E1. Neotectonics of the Indo-Australian plate

E2. Aims and background

While continents are made and destroyed by plate boundary interactions, the distribution of earthquakes in stable continental regions (SCRs) such as Australia (Fig. 1a[1]) suggests continents continue to be shaped, episodically, by mild tectonic activity in intraplate settings. A clue as to the magnitude of this activity is provided by strain rate estimates derived from the seismic moment release of SCRs. Seismogenic strain rate estimates for Australia are of order 10^{-17} s^{-1} ([1], Fig. 1b), implying, for the *in situ* stress regime, the continent is currently shortening at a rate of about 1 km/per million years. If such strain rates are representative of the long-term (ie., 10^7-10^8 years), then the resulting strains should leave indelible imprints in the structural architecture of continental interiors. One indicator of the importance of intraplate tectonics is provided by the low-temperature thermochronologic record of continental interiors [3]; a record that demands episodes of significant denudation hundred of millions to billions of years after crust formation. Despite this thermochronologic record, we still have little understanding of the nature of intraplate processes and the role they play in shaping the continental crust, or how these processes relate to dynamics at the plate-scale. The **primary aim** of this project is to establish the links between the plate scale-dynamics and the geological record of intraplate tectonic activity, using the Indo-Australian plate (IAP) as the natural laboratory. The primary emphasis is on the Australian continental record, particularly its topographic response to changes in plate-scale forcing due to plate-boundary interactions and from the convective mantle beneath. As the fastest moving continent, embedded in a plate that has experienced a complex evolution in its plate-boundary interactions, Australia is uniquely suited to this purpose. The project will also make comparative assessment with SCRs in other continents through collaboration with international partners.

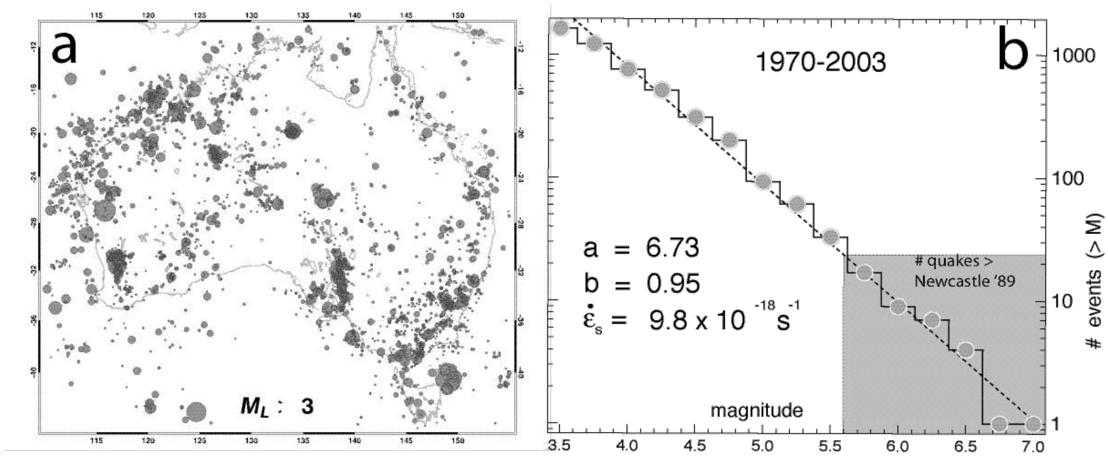

Figure 1: (a) Distribution of M_w >3 Australian earthquakes. (b) Gutenberg-Richter statistics for Australian earthquakes (1970-2003) which yield a notional seismogenic strain rate of ~10^{-17} s^{-1} for the continent as a whole [1]. Note that earthquakes M > Newcastle '89 are expected every 1-2 years. While M6.5+ quakes are expected every 15 years or so.

Australia is 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 [4], ignoring the evidence for youthful activity that signal both climate change [5] and neotectonic activity [6]. For example, Australia has an extraordinary record of surface-breaking fault ruptures (with 5

[1] High resolution versions of images are available at http://jaeger.earthsci.unimelb.edu.au/Others/arc/DP0556133.html

historic and 7 prehistoric examples now documented). In the most dramatic evidence for fault-related landscaping, the Murray River was diverted some 50 km by a ~8m throw on the Cadell Fault around 50,000 years ago [7]. More spectacularly, about 3 million years ago ~130 m uplift of the western Victorian upland systems may have been enough to defeat the ancestral Murray River, leading to a major reorganisation of the Australia's largest river system [see additional material **section E4**]. A **secondary aim** of this project is to reassess the role played by young tectonic activity in shaping the Australian landscape, with an emphasis on continental-scale relief and drainage organization.

