D1 Title

Continental dynamics: understanding how continents work

D2 Aims

Over the last 30 years, the theory of plate tectonics has provided an extraordinary framework for understanding the basic workings of our planet. The greatest achievement of plate tectonic theory lies in its explanation of oceanic crust. We now have an essentially complete understanding of the way in which oceanic crust is created and destroyed in a single plate tectonic cycle. In comparison, plate tectonics provides a less compelling explanation of the structure and evolution of the continents. While we now understand that the continents represent an amalgam of inherited fragments and new crustal additions accumulated over many plate tectonic cycles, there is little consensus on the basic physical processes that shape the continental crust. Continental tectonism involves phenomena such as earthquakes and rupture of discrete faults, distributed deformation associated with the flow of large volumes of rock, and the generation and movement of magmas and hydrothermal fluids. In the continents, unlike in the oceans, these processes affect not only plate boundaries but also regions extending far into intraplate settings. Correspondingly the geological, geophysical and geochemical structure and evolution of the continents is still not clearly understood, nor can the processes that control continental phenomena always be interpreted unambiguously within the plate tectonic paradigm. As a consequence, the study of the dynamic evolution of continents continues to provide a major focus and challenge for research in the earth sciences.

This proposal aims to establish a dedicated continental dynamics research group focussed on the tectonic processes that have shaped and continue to modify the Australian continent. In addition to providing fundamental insights into the workings of the continents, this geographic focus will maximize the potential for economic and social benefits for Australians and our nearest neighbours, including the search for deep earth resources (metals, hydrocarbons and geothermal energy), earthquake hazard assessment, the origins of our distinctive Australian landscapes and the role played by Australia in long-term global change.

D3 Background

The continental crust has been shaped through time by repeated tectonic processing, involving reworking of older crust and new additions from the mantle. This tectonic processing is responsible for both the concentration of mineral deposits and energy resources that continue to underpin our national wealth and the earthquakes that jeopardize infrastructure and life in so many parts of the world including Australia [1]. Through associated geochemical cycling [2] and atmospheric and oceanic forcing [3], this tectonic activity also exerts a primary control on long-term global climate change. To the extent that tectonic processing is imprinted in all continental landscapes [1] it impacts on the functioning of all terrestrial ecosystems. Understanding the tectonic processes that govern continental evolution is therefore essential for understanding the basic workings of our planet, for securing future economic well-being through efficient exploration of deep earth resources, for mitigation against the catastrophic consequences of large earthquakes and for understanding the evolution and natural functioning of our landscapes. This section identifies some of the *key issues* in the field of continental dynamics research, with emphasis on those most relevant to the evolution of the Australian continent.

The range of phenomenon associated with continental tectonic activity covers such an extraordinary range of temporal and spatial scales, from the rupture of individual earthquakes to the steady creeping motion of tectonic plates that a truly unified view of just how continents "work" has yet to be realized. While a fundamental geochemical organization of the continental lithosphere into crust and mantle has long been evident we have little understanding of the underlying physical processes that lead to the specific manifestations of this organization, such as the thickness of the crust or the distribution of the heat producing elements. The role of various "feedback" mechanisms (Fig. 1) appears crucial to the long-term emergence of a geochemically-, thermally- and mechanically-structured lithosphere [4]. However, the characteristic signatures, including the temporal and spatial scales, of the various feedback mechanisms are yet to be fully elucidated. Putting it bluntly, we are yet to achieve a dynamic synthesis that accounts for many basic aspects of continental evolution and one of the main challenges in continental dynamics research *is to determine the various mechanisms of the continental tectonic feedback system*. As we strive to realise this challenge, the question of "*how do continents work?*" is emerging as a guiding motivation for the international earth science research community.

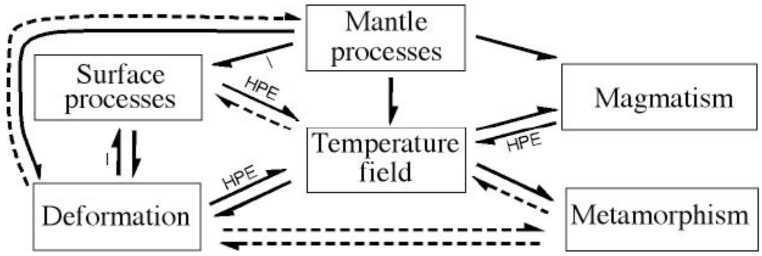

Figure 1: Some of the feedback mechanisms that modulate the interactions between tectonic processes. Solid lines imply a major control, dashed lines imply a second-order control. HPE signifies a process that re-distributes heat producing elements. These are fundamental because they link the geochemical organization of the crust to its thermal and mechanical structure [4].

