15. Aims, significance and expected outcomes

The thermal energy that drives metamorphism is ultimately related to the processes of heat loss from the interior of the earth. As such, metamorphism must be seen as a consequence of the conductive and advective heat transfer phenomena associated with lithospheric processes such as deformation, erosion and magma transport. Metamorphism at gradients in excess of about 40°C/km results in intermediate- to high-temperature, low-pressure metamorphism in the middle crust. The physical causes of such high geothermal gradient metamorphism (HGGM) have received considerable attention in recent years with much of the emphasis on the role of transient advective processes such as magma ascent (e.g. Lux et al., 1986; Sisson et al., 1989; DeYoreo et al., 1991; Collins & Vernon, 1991; Sandiford & Powell, 1991; Sandiford et al, 1991). In many HGGM terranes the close spatial and temporal association between metamorphism and magma emplacement clearly supports this interpretation (Sisson et al. 1989) which remains the governing paradigm (e.g., Barton & Hanson, 1989). Metamorphism governed by advective heat transfer should be characterised by dramatic lateral variations of grade and temporal transience. As shown by Sandiford et al. (1991), the inverse exponential temperature dependence of crustal strength provides a logical reason for the coupling of deformation and heating in such terranes (eg, Karlstrom & Williams 1995). In convergent orogens, such a thermo-mechanical coupling may be expected to be evidenced by “anticlockwise” PTt paths. While the notion of advection remains the principal paradigm for HGGM, several recent thermochronologic studies have raised the possibility that other mechanisms may play a significant or even dominant role. For example, Chamberlain & Bowring (1990), Hodges et al. (1994), Williams et al. (1996) and Karlstrom et al. (1997) have pointed to evidence for extended periods of HGGM, with the elevated geothermal regimes apparently lasting many 10’s of millions of years; much longer than would normally be associated with a predominant advective mode. In several Australian Proterozoic HGGM terranes with *prima facie* evidence for magmatic advection of heat (in as much as metamorphism is spatially associated with granitic batholiths), recent geochronological studies have shown that the HGGM metamorphism postdates the emplacement of the batholiths by more than 100 Ma (Conners & Page, 1995; Vry et al, 1996; Williams et al., 1996). These studies seem to preclude metamorphism being driven primarily by magmatic activity or rapid tectonic denudation (based on the retrograde P-T paths), raising the questions about the physical cause(s) of the high geothermal gradients associated with the HGGM metamorphism. A specific difficulty relating to HGGM metamorphism in the absence of magmatism, is how steep geothermal gradients are sustained in the mid-upper crust, while temperatures in the deep crust are sufficiently low to inhibit large scale melting. In the absence of advective heat transfer processes, metamorphism must represent the conductive response to burial of rocks, with the elevated geotherms associated with HGGM reflecting either unusually elevated heat production in the crust, and/or high heat flows from the mantle. The role of high mantle heat flows has been addressed by Sandiford & Powell (1986, 1991), however it is difficult to generate conductive thermal regimes appropriate to HGGM at mid-crustal levels by enhancing mantle heat flows without generating significant quantities of magma in the deeper crust, with the likely result that the advection of the generated magma would contribute to the observed HGGM signature.

The role of anomalous crustal heat production in promoting HGGM has been addressed by relatively few workers (eg, Chamberlain & Sonder, 1990; Sandiford & Hand, 1998- see Appendix 1 for abstract). Sandiford & Hand (1998) postulated that heat production distributions consistent with both modern heat flows and measured surface heat production in a number of Australian Proterozoic HGGM terranes, can generate the conditions required for HGGM in the mid-upper crust without necessarily generating significant quantities of melt in the deep crust (provided mantle heat flows are low). Sandiford & Hand’s (1998) approach was essentially parametric in as much as they did not address the geological setting in which such conditions are likely to prevail. More recently, Sandiford et al (submitted -see Appendix 1 for abstract) have developed a coupled thermal-isostatic model to show that such conditions will naturally develop as a consequence of burial of a radioactive sequence (such as a granitic basement complex) during thermal subsidence following rifting. This model makes important predictions (see Fig. 1) about the nature of the thermal regimes in the upper crust, the duration of metamorphism, and the rates of heating and cooling that are very different from that expected where metamorphism is driven by emplacement of magmas (eg. Sandiford et al, 1991). Importantly, these predictions can be tested using modern thermochronological techniques.

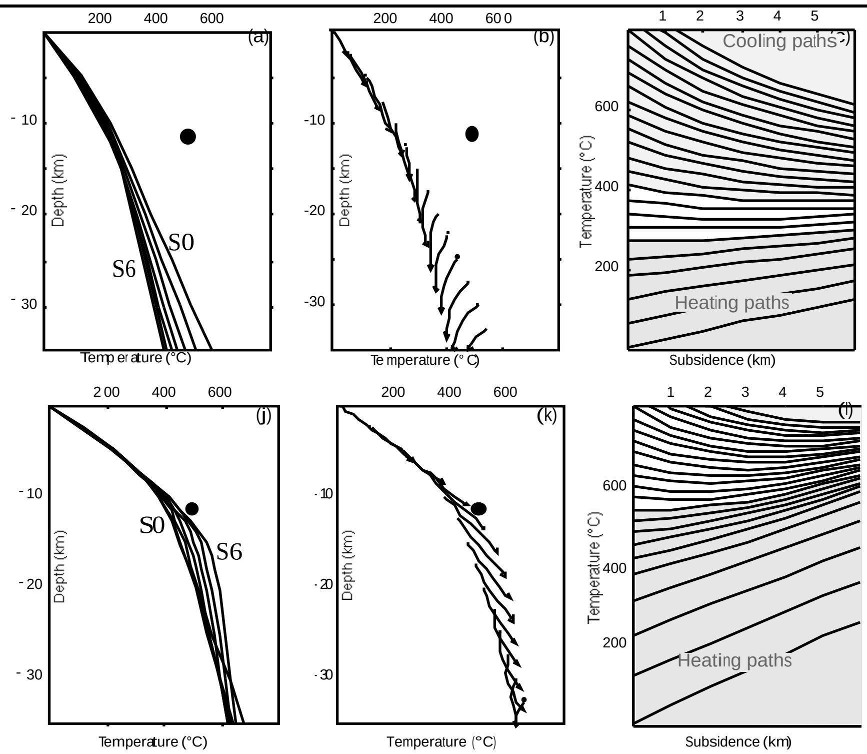

Fig 1. Thermal structure of the crust during thermal subsidence represented by a family of curves S0 (before subsidence) to S6 (6 km of subsidence). The top layer shows geotherms (left), PT paths (centre), and T-subsidence (equivalently Tt) paths (right) for a crust with normal concentrations of heat producing elements (q_c = 30 mWm^{-2}), while the bottom layer shows the effects of an anomalously radioactive basement (q_c = 90 mWm^{-2}) as appropriate to Mt Painter (see text for discussion). The dot shows estimated metamorphic conditions observed in the lowest part of the cover sequence at Mt Painter (Mildren & Sandiford, 1995).

