Use of $^{40}\text{Ar}/^{39}\text{Ar}$ K-feldspar thermochronology in basin thermal history reconstruction: an example from the Big Lake Suite granites, Warburton Basin, South Australia

Sandra McLaren and W. James Dunlap

Research School of Earth Sciences, Australian National University, Acton, ACT, Australia

ABSTRACT

The potential use of $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronologic data from K-feldspars in reconstructing basin thermal history has been evaluated using the example of the Warburton/Cooper/Eromanga Basin, Australia's largest onshore oil- and gas-producing basin. Results from $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating experiments reveal details of the evolution of the basin system, including the following: (1) the operation of high geothermal gradient regimes during the earliest basin evolution, suggesting that basin formation was active rather than passive; (2) slow cooling from a Permo-Triassic temperature peak of at least 250–300 °C; (3) a rise in thermal gradients to contemporary bottom hole temperatures in the last 5–10 Myr; and (4) spatially variable recrystallization events between 100 and 50 Ma and at around 20 Ma. Initial microstructural observations serve as a useful predictor of the quality and nature of the obtainable age information. Data from 'pristine' K-feldspars may constrain the peak temperature conditions experienced in the basin, the basin's early thermal history and also any recent changes in thermal gradient. Contrasting data from texturally modified K-feldspars may constrain times of thermal transients and/or fluid flow, with the preferred interpretation that K-feldspars recrystallize in response to such events. The Warburton/Cooper/Eromanga Basin example suggests that the $^{40}\text{Ar}/^{39}\text{Ar}$ technique may serve as a useful adjunct to apatite and zircon fission track analysis and conventional organic maturation indices in basin thermal history analysis.

INTRODUCTION

Basin thermal history reconstruction is a useful tool for understanding basin formation mechanisms and also for the evaluation of petroleum resource potential. Most commonly, the maximum temperature of burial within a basin is determined by organic maturation index methods, such as vitrinite reflectance (e.g. He *et al.*, 2002). Fission track analysis may also be used to determine the low-intermediate temperature history (e.g. Tingate & Duddy, 2002). However, vitrinite reflectance methods are subject to significant analytical uncertainty, and absolute time constraints on basin temperatures are not available; in the fission track method, detailed preparation and analysis is required such that the method is generally limited to only a few wells within a basin.

Despite these approaches being well established in basin analysis, we note that the $^{40}\text{Ar}/^{39}\text{Ar}$ K-feldspar thermochronometer is also sensitive to temperatures appropriate to many basin settings. The $^{40}\text{Ar}/^{39}\text{Ar}$ method is based on the decay of ^{40}K to ^{40}Ar , and is a well-established thermo-

chronological technique for dating K-rich minerals such as muscovite, biotite, hornblende and K-feldspar (McDougall & Harrison, 1999). In these minerals, argon is quantitatively retained below a characteristic closure temperature. Recent work has suggested that K-feldspars may be sensitive to argon loss over a range of temperature as large as 150–350 °C. Preliminary studies by Harrison & Bé (1983) and Gallagher (1988) have suggested that K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ age data may provide useful insights into the thermal evolution of sedimentary basins, but few detailed studies have been undertaken to evaluate the methodology. Moreover, since this early work, Lovera *et al.* (1989) have developed a detailed mathematical approach for the interpretation of K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ data that may allow temperature–time paths to be reconstructed. This method, termed the multiple-diffusion-domain (MDD) model, has been shown to yield detailed quantitative thermal history information in a variety of basement settings, including the Tibetan Himalaya (e.g. Richter *et al.*, 1991; Quidelleur *et al.*, 1997), the Caledonian Orogen of Southern Norway (Dunlap & Fossen, 1998) and the Adelaide Fold Belt in South Australia (McLaren *et al.*, 2002).

Here, we evaluate the potential of the $^{40}\text{Ar}/^{39}\text{Ar}$ K-feldspar thermochronometer as a tool for constraining basin thermal history. In contrast to basement settings, rocks in

Correspondence: Sandra McLaren, School of Earth Sciences, University of Melbourne, Vic. 3010, Australia. E-mail: mclarens@unimelb.edu.au

basin settings experience a reheating history, rather than a cooling history, and the robustness of the method in such settings has yet to be evaluated. We use both conventional interpretation of step-heating experiments, and also the MDD approach of Lovera *et al.* (1989). We present new $^{40}\text{Ar}/^{39}\text{Ar}$ K-feldspar thermochronologic data from granites of the Big Lake Suite that intrude the Warburton Basin at the base of the Cooper/Eromanga Basin in northern South Australia (Fig. 1). The tectonic and stratigraphic framework of the region is relatively well known owing to the extensive petroleum resources contained within the basin system, but the chronology and thermal history is known only from previous apatite fission track analyses (Duddy & Moore, 1999). Fission track thermochronology is sensitive to a much lower range of temperature than $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology, and so rather than attempting a comparison of the two methods, in this paper we aim to evaluate only the potential of $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology to provide a useful adjunct to established methods of basin analysis.

We use K-feldspars obtained from the Big Lake Suite granites that intrude the Warburton Basin before the deposition of the Cooper and Eromanga Basins (Figs 1 and 2). K-feldspars from the Big Lake suite granites were obtained from core material from three petroleum exploration wells: (1) Big Lake-1; (2) Moomba-1; and (3) McLeod-1. Drill chip material from Habanero-1, a deep well drilled for Hot Dry Rock geothermal energy exploration, was also analysed (Table 1). All K-feldspars were sub-

ject to basic microstructural analysis and to $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronological analysis, including detailed diffusion experiments.

GEOLOGIC SETTING

The Warburton Basin is a Cambro-Ordovician subsurface depocentre in central Australia (Fig. 1). It comprises a variable thickness marine and non-marine sedimentary package (around 1800 m) and covers an area over 45 000 km² (Moore & Pitt, 1984). The Warburton Basin formed in an intracratonic setting in the foreland of a regional fold and thrust belt in South and Central Australia (Sun, 1997). The Warburton Basin is overlain by sediments of the Cooper and Eromanga Basins (Hill & Gravestock, 1995), which form Australia's largest onshore oil and gas petroleum system, accounting for more than 6% of Australia's annual total petroleum production and including 46% of Australia's natural gas (APPEA, 2003). The Warburton Basin has itself also shown evidence of marketable petroleum shows through down-dip migration from Cooper Basin sources.