The primary focus of my research effort is on this challenge, specifically on the *key issues* relating to:

1. *The mechanics of continental deformation* [5]: The widespread distribution of historic earthquake activity within continental interiors, including comparatively stable regions such as Australia (Fig. 2a) imply a characteristic deformation regime that differs fundamentally from the more rigid, plate-like oceanic realm. However, we do not yet understand how the continental lithosphere responds to external tectonic forcing on geological time-scales or at the much shorter time-scales appropriate to the rupture of earthquakes. For example, is the continental lithosphere better characterized as a viscous sheet distributing deformation in a diffuse fashion [6] or as an imperfect plate in which the distribution of faults provides the primary control on the deformation field [7]? While the long known Gutenberg-Richter scaling of continental earthquakes (Fig. 2b) is suggestive of a "self-organized" critical dynamic regime [8] the potential reasons why continents behave in such a fashion is not clearly understood, hampering our ability to predict earthquakes. An important step towards furthering our understanding in the basic mechanics of continental deformation is the meshing of plate velocity fields derived from satellite technologies (GPS, InSAR), the historic seismic moment release rates and the longer-term deformation fields derived from geological observations such as palaeoseismic and faulting records.
2. *The coupling between continental lithosphere and mantle convection* [9]: Continental drift is clearly one of the first-order manifestations of the deep convective processes in the earth that drive plate motion, yet our understanding of the coupling between deep mantle convection and surface plates remains rudimentary. For example, no consensus yet exists on the influence of mantle flow on critical geophysical "observables" such as the *in situ* stress field within continental interiors and their surface elevation (the so-called dynamic topography) [10-11]. In particular, one fundamental controversy in geodynamics relates to the so-called dynamic topography field [10-11] induced by mantle convection. The amplitude of the dynamic topographic field and its relation to long-wavelength geoid anomalies is sensitive to, and provides a crucial constraint on, the viscosity structure of the mantle [12]. Numerical simulations consistently overestimate the amplitude of dynamic topography [11], while geological observations relating to the dynamic topographic signal remain contentious [10-11]. For example, whereas [11] predict a dynamic topographic subsidence of southeast Asia of several hundred metres over the Cainozoic, others [10] find no compelling evidence for dynamic topography in this region. To quote a recent review [13] "*Future progress in understanding global (plate) motion requires…(more) comprehensive comparison of global plate/mantle dynamics with geologic data, especially indicators of the intraplate stress and strain, and constraints on dynamic topography*."

3. *The relationship between intraplate deformation and plate boundary forcing* [1]: Some of the largest, most catastrophic earthquakes of recent decades have occurred in continental intraplate settings (eg., the 2001 Bhuj ~M7.7 quake in northwestern India with ~ 20,000 deaths and the 1976 Tangshan ~M7.8 quake in northeastern China with ~ 240,000 deaths) providing awesome testimony to the power of intraplate tectonism. The relationship between intraplate deformation and activity at distant plate boundaries [14-15], and the factors that localize intraplate deformation in continental interiors remains poorly understood. At a more general level the role of intraplate processes in shaping the continents in the past continues to be a controversial issue.