An ideal natural experiment enabling testing of this hypothesis is provided in the Mount Painter province in the northern Flinders Ranges, South Australia. In this region an extraordinarily radioactive Meso-proterozoic basement sequence has been buried beneath a thick sequence (~10 km) in response to, firstly, rifting and then thermal subsidence during the Neoproterozoic and early Cambrian. Both basement and cover were mildly deformed (~ 20% shortening), and exhumed, during the Cambro - Ordovician Delamerian Orogeny, and the region now exposes a more or less complete upper crustal section with ~ 13 km of structural relief (Figs 2 & 3). The lower parts of the cover exhibit a spectacular style of 'unconformity related contact metamorphism', which Sandiford et al. (submitted) have shown may be explained as a consequence of burial of the radioactive basin beneath the thick sedimentary cover.

The first aim of this proposal is to test this notion by detailed evaluation of the thermal evolution of the Mount Painter sequences using thermochronology, in conjunction with conventional PT thermobarometry and structural and stratigraphic analysis. A secondary aim is to evaluate the thermal conductivity structure of the sedimentary pile at Mount Painter, and its impact on attendant thermal regimes. The thermal conductivity of sediments typically shows large changes as a function of temperature, diagenesis and, if applicable, metamorphic alteration (Brigaud & Vasseur, 1989; Lerche, 1991). Therefore, the evolving thermal conductivity structure of the sedimentary pile should be expected to exert a profound influence on the thermal structure of the deeper parts of the crust.

Finally, this proposal seeks to continue an ongoing program involving the CI and his students that is documenting the geology of the older Mesoproterozoic metamorphic record of the basement in the Mount Painter region, about which hitherto very little has been known. To date this work has seen some 10 honours theses completed and 2 PhD programs (still in progress) under the supervision of the CI, and the future work will continue to contribute valuable new data concerning the evolution of one of the less-well known Australian metamorphic terranes. Importantly, this ongoing work will enable comparisons to be made with other Proterozoic terranes in Australia and elsewhere, where the contribution of internal heat sources is suspected (Sandiford & Hand, 1998) but is yet to be fully evaluated.

The significance of the proposed work can be appreciated in the light of our current understanding of the physical causes of metamorphism. In the last 30 years, since the formulation of plate tectonics, physical modellers have framed "metamorphism" in terms of plate boundary interactions. Implicitly, metamorphic geologists have come to see physical conditions of metamorphism as reflecting the "plate tectonic" boundary conditions through such things as rates of convergence and tectonic denudation. While this approach has been tremendously successful, it has obscured the role played by the internal configuration (or starting conditions) of thermal variables such as heat production and thermal conductivity within metamorphic belts. One of the main challenges now confronting physical metamorphic geology is to determine the metamorphic signals that reflect the 'boundary conditions' and those that reflect 'starting conditions'. By exploring the hypothesis that the intrinsic properties of the continental interiors (specifically heat production of the middle crust) may exert an important influence on the long term thermal evolution of the continental lithosphere, this project directly tackles the role of the 'starting conditions'. Furthermore, as the mechanical strength of the lithosphere is closely allied to the thermal regime, the results of this project should have considerable impact on our understanding of the long-term mechanical behaviour of the lithosphere.

16. Research plan, methods, techniques and proposed timing

Background

Sandiford & Hand (1998) and Sandiford et al (submitted) have shown that the burial of an anomalously radioactive crust during thermal subsidence allows the possibility of HGGM metamorphism, providing the total contribution of the crustal heat sources is greater than about 70 mWm^{-2} (that is about twice normal crustal abundance of heat producing elements). As a prelude to the research plan, this section describes the features of the Mount Painter province that suggest an extraordinarily radioactive crust contributed significantly to the observed HGGM signature during "thermal subsidence", thus providing an ideal setting to empirically test the Sandiford et al (submitted) hypothesis.

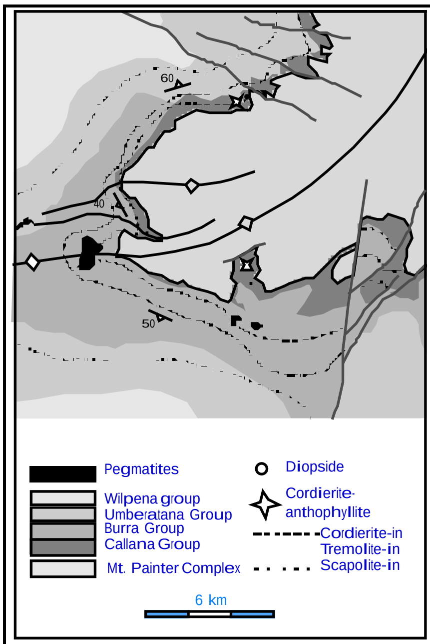

Fig 2: Metamorphic geology of the SW Mt Painter Inlier showing isograds in the cover succession concordant with the basement-cover interface, and folded about the Yankannina Anticline (after Mildren & Sandiford, 1995). The line of the section shown in Fig 3 is along the western (left-hand) boundary of this map.

The Mount Painter province occurs in the northern Flinders Ranges in South Australia. It consists of two inliers (the Painter and Babbage Inliers) of Mesoproterozoic granitic gneisses and metasediments exposed over ~ 780 sq. km. The basement gneisses are overlain by a thick (~7-12 km) Neoproterozoic sedimentary succession forming part of the Adelaide geosyncline. The Neoproterozoic cover succession was deposited over some ~250 Ma during a succession of rift-thermal subsidence episodes, with deposition terminated during a regional basin-inversion event at ~500 Ma (the Delamerian Orogen) which deformed and metamorphosed both the Mesoproterozoic basement and its Neoproterozoic cover sequence (e.g. Jenkins, 1991). In the region of the Mount Painter province, the cover sequence thickens towards the south and west from ~ 7 km near the Babbage Inlier in the north to ~11 km near the south western part of the Painter inlier (Paul et al., 1998). Delamerian deformation resulted in shortening of ~20% and the propagation of large amplitude, basement-cored, upright folds (Figs 2 & 3, Paul et al., 1998). The SW part of the basement inlier defines the west-plunging Yankannina Anticline which folds the basement-cover unconformity on a regional scale (Fig. 2 & 3). Importantly, the relatively steep westerly-plunge on the Yankannina Anticline (~40-50°), due in part to post-Delamerian (?Mesozoic-Cainozoic) ramping of this basement on the Paralana Fault, has resulted in the exposure of an oblique profile through a more-or-less complete upper crustal section with some 13 km of structural relief (Paul et al., 1998). In this area, a succession of isograds in the lower part of the