Sediments of the Warburton Basin are intruded by granites of the Big Lake Suite. These granites have been dated by sensitive high-resolution ion microprobe (SHRIMP) analysis of zircons from material from the Moomba-1 and McLeod-1 wells (Fig. 1). Measured ages are 323 ± 5 and 298 ± 4 Ma, respectively (Gatehouse *et al.*, 1995), suggesting a 20–30-Myr period of elevated geother-

Fig. 1. (a) Location of the Warburton, Cooper and Eromanga Basins in central Australia; states and territories are indicated: NT, Northern Territory; SA, South Australia; QLD, Queensland; NSW, New South Wales; WA, Western Australia; Tas, Tasmania (map modified after Drexel & Preiss, 1995) (b) Location of sampled wells. Habanero-1 is 450 m west of McLeod-1. Sample numbers of K-feldspars analysed shown alongside corresponding wells. (c) Shaded contour map showing depth to the pre-Permian basement (i.e. top of the Warburton Basin) in the South Australian portion of the Cooper/Eromanga basin. Major structural elements are shown, GMI, Gidgealpa, Merrimelia, Innamincka Ridge; BTR, Birdsville Track Ridge; NT, Nappamerri Trough; PT, Patchawarra Trough. Map courtesy of Primary Industry and Resources, South Australia.

Fig. 2. Stratigraphic relationship summary for sediments, volcanics and intrusives of the Warburton, Cooper, Eromanga and Lake Eyre Basins (age and stratigraphic information from Moore & Pitt, 1984; Burger, 1986; Cook, 1986; Powell *et al.*, 1989; Drexel & Preiss, 1995; Sun, 1997; Gravestock *et al.*, 1998). Wavy lines indicate unconformities; black quadrilaterals indicate basaltic intrusions. Sedimentary thicknesses not to scale. Intervals A, B and C represent the main aquifers of the Great Artesian Basin, A, watertable; B, Upper confined aquifer and C, Main artesian aquifer (Armstrong & Aldam, 1995).

Table 1. Sample details

K-feldspar sample	Well	Well location latitude/longitude		Age (if known)	Sample type	Depth interval (m)	Contemporary BHT (°C) (uncorrected)	Total gas $^{40}\text{Ar}/^{39}\text{Ar}$ age (Ma)
02-147	Big Lake-1	140.333	– 28.208		Core	3056.7–3057.8	187	43 ± 1
02-149	Moomba-1	140.269	– 28.151	323 ± 5 Ma	Core	2895.2–2895.3	159	269 ± 2
02-152	McLeod-1	140.759	– 27.815	298 ± 4 Ma	Core	3748.8–3748.9	230	27 ± 0.6
02-229	Habanero-1	140.754	– 27.816		Cuttings	3983.7–3986.8	~210	80 ± 1.6
02-230	Habanero-1	140.754	– 27.816		Cuttings	4008.1–4011.2	~210	70 ± 1
02-231	Habanero-1	140.754	– 27.816		Cuttings	4044.7–4047.7	~210	151 ± 2
02-232	Habanero-1	140.754	– 27.816		Cuttings	4090.4–4093.5	~210	93 ± 1.6

Granite ages from Gatehouse *et al.* (1995).

mal gradient throughout the region. Sun (1997) associates the intrusion of these granites with a major regional compressive tectonic event related to the Alice Springs Orogeny, a major tectonothermal event that occurred throughout central Australia (e.g. Dunlap & Teyssier, 1995; Sandiford & Hand, 1998). The granites are overlain by a thin but continuous sequence of late Carboniferous clastic sediments, suggesting that the intrusion–uplift–burial cycle was completed within a very short period of time (around 5–10 Myr).

The Cooper Basin comprises a thick (1500 m), non-marine Permian to early Triassic sedimentary succession of sandstones, siltstones and shales (Fig. 2). Owing to its petroleum prospectivity, the stratigraphic and structural history of the Cooper Basin has previously been described in detail (for example Drexel & Preiss, 1995; Gravestock *et al.*, 1998; Draper, 2002; Deighton *et al.*, 2003). Like the underlying Warburton Basin, the Cooper Basin also formed in an intracratonic setting. The basal sediments of the Merrimelia Formation were deposited around 295–305 Ma and unconformably overlie the Warburton Basin. Subsidence during these early stages of basin evolution was largely fault controlled. The Cooper Basin is divided into southern and northern parts by a series of dominantly EW anticlinal ridges in SW Queensland that separate predominantly Permian depocentres in South Australia from dominantly Triassic depocentres in Queensland. In South Australia, the basin is dominated by major NE-orientated structures including the Birdsville Track Ridge and the Gidgealpa–Merrimelia–Innaminka ridge (Fig. 1). Maximum structural relief on the Gidgealpa–Merrimelia–Innaminka ridge is around 1000 m and the major structural culminations along its length are largely fault controlled (Thornton, 1979).

The Cooper Basin is in turn overlain by the Jurassic–Cretaceous Eromanga Basin and the Cainozoic Lake Eyre Basin (Figs 1 and 2). The Eromanga Basin sedimentary record extends without major unconformity from the early Jurassic to the mid-Cretaceous and consists of a cyclic succession of sandstone and mudstone units in three major packages: (1) a thick mid-Jurassic to Early Cretaceous sequence of non-marine sandstone, siltstone and shales; (2) a moderate thickness of marine mudstone and siltstone

deposited rapidly during the late Early Cretaceous; and (3) a thick (900 m) sequence of non-marine siltstone deposited in the mid-Cretaceous (Moore & Pitt, 1984; Burger, 1986). Like the Cooper Basin, the Eromanga Basin is a prolific oil and gas producer. Much of the Eromanga Basin oil is thought to have migrated from Permian source rocks in the underlying Cooper Basin, but several formations of significant source potential have been identified, including the Murta Formation and the Poolawanna Formation (e.g. Cook, 1986; Powell *et al.*, 1989).