The project is structured around four broad themes, each with specific aims as summarised below.

1. The neotectonic intraplate record of the IAP: Until recently there has been little understanding that the historical pattern of Australian seismicity (Fig. 1) is reflected in the geological record of young (neo) tectonic deformation (indeed few Australian geologists have been aware that there is a neotectonic record!). However, in a series of recent papers, the CI has shown that in southeast Australia there is a profound, ongoing record of neotectonic activity consistent with the historical seismicity ([6,8], see also review in *New Scientist*, June 7th, 2003, p. 17). For example, as much as half of the present-day relief in the southern upland systems (eg., Flinders, Otway Ranges) can be attributed to Quaternary and Pliocene faulting. Available chronological data suggest range-bounding faults have been slipping at ~ 50 metres per million years, for the last ~5 million years, at rates compatible with seismogenic strain rates (Fig. 3) and with a movement pattern consistent with the *in situ* stress field [9]. While the Quaternary faulting record is the most obvious signal of neotectonic activity, a distinct deformation mode involving intermediate-wavelength (order 10^2 kms) buckling is evident in the landscape pattern of South Australia involving upland systems (Flinders Ranges) surrounded by unusually depressed topography now occupied by playa lake systems (eg., Lake Eyre, Frome, Torrens). The topographic wavelength suggests a lithosphere buckling, similar to the buckling of the central Indian Ocean over the last 5-10 million years [10] that has been related to an increase in stress transmitted to the interior of the plate from changes in plate boundaries [11]. The aims of this theme are: **[a]** to extend our knowledge of the neotectonic deformation field to the whole continent, including an assessment of the various modes of deformation, and **[b]** to provide new quantitative constraints on neotectonic deformation rates.

2. Comparative evaluation of neotectonic and seismotectonic deformation fields in the IAP: Only ~ 5% of the seismic energy release of the earth occurs within the interior of tectonic plates, and within SCRs, such as Australia and the Indian sub-continent, the total moment release is about 0.5% of the total [1]. Nevertheless, potentially catastrophic earthquakes do occur in SCRs, as evident by the 1818 New Madrid (USA) sequence of ~M7-8 earthquakes, the 2001 Bhuj (India) M7.7 earthquake (~20,000 deaths, 600,000 homeless) and, closer to home, the 1989 Newcastle M5.6 quake (13 deaths, > $1 billion damage). The long-term pattern of SCR seismicity is poorly understood, because the recurrence interval of the largest quakes (typically ~ 10^3-10^4 years) means that historical records (especially in Australia) are incomplete [1,2]. In particular, potentially damaging earthquakes in SCRs occur with such low frequency that they are extremely problematic for risk assessment. One approach to help alleviate this problem is to incorporate longer-term records of the seismic moment derived from geological observations, such as the neotectonic deformation field. The aim of this theme is to make a comparative evaluation of the historical seismic moment release rate in relation to the neotectonic-deduced strain rates for each of the main seismically active zones in Australia (Figure 1a).

3.The dynamic topographic field of the IAP : A fundamental ongoing controversy in geodynamics relates to the Earth's dynamic topography [12, 13], the topography associated with the vertical deflections of the earth's surface 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 [14]. Numerical simulations consistently overestimate the amplitude of dynamic topography [12], while geological observations relating to the dynamic topographic signal remain contentious [12, 13]. For example, whereas Lithgow-

Bertollini & Gurnis [12] predict a dynamic topographic subsidence of SE Asia of several hundred metres over the Cainozoic, Wheeler & White [13] find no compelling evidence for dynamic topography in this region. Intriguingly, while not explicitly mentioned by Lithgow-Bertollini & Gurnis [12], their modelling as shown in their figure 1B predicts that Australia should have tilted north side down by several hundred meters over the Cainozoic. Verification of such a tilting (or otherwise) would provide a powerful independent test of dynamic topography and mantle viscosity structure.