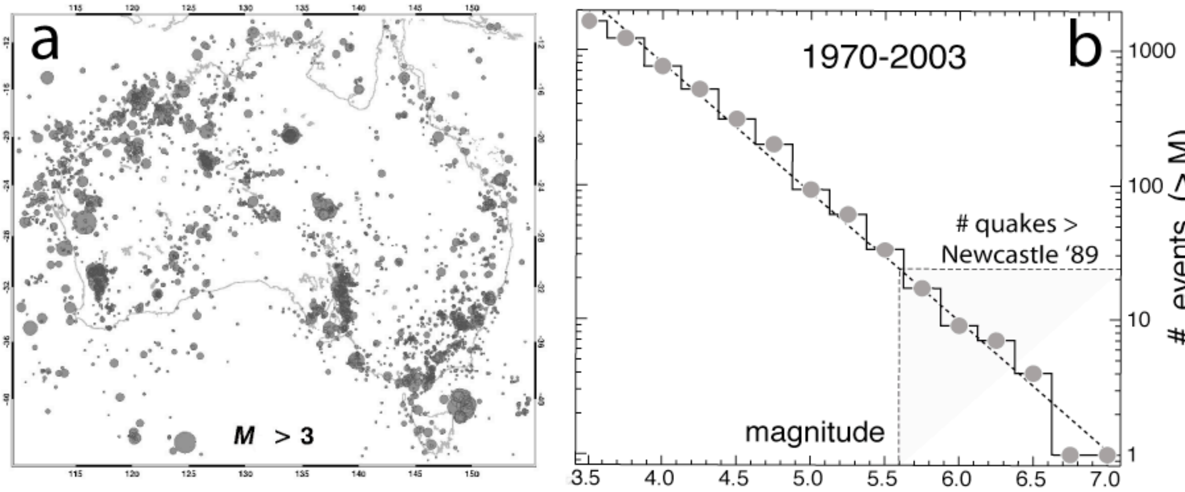

Figure 2: (a) the widespread distribution of Australian earthquakes implies that the continent is actively deforming in a diffuse fashion, albeit at very slow rates. (b) Frequency-magnitude distribution for the quakes shown in Fig. 2a. The classic (Gutenberg-Richter) log-linear scaling implies a self-organized critical state [8] with estimated seismogenic strain rates locally as high as ~ 10^{-16} s^{-1} [16]. Quakes with magnitude greater than the '89 M 5.6 Newcastle earthquake (~$4 billion damage, 13 lives lost) occur every 1-2 years in Australia, while M > 7 events (which release ~50 times the energy of the Newcastle quake) are expected every ~20-30 years.

4. *The surface process - tectonics feedback system* [15]: The change in position of the continents and the distribution of relief associated with formation of mountain belts provides a fundamental control on oceanic and atmospheric dynamics [2-3] that links tectonics to long-term climate change. In turn, climate provides a primary control on weathering, erosion and the transport of sediments, thereby impacting on the thermal and mechanical structure of the lithosphere [15]. The extent to which such surface processing modulates the tectonic response of the continents is one of the most hotly debated topics in continental dynamics research. The long-term climate forcing induced by tectonics is so strong that resolution of the relative importance of tectonics and climate change in shaping continental landforms has proved to be a difficult and enduring problem [17], and provides a key barrier to understanding the extent to which tectonic events are globally synchronized [18].
5. *The nature of the tectonic process through time* [19]: Since the mid-Archaean when the oldest parts of the Australian crust were stabilized, the thermal output due to radioactive heating in the Earth has declined by a factor of three. Given the strong temperature dependence of rock strength, associated long-term changes in the Earth's thermal structure should be expected to influence styles of tectonism, yet we still do not fully understand whether tectonic processes that shape continents today were also responsible for the growth and stabilization of the continents in the early stages of earth history. Given that the great majority of Australia's mineral wealth derives from ancient (Archaean - Proterozoic) terranes, this uncertainty compromises the development of a predictive framework for the exploration of further resources.

D4 Significance and innovation

The question at the heart of this proposal "*how do continents work?*" provides the crucial framework that will focus much of the international solid-earth science research effort over the next decade. The significance of this proposal can therefore be measured against the potential outcomes that flow from the resolution of the key issues outlined in section D3. For example, resolving how the spatial and temporal (frequency-magnitude) distribution of earthquakes relates to the long-term deformation field of the continental crust will provide a major step towards improving our understanding of earthquake hazard assessment in continents such as Australia. Resolving how the continents attain their geochemical structure is an essential requirement to developing a comprehensive, integrated framework for continental lithospheric evolution of comparable sophistication to our contemporary understanding of the ocean lithosphere. Resolving the nature of the coupling between deep mantle convection and surface plates will provide a crucial constraint on the energetics of plate motion. Finally, resolving how the tectonics-climate feedback system works will be essential for understanding long-term global change.

Our ability to resolve these questions will require innovative approaches stemming from new and rapidly developing technological advances in the fields of geochemical analysis, computer modelling and geophysical imaging (including remote sensing) applied in novel ways. This new arsenal of analytical and observational techniques will form a core ingredient of the proposed continental dynamics research facility, and includes:

1. The new range of geochronological analytical methods that allow quantification of the age and rates of geological processes. Of particular relevance to this application are the range of new techniques relevant to quantifying landscape evolution in actively deforming zones, including the rupture history of surface-breaking faults. These techniques include the optically-stimulated luminescence (OSL), cosmogenic nucleide (CRN), U-series and apatite (U-Th)-He dating methodologies, all of which are currently being developed in the *Melbourne University School of Earth Sciences* (MUSES).
2. New computer modelling methodologies that enable simulation of the large-scale, highly non-linear processes that shape the continental crust, such as those being developed by a consortium of Australian scientists (including myself) under the umbrella of the *Australian Computational Earth Systems Simulator* (ACcESS) as part of the Federal Government's *Major National Research Facility* (MNRF) program, in partnership with the *Victorian Partnership for Advanced Computing* (VPAC).
3. Extraordinary advances in geophysical remote sensing capabilities introduced by various satellite technologies, including multispectral imaging (Landsat, ASTER, SPOT), satellite altimetry (SRTM), and interferometry (InSAR) and GPS monitoring of the velocity field.