The tectonic history during and after the deposition of the Warburton and Cooper Basins produced a pre-Eromanga surface of highly variable topography, and this contributes much of the structural style to the overlying basin (e.g. Drexel & Preiss, 1995). The subsidence history of the Eromanga Basin was steady until around 100 Ma when the basin was characterized by very rapid subsidence that continued until around 70 Ma (Deighton *et al.*, 2003). Sun (1997) reports two major phases of structural development in the Warburton–Cooper–Eromanga Basin system. The first phase occurred in the late Carboniferous to middle Jurassic and is characterized by mild compressional tectonic events, and that was probably an intraplate response to a change in far-field plate tectonic configuration. The second phase extended from the Middle Jurassic to the Tertiary and is dominated by a major Tertiary folding event.

The Eromanga and Lake Eyre Basins also host the Great Artesian Basin, one of the world's largest groundwater basins (Armstrong & Aldam, 1995). The Great Artesian Basin is a multi-aquifer system (Fig. 2) that flows from southern Queensland to the southern margin of the Cooper Basin and that extends into New South Wales and the Northern Territory. It is characterized by hydrothermal mound-springs along its margins and in South Australia, the aquifer thickness ranges from less than 50 m to more than 500 m (Armstrong & Aldam, 1995).

BASIN THERMAL REGIME

Measured surface heat flow data provide a first-order constraint on the thermal regime in the Warburton/Cooper/Eromanga Basin system. Measured surface heat flow varies

from around 70 mWm^{-2} in wells that do not intersect the Big Lake Suite Granites, to over 120 mWm^{-2} in wells that do intersect the granites (Middleton, 1979; Gallagher, 1988). Even the lowest values of measured surface heat flow are well above the global average for Palaeozoic terranes of around 54 mWm^{-2} (Taylor & McLennan, 1985), and the highest measured values are more than twice this value. Although these values are elevated, they are not anomalous when compared with other measurements in central South Australia (the so-called South Australian Heat Flow Anomaly) that average $92 \pm 10 \text{ mWm}^{-2}$ (Neumann *et al.*, 2000).

In the case of the Cooper Basin measurements, much of the high measured surface heat flow is thought to originate from the Big Lake Suite granites that are enriched in the heat-producing elements: U, Th and K. Measured concentrations are between 13.7 and 16.5 p.p.m. uranium, 46 and 74 p.p.m. thorium and 5.2 and 6.0 wt% K_2O (Middleton, 1979), giving a total volumetric heat production in the range of $7.5\text{--}10.3 \mu\text{Wm}^{-3}$. The presence of such highly radiogenic intrusives within 3–4 km of the surface generates extraordinarily high geothermal gradient regimes ($> 60^\circ\text{C km}^{-1}$), and as a consequence the region has recently attracted considerable attention in the exploration for geothermal energy (e.g. Chopra, 2003).

The granites are distributed widely throughout the Warburton Basin and are thought to underlie much of the south and central Cooper Basin (Boucher, 2002); however, the exact distribution of sub-crop is not yet well constrained. Existing interpretation is based on gravity and magnetic data and known basement intersections. Where the granite does occur, its extraordinary heat-producing element enrichment must have exerted an important effect on geothermal gradients and the long-term thermal history of the overlying basin (e.g. Sandiford & McLaren, 2002).

A combined apatite and zircon fission track study has been performed on several wells from the Cooper/Eromanga Basin by Duddy & Moore (1999). Interpretation focuses on the role of transient thermal pulses in the more recent evolution of the basin and principal findings include the following: (1) that maximum palaeotemperatures were reached between 97 and 75 Ma, coinciding with a period of elevated basal heat flow and the time of maximum petroleum maturation; (2) that regional cooling following this palaeotemperature peak was associated with a decline in palaeogeothermal gradient with little associated erosion; and (3) the basin experienced an increase in geothermal gradients in the last 2–5 Ma to yield observed contemporary bottom-hole-temperatures. Owing to the high temperatures achieved in the Cretaceous and Tertiary, the fission track approach is unable to constrain reliably the earlier stages of the basins thermal history.

MICROSTRUCTURAL OBSERVATIONS

The link between microstructure and the type and quality of $^{40}\text{Ar}/^{39}\text{Ar}$ age data is an area of active research. Follow-

ing criticisms of $^{40}\text{Ar}/^{39}\text{Ar}$ K-feldspar thermochronology, and particularly of the MDD method (e.g. Parsons *et al.*, 1999), it has become increasingly clear that textural modification of K-feldspars can impact on argon systematics and thus the $^{40}\text{Ar}/^{39}\text{Ar}$ ages recorded.

Here, we use observations from optical microscopy and scanning electron microscopy, using back-scattered electron (BSE) imagery, to investigate the gross microstructure of each K-feldspar. Electron microscopy was performed at the Australian National University Electron Microscopy Unit using a Cambridge S360 Scanning Electron microscope with an accelerating voltage of 20 kV and at a working distance of 20 mm. Our observations indicate a variety of microstructures within the suite of samples (Fig. 3).

K-feldspar 02-147 shows evidence for textural modification at the grain and sub-grain scales. At the grain scale, the sample is characterized by moderate development of 10–50 μm diameter clay mineral, mica laths and diffuse perthitic exsolution textures.

K-feldspar 02-149 is the most pristine of the samples analysed. Individual mineral grains are euhedral and show good perthite development, and an almost total absence of alteration features such as dissolution pits or laths and/or alteration reaction products, such as clay minerals or micas. Optical observation reveals highly lustrous euhedral crystal faces, and clear inclusion-free grains.

In contrast, K-feldspar 02-152 shows an extremely disrupted microstructure. Grains are characterized by large pits, laths and inclusions of highly altered micas and clay minerals. Both K-feldspars 02-152 and 02-147 are anhedral and exhibit a dusty lustre when observed optically; 02-152 is characterized by a granular, sugary texture.