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 [15]. 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^{-1}), transiting one of the largest geoid anomalies on the planet (~70 m), 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 unrecognised 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 (Fig. 2). Such evidence would appear to provide strong confirmation of the models of [12]. However, we know little in detail of the timing of tilting and its relation to Australia's northern motion. The aim of this theme is to define the continental-scale, planform and timing of the tilting associated with Australia's Cainozoic northward motion, and relate it to dynamics of the convective mantle beneath. A particular focus will be the dynamic response of the southern margin during its drift across the mantle now located beneath the Australian-Antarctic discordance (AAD).

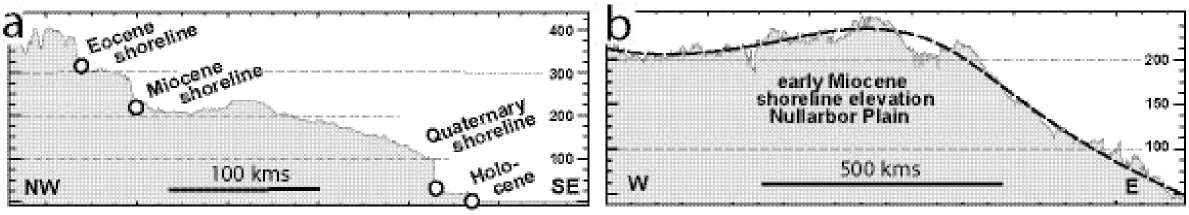

Figure 2. The Nullarbor Plain on Australia's southern margin has the most extensive onshore Cainozoic carbonate platforms known, with well-preserved palaeo-shorelines that constrain Australia's evolving dynamic topographic field. (2a) In the western Nullarbor Eocene (~43 Ma) and Oligocene-Mid Miocene (>15 Ma) shorelines occur at elevations up to 300m and 220m, respectively. (2b) Along strike, palaeo-shoreline elevations vary byf more than 150m (2b) implicating a dynamic topographic signal, as does the more or less complete absence of an onshore marine Cainozoic record along the northern margin of the continent. Topographic profiles derived from the preliminary (30 arcsecond) SRTM data release.

<u>*4.The evolution of the IAP stress field:*</u> The tectonic stress field inferred from earthquake fault mechanisms and other *in situ* stress indicators in the IAP forms an organised pattern that can be 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 [17-19], with a second order control provided by lateral variations in the rheological structure of the lithosphere [20]. Changes in the plate-boundary forcing, particularly those associated with the development of collisional orogens around the IAP 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 [10], leading to the progressive fragmentation of the plate [21], which has been related to a response of the intraplate stress pattern to the rise of the Tibetan plateau [11]. 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 from New Zealand to Macquarie Island (Fig. 3, [9,22]). To date, there has been no attempt to model the

way in which the intraplate stress field may have evolved in response to the evolving boundary conditions, or how that evolution is reflected in intraplate tectonics at the plate scale. One question is whether the intraplate deformation fields respond to changes in the plate-boundary forcing by a smooth transition from one steady creeping regime to another (as would be expected in a viscous medium) or by a phase of accelerated deformation as might be expected during the readjustment of a set of interlocking faults that readjust from one 'stable' state to another (as would be expected for a geometrically-limited, fault-controlled rheology). Another question relates to the factors responsible for localisation of the intraplate deformation as evident in both the pattern of seismicity (Fig. 1a) and the distribution of Quaternary faulting [6]. In particular, the distribution of Australian seismicity shows prominent peaks 50-200 kms inboard of continental margins with high resolved compressive stress [19], suggesting the important rheological influence of the ocean-continent transition.

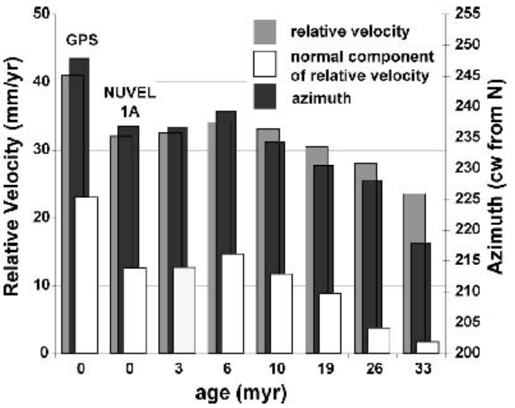

Figure 3, Synopsis of the velocity of the Pacific plate relative to the Australian plate at a location (165°E, 48°S) presently at the southern tip of the South Island of New Zealand. Rotation pole data derived from [22]. An increased coupling between the Pacific and Australian plates during the Neogene has been suggested as being responsible for the unusual NW-SE pattern compression in southeast Australia, as argued in [9]. The crucial test of this hypothesis is in the Neogene tectonic deformation field of southeast Australia.