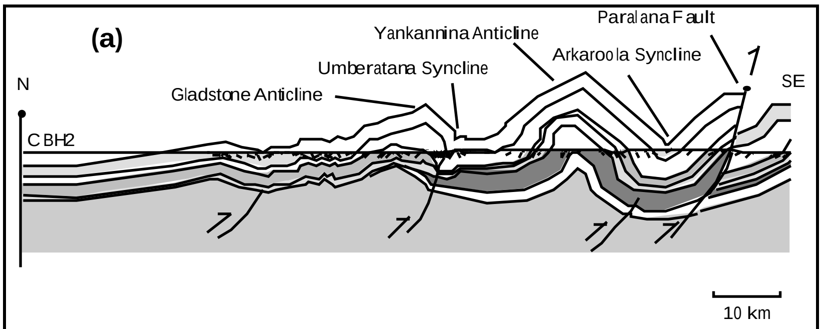

Figure 3. N-S section immediately west of Mt Painter Inlier showing exposure of the almost complete sequence sedimentary sequence is exposed on either side of the Yankannina Anticline (after Paul et al., submitted).

cover succession are essentially concordant with the basement unconformity and indicate a dramatic increase in grade towards the unconformity (Mildren & Sandiford, 1995). The isograds defining this unique style of 'unconformity related contact metamorphism' are marked by the progressive appearance (in rocks of suitable composition) of scapolite, tremolite, cordierite and diopside (Fig 2). The presence of cordierite-anthophyllite and diopside bearing rocks immediately above the unconformity indicates temperatures of at least 500°C. Metamorphic pressure estimates based on thermobarometry are less well constrained but the widespread association of cordierite-biotite-muscovite is consistent with pressures of about 3 kbars, which suggests that the principal mode of burial was achieved by the deposition of the Neoproterozoic cover, and that during metamorphism the average vertical thermal gradient in the upper-crust was ~50°C/km.

The basement granitic gneisses are exceptionally good heat producers, with heat production rates typically in excess of 10 μWm^{-3}, and locally as high as ~50 μWm^{-3}, and an area-averaged estimate of the mean heat production for the inliers of 9.9 μWm^{-3} (Sandiford et al., submitted). The extraordinarily enriched nature of the Mount Painter basement is evident when these values are compared with typical upper-crustal heat production rates of ~3 μWm^{-3}. A single surface heat flow record based on drill hole measurements of 129 mWm^{-2} from the northern part of the Mount Painter Inlier is consistent with the extraordinarily high heat production rates, as are the broadly elevated heat flows through the Flinders Ranges and the adjacent Stuart Shelf and eastern Gawler Craton (Cull, 1982; Houseman et al., 1989), where some 11 measurements fall in the range 72 - 130 mWm^{-2} with a mean of ~85 mWm^{-2}. Evidence for thick (~250 km) lithosphere throughout this region (Zeilhaus & van der Hilst, 1996) implies low contemporary mantle heat fluxes (~10-15 mWm^{-2}) and suggests that elevated surface heat flows are dominated by crustal contributions; with q_c in excess of 100 mWm^{-2} for the Painter Inlier, and ~ 70 mWm^{-2} for many other parts of the Flinders Ranges.

Research Plan and methodologies: The research plan focuses on testing the notion that metamorphism at Mount Painter is due to the anomalous heat production in the basement gneisses, as opposed to transient heating associated with emplacement of magmas at depth. The test of this hypothesis is possible because the two models make very different predictions about the nature of the thermal regimes in the upper crust, the duration of metamorphism, and the rates of heating and cooling (Fig. 4). These predictions can be evaluated using modern thermochronological techniques. The thermal subsidence model involves heating in response to a long-lived heat source and implies that thermal regimes during metamorphism are similar to the steady-state geotherm. Consequently, anomalous temperatures would be expected at all levels above the (basement) heat source, with the precise form of thermal structure reflecting not only the heat contributed by the anomalous radioactivity, but also the thermal conductivity structure of the upper crust (Curves A and C, Fig 4), with vertical metamorphic field gradients (or T_{max}) comparable to those associated with the steady-state geotherm. Because the heating occurs in response to burial it will be a very long-lived process, with the cooling reflecting the timescales of denudation processes (erosion and/or deformation) that have exhumed the rocks. In contrast, the advective heating model is a transient process in which metamorphism is spatially restricted to the immediate environment of the emplaced magmas. The thermal structure changes rapidly during metamorphism, with anomalously high temperatures recorded adjacent to the heat source as shown by the grey field bounded by the B' and B curves in Fig 4. Importantly, preserved metamorphic field gradients above a magmatic heat source would be much greater than plausible steady state geotherms (Fig. 4). For simple 1-stage magmatic emplacement histories the heating-cooling cycle should be expected to be over within the 1 Ma time scale.