The proposal seeks to establish a research group and facility that is uniquely positioned to combine the advanced analytical capability at MUSES with the world class modelling capability being developed with ACcESS, and a focus on the extraordinary natural laboratory provided by the Australian continent, its nearest neighbors (Timor, Papua-New Guinea, New Zealand) and its host tectonic plate (the Indo-Australian plate). In addition to the links with MUSES, the ACcESS MNRF and VPAC (as listed above) the proposal will build on established links with other key players in Australian earth science including the proposed ARC Centre of Excellence in Earth Dynamics (with a pending application by a consortium of Australia's leading earth scientists at Macquarie University, ANU, Melbourne and Monash University to the 2005 ARC Centre of Excellence program), Geoscience Australia and the *pmd**CRC based at Melbourne University.

D5 Approach

The traditional approach to continental dynamics research typically involves the concept of a field laboratory. In the past such field laboratories have largely concentrated on orogenic systems at plate margins, with little attempt to link orogenic dynamics to other phenomenon operating elsewhere in the plate. The primary objective here is to take a more ambitious approach that links the behavior of continental lithosphere at the continental scale, relating processes operating from plate boundaries to those that affect the interior of the plate. Australia provides an ideal geographic focus for such a study because it is the fastest moving of all continents and is embedded within the most complex and dynamic of the Earth's large tectonic plates, the Indo-Australian plate. The proposed research program will involve three interlinked themes relevant to both the broad question of understanding how continents work and the evolution and dynamics of the Australian continent. These themes will link new analytical and modelling capabilities with observations and constraints derived from field-based and remote-sensing studies. A brief, and necessarily non-exhaustive, outline of the intended research, main outcomes and funding sources is given below (associated supporting or pending competitive grant applications and relevant manuscripts currently in press are detailed on my web site - http://jaeger.earthsci.unimelb.edu.au/grants). Endnotes provide relevant supporting data and observations that relate to ARC-supported work currently in press. Funding to be provided by the University of Melbourne in support of this proposal (see section E), relates to two research fellows and two PhD projects. One of major initiatives of this project will be the appointment of Dr David Coblentz, a world authority in stress modeling. The focus of the other fellowship (PD1) and PhD projects (PG1 & PG2) are briefly outlined below.

Theme 1: The Australian neotectonic record

Main outcomes: A new mapping of the neotectonic deformation field of the Australian continent including a seismic moment release model at the 100-100,000 year timescale that informs earthquake risk assessment.

My recent studies (see *New Scientist*, June 7th, 2003, p. 17) have shown that southeastern Australia contains a profound, ongoing record of young (neo-) tectonic activity consistent with the energy release associated with historic seismicity. For example, about half of the relief in the southern upland systems such as the Flinders and Otway Ranges can be attributed to young faulting with demonstrated slip-rates of ~ 50 metres per million years over the last 5 million years [16]. The primary aim of this theme is to extend our knowledge of the neotectonic deformation field to the whole continent, including an assessment of the various modes of deformation, and back through time over the last 50 million years. Unlike plate boundary zones, the internal deformation in relatively stable regions such as Australia cannot currently be detected using GPS methods [20]. Thus it has not yet been possible to validate numerical models of neotectonic deformation of Australia against geodetic velocity fields to derive quantitative constraints of fault strength and seismogenic coupling in the Australian continent [21]. This has greatly limited our ability to understand faulting mechanisms in our region, including the rupture events that lead to earthquakes. However new satellite radar (InSAR) interferometric methods can now resolve such displacements and the challenge is to mesh these with quantitative constraints on the longer-term deformation field from geological observations. Field observations and remote sensed data, such as the extraordinary new SRTM digital topography, will be used to evaluate the neotectonic displacements including the various modes of deformation[1], and to target samples amenable to geochronological analysis that constrain deformation rates. Quantitative assessment of slip rates will be undertaken using OSL, CRN and U-series analysis of fault-related sediments and associated geomorphic surfaces. The neotectonic displacement field will be compared to that derived from InSAR interferometry and seismic moment release, to constrain fault strength and seismogenic coupling in the Australian crust. Our understanding of the long-term pattern of seismicity within stable continental regions is limited because the recurrence interval of the largest quakes (typically ~ 1000-100000 years) is much greater than the historic record (~100 years). A particular concern for risk assessment is the distribution and frequency of potentially damaging earthquakes (M>5.5), requiring constraints from longer-term records of the seismic moment derived from geological observations such as the neotectonic deformation field. In this regard, a crucial source of information relates to the magnitude of the maximum likely event. Samples obtained from trenching (to be carried out in conjunction with Geoscience Australia) of large prehistoric surface breaking ruptures, such as the Cadell and Lake Edgar Faults[2], will be used to constrain characteristic Australian fault rupture sequences (using OSL and U-Th dating techniques). Primary funding will be provided by ARC discovery grant DP0556133 (see Section C1), with PD1 dedicated to the application of quantitative chronology and PG1 focused on the palaeoseismology of Australia's largest earthquake events.