K-feldspars 02-147, 02-149 and 02-152 obtained from core are all located within 0–3 m of the Warburton–Cooper Basin unconformity and the recrystallization observed in 02-147 and 02-152 is probably the result of concentrated fluid flow along the interface at various stages in basin evolution.

The suite of four samples from Habanero-1 all show similar microstructural features. The samples span an interval of 110 m from 3983 to 4093 m depth (13 070–13 430 ft). All Habanero-1 K-feldspars show diffuse subhedral to anhedral perthitic exsolution features, which contrast with the linear exsolution features of K-feldspar 02-149 (Fig. 3). All samples show evidence for variable sericitic and chloritic alteration.

$^{40}\text{Ar}/^{39}\text{Ar}$ ANALYSIS

The decay of ^{40}K to ^{40}Ar is the basis of the K/Ar geochronological technique, first developed in the early 1950s (see McDougall & Harrison, 1999). At very high temperatures, all the radiogenic argon ($^{40}\text{Ar}^*$) produced by decay of ^{40}K is expected to be lost continuously from a crystal lattice by volume diffusion. As a mineral cools, it will reach a temperature below which argon diffusion is negligible, so that

Fig. 3. Representative atomic number contrast (back-scattered electron) images of epoxy mounted K-feldspar grains for (a) 02-147; (b) 02-149; (c) 02-152; (d) 02-229; (e) 02-230; (f) 02-231 and (g) 02-232. The lighter colour is K-feldspar; the darker colour is plagioclase.

the argon daughter product is retained quantitatively. The $^{40}\text{Ar}/^{39}\text{Ar}$ method was developed in the mid 1960s, and is based on the conversion of ^{39}K into ^{39}Ar during neutron irradiation. As the ratio of ^{39}K to ^{40}K is constant in nature, the method enables isotopic ratios to be measured on a single aliquot of sample (cf. K/Ar analysis).

A K/Ar age or a $^{40}\text{Ar}/^{39}\text{Ar}$ total fusion age essentially records the time since closure of the mineral to argon diffusion. In general, for cooling rates typical of orogenesis (Dunlap, 2000), the temperature interval over which a mineral passes from little accumulation to full retention of radiogenic argon is restricted (e.g. a few tens of degrees). Dodson (1973) defined a closure temperature (T_c) corresponding to the apparent temperature at which the mineral becomes closed to diffusive loss. Common potassium-bearing minerals have a large range of closure temperature with respect to argon accumulation. K-feldspar appears to exhibit a range of closure temperatures from about 350 to 150 °C (Lovera *et al.*, 1989). Slow cooling of a mineral can result in the development of radiogenic argon concentration gradients, which may be especially pronounced adjacent to grain boundaries as argon is lost from the outer parts of the crystal. If the mineral remains thermodynamically stable during at least part of the vacuum heating experiment, step heating may reveal variations in the $^{40}\text{Ar}^*/^{39}\text{Ar}$ ratio (which is proportional to age) as a reflection of such gradients. We note that unlike muscovite, biotite or amphibole, K-feldspars do not break down and undergo little textural change during vacuum heating over several days or more (e.g. Fitzgerald & Harrison, 1993).

Here, K-feldspars were subject to detailed step-heating experiments involving 43 individual heating steps at temperatures between 450 and 1450 °C. The heating schedule includes a number of duplicate and triplicate isothermal steps (*supplementary data*). These experiments provide excellent detail of the argon release and, importantly, enable the diffusion characteristics of the sample to be determined. The Appendix contains a detailed description of the analytical method used. We show results as an age spectrum (Fig. 4), a plot of the age of each step against the cumulative proportion of ^{39}Ar released. The age spectrum, or $^{40}\text{Ar}/^{39}\text{Ar}$ release pattern as it is also known, is the standard method of presenting step-heating data (McDougall & Harrison, 1999).

With the exception of K-feldspar 02-152, all the samples analysed show evidence for excess argon ($^{40}\text{Ar}_E$) in the first 20% of the gas released. Excess argon is that component of the total ^{40}Ar , excluding the component arising from the atmosphere, that is incorporated into samples by processes other than *in situ* radioactive decay of ^{40}K (McDougall & Harrison, 1999). Excess argon can come from several sources and manifest itself in several forms on an age spectrum plot. Most commonly, saddle-shaped release patterns characterize samples where $^{40}\text{Ar}_E$ is located within two different lattice sites of the mineral (which degas differently). Excess radiogenic argon is also indicated by inappropriately old ages (e.g. the 5030 Ma biotite age reported by Pankhurst *et al.*, 1973) and in these cases results

cannot be usefully interpreted. In other cases, the effect of $^{40}\text{Ar}_E$ is not so dramatic, and can be confidently corrected. In many K-feldspar samples, including the Warburton Basin samples, we observe a characteristic pattern of large differences in the age of isothermal duplicate steps (Fig. 4). Harrison *et al.* (1994) interpret such a pattern as the result of excess argon trapped within fluid inclusions within the K-feldspar (the strong correlation with Cl indicates sitting in fluid inclusions). As the blank, atmospheric and K-derived contributions to the total measured gas are known, the contribution of the Cl-correlated component can be determined following the method of Harrison *et al.* (1994). Age correction of the excess argon-contaminated gas in the Warburton Basin samples following this method yields zero ages. Ages around zero in this earliest released gas demand that the Warburton Basin K-feldspars are losing argon by diffusive loss in the modern environment. This result is expected given the borehole temperatures observed. Our findings are also consistent with K-feldspar results from the KTB deep scientific borehole in Germany, where contemporary temperatures are in the range of 180–250 °C (Warnock & Zeitler, 1998).

K-feldspar 02-149 records the oldest $^{40}\text{Ar}/^{39}\text{Ar}$ ages. The measured age spectrum shows evidence of excess argon in the first 18% of the gas release (reading the age spectra from left to right). Thereafter, the range of ages increases from around 200 Ma to a maximum of 260 Ma. This oldest recorded age approaches the intrusion age of the granite (Table 1) and suggests that this sample may retain some quantitative temperature information on the basin's early history.