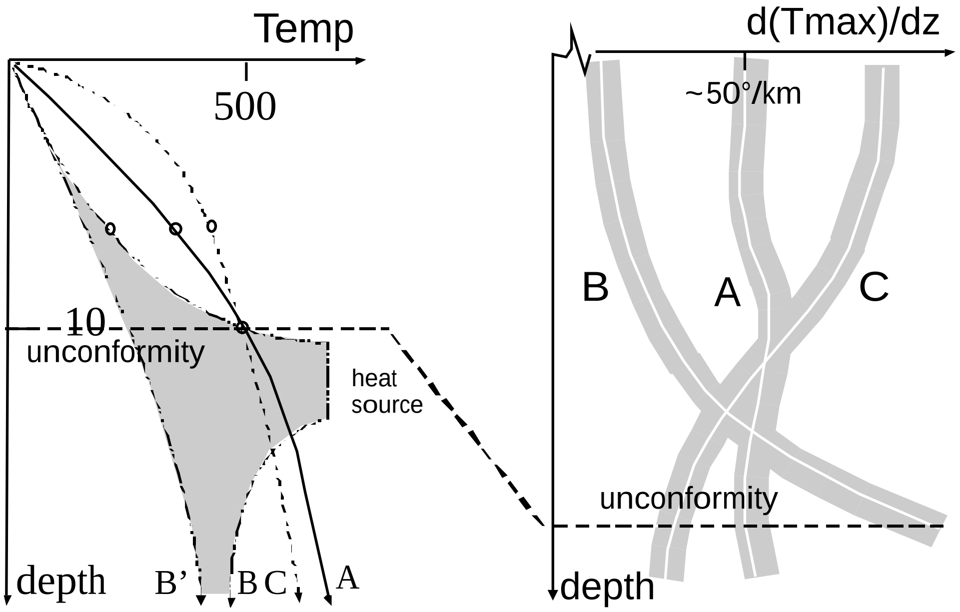

Fig 4. Schematic illustration of the thermal structure (left) and expected vertical field gradients (right) associated with different potential heating mechanisms for Mt Painter metamorphism. Curve A represents a geotherm dominated by a buried radioactive source, B and B' define the limits to a family of geotherms developed following emplacement of a magmatic body at depth into a typical crust, and C' represents the effect of a very low conductivity sedimentary sequence. Each mechanism produces very different vertical temperature gradient structures (right) that should be testable using Tt data derived from feldspar thermochronology over a range of stratigraphic levels (Fig. 5).

The preservation of a more or less complete, ~13 km thick upper crustal section (Paul et al., 1998) folded about the Yankannina Anticline, provides an unparalleled opportunity to investigate the vertical thermal structure of the metamorphic pile (Figs 2 & 3), and therefore test the mechanism of heating. In this project we intend to apply thermochronology (based principally on the $^{40}Ar/^{39}Ar$ system but also Rb-Sr and U-Pb systems to a range of minerals) to reconstruct the temperature-time (Tt) evolution at various depths within the metamorphic pile.

The $^{40}Ar/^{39}Ar$ technique is well suited to this problem because several minerals are amenable to analysis, each of which has Ar diffusion characteristics which have been characterised both experimentally and empirically (eg Harrison, 1981; Harrison and Fitzgerald, 1985; Harrison et al, 1985). In particular, the closure temperature for Ar accumulation is relatively well known for these commonly dated minerals (e.g. hornblende, Tc~500°C; muscovite, Tc~350°C; biotite, Tc~300°C; McDougall & Harrison, 1988, and references therein), and thus apparent $^{40}Ar/^{39}Ar$ ages can be interpreted as the time at which the sample cooled below a particular temperature. Ages from several minerals can therefore be combined to reconstruct the Tt evolution of a sample. K-feldspar is particularly useful for thermochronology because, being anhydrous and therefore not subject to structural changes upon dehydration during laboratory heating, gradients in apparent age during a heating experiment can be interpreted in terms of Ar diffusion during natural cooling of the sample. Considerable work over the past decade has seen the development of a theoretical and experimental approach which maximises the thermal information which can be recovered from K-feldspars. Forward modelling of K-feldspar $^{40}Ar/^{39}Ar$ experimental results typically leads to a best fit thermal history constrained over a temperature range typically between ~120 and 320°C (eg. Zeitler, 1987; Richter et al., 1991; Lovera et al., 1989; Lovera et al., 1991; Lovera, 1992).

The K-feldspar diffusion experiment approach will be used together with conventional $^{40}Ar/^{39}Ar$ step heating of hornblende, muscovite and biotite samples, to reconstruct thermal records from different metamorphic grades and different stratigraphic levels. At Mt Painter, the preservation of a relatively intact but variably metamorphosed sedimentary sequence allows for absolute depth estimates during the depositional history of the basin, and relative depth estimates during the exhumation history associated with deformation. Such depth information, in combination with the thermochronological record will allow reconstruction of the vertical temperature gradients

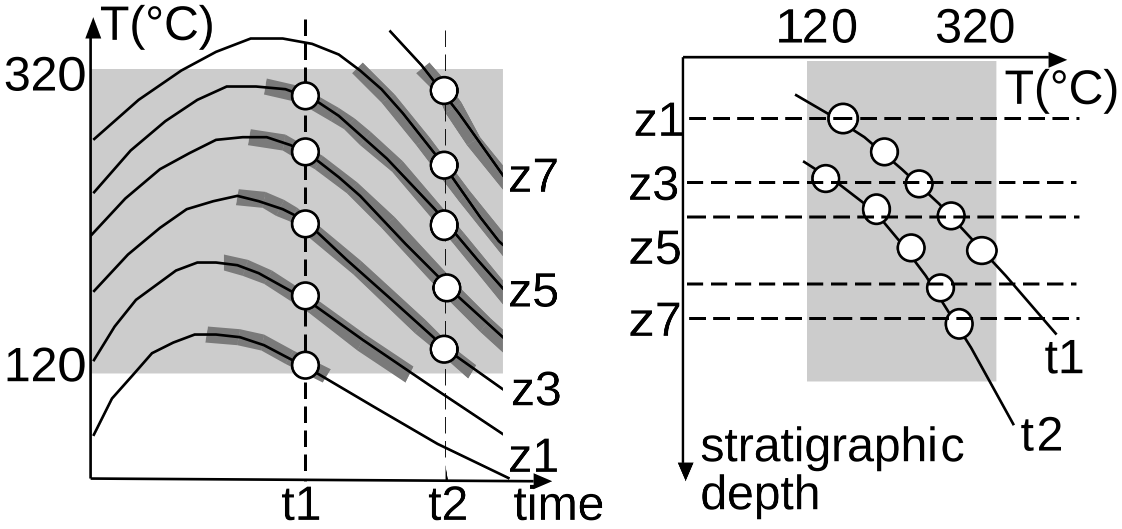

Fig 5. Schematic illustration of the proposed reconstruction of syn- to post-metamorphic geothermal gradients using Tt information from feldspar thermochronology. The diagram on the left shows a schematic Tt record for suite of feldspars from different stratigraphic levels (z1-z7), with the mapping of this data onto the T-depth plane (right) yielding direct estimates of geothermal gradients. Dark grey lines (left diagram) indicate the Tt record preserved in individual feldspars.

during and following metamorphism; evidence critical for distinguishing between ambient and transient heat sources (see Fig. 4). To establish this, samples will be collected from a range of stratigraphic levels (and metamorphic grades), focussing on regions primarily within the Neoproterozoic sedimentary cover sequence, but also from the Mesoproterozoic basement. Sampling at stratigraphic depth intervals of ~ 500 m will enable tracking of Tt records of rocks showing estimated average temperature differences of about 25°C. Because this represents a small difference compared with the temperature record typically preserved in individual feldspars (~200°C), overlaps in the temporal record of up to 5 or more adjacent samples will be expected allowing recovery of information about geothermal gradients (Fig 5). It should be noted that because feldspars in the cover sequence are mainly detrital (for example, in granite pebbles), the samples will have a pre-Delamerian thermal history which is likely to be variably preserved in the $^{40}Ar/^{39}Ar$ signature, depending on the intensity of Delamerian resetting. Indeed, the extent to which the Proterozoic isotopic record is reset will provide an important clue as to maximum temperatures reached during Delamerian metamorphism, and will complement evidence gained from conventional mineral thermometry.