The aim of this theme is to numerically evaluate the response of the Australian continent to evolving boundary plate boundary conditions associated with the Himalayan, New Zealand, New Guinea and Timor collisions, including an assessment of the controls on the spatial and temporal variation in the neotectonic deformation field in the Australian continent, and the way it responds to distant boundary forcing.

E3. Significance and Innovation

Three aspects of *significance* motivate this research, appropriate to the ARC Discovery support for fundamental research:

1. Understanding the geodynamics of our planet: One of the central concerns of geodynamics is the dynamics of plate motions. In a recent review, Lithgow-Bertollini & Richards[23] concluded that "*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 derived from the stratigraphic record of sea level change*". The significance of this project lies in its contribution towards this agenda. The central aims of the project focus on the intraplate stress and strain record, as well as the dynamic topographic record, of the Australian continent in the context of the dynamics of the Indo-Australian plate. As the fastest-moving continent, within a plate with a complex evolution of its boundary conditions and which has moved across a complexly structured mantle (evident in the long-wavelength geoid field and in the unusual sea-floor bathymetry associated with the AAD), Australia contains a unique, hitherto largely unexplored record covering the last 45 million years. This unique record from the fastest continent has the potential to contribute significantly to **understanding of plate motion dynamics**.

2. Understanding earthquake risk in stable continental regions such as Australia: The '89 Newcastle earthquake was only comparatively mild at M5.6, yet resulted in excess of A$1 billion damage and 13 lost lives. We expect earthquakes of this magnitude, or higher, every 1-2 years (Fig.

1b). So far, most have been in remote areas, yet we do not understand why. A M6.5+ earthquake beneath a major city such as Sydney or Melbourne represents a $20 billion dollar insurance risk and it is pertinent to ask whether such an earthquake is a credible possibility (quakes of this magnitude occurs every 15 years or so across the country (Fig. 1b), but all so far have been in remote areas). Over half of Australia's annual ~$800 million reinsurance bill (paid to global reinsurance corporations) can be related to earthquake risk [Dr George Walker, EonRe, pers. comm., 2003], reflecting uncertainties in our understanding of earthquake risk. In as much as this project will contribute new observations and analysis pertinent to Australian seismotectonics, it has the potential to contribute significantly to improved **earthquake risk assessment in Australia**.

3. Understanding our landscape and our place in it: 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. In consort with climate change, and low relief landscape, tectonic derangement of drainages over the last few millions of years appears to have seriously compromised the efficiency of our major fluvial systems in the Murray-Darling Basin (see additional material **section E4**). The proposed defeat of the ancestral Murray River some 3 million years ago and consequent damming of a major continental drainage by an uplift of no more than 100-200 m implies an extraordinarily susceptible natural system, prior to the onset of human impact. 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**.

Several unique aspects of the Australian continent make this project innovative. Australia is the fastest moving of all continents, embedded in a plate that has shown the most dramatic changes in plate boundary evolution over the last 50 million years ago, including the amalgamation with the Indian plate, development of the largest continental collision system in the Himalaya, and comparatively recent collisions in New Guinea, Timor and New Zealand. As the flattest of all continents, located in a sub-tropical high pressure belt characterised by an arid climate, it has extremely inefficient fluvial surface processing reflected in extremely low denudation rates [24] These factors mean that very small surface tectonic displacements, associated with the mild neotectonic activity can be resolved, potentially allowing the development of new approaches to the tectonic geomorphology of SCRs. The resolution of these subtle features in both time and space is being aided by technological advances on two fronts. Firstly, the advent of the SRTM elevation data, and new satellite imaging technologies (eg., the ASTER sensor), provides an hitherto unrivalled opportunity to map subtle landform modification at spatial resolutions down to as little as 15 m. In particular the SRTM mission has increased our knowledge of the topography of the planet by several orders of magnitudes. This Australian SRTM 1 arcsecond data is scheduled for release during 2004, and this project will be one of the first to utilise these data. Finally, the last decade has seen dramatic advances in our ability to quantify the age of landform events, through the development of a new arsenal of chronological techniques including optically-stimulated luminescence (OSL) and cosmogenic radionuclide (CRN), and new applications of U-Th disequilibrium dating of pedogenic carbonate [35-36].