In contrast, K-feldspars 02-147 and 02-152 record dramatically younger ages. The age spectrum of K-feldspar 02-147 is heavily contaminated by excess argon for the first 25% of the gas release and is also characterized by a subtle age maximum at around 45% of the gas release before finally rising to a maximum age of 35 Ma. K-feldspar 02-152 shows an unusual concave-upward age spectrum that increases from around 0 to 100 Ma for the oldest released gas. This spectrum contrasts sharply with that of 02-147 in the initial release. Excess argon contamination is almost imperceptible in 02-152 (constituting less than 8% of the gas released), whereas it dominates the initial release of 02-147. This is the opposite of what one might expect from the texture of the samples (Fig. 3) as the original igneous texture of 02-152 appears to be completely obliterated by granular recrystallization. Such textural reworking, accompanied by strong flushing of the sample by meteoric water of atmospheric composition, may be the reason for the absence of excess argon.

K-feldspars 02-229, 02-230, 02-231 and 02-232 yield age spectra of remarkably similar shape. All samples are contaminated by excess argon in around the first 20% of the gas release. They are also characterized by age spectra that rise to a maximum age at around 30–40% of the gas release before decreasing to younger ages and then increasing monotonically for the higher temperature steps. This intermediate age maximum is well documented in the

literature (e.g. Lovera *et al.*, 2002) and generally characterizes samples that have undergone low-temperature recrystallization and/or low-temperature deformation (e.g.

Warnock & van der Kamp, 1999). Samples 02-229, 02-230 and 02-232 in particular show almost identical age spectra; however, some of this similarity may be the result of

homogenization of sample material from different depths as the drill cuttings are returned to the surface. If this is the case, then the similarity of the results also provides important support for the validity and reproducibility of the analytical method.

THERMAL HISTORY RECONSTRUCTION

The range of microstructures and ages recorded by the samples, together with the known geological constraints, allow some details of the thermal history of the basin to be reconstructed. We have attempted to interpret the age spectra using conventional methods and also by applying the MDD method described by Lovera *et al.* (1989) and Richter *et al.* (1991).

The MDD method assumes that the release of argon is by a thermally activated diffusion process described by the Arrhenius equation. Arrhenius relationships (usually plotted as $\log D_0$ vs. $1/T$, where $D = D_0 \exp[E_a/RT]$, R being the gas constant and E_a is the activation energy) can be calculated for each sample based on the argon loss characteristics during the laboratory experiment, and by assuming a diffusion geometry (in this case a slab-like geometry). The slope of the first released ^{39}Ar gives the E_a (e.g. Dodson, 1973). Current MDD modelling software then performs all subsequent calculations for 10 activation energies normally distributed about this best-fit value. Calculation of the Arrhenius relationship allows a non-unique domain distribution to be determined, which is based directly on the laboratory argon loss characteristics (Lovera *et al.*, 1991). Description of the domains is by volume fraction and relative size (normalized to the size of the largest domain). The calculated domain distribution can then be inverted to yield temperature–time histories, by exposing the calculated domain distribution to the laboratory heating schedule and comparing the results. This process can be performed automatically for monotonic cooling histories, or by an iterative trial-and-error method for re-heating histories. Using an iterative approach, we commence with a guessed thermal history based on the known geological setting and history of the sample. The fit of the modelled and laboratory age spectra are then adjusted by making changes to the input thermal history until the differences between the laboratory and modelled age spectra are minimized and a good match is obtained. In general terms, the uncertainty in determining the activation energy of a particular K-feldspar means that the uncertainty in the modelled temperatures is around $\pm 20^\circ\text{C}$. As noted above, the Big Lake Suite granitic K-

feldspars are at the base of a thick sedimentary pile, such that they have actually experienced a reheating history following intrusion, rather than a cooling history.

As noted in Microstructural Observations and $^{40}\text{Ar}/^{39}\text{Ar}$ Analysis, microstructural observations and the overall shape of the age spectra of K-feldspars 02-147, 02-152, 02-229, 02-230, 02-231 and 02-232 suggest that these samples have been modified by recrystallization (see also Parsons *et al.*, 1999). Thus, we have used the MDD method in a forward modelling sense only in order to explore different scenarios relating to the time and magnitude of the recent argon loss. Inverse modelling to obtain cooling histories on these samples has not been attempted. In contrast, K-feldspar 02-149 does not appear to have experienced significant textural modification, and we are able to perform detailed inverse modelling in order to make inference on the temperature–time history experienced by this sample.

Permo-Jurassic history

Using the iterative trial-and-error method described in the previous section, we are able to produce good fits between the laboratory and modelled age spectra of K-feldspar 02-149 (Fig. 4). The oldest recorded ages in sample 02-149 are around 260 Ma, some 60 Myr younger than the known intrusion age (Gatehouse *et al.*, 1995), and 30–40 Myr younger than the oldest sediments in the overlying basin. As there is no evidence of recrystallization through textural modification of this sample, this observation implies that the sample was open to complete argon loss at some stage before 260 Ma. High temperatures would have been required to reset the K-feldspar and remove any record of cooling associated with the emplacement of the granite (Fig. 5a). The temperature required to outgas K-feldspars depends on the diffusion geometry, the heating rate and the activation energy. Although the precise temperature required to completely outgas the K-feldspar at this time may be subject to debate because of these various contributing factors, it is likely to be in the range of at least $250\text{--}300^\circ\text{C}$. The key observation from this result then is that the sample must have been at relatively high temperatures at this time. We also know that throughout this period (Fig. 2), the granite was being buried beneath the developing Cooper Basin and together these observations imply that the developing sedimentary depocentre was characterized by high geothermal gradients, or extensive hydrothermal conditions without attendant recrystallization, from the mid-Carboniferous until the mid-Triassic.