In addition to the $^{40}Ar/^{39}Ar$ technique, Rb/Sr mica ages provide additional constraints on cooling histories in the interval 350-500°C. Also, because Rb/Sr analysis can be done in-house at Adelaide University, and is a relatively straight forward and inexpensive procedure, it can be as a “reconnaissance” tool to help identify the first-order details of the thermal structure and will help to focus the more detailed, but time-consuming, $^{40}Ar/^{39}Ar$ feldspar thermochonology. Because of their high closure temperature (Tc ~ 500-600°C depending on grain size), the U/Pb ages of sphene grown in marbles near the base of the Neoproterozoic sequence afford the prospect of directly dating the timing of prograde metamorphic crystallisation, which will provide critical evidence in relation to the duration of metamorphism.

While the basic hypothesis to be tested here is that the HGGM in the Mount Painter region reflects the anomalous heat production in the basement, it is also recognised that the thermal regimes attendant with this metamorphism must reflect the evolving thermal conductivity structure of the upper crust, about which there is considerable uncertainty. Another aim of this project is to constrain the evolution of the thermal conductivity structure in the sedimentary/metamorphic pile by using a combination of direct measurement of thermal conductivity of natural samples at elevated temperatures and inversion of the thermochronologic data. Of particular relevance is the conductivity structure of the upper few kilometres of the sedimentary sequence. Due to high porosity, such sequences would be expected to initially have very low conductivities (eg., Gallagher 1987; Brigaud & Vasseur. 1989). Any changes in thermal conductivity due to diagenesis could therefore lead to significant changes in temperature in the deeper crust. For example, for Mt Painter like heat flows a plausible, long-term increase in the thermal conductivity from 1.5 to 2.5 $Wm^{-1}K^{-1}$ in the upper 2 kms of sediment due to diagenesis would decrease temperatures at deeper levels by ~60°C. This example raises the intriguing possibility that isobaric cooling paths associated with many HGGM metamorphic terranes may partly reflect spontaneous changes in thermal conductivity structure of the upper crust. A low conductivity near surface sequence will lead to geotherms strongly bowed towards the temperature axis, with concomitant reductions in the thermal gradients at deeper crustal levels (cf, curves C and A in Fig. 4). Consequently, high quality thermochronological data pertinent to thermal regimes at deeper crustal levels could, in theory, be used to assess the existence, or otherwise, of such a low-thermal conductivity sequence. Such 'inversion' techniques have been successfully applied to reconstruct the low-temperature thermal character of sedimentary basins (eg., Lerche, 1989), but have yet to receive attention from the metamorphic fraternity.

Timetable: The work plan for this project involves a three-year program of geological mapping and sampling, and of petrological, thermochronological, thermal conductivity, and numerical analysis. Field work will continue through the duration of the program, in conjunction with honours students (~ 2 per year, with field seasons of 6 weeks duration) with the aims of compiling a new geological map of the Mount Painter Inlier and environs, with the main field seasons in April through May. Petrological analysis aimed at elucidation of the PT record of samples both from the cover sequence and the basement gneisses will commence at the beginning of the project with a review of existing collections, and new work based on material collected during the field work campaigns. The $^{40}Ar/^{39}Ar$ thermochronology will be undertaken at ANU RSES in conjunction with Prof. I. McDougall (who has indicated his support for this project, and will provide access to his laboratory). This work will involve some 35 analyses, commencing during the later part of the first year with further analytical work during the second and early parts of the third year of the project. The theoretical aspects of inversion of thermochronologic data will be developed in parallel with the analytical program. The later part of the third year of the project will be devoted to presentation of the results for publication. As a finale to this project it will be planned, in conjunction with the Australian Geological Society Specialist Group in Geochemistry Mineralogy and Petrology, to convene a field trip/conference using the facilities at Arkaroola. Initial discussions regarding this possibility have already taken place, and it will provide an ideal venue to present the results of this project to the broader metamorphic research community.

References cited in sections 15 & 16:

Barton, M.D. & Hanson, R.B. 1989, Geol. Soc. Am. Bulletin. 101, 1051,1065
Brigaud, F. & Vasseur, G, 1989, Geophysical Journal, 98,525-542
Chamberlain, K.R. & Bowring, S.A. 1990. Journal of Geology. 98, 399-416.
Chamberlain, C.P. & Sonder, L.J. 1990. Science, 250, 763-769.
Collins, W.J. & Vernon, R.H. 1991. Geology, 19, 835-838.
Connors, K.A. & Page, R.W. 1995. Precambrian Research, 71, 131-154.
Cull, J.P., 1982, BMR Journal of Australian Geology and Geophysics, 7, 11-21.
DeYoreo, J.J., Lux, D.R., & Guidotti, C.V. 1991, Tectonophysics, 188, 209,238.
Dovenyi, P., Horvath, F. 1988. AAPG Memoir 45, 195-233.
Gallagher, K, 1987, Exploration Geophysics, 136, 191-200.
Harrison, T. M. and FitzGerald, J. D., 1985. Geochim.Cosmochim. Acta, 50, 247 - 253.
Harrison, T. M., 1981. Contributions to Mineralogy and Petrology, 78, 324 - 331.
Harrison, T.M., Duncan, I. & McDougall, I., 1985. Geochim. Cosmo. Acta, 49, 2461-2468.
Hodges, K.V., Hames, W.E. & Bowring, S.A. 1994. Geology, 22, 55-58
Houseman, G.A., Cull, J.P, Muir, P.M., Paterson, H.L. 1989. Geophysics, 54, 158-170.
Jenkins, R.F.J, 1991, Geological Society of Australia, Special Publication, 16, 296-420.
Lerche, I., 1989, Basin Analysis, Quantitative methods, Academic press, pp 562.
Lerche, I., 1991, Pure & Applied Geophys., 136, 191-200.
Lovera, O. M., 1992. Computers & Geosciences, 7, 789 - 813.
Lovera, O.M., Richter, F.M., & Harrison, T.M., 1989. JGR, 94, 17,917-36
Lovera, O. M., Richter, F. M., & Harrison, T. M., 1991.JGR, 96, B2, 2057 - 2069.
Lux, D.R., DeYoreo, J.J., Guidotti, C.V. & Decker, E.R., 1986,Nature, 323, 795-797.
Karlstrom, K, & Williams, M., 1995, Journal Structural Geology,17, 59-81
Karlstrom, K., Dallmeyer, R.D., & Grambling, J.A., 1997, J. Geology, 105, 205-223