E4. Approach

The research will involve field-based observations, and geochronological and numerical analysis, designed to provide a comprehensive overview of Australian neotectonic evolution. The approaches to be adopted are described below against each of the 4 themes listed in section E1. Research on each of these themes will be carried out in parallel over the five years of the program.

Theme 1: The primary geological observations informing this project derive from the CI's ongoing field studies in southeastern Australia, in the Flinders Ranges and in the Southern Uplands of

Victoria [6]. These studies will be extended to other seismically active belts in Australia, including (1) the Eastern Highlands (where a number of Quaternary faults were revealed during construction of the hydroelectric schemes in 1960's), (2) the southwest seismic zone of WA, which contrasts with the Flinders seismic zone in that there is no distinctive pattern of relief coinciding with the historical seismicity, (3) the northwest seismic zone, including the Cape Range (where fault bound Miocene marine sequences are reported at elevations of 250 m ASL [16]). The objective of these studies will be to identify the movement history on neotectonic structures, and their role in relief generation. Field observations will be used to evaluate palaeo-stress states and displacements, and to target samples amenable to geochronological analysis that constrain neotectonic deformation rates.

The notion that the Eyre Basin represents a lithospheric buckling phenomenon will be tested by reconstructing palaeo-topography using palaeo-current data from the extensive fluvial Palaeogene (eg., Eyre Formation) and Neogene sedimentary successions exposed throughout these basins, and by reconstructing the location of basin depocentres through time [25]. Of particular interest is the indication that the Lake Frome depocentre has migrated some 20 kms or so closer to the Flinders Ranges in the last ~1 million years [25]. If the location of the depocentres is stress controlled, then such a migration could logically only be explained in terms of an increase in the in-plane stress, or a progressive change in the effective elastic thickness of the lithosphere. A succession of more than 10 stranded Quaternary beach ridges provide an ideal opportunity to date this depocentre migration with the OSL method.

Unlike plate boundary zones or sones of diffuse continental deformation, the internal deformation in SCRs are not currently detectable by GPS geodetic methods [38], and thus it not currently possible to validate numerical models of neotectonic deformation against geodetic velocity fields, as has been successfully applied in more active parts of the world, to derive quantitative constraints of fault strength and seismogenic coupling [eg, 39]. Rather the challenge in SCR neotectonic studies is to deduce quantitative constraints on the deformation field from geological observations. Quantitative assessment of slip rates will be undertaken using OSL, CRN and U-Th analysis of fault-related sediments and associated geomorphic surfaces. OSL, U-Th analyses and CRN-target will be carried out at the University of Melbourne. The principal focus of this work will be on fault systems, and associated alluvial fan sequences, bounding the Flinders Ranges. The Flinders Ranges alluvial fans include significant late Quaternary deposition, but available age dating based on ^{14}C [26] is only appropriate to the youngest stages of fan building. In places, dissected fan sequences almost certainly extend into the Pliocene, beyond the range of OSL or U-Th techniques, and CRN chronology will be used to constrain the chronology of these older sequences. Promising new applications of U-Th dating of pedogenic carbonate rinds on pebbles in the alluvial fans sequences [35] will provide key new data. The U-Th technique in use at the University of Melbourne is currently able to date samples containing as little as 200 pg U, about four orders of magnitude less than required by alpha spectrometric techniques, and two orders of magnitude less than commonly used by other labs [36]. The Flinders Ranges fan sequences are particularly appropriate to this technique because of the very variable radioelement concentrations in the basement lithologies [37].

In as much as the primary aim of this project is to relate the intraplate neotectonic response of the IAP to plate boundary forcing, it is imperative to have a good understanding of the evolution of plate boundaries. To a large extent this study will rely on independent analysis of the evolution of the plate-boundary forcing (eg., [27] for New Guinea, [28-29] for New Zealand). One of the poorest known and potentially most interesting changes in plate boundary configuration impacting on the intraplate stress field has been the development of the Timor collision in the last ~ 10 million years [30]. The Timor collision has developed as a result of impingement of the leading edge of the Australian continent in the Banda Arc, and is progressively blocking an already established subduction zone. This can be contrasted with the orogenic process in the New Zealand Southern Alps which have grown over a similar time frame in response to increased convergence between the

Pacific and Australian plates (Fig. 3), leading to subduction initiation along the Puysegur trench [31]. In detail, little is known of the timing and kinematics of the Timor collision, largely because of restricted access from 1975-2002. In collaboration with Dr Myra Keep of UWA, the CI has already initiated a research program designed to improve our understanding of Timor tectonics, with the CI starting a PhD student project on Timor neotectonics commencing in 2004.