Fig. 4. Measured $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for K-feldspar samples (a) 02-147; (b) 02-149; (c) 02-152; (d) 02-229; (e) 02-230; (f) 02-231; and (g) 02-232. Each figure shows the measured age against the fraction of ^{39}Ar released for the laboratory results. For K-feldspar 02-149, the best-fit model from the MDD modelling approach is also shown. Note that this model corresponds to the cooling history shown in Fig. 6. Note that the large differences in the ages of adjacent temperature steps are a characteristic pattern indicating contamination due to Cl-derived excess argon (e.g. Harrison *et al.*, 1994). For 02-147, 02-229, 02-230, 02-231 and 02-232, Cl-corrected ages are also shown for this contaminated early released gas. As noted in the text, the corrected ages of around zero indicate recent argon loss.

Fig. 5. (a) Comparison of laboratory age spectrum and a calculated age spectrum for K-feldspar 02-149. Calculated age spectrum (1) shows the case of rapid cooling following granite intrusion with no subsequent temperature rise above 200 °C; ages approaching the age of intrusion of the granite are recorded, reflecting cooling following emplacement. Calculated age spectrum (2) is the best-fit model appropriate to the cooling history shown in Fig. 6 and is shown for comparison. (b) Calculated age spectrum appropriate to an end-member thermal history in which contemporary bottom-hole temperatures have characterized basin evolution since the cessation of sedimentation. Such a scenario would result in significantly more argon loss than that observed, and much younger ages. Thus, temperatures must have increased to measured bottom-hole values in the recent past. All other samples show similar behaviour. Only uncorrected bottom-hole temperature data are available (Table 1). (c) Iterative models illustrating the effect of an increase in temperature at 0.5, 5, 10, 15 Ma on the shape of the age spectrum for K-feldspar 02-229. Models with a temperature increase around 5–10 Ma show best fits for this and other samples.

The spread of ages from 260 to 200 Ma in sample 02-149 suggests slow cooling throughout this interval. Although the lowest temperature experienced by the sample in this period is unconstrained, it is unlikely to have been less than 120 °C based on the thickness of overlying sediment, and thus the cooling rate is likely to have been around 3.5 °C Myr⁻¹. This cooling appears to have occurred *during* burial and sediment accumulation in the overlying Cooper Basin and implies that the decay of the transient high geothermal gradient regime occurred much faster than heating due to increased burial.

The form of the cooling history in the interval between 200 and 100 Ma is not well constrained by this, or any other samples in this study. Apatite fission track analysis suggests a probable thermal peak around 110 Ma, coinciding with the time of increased early Cretaceous sediment deposition in the Eromanga Basin. The magnitude of this temperature peak in particular locations within the basin is dependent on the amount of sediment and the presence

or absence of radiogenic basement rocks. Although our data cannot provide direct evidence for this event, the preservation of ages older than 110 Ma in K-feldspar 02-149 constrains any recent thermal peak to have had a maximum temperature of less than 260 °C.

Recrystallization events

The shape of the age spectra recorded by K-feldspars 02-147, 02-152, 02-229, 02-232, 02-230 and 02-231, together with microstructural observations, suggest that recrystallization events have resulted in the loss of accumulated radiogenic argon within these K-feldspars. We can approximate the timing of these events from the minimum age of the gas in the saddle-shaped part of the spectrum. These ages are 20 Ma (02-147), 55 Ma (02-229), 50 Ma (02-230), 60 Ma (02-232) and 100 Ma (02-231). K-feldspars 02-229, 02-230 and 02-232 give a consistent range of ages from 100 Ma to around 50 Ma. K-feldspar 02-152 records a max-

imum age of 100 Ma. This range of ages points towards variable regional recrystallization events throughout this interval, which corresponds well with the timing of the early Cretaceous Eromanga burial pulse, when the basin was characterized by rapid sediment accumulation and probably structural modification.

The younger ages recorded by K-feldspar 02-147 probably represent a separate recrystallization event, which possibly related to fluid flow along the Warburton–Cooper Basin contact, or minor structural modification associated with Tertiary folding. We do emphasize, however, that the timing of these intervals of recrystallization is only approximate as there is no way of knowing exactly how the distribution of argon within the crystals has been modified by these events. The timing of these events could be more accurately constrained by K/Ar analyses of the muscovite and sericite alteration products growing within the K-feldspars. Such data may also have implications for our understanding of the timing of diagenesis in the basin.

Recent temperature increase

As outlined in $^{40}\text{Ar}/^{39}\text{Ar}$ analysis section, age correction of the first 15–20% of the gas released for all samples (with the exception of K-feldspar 02-152) yields zero ages. These zero apparent ages indicate contemporary $^{40}\text{Ar}^*$ loss, and this is not unexpected given the range of observed bottom-hole temperatures. However, if the present-day temperatures had characterized the basin throughout its evolution, or at least for much of the time since basin sediments stopped accumulating, we would expect very young ages for much of the gas released, as shown in Fig. 5b. We do not observe this and the preservation of older ages is sig-

nificant, implying that the present-day temperatures have been operative for only a short time (Fig. 5). Evidence for a recent increase in geothermal gradient is also recorded by fission track analyses Duddy & Moore (1999) and by vitrinite reflectance data (Kantsler *et al.*, 1986).

To constrain the time of the recent temperature increase, we performed a series of forward modelling experiments using the trial-and-error method described in Thermal History Reconstruction section. For the recrystallized K-feldspars in which the early released gas is contaminated by excess argon, we are looking at the style and shape of the age spectrum in assessing the fit. We assume that the contemporary bottom-hole temperatures represent the peak temperature achieved during any recent temperature increase. For this scenario, models that give best fits to the laboratory data are obtained if we allow that the ambient temperatures in the basin increased to contemporary levels between 5 and 10 Ma (Fig. 5c). If temperatures in the recent past were higher than the contemporary bottom-hole temperatures (i.e. if the temperature anomaly has already begun to decay from its earlier maximum), then the timing of the temperature increase may have been more recent.

Summary

Figure 6 shows a summarized thermal history model for the Warburton, Cooper and Eromanga Basins, as derived from the K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ results.