McDougall, I. and Harrison, T.M., 1988. Oxford University Press, New York.
Mildren, S. & Sandiford, M. 1995. Australian Journal of Earth Sciences, 42, 241-247.
Page, R., Sun, S-s. & Carr, G. 1994. Australian Journal of Earth Sciences, 37, 334-335.
Paul E., Flottman T. & Sandiford M, Australian Journal of Earth Sciences, submitted
Richter, F. M., Lovera, O. M., Harrison, T. M., & Copeland, P., 1991.EPSL 105, 266-278.
Rubenach, M. J. 1992. Journal of Metamorphic Geology, 10, 333-346.
Sandiford, M., Martin, N., Zhou, S., & Fraser, G. 1991. EPSL, 107, 164-172.
Sandiford, M., & Powell R. 1986, Earth and Planetary Science Letters, 79. (1-2), 151-158.
Sandiford, M., & Powell, R. 1991. Journal of Metamorphic Geology, 9, 333-340.
Sandiford M., & Hand M. 1998. Geol Soc London, Special Publication, in press.
Sandiford, M., Hand, M., Mclaren, S., EPSL, submitted.
Sisson, V.B., Hollister, L.S., & Onstott, T.C. 1989. JGR, 94, 4392, 4410.
Williams, I.S., Buick, I.S. & Cartwright, I. 1996. Journal Met Geology, 14, 29-47.
Vry, J., Compston, W. & I. Cartwright, I. 1996. J Metamorphic Geology, 14, 566-587.
Zielhuis, A., and van der Hilst, R.D. 1996. Geophysical Journal International, 127, 1-16.
Zeitler, P. K., 1987. Chemical Geology (Isotope Geoscience Section), 65, 167 - 181.

17. Relevance of applicants skills

The CI has devoted much of his research to the physical problems associated with crustal metamorphism, with this project representing the culmination of several years consideration of the specific problems raised by HGGM in the Australian setting. The observations forming the basis of the hypotheses to be tested in this project have been submitted for publication (see appendix 1) and the work has already received considerable international attention as witnessed by recent invitations to present keynote address on the role of heat production in crustal metamorphism at two international conferences (Geological Society of London conference "What Controls Metamorphism" Kingston, UK, 1996, and the Penrose conference entitled "Processes of crustal differentiation: Crust-mantle interactions, melting and granite migration through the crust" to be held at Verbana, Italy, 1998).

18 Role of chief investigator and other participants

In addition to overseeing the project, the CI will be responsible for all computational aspects of the project, for the setup and operation of the thermal conductivity analysis, for supervision of honours student programs and for the development of algorithms for inversion of thermochronological data. The thermochonological analytical program will be the responsibility of the appointed RA (Dr. G. Fraser), with this work being carried out in close collaboration with Prof. I McDougall in the ANU RSES Ar-facility. In addition, the RA will be expected to undertake the petrological analysis and partake in the field mapping program.

19 Explanatory statement of track record

See comments in section 17.

20 Justification of Budget

Personnel: The project requires full-time participation of an experienced thermochronologist, preferably with experience in metamorphic petrology and field mapping. To this end, the major item of the budget is for a research associate. The nominated candidate for this position is Dr G. Fraser, who is currently working with the CI on an ARC-supported grant due to finish in 1998. Dr Fraser did his BSc(Hons) research under the supervision of the CI, and a good working relationship is in evidence by a number of co-authored publications stemming from this research. Dr Fraser completed his PhD in 1997 at the ANU RSES under the supervision of Prof. I McDougall and Dr. D. Ellis. His PhD research involved extensive thermochronology, including $^{40}Ar/^{39}Ar$ analysis of the type proposed here, metamorphic petrology and field mapping, making Dr Fraser an ideal candidate for the position (see brief c.v. below). At the time of commencement of the project, Dr Fraser will have already completed 14 months as a research associate, and thus appointment at ADP level 2 is requested. Note that Dr Fraser has independently applied to the ARC fellowship scheme for a Australian postdoctoral fellowship, and if successful, this budget item will not need funding through this application.

Equipment: the CI has recently installed a divided bar apparatus to measure thermal conductivities of metamorphic sequences. This apparatus is currently based on water heating systems and thus measurements are confined to low temperatures. As outlined above, thermal conductivities show considerable temperature dependence, often reducing by a factor of ~2 in the temperature range 0-500°C, and it is therefore desirable to be able to characterise conductivities of rocks over a reasonable temperature range. The use of oil baths (@$4000each) will enable operation of the existing thermal conductivity apparatus to ~300°C.

Maintenance: Maintenance is requested to cover the costs of ongoing analytical procedures within the department and at ANU. Polished thin sections are charged at $20/section within the Department, while access to the electron microprobe is charged at $35/hour. Prof. McDougall has indicated a collaborative research price of $1000 per conventional $^{40}Ar/^{39}Ar$ analysis and $1500 per feldspar experiment. Preparation of samples for Rb/Sr and U/Pb analysis are charged internally within the department at $150 each, with mass-spectrometer use charged at $200/day.

Travel: Travel is required to support ongoing field programs and to carry out $^{40}Ar/^{39}Ar$ analysis at ANU. Field programs of 6 weeks duration each year will require 4WD support, with field allowances totalling 8 weeks to cover involvement of both the RA and the CI). The estimated mileage is ~ 10,000 km each year at the departmental internal rate of 40c/km for 4WD use. The standard Adelaide-Canberra return airfare is $654. A rate of $110/day is requested to cover living expenses incurred by the RA during his analytical program at ANU. A request is made to enable the RA to attend the Geological Society of America conference during the third year of this project. While not essential for the progress of the research, this will provide an important opportunity to present the results of this study in an international forum and, more importantly, provide an important career development experience for the RA, for which no other sources of funds are likely to be available.

Brief C.V. : Geoffery Lodge Fraser

Date of Birth: 3/10/1968

Current Position : Postdoctoral fellow, University of Adelaide, funded under ARC large grant to Dr. Mike Sandiford (commenced September, 1997)

Education :

1993-1997: PhD (RSES, ANU). Geochronological constraints on the metamorphic evolution and exhumation of the Lützow-Holm Complex, East Antarctica.