Theme 2: Plate boundary forcing, slab-plate coupling and dynamic topography in the Indo-Australian plate

Main outcome: A new thermo-mechanical model of the Australian continent linking the deformation field to the forces that drive plate motion that informs our understanding of the evolution of the Australian landscape over the last 50 million years.

The tectonic stress field in the Indo-Australian plate forms an organized pattern that we have explained in first order terms by a balance between the forces that drive the plate northwards, and resistance associated with continent collision at convergent plate boundaries [16,23]. Changes in the plate-boundary forcing, particularly those associated with the collisional mountain belts of the Himalaya, Timor, Papua New Guinea and New Zealand should therefore be expected to be reflected in the intra-plate stress field. A *prima facie* case for a plate-scale response to plate-boundary forcing is provided by the onset of diffuse deformation in the central Indian Ocean in the last 5-10 million years [24-25] that has been related to an increase in intraplate stress due to the rise of the Tibetan plateau [26]. In southeast Australia the onset of neotectonic deformation at around 5-10 million years ago has been attributed to plate-boundary stress derived from increased coupling across the Pacific-Australia plate-boundary segment in New Zealand [16]. Past attempts to identify dynamic topography have relied to a large extent on departures of palaeo-sea-level indicators from expected eustatic sea-level heights [27]. Surprisingly there has been little attempt to understand the dynamic topographic signal from differential continental tilting associated with plate motion over heterogenous mantle. As the fastest moving continent (~6.5 cm/yr), transiting one of the largest geoid anomalies on the planet, the Cainozoic record of sea-level change around Australia is ideally suited to an evaluation of the dynamic topography field. The case for an extraordinary dynamic topographic signal in the Australian continent is provided by hitherto largely unrecognized evidence for ~ 300 m north-side down, continental-scale tilting implied by the starkly contrasting Cainozoic stratigraphic records of the Australian northern and southern margins. Such evidence would appear to provide strong confirmation of the models of [11]. However, we know little in detail of the timing of tilting and its relation to Australia's northern motion. The primary aim of this theme is to relate the intra-plate tectonic response (as for example deduced in theme 1) to plate boundary forcing, to define the continental-scale, planform and timing of the tilting associated with Australia's northward motion and relate it to dynamics of the convective mantle beneath. Quantification of the dynamic topographic field of the continent will involve construction of differential motions of the continent based on palaeo-shoreline features and drainage derangement in the continental interior for time slices that cover the Cainozoic. The maps of differential vertical motion will provide a first-order constraint on mantle numerical models of convection incorporating Australia's northward plate motion across a convecting mantle. The active tectonics of the Indo-Australian plate contains a unique record of slab-plate coupling[3] and this theme will provide further constraints on the evolution of the slab-plate coupling through time. Our understanding of lithospheric dynamics has benefited from application of geologically constrained numerical modelling based on continuum mechanical principles, with much effort expended in recent years on numerical algorithms that encode the fundamental physics (eg., ACcESS MNRF). This theme will utilize plate-scale numerical modelling strategies developed in collaboration with Dr David Coblentz and the ACcESS MNRF designed to demonstrate how changes in plate boundary forcing through time has impacted on the intraplate stress field and isolate intrinsic properties of the lithosphere (eg., theme 3) that contribute to localized failure in response to regional stress field. This theme requires a thorough understanding of the changes in plate boundary configuration. One of the poorest known and potentially most interesting changes in plate boundary configuration has been in Timor, where the leading edge of the Australian continent has impinged on the Banda Arc in the last 5-10 million years. Because of restricted access from 1975-2002, little is known of the timing and kinematics of the Timor collision and part of the aim of this theme will be to document the history of orogenic activity that has built Timor (in conjunction with Timor Leste Energy and Mineral Resources Directorate). Primary funding will be provided by ARC discovery grant DP0556133 and will build on ongoing ACcESS MNRF programs. PG2 will be allocated to the study of Timor tectonic evolution.

Theme 3: The thermal evolution of the Australian crust

Main outcomes: (a) A new thermal model of the Australian crust based on an improved heat flow database that informs geothermal energy exploration strategies and (b) an improved understanding of the mechanisms and time-scales of the processes that have contributed to the shaping of the Australian continent through time that informs metal resource exploration strategies.