Comparative assessment with SCRs from other continents will be facilitated by international collaboration with European partners (Prof Soren Nielsen and Dr David Hansen of University of Aarhus, Denmark) and USA (Prof. Steven Marshak, University of Illinois).

Theme 2 : Seismogenic strain rate estimates can be estimated from the moment release rate in a given crustal volume [32], by summing all events over a time-interval obtained by extrapolating earthquake recurrence rates to an estimated maximum likely event interval (Fig. 4). Of course, estimates of seismic strain derived in this way are subject to numerous uncertainties. For example, the thickness of the seismogenic crust, the statistically low number of events used to derive long-term recurrence relations, and the fact that aftershocks may relax strain accumulated during earlier main-sequence events. However, the main uncertainty lies in the estimate of the maximum likely event (M_{max}) since the great majority of the seismic moment is carried by the largest few events. The most likely candidate for Australia's largest earthquake sequence is the Cadell Fault [7], where an ~ 8 m displacement along a 60 km fault trace was sufficient to divert the Murray River some 50,000 years ago. While the rupture sequence is essentially unknown, a single rupture event would suggest a magnitude close to M_w 7.5. In collaboration with Dr Dan Clark, Gesoscience Australia, this fault will be trenched in 2004, and samples collected for a detailed OSL and U-Th dating campaign designed to determine its rupture sequence from fault-related deposits. The established chronology will help constrain the maximum likely magnitude of Australian earthquakes. Reprocessing of the Australian earthquake database to estimate characteristic recurrence times of M_{max} events, will be carried out on a regional basis, with deduced seismogenic strain rates compared with the neotectonic deformation rates elucidated in theme 1. Data reprocessing will be conducted in collaboration with Dr Mark Leonard at Geoscience Australia, who will incorporate the results into ongoing seismic hazard assessment.

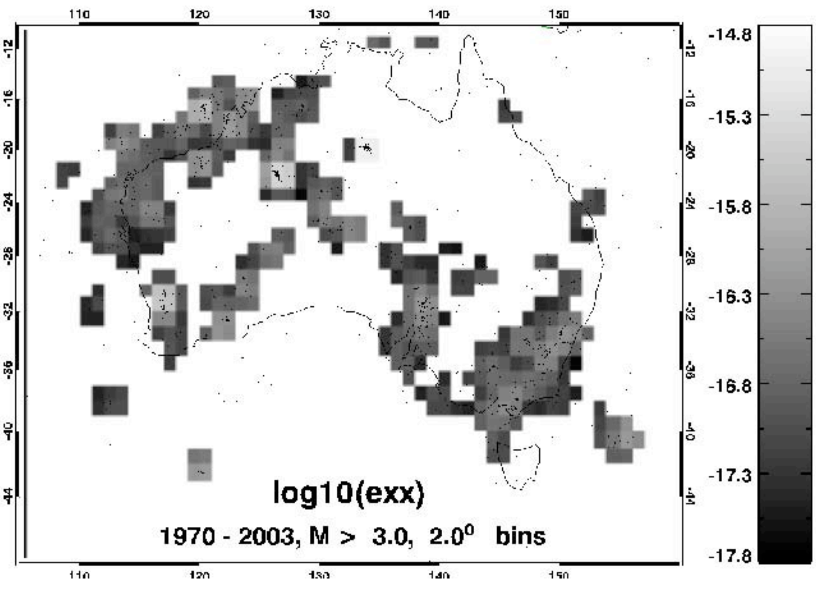

Figure 4. Calculated seismogenic strain rates based on the 1970-2003 Geoscience Australia earthquake database (M>3) assuming a seismogenic zone some 25 km thick and a maximum moment magnitude of M_w= 7. Unshaded regions have seismogenic strain rates of less than 10^{-18} s^{-1}. Strain rates in log10 (s^{-1}).