An extended period of high geothermal gradient conditions, or extensive hydrothermal circulation, has been identified from the middle Carboniferous to the middle Triassic. Temperatures of at least 250–300 °C are needed

Fig. 6. Temperature–time path for the thermal evolution of the Cooper–Eromanga Basin from $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of basement K-feldspars. Events (1)–(4) are best constrained by this method. The dashed lined indicates where unconstrained. We are able to provide upper and lower constraints on the temperature experienced in the interval 220 Ma to *ca.* 10 Ma, and we are able to constrain a further temperature increase between 120 and 80 Ma. The solid lines indicate cooling histories with equally good fits. These cooling histories correspond to the best-fit model for 02-149 shown in Fig. 4.

in this interval in order to reset K-feldspar 02-149 and to remove any record of source cooling. It is likely that these high-temperature conditions are the result of (1) burial of the high heat producing Big Lake Suite granites beneath recently deposited sediments, which are known to be characterized by low thermal conductivity (Periera *et al.*, 1986); (2) periods of transient high geothermal gradient regime associated with at least two pulses of magmatic activity, as suggested by the known intrusive ages of 323 and 298 Ma; and (3) hydrothermal circulation along high permeability zones associated with active extension related to basin formation. We note however, that hydrothermal circulation is a less likely mechanism to account for the high-temperature conditions given that K-feldspar 02-149 shows no evidence for textural modification. Extension via homogeneous lithospheric thinning would induce transient high geothermal gradients, as would any type of structural thinning that would bring the asthenosphere closer to the surface. Modern-day seismic tomography may have the potential to reveal such mantle features; however, such effects would almost certainly result in regional rather than localized heating. Notwithstanding this observation, the highest temperatures would still have been reached in areas directly underlain by Big Lake Suite granites, as in these regions rocks would have seen the added effect of heating due to burial of the high heat-producing granites.

The increase in geothermal gradients in the Tertiary as indicated by our K-feldspar data, and previously identified by Duddy & Moore (1999), Kantsler *et al.* (1986) and Gallagher (1988), is difficult to understand within the known geological framework. As noted by Gallagher (1988), there is no topographic or geophysical evidence to suggest the presence of a deep mantle plume or a localized magmatic intrusion, and the thin and discontinuous Tertiary sediments are also unlikely to have affected a regional increase in geothermal gradient of around $15\text{ }^{\circ}\text{C km}^{-1}$. Increased flow of Great Artesian Basin aquifers in the upper portion of the sedimentary pile (Fig. 2) has been suggested as a source of these increased geothermal gradients (Duddy & Moore, 1999), but fluid flow is not generally suspected to affect such dramatic changes in the thermal regime of broad intracratonic basins in the quasi steady state. Although the origin of this temperature increase remains enigmatic, one possibility is that this heating may have resulted from dramatic changes in the hydrological regime that might have been the result of climate change in the catchment regions (such as a dramatic increase in precipitation) and/or modification of the basin structure that allowed tectonic forcing of the groundwater system (such as the modification of aquifer pathways through unroofing or tilting). Evidence for tectonic activity at this time is likely to be found in the record of neotectonic activity in surrounding basement blocks. Sandiford *et al.* (2004) report an angular unconformity between Miocene and Pliocene sediments in offshore basins in south-eastern Australia and rejuvenated escarpments in the Flinders and Otway Ranges. Sandiford *et al.* (2004) suggest that these observations may point to a significant increase in tectonic activity

throughout south-eastern Australia at around 5–6 Ma and we note that this tectonic activity may also have re-activated weak zones (such as old extensional structures) within the lithosphere below the Cooper Basin. Geodetic work in northern South Australia may be a useful tool in determining the extent of active deformation within the basin.

The thermal history obtained from K-feldspar thermochronology provides contrasting data to that available from apatite fission track analyses. Key differences relate to our understanding of the earliest basin evolution, with the higher temperature sensitivity of the K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronometer potentially allowing the K-feldspars to record details of the earliest basin evolution. It would be interesting to compare the information obtainable from K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology with that obtainable from the higher temperature zircon fission track system. The most useful comparison of the different methods would be made using the same sample sets.

K-feldspar thermochronologic data have shown that the history of the Cooper Basin is most consistent with thermal evolution under high geothermal gradient conditions, where transient thermal spikes associated with hydrothermal circulation also play an important role. We suggest that the heat production enrichment of the Big Lake Suite granites has played an important role in the long-term thermal evolution and is almost certainly responsible for elevated geothermal gradients at shallow depths and the temperatures experienced by our samples, particularly in the earliest stages of the basin evolution. We also emphasize the heterogeneous nature of the thermal regime throughout the Cooper/Eromanga Basin. The basin system is large and is characterized by complex basement topography (Fig. 1) and a heterogeneous distribution of the high heat-producing Big Lake Suite granites. In part, the elevated temperatures may be a localized effect in areas where sediments directly overlay the enriched granites. For example, in the steady state, for each kilometre of additional burial, the temperature in sediments immediately above the highly radiogenic Big Lake Suite granites would increase by 40–50 $^{\circ}\text{C}$, depending on the thickness of the granite and the thermal conductivity of the overlying sediments. Further detail of the distribution of the granites and the lateral variation in heat-producing element enrichment would be needed to evaluate 3-D variations in thermal regime rigorously.

DISCUSSION

The implications of our study are two-fold. First, our results show that K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology from well-chosen samples has the potential to provide useful data for the reconstruction of basin thermal histories. The K-feldspar approach may help to provide basin-scale constraints on the cooling history. It has the potential to serve as a useful reconnaissance tool as well as an appropriate method for detailed analysis; however, we note that it is unlikely to yield useful results in all basin

settings. The presence or absence of evidence for resetting of K-feldspars provides first-order constraints on the maximum temperatures obtained during basin evolution. As K-feldspars of different chemistry commonly have different activation energies, and therefore variable retentivity, the analysis of a suite of K-feldspar samples, for example from detrital K-feldspars from different palaeo-depths in the sedimentary pile, together with K-feldspars from the basement, may allow the full temperature–time history of the basin to be reconstructed. Given the range of likely closure temperature over which K-feldspars are sensitive, the information obtainable using this method is more likely to be of interest to those seeking to understand basin formation and evolution, rather than petroleum maturation.