Perhaps my most significant contribution to understanding how continents work is the idea of "tectonic feedback", providing a self-consistent mechanism linking the geochemical, thermal and mechanical structure of the continental crust ([4], Fig. 1). This hypothesis makes important predictions about the abundance and spatial distribution of heat sources in the crust that can, in theory, be tested against well constrained heat flow data[4]. The slow deformation of continental interiors such as Australia hints at an extraordinarily sensitive coupling in the system dynamics. Is it just coincidence that intraplate stress levels are sufficient to deform continental interiors or is it because deformable continents are essential for plate tectonics[5]? Much of the approach articulated above is directed to understanding this fundamental question in relation to the recent dynamics of the Australian continent and the Indo-Australian plate. However this apparently sensitive coupling also raises important questions about the past evolution of the continents, particularly early in earth history, when heat production rates were substantially greater than today, thermal regimes necessarily hotter and by inference, continents weaker. Just how did continents behave in times past and what role did tectonic feedback processes play in shaping the early crust? These questions are crucial not only in terms of our understanding of the long-term evolution of the continents but also for understanding the distribution of deep earth resources through time, an essential prerequisite for effective resource exploration strategies. The Australian continent preserves an extraordinary 4 billion year record of crustal growth and reworking [28] and the potential role of tectonic feedback in shaping the ancient Australian crust has been highlighted by my work [19]. However, this work is in its infancy and we still have much to learn about the nature of tectonic processes in early earth history and the role they have played in shaping the crust, its thermal evolution and mineralization history. Importantly, my group's work has shown that parts of the Australian crust are unusually enriched in heat producing elements [29-30] thereby providing a significant stimuli for the emerging geothermal energy sector (see section D6). This theme will continue this line of research connecting the evolving thermal structure of the Australian lithosphere and its tectonic evolution, using methodologies as elaborated in detail in a number of recent publications [4,29-30]. It will instigate a program of new heat flow measurement and generate a new continental-scale thermal model. In addition to providing crucial tests of tectonic feedback, the new thermal model will form a prime input for theme 2 and will help guide exploration strategies in the emerging geothermal industry sector. The work will build on existing ARC funded programs (ARC grants DP0209157 and F10020050) designed to elucidate the role of tectonic feedback processes in shaping the Australian crust [29-30] with anticipated funding for further work through the ARC Centre of Excellence program (CEDy - application pending). The funding for the acquisition of new heat flow data will be sought through the ARC linkage scheme in collaboration with industry (Scopenergy), government (Primary Industries and Resources South Australia, Australian Greenhouse Office) and academic (Dr G. Beardsmore, Monash University) partners.

An important overlay connecting the themes relates to the evolution of the Australian landscape and its unique archive of global change [31]. Australia is often viewed as the archetypal ancient continent, with its geological architecture established hundreds of millions of years ago. The low relief imbues an apparently timeless nature to the landscape, contributing to the view of an ancient continent little changed in form since Australia separated from Gondwana almost 100 million years ago. Wittingly or unwittingly, much of the geomorphic literature has emphasized the antiquity of Australian landscapes concentrating on the recognition of surface elements that are many 10's if not 100's of million of years old [32] while ignoring the evidence of more youthful activity that signal both climate change [31] and neotectonic activity [1]. For example, Australia has an extraordinary record of surface-breaking fault ruptures [33]. In the most dramatic evidence for fault-related landscaping, the Murray River was diverted some 50 km by a ~8 m throw on the Cadell Fault around 50,000 years ago [22]. More spectacularly, about 3 million years ago ~130 m of tectonic uplift in western Victorian appears to have defeated the ancestral Murray River, leading to a major reorganization of the Australia's largest river system[6]. Australia is implicated in driving long-term global climate change, with its northward drift restricting the oceanic circulation between the Pacific and Indian Oceans leading to a drying of the surrounding continents [3] and thereby providing an intriguing link between Australian tectonics and the emergence of *Homo sapiens*. Australia's low relief landscapes provide an extraordinary archive of long-term global change, particularly the onset of aridity in the last few million years [31]. Long-term disequilibrium related to this drying is clearly evident in many of the landscapes of our arid interior [31]. Since many of these landform systems also testify to the ongoing faulting record over the last few million years [1], they provide an important new avenue to resolving long-standing questions of relative impacts of climate change and tectonics in landform change. Through application of quantitative analysis of landscaping events (continental-scale relief, drainage organization and sediment production) this proposal will therefore yield a entirely new set of data relevant to the role played by both tectonics and climate change in landscape evolution, providing a new and deeper understanding of the evolution of our distinctive Australian landscapes and our place in them.