A unique opportunity to evaluate Australia's background seismic moment release rate is provided by the Nullarbor Plain. The Nullarbor Plain is an Eocene to Early Miocene carbonate platform, the surface of which has essentially remained intact since deposition stopped around 15 million years ago. Numerous small (< 10 m) fault scarps displacing this surface are clearly evident in the preliminary SRTM digital elevation data, preserved by virtue of a near complete absence of fluvial activity on the carbonate platform. The extraordinary preservation of these scarps allows the reconstruction of a ~15 million year seismic moment record, which can be used constrain the background seismogenic strain rate for one of the more seismically inactive parts of the continent.

Theme 3: As evidenced in Fig. 2, the southern margin includes an extraordinary record of palaeo-shoreline record extending from the inception of fast sea-floor spreading in the Southern Ocean at around 43 Ma (when Australia was some 3000 km further south). The anomalous topographic evolution of the southern margin, involving extensive flooding followed by long-wavelength uplift, reflects Australia's northward drift across the anomalous mantle now located beneath the AAD - a region with one of the most significant residual bathymetric anomalies known. Simultaneously, the complete absence of any onshore marine from the northern margin of the continent implies a north-down tilting exceeds the long-term Cainozoic lowering of sea level (order 100 m). 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. Palaeo-shoreline elevations will be constrained by the onshore shore-face facies (ie. strandlines and coastal barrier systems [8]) that are spectacularly preserved along much of the southern margin (Fig. 2), and offshore seismic records to identify buried-barrier systems along the northern margin [33].

The maps of differential vertical motion will provide a first-order constraint on mantle numerical models of convection incorporating Australia's northward plate motion. The SNARK modelling software being developed by ACcESS MNRF will be used to identify the coupling between lithosphere and mantle convection. The convection models will be coupled to a surface process model being developed by the CI as part of the ACcESS consortium, to explore drainage response to generation of dynamic topography on the low-relief Australian continental surface.

Theme 4**:** Our understanding of lithospheric dynamics have 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., 34]. The objectives of theme 4 will utilise plate scale numerical modelling strategies designed to (1) explore how changes in plate boundary forcing impact on the intraplate stress field using both elastic and thin viscous sheet models of lithospheric rheology, and (2) isolate intrinsic properties of the lithosphere that contribute to localised failure in response to regional stress field using elasto-plasto-viscous rheological models. Important strain compatibility requirements must limit the extent of intraplate deformation in a continent surrounded by stiff, essentially undeformable, oceanic "matrix". These limitations relax once a continent engages with a "freely-deformable" plate-boundary, as Australia did in the Noegene (eg [27]). The capacity for ongoing deformation of the Australian continent may therefore be controlled by the plate-scale geography, in addition to the intraplate stress field. This hypothesis has important ramifications for other modes of continental deformation including rift-related fragmentation of continents such as Africa. One of the objectives of the modelling will be to explore the role played by the evolving palaeogeography of the IAP in allowing intraplate deformation to accumulate. Numerical modelling methods will be developed in conjunction with Drs David Hansen (University of Aarhus, Denmark), David Coblentz (Los Alamos National Labs, New Mexico), and jean Braun (ANU) all of whom have had ongoing association with the CI related to this project, and who have considerable expertise in implementing numerical models of lithospheric deformation.

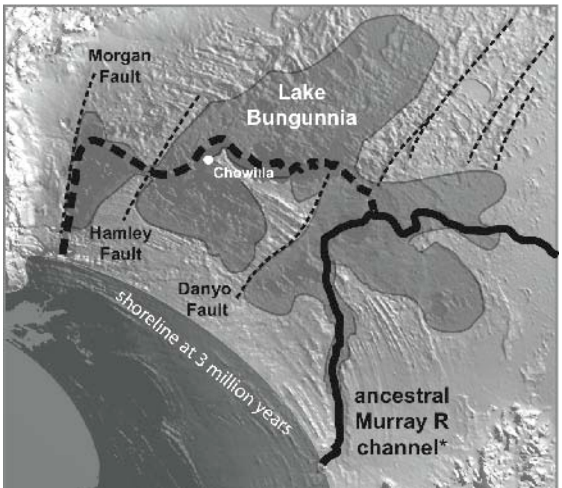

Figure 5. The Pliocene defeat of the Murray hypothesis. Imaged region is ~ 400 km in width, covering western Victoria and SE South Australia.