1990: BSc (hons), (University of Adelaide), "High T- Low P metamorphism in the Kanappa Hill area: implications for the thermal evolution of the southern Adelaide Fold Belt".

1987-1989: BSc (University of Adelaide), majors in Geology and Geophysics.

Publications:

Shimura, T., Fraser, G., Tsuchiya, N., and Kagami, H., 1998. Genesis of the migmatites at Breidvagnipa, East Antarctica. Proc. NIPR Symp. Antarc. Geosci, submitted.

Fraser, G., Ellis, D. J. and Eggins, S., 1997. Zirconium abundance in granulite-facies minerals, with implications for zircon geochronology in high-grade rocks. Geology, v.25, no. 7, p. 607 - 610.

Fraser, G., and McDougall, I., 1995. K/Ar and 40Ar/39Ar mineral ages across the Lützow-Holm Complex, East Antarctica. Proc. NIPR Symp. Antarc. Geosci., 8, 137-159.

Sandiford, M., Fraser, G., Arnold, J., Foden, J., and Farrow, T., 1995. Some causes and consequences of high-temperature, low-pressure metamorphism in the eastern Mount Lofty Ranges, South Australia. Aust. J. Earth Sci., 42, 233-240.

Motoyoshi, Y., Ishikawa, M., and Fraser, G., 1995. Sapphirine-bearing silica -undersaturated granulites from Forefinger Point, Enderby Land, East Antarctica: Evidence for a clockwise P-T path? Proc. NIPR Symp. Antarc. Geosci., 8, 121-129.

Ishikawa, M., Motoyoshi, Y., Fraser, G., and Kawasaki, T., 1994. Structural evolution of Rundvågshetta Region, Lützow-Holm Bay, East Antarctica. Proc. NIPR Symp. Antarc. Geosci., 7, 69-89.

Ishikawa, M., Motoyoshi, Y., and Fraser, G., 1994. Preliminary report on structures of Forefinger Point, Enderby Land, East Antarctica. Proc. NIPR Symp. Antarc. Geosci., 7, 90-100.

Motoyoshi, Y., Ishikawa, M., and Fraser, G., 1994. Reaction texures in granulites from Forefinger Point, Enderby Land, East Antarctica: An alternative explanation of the metamorphic evolution of the Rayner Complex. Proc. NIPR Symp. Antarc. Geosci., 7, 101-114.

Sandiford, M., Martin, N., Zhou, S., and Fraser, G., 1991. Mechanical consequences of granite emplacement during high-T, low-P metamorphism and the origin of "anticlockwise" PT paths. Earth and Planetary Science Letters, 107, 164-172.

Appendix 1: Abstracts from relevant publications currently in press or submitted

Australian Proterozoic high-temperature, low-pressure metamorphism in the conductive limit,

Mike Sandiford & Martin Hand,

In "What Drives Metamorphism and Metamorphic Reactions", (ed) Treloar, P., & O'Brien, P, Geological Society of London Special Publication, in press.

High-temperature, low-pressure (HTLP) metamorphism often reflects transient advection of heat due to magma ascent. However, the origin of HTLP metamorphism in a number of Australian Proterozoic terranes remains contentious either because of the deficiency of magmatic bodies in the terranes, or because the long time delay (> 100 Ma) between magmatism and metamorphism precludes heating by existing magmatic bodies. Furthermore a number of Australian Proterozoic HTLP terranes (such as the Reynolds Range in central Australia) show evidence of an extended history (~30 Ma) of HTLP mineral growth suggesting metamorphism during a thermal regime dominated by conduction at lithospheric length scales. Australian Proterozoic metamorphic terranes are characterised by both elevated modern day heat flows (averaging ~ 85 mW/m^2) and granitic gneisses with anomalously high heat production rates (commonly > 5 - 10 $\mu W/m^3$). We show that the conditions required for HTLP metamorphism may result from conduction if the crustal heat production responsible for modern day heat flows is concentrated at mid crustal levels (15-20 km). Importantly, for low-intermediate mantle heat fluxes (10-20 mW/m^2) and moderate syn-metamorphic crustal thicknesses (~ 45 km), the conductive geotherms attendant with such HTLP metamorphism do not necessarily lead to significant melting of a refractory lower crust. Importantly, the thermal regimes are very sensitive to the depths at which crustal heat production is localised. The strong dependence of the resulting geotherms on the depth of the heat producing layer has the important consequence that only minor burial may be required to induce HTLP metamorphism, while only minor erosion (~ 5 km) is necessary to terminate the event.

High geothermal gradient metamorphism during thermal subsidence

Mike Sandiford, Martin Hand, Sandra McLaren,

submitted to Earth and Planetary Science Letters, December 1997

Abstract: The burial of a basement sequence enriched in heat producing elements during thermal subsidence following rifting produces two concomitant changes in the thermal structure of the crust. Firstly, the burial of the enriched layer produces high geothermal gradients in the overlying sedimentary succession, with the high gradients propagating down into, but not through, the enriched basement sequence. Secondly, the deep lithospheric cooling that drives thermal subsidence reduces the heat flowing into the deeper crust from the mantle. Because the process of thermal subsidence promotes burial, it naturally increases the depth extent of the high geothermal gradients in the upper crust, potentially inducing very significant temperature increases in the mid-upper crust during burial. The lowering of the thermal gradients in the deep crust accompanying burial severely limits the temperature changes affecting the Moho; potentially allowing Moho cooling while the mid-upper crust heats. We show that these combined effects can promote high geothermal gradient (> 40°C/km) metamorphism in the mid-upper crust without inducing significant melting in the lower crust, providing the basement heat production contributes > ~70 mWm^{-2} to the surface heat flow and that the horizontal length scale for the basement heat production anomaly is > ~50 kms. These conditions appear to be met in several Australian intermediate- to high-temperature, low-pressure metamorphic terranes where the thermal causes of metamorphism have hitherto remained enigmatic. One of these terrains, the Mt Painter province in the northern Flinders Ranges, South Australia, is used to illustrate some of the attributes of the model.

21 Chief investigator publication list, last five years.

**papers relevant to this application are marked with asterisks*

Sandiford, M., Mechanics of basin inversion, submitted to Tectonophysics

Sandiford, M., and Hand., M., Controls on the locus of Phanerozoic intraplate deformation in central Australia, submitted to Earth and Planetary Science Letters.

*Paul,E., Flottmann, T., Sandiford, M., Structural geometry of the northern Flinders Ranges in the Adelaide Fold Belt, South Australia, submitted to Australian Journal of Earth Sciences.