D6 National benefit

The primary objective of this research relates to questions of continental geodynamics, the coupling between the forces responsible for plate motion and the geological response of the continental crust and its impacts on landscape evolution at the continental scale. The proposal seeks to build a unique research capability by assembling a team of young scientists with a world-class analytical and modelling capacity provided by parallel developments of the ACcESS MNRF and the MUSES analytical laboratories. A primary national benefit of this proposal is therefore in terms of the ARC's core objective of generating fundamental knowledge. In addition, this project will contribute to the ARC Priority area of "deep earth resources" in three fundamental ways:

1. Geothermal energy resources are ultimately related to anomalous concentrations of heat producing elements beneath insulating sedimentary basins. Future exploration for geothermal energy will require a more thorough understanding of the thermal structure of the Australian crust (Theme 3).
2. Understanding the nature and evolution of the stress field (Theme 2) aids in the evaluation of hydrocarbon resource potential.
3. Understanding the nature of past tectonic processes (Theme 3) is key to defining appropriate mineral exploration strategies within Australia's ancient geological terranes.

Evidence of the national benefit of my work is demonstrated with the extraordinary private sector interest in the geothermal energy resources associated with the South Australian heat flow anomaly, first identified by my group [29] under the auspices of ARC discovery grants (A39943129, F10020050). The recognition of this anomaly provided a prime scientific impetus for the successful float of Petratherm on the Australian Stock exchange (ASX) in June 2004. Similarly, my research on the thermal structure of the South Australian crust provides the scientific framework that underpins Scopenergy's (a NSW-based geothermal energy consortium with interests in South Australia) preparation for an ASX float in early 2005. Constraints on the evolution of the stress field will have important implications for petroleum resource exploration. For example, the integrity in fault-related oil-traps can be severely compromised by reorientation of the tectonic stress field through time. Characterization of the evolution of the stress field in relation to the existing fault geometries therefore provides an important *a priori* constraint on risk in 'green-fields' exploration.

To the extent that the proposal will contribute fundamental new insights into Australian seismic risk assessment (Theme 1) and landscape evolution (Themes 1 & 2), it will yield both social and economic benefit. For example the comparatively mild Newcastle earthquake (M5.6) resulted in 13 lives lost, $1 billion insured loss and an estimated $4 billion total damage. Quakes with magnitude greater than the Newcastle quake occur every 1-2 years in Australia, while M > 7 events (which release ~50 times the energy of the Newcastle quake) are expected every ~20-30 years. Thankfully most potentially damaging earthquakes (M > 5.5) recorded thus far have been located in remote regions, yet we have little understanding of just how indicative this is in terms of the longer-term distribution of such potentially catastrophic earthquakes. As a consequence of this uncertainty, earthquake risk currently accounts for about half of the annual ~$1 billion reinsurance bill paid by Australia to global reinsurance corporations [Dr G. Walker, EonRe, 2003]. Improvements in our understanding of the earthquake hazard will be essential if we are to reduce this recurrent drain of monies. While the objectives of this project are clearly focussed on the tectonic imprints in the Australian landscape, any attempt to delineate and constrain landscaping events over the last few million years must contribute to our understanding of the role of long-term climate change, since the dynamics of surface processes over this timescale are so strongly controlled by climate variability. We Australians are rightly concerned with our changing natural landscapes, believing that our impacts are producing change at rates hitherto rarely witnessed in the geological record. In order to understand our place in the landscape and our impacts on it, it is essential to have a thorough understanding of how the landscape has evolved. While many elements of our landscape are ancient, there is clear evidence of tectonic influences at the continental scale seriously compromising the efficiency of our major fluvial systems. The proposed defeat of the ancestral Murray River some 3 million years ago[5] and consequent damming of a major continental drainage by an uplift of ~130 m implies an extraordinarily susceptible natural system. In as much as this project provides the first comprehensive analysis of neotectonic landform evolution at the scale of the continent, it will contribute towards the understanding of our landscapes and our place in them. One important outcome of this project, related to the quantification of landscaping events, will be a more robust dataset for evaluating the imprints of long-term climate change in our landscape and the nature of our landscape response to climate change. Finally this proposal will enhance Australia's standing in the region by contributing to the knowledge base of Timor Leste, one of our nearest and poorest neighbours, thereby helping it in its search for a resource base that can provide a chance of economic independence.

