988-1999)

At Adelaide University I have been heavily involved in undergraduate teaching where I have routinely taught courses in field geology, mineralogy, petrology and geodynamics. I have supervised some 28 Honours students (14 continuing on to PhD research programs) and 8 PhD students. Two of my honours students have received University medals awarded to the 10 best graduates across the University.

Key publications

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