*Sandiford, M., Paul,E., & Flottmann, T., Sedimentary thickness variations and deformation intensity during 'basin inversion' in the Flinders Ranges, South Australia, submitted to Journal of Structural Geology.

*Sandiford, M., Hand., M. and McLaren, S., High geothermal gradient metamorphism during thermal subsidence, submitted to Earth and Planetary Science Letters.

Foden, J., Dougherty-Page, J., Sandiford, M., and Willliams, I., The age and significance of the Rathjen Gneiss, submitted to Australian Journal of Earth Science.

*Sandiford, M., and Hand, M., 1998, Australian Proterozoic high-temperature metamorphism in the conductive limit, In What Drives Metamorphism and Metamorphic Reactions, (ed) Treloar, P., & O'Brien, P, Geological Society of London Special Publication, in press.

Coblentz, D.D., Zhou, S, Hillis, R., Richardson, R.M., and Sandiford, M., 1988, Topography, plate-boundary forces and the Indo-Australian intraplate stress field, Journal of Geophysical Research, in press.

Hillis, R.R., Sandiford, M., Coblentz, D.D. & Zhou, S., 1997, Modelling the Contemporary stress field and its implications for Hydrocarbon exploration, Exploration Geophysics, 28, 88-93

*Turner, S., Kelly, S.P, Vandenberg, A.H., Foden, J., Sandiford, M., Flotmmann, T., 1996, Source of Delamerian fold belt flysch links to convective removal of the lithospheric mantle and rapid exhumation of the Delamerian-Ross fold belt, Geology, 24, 941-944.

Zhou, S., Hillis, R , Sandiford, M., 1996, A supplement to 'A study of inclined wellbores with regard to both mechanical stability and fracture intersection and its application to the Australian North West Shelf', Journal of Applied Geophysics, 36, 145-147.

Zhou, S., Hillis, R , Sandiford, M., 1996, On the mechanical stability of inclined boreholes, SPE drilling, 11, 67-73

*Turner, S., Sandiford, M., Flottman, T., Foden, J, 1995, Rb/Sr dating of differentiated cleavage from the Adelaidean metasediments at Hallet Cove, southern Adelaide Fold Belt: Reply to disucssion by W.V. Preiss, Journal of structural Geology, 17, 1801-1803

Arnold, J., Sandiford, M. and Wetherly, S., 1995, Metamorphic events in the Eastern Arunta Inlier, Part 1. Metamorphic petrology, Precambrian Research, 71, 183-205.

Coblentz, D., Sandiford, M., Richardson, R, Zhou, S., and Hillis, R., 1995, The origins of the Australian stress field, Earth and Planetary Science Letters, 133, 299-309.

Sandiford, M., Coblentz, D., and Richardson, R.M., 1995, Focusing ridge-torques during continental collision in the Indo-Australian plate, Geology, 23,653-656.

Stuwe K., and Sandiford M., 1995, Description of Metamorphic Pressure-Temperature-Time paths in the Low-P High-T Environment. Physics of the Earth and Planetary Interiors, 88, 211-221.

Stuwe, K. and Sandiford, M., 1995, Mantle lithospheric deformation and crustal metamorphism, with some speculations on the thermal and mechanical significance of the Tauern event, Eastern Alps, Tectonophysics, 214, 115-132.

*Sandiford, M., Fraser, G., Arnold, J., Foden, J. and Farrow, T., 1995, Some causes and consequences of High-T, Low-P metamorphism, Mount Lofty Ranges, Australian Journal of Earth Sciences, 42, 233-240.

*Mildren, S. and Sandiford, M., 1995,A heat refraction mechanism for Low-P metamorphism in the northern Flinders Ranges, South Australia, Australian Journal of Earth Sciences, 42, 241-247.

Cartwright, I., Vry, J., and Sandiford, M., 1995, Changes in stable isotope ratios of metapelites and marbles during regional metamorphism, Mount Lofty Ranges, South Australia: Implications for crustal scale fluid flow, Contributions to Mineralogy and Petrology, , .

Zhou, S., Hillis, R , Sandiford, M., 1994, A study of inclined wellbores with regard to both mechanical stability and fracture intersection and its application to the Australian North West Shelf, Journal of Applied Geophysics, 32, 293-304.

Coblentz, D., and Sandiford, M., 1994, Tectonic stress in the African plate: Constraints on the ambient stress state, Geology, 22, 831-834.

Coblentz, D., Richardson, R.M., and Sandiford, M., 1994, On the gravitational potential of the Earth's lithosphere, Tectonics, 13, 929-945.

Ehlers, K., Stuwe, K., Powell, R., Sandiford, M., and Frank, W., 1994, Thermometrically inferred cooling rates from the Plattengneis, Koralm Region - Eastern Alps, Earth and Planetary Science Letters, 125, 307-321.

Sandiford, M., and Coblentz, D., 1994, Plate-scale potential energy distributions and the fragmentation of ageing plates, Earth and Planetary Science Letters, 126, 143-159.

Stuwe, K., and Sandiford, M., 1994, A possible contribution of deviatoric stresses to metamorphic PT paths; an example appropriate to low-P, high-T metamorphism, Journal of metamorphic Geology, 12, 445-454.

*Turner, S., Sandiford, M., Flottman, T., Foden, J, 1994, Rb-Sr dating of differentiated cleavage: an example form the Adelaidean metasediments at Hallet Cove, with implications for the tectonic evolution of the southern Adelaide Fold Belt, Journal of structural Geology, 16, 1233 - 1242.

Stuwe, K., and Sandiford, M., 1994, Some remarks on the geomorphological evolution of the eastern Alps, constraints on Cretaceous nappe tectonics, Mitteilungen der Osterreichischen geologischen Gesellschaft, 86, 165-176.

Stuwe, K., and Sandiford, M., 1993, A preliminary model for the 500 Ma event in the East Antarctic Shield, In: Gondwana Eight (eds. Findlay, Unrug and Veevers), Balkema, 125-130

Turner, S., Foden, J., Sandiford, M., and Bruce, D., 1993, Sm-Nd isotopic evidence for the provenance of sediments from the Adelaide Fold Belt and southeastern Australia with implications for crustal growth models, Geochemica Cosmochemica Acta, 57, 1837-1856.

*Stuwe, K., and Sandiford, M., and Powell, R., 1993, Episodic metamorphism and deformation events in Low-P, High-T terrains, *Geology,* 21, 829-832.

*Scrimgeour, I., and Sandiford, M., 1993, Early Proterozoic metamorphism at the Granites, northern Territory, implications for fluid production in high T - low P terrains, *Economic Geology*, 88, 1099-1113.