D7 Communication of results

My publications testify to an outstanding record of new conceptual work in the leading Earth science forums (*Earth and Planetary Science Letters*, *Geology*), as well as in the more focussed, leading specialist journals (*Tectonics*, *Basin Research*, *Tectonophysics* and *Journal of Metamorphic Geology* - see section B9.3). At the same time I have published extensive, basic geological data relevant to the evolution of the Australian continent in forums (*Australian Journal of Earth Science*) appropriate to national user groups (exploration sector, government agencies etc). The results of this project will continue to be presented in these high impact journals, as well as at international conferences and in forums relevant to Australian interests. With my recent appointment as Editor-in-chief of *Tectonophysics*, the pre-eminent international journal in the field, I am in the ideal position to initiate volumes focussed on the specific questions to be tackled in this proposal. My strong informal links with the *pmd**CRC, including occasional involvement with their science review panel, will facilitate rapid take-up of relevant results by Australian mineral exploration groups (*pmd**CRC is a cooperative research centre based in the University of Melbourne whose mission is to define new predictive mineral exploration strategies). In recent years I have given numerous public lectures and radio interviews aimed at articulating the benefits of my research for the lay audience (see section B9.5). This focus will continue with the long-term plan to produce a documentary on the "*making of the Australian continent*" in which the results of the research to be undertaken as part of this proposal will be explained in terms of the Australian landscape.

Notes: summary of relevant ARC-supported work currently in press

[1] While the faulting record is the most obvious signal of neotectonic activity [1], a distinct deformation mode involving gentle buckling is evident in the landscape pattern of South Australia involving upland systems (Flinders Ranges) surrounded by unusually depressed topography now occupied by salt lakes (eg., Lake Eyre). [Celerier, J., Sandiford, M., Hansen, D.L., Quigley, M., Modes of active intraplate deformation, Flinders Ranges, Australia, *Tectonics,* submitted] suggest this reflects a lithospheric buckling, similar to the buckling of the central Indian Ocean over the last 5-10 million years [24-25] that has been related to changes in plate boundary forcing associated with the rise of the Tibetan plateau [26].

[2] A candidate for Australia's largest earthquake sequence in the recent past is the Cadell Fault, where an ~ 8 m displacement along a 60 km fault trace was sufficient to divert the Murray River about 50,000 years ago [22]. While the rupture sequence is essentially unknown, a rupture of this dimension implies an energy release equivalent to ~200 Newcastle quakes or ~M7.5. [Clark, D., Cupper, M., Sandiford, M., Kiernan, K., Style and timing of late Quaternary faulting on the Lake Edgar Fault, southwest Tasmania, Australia, *Geological Society of America, Special Publication*, in press] show that Lake Edgar Fault, Tasmania, records a rupture sequence of 3 ~ M7 events over the last 60,000 years.

[3] [Sandiford, M., Coblentz, D., Schellart, W.P., Evaluating slab-plate coupling in the Indo-Australian plate, *Geology*, in press] show how earthquake mechanisms in the central Indian Ocean provide a profound constraint on the extent of slab-plate coupling, with the effective pull of slabs on the modern-day plate no more than 10% of the density defect driving slab descent.

[4] [Sandiford, M., McLaren, S., Thermo-mechanical controls on heat production distributions and the long-term evolution of the continents, In (eds, Brown, M. & Rushmer, T.) *Evolution and differentiation of the continental crust,* in press] show that the notion of tectonic feedback makes important testable predictions about the distribution of heat sources, namely (a) an inverse correlation between the total abundance of heat producing elements and the characteristic vertical length-scale of heat production, and (b) horizontal variability in heat production distributions should have a characteristic length-scale comparable to the thickness of the crust. The available heat flow data from Australia suggest that Archeaen terranes are characterized by much smaller vertical length-scales than younger terranes [Bodorkos, S., Sandiford, M., Thermal and mechanical controls on Archaean crustal deformation: examples from Western Australia, (ed) Benn, K, *AGU Monograph*. submitted], in keeping with their relatively high heat production character at the time of formation. However, the available heat flow data are far from compelling and more extensive data are needed to test the hypothesis. Moreover, there are currently no data of sufficient quality to evaluate horizontal length-scales.

[5] [Sandiford, M., McLaren, S., Thermo-mechanical controls on heat production distributions and the long-term evolution of the continents, In (eds, Brown, M. & Rushmer, T.) *Evolution and differentiation of the continental crust*, in press] postulate that the notion of tectonic feedback is compatible with the thermo-mechanical properties of the lithosphere being attracted to a quasi-deformable state, through the modification of heat producing element distributions during repeated tectonism.

[6] The Murray-Darling system, the major drainage system in the continent, potentially demonstrates a spectacular example of neotectonic derangement. Ongoing unpublished research in collaboration with Dr Malcolm Wallace, to be further investigated in this proposal, suggests that until ~ 3 million years it drained through western Victorian. This ancestral river was defeated by mild uplift of the western Victorian highlands [Wallace, M., Dickinson, J.A., Moore, D., Sandiford, M., Late Neogene strandlines of Southern Victoria: A unique record of eustasy and tectonics in southeast Australia, *Australian Journal of Earth Sciences*, in press] creating the huge inland that eventually drained around 800,000 years ago, thereby establishing the course of the modern lower Murray River.

D8 References

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