Final comments: Of course, ongoing tectonic deformation of a continent represents the sum of a whole range of processes, operating over an enormous range of spatial and temporal scales from the modes of mantle convection to the rupture of individual quakes. One of the objectives of the ACcESS MNRF, with which the CI is closely involved as a project leader, is to develop the software capacity to tackle such computationally complex range-of-scale phenomena. The nature of this project fits neatly into the category of "demonstrators" that can showcase ACcESS' capacity, and it is anticipated that there will strong linkages throughout this program, in terms of utilising the developing ACcESS computational resource.

Additional material relevant to this application:

The Murray Darling system is the major drainage system in the continent. Its evolution potentially demonstrates a spectacular example of neotectonic modification of Australian landforms. While the lower reaches now drain through South Australia, Malcolm Wallace at the University of Melbourne (unpublished research) has proposed that until ~ 3 million years it drained through western Victorian along a prominent, N-S trending, underfilled valley known as the Douglas Depression (Fig. 5). Mild tectonic uplift of the western Victoria highlands of ~ 130m is evident in the along strike elevation changes of the Pliocene strandline system [6,8]. Wallace proposes that this uplift defeated the ancestral Murray River and was responsible for creating the huge inland Lake Bungunnia. This lake eventually drained around 800,000 years ago, at which time the course of the modern lower Murray River was established [25]. The Neogene evolution of the Murray Basin is the subject of independent ARC Discovery application by Wallace, Sandiford and Gallagher (DP0558705).

E5. National Benefit

The primary outcomes of this research relate to understanding of geodynamics, and the coupling between the forces responsible for plate motion and the geological response of the plate interior. However, as discussed in **section E3**, it is anticipated that this project will also contribute towards understanding Australian seismic risk assessment and landscape evolution. The national benefit of this project can therefore be evaluated in light of its contribution to the social and economic repercussions of earthquakes and our understanding of our landscapes and our place in them.

This project will contribute to the ARC Priority area of "*an environmentally sustainable Australia*" with the goals of "*water- a critical resource*" and "*deep earth resources*" to the extent that (1) understanding the evolution of the Australian landscape is crucial to understanding of Australia's natural hydrology (river and groundwater systems), and (2) understanding controls on the evolution of the stress field is an essential to evaluating hydrocarbon resource potential.

Finally, 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. It is anticipated that one of the spin-offs of this project, particularly the quantification of landscaping events in and around the Flinders Ranges, will be a more robust dataset for evaluating the imprints of climatic change in our landscape, and the nature of landscape response to climate change.

E6. Communication of results

The CI has a strong record of publishing new conceptual work in high profile international journals (see **section B10**), and the results of this project will continue to be presented in these journals, as well as at international conferences. In addition, the CI is well versed in the use of the world-wide-web as a venue for distributing the results of research, especially in the fields of computational geology (see *http://jaeger.earthsci.unimelb.edu.au)*. In recent years the CI has been involved in a number of public lectures, radio and television interviews aimed at articulating his research for the lay audience. It is anticipated that this public aspect of the work will continue, with a long-term aspiration being the making of a TV documentary on the "making of the Australian continent".

E7. Description of personnel

As an ARC professorial fellow, the CI will be full-time engaged in this research program and will conduct the great proportion of the research. The CI will carry out detailed field work (in collaboration with research students) oversee sample collection, and sample analysis (in conjunction with research students), and contribute to the design of, and implement, the numerical models. Numerical modelling strategies will be developed in collaboration with Drs David Coblentz (Los Alamos National Labs), David Hansen (University of Aarhus), and Jean Braun (ANU) all of whom the CI has worked actively with in the last few years. This proposal is complementary to that of Braun, Pulford, and Cummins (DP0558817) in that both aim to better document and understand tectonic and landforming events that have recently affected the Australian continent while using different approaches and methods. We propose to coordinate field trips and CNR sampling strategies to avoid overlap and maximise data coverage. Theme 2 will involve close collaboration with Geoscience Australia seismologists (Dan Clark and Mark Leonard). Comparative studies with other SCRs will be facilitated by ongoing collaboration with Profs Soren Nielsen (University of Aarhus - neotectonics of north-western Europe), and Steven Marshak (University of Illinois- neotectonics of the Americas). A technical assistant will assist with routine sample preparation, map drafting and field assistance. Three PhD research students will be involved in this program, over its duration. One project, commenced in 2004, will focus on the neotectonics of Timor. The other two projects, for which funding is explicitly requested through this project, are (1) quantifying landscape evolution process rates in the Flinders Ranges, and (2) palaeo-seismicity and seismic risk assessment implications of Australia's largest earthquakes.

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