Second, our results highlight the importance of preliminary microstructural analysis before $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronological studies. For the Warburton Basin, initial microstructural observations were a useful predictor for the quality and type of information obtained from geochronological analysis. Data from clean perthitic K-feldspar help to constrain peak temperature conditions, the basin's early thermal history and recent changes in thermal gradient. Data from altered K-feldspars may help to constrain times of thermal transients, fluid flow and/or recrystallization. Microstructural pre-screening is particularly recommended for detrital K-feldspars from basin sediments, which are more likely to have undergone chemical or textural modification following deposition. In such altered K-feldspars, dating the products of fluid-K-feldspar reactions, such as sericite or chlorite, directly using the K/Ar and/or $^{40}\text{Ar}/^{39}\text{Ar}$ methods may potentially provide details on the timing of recrystallization and/or diagenetic events.

Owing to recrystallization over a long and complex basin history, the MDD model was only applied to one K-feldspar from our study. In regions where recrystallization is less extensive, we would expect that broad application of the MDD model may be particularly powerful in constraining the temperature–time history. The different portions of the thermal history obtained from the K-feldspar and apatite fission track methods reflect the range of temperatures over which the two thermochronometers are sensitive and highlights the need for all available methods to be used for detailed thermal history reconstruction.

ACKNOWLEDGEMENTS

Jamie Burgess and Robert Menpes are thanked for helpful discussions and for sharing their knowledge of the Cooper Basin. John Mya, Robyn Maier, Xiaodong Zhang and Shane Paxton provided much appreciated technical assistance. Mark Harrison and Oscar Lovera are thanked for initial guidance with MDD modelling. John FitzGerald is thanked for assistance with microstructural analysis. Samples from core were obtained with the permission of Pri-

mary Industry and Resources South Australia Petroleum Division. Samples from Habanero-1 were obtained courtesy of Prame Chopra and Fiona Holgate with kind permission of Geodynamics Ltd. Irradiations were undertaken by the Australian Nuclear Science and Technology Organization, through the Australian Institute of Nuclear Science and Engineering. Electron microscopy was performed at the Australian National University Electron Microscopy Unit (EMU) with assistance from staff. S.M. acknowledges the support of an ARC Australian Postdoctoral Fellowship and Discovery Grant. Rene Jonk and Kerry Gallagher are thanked for their detailed reviews of the manuscript. Joe Cartwright is thanked for his editorial handling.

APPENDIX: ANALYTICAL PROCEDURE

Mineral separation was carried out using routine heavy liquid flotation and magnetic methods. All samples were concentrated to better than 99%, with the principal impurities being mineral and fluid inclusions. Samples were sized between 180 and 500 μm using standard mesh sieves.

For the $^{40}\text{Ar}/^{39}\text{Ar}$ analysis, samples were irradiated for either 72 h (K-feldspars 02-147 and 02-152), 576 h (K-feldspar 02-149) or 192 h (K-feldspars 02-229, 02-230, 02-231 and 02-232) in facilities X33 or X34 of the Australian Nuclear Science and Technology Organization HIFAR reactor, Lucas Heights, NSW. All samples were analysed at the Australian National University. The sample can was inverted 180° three times during the irradiation to minimize the effect of the large neutron fluence gradient along the length of the can; a cadmium liner was used to minimize interference from thermal neutrons. Biotite standard GA1550 (with K/Ar age of 98.8 Ma, McDougall & Roksandic, 1974; Renne *et al.*, 1998) was used as the fluence monitor. Supplementary tables containing further details are available from the authors.

During step-heating experiments, the temperature was monitored using a thermocouple at the base of a tantalum crucible within a double-vacuum resistance furnace. Samples were subject to a series of 43 steps at temperatures between 450 and 1450 °C (including many duplicate or triplicate isothermal steps). The schedules of heating times and temperatures for each sample are listed in the supplementary data tables.

After each temperature step, the gas released was exposed to Zr–Al getters to remove all active gases; gettering time in the vacuum line was generally ~10 min. Subsequently, the purified argon was isotopically analysed using a VG 3600 gas source mass spectrometer. Measurement was made using a Daly detector and a photomultiplier with overall sensitivity $3.5 \times 10^{-17} \text{ mol mV}^{-1}$. Corrections for argon produced by interactions of neutrons with K and Ca were made (Tetley *et al.*, 1980). ^{40}K abundance and decay constants are taken from standard values recommended by the IUGS Subcommittee on Geochronology (Steiger & Jäger, 1977).

REFERENCES

- APPEA, (2003). *Development and Production Statistics*. Australian Petroleum Production and Exploration Association Limited, Canberra.
- ARMSTRONG, D. & ALDAM, R. (1995) Economic resources, groundwater. In: *The Geology of South Australia, Vol. 2, The Phanerozoic* (Ed by J.F. Drexel & W.V. Preiss), *S. Aust. Geol. Survey Bull.*, **54**, 126–127.
- BOUCHER, R.K. (2002) Warburton Basin GIS data atlas (CD-ROM). Government of South Australia Report 2001/019, Department of Primary Industries and Resources.
- BURGER, D. (1986) Palynology, cyclic sedimentation, and palaeo-environments in the Late Mesozoic of the Eromanga Basin. In: *Contributions to the Geology and Hydrocarbon Potential of the Eromanga Basin* (Ed by D.I. Gravestock, P.S. Moore & G.M. Pitt), *Geol. Soc. Aust. Spec. Publ.*, **12**, 53–70.
- CHOPRA, P. (2003) The search for hot dry rock energy. *Preview Austral. Soc. Expl. Geophys.*, **107**, 34–36.
- COOK, A.C. (1986) The nature and significance of organic facies in the Eromanga Basin. In: *Contributions to the Geology and Hydrocarbon Potential of the Eromanga Basin* (Ed by D.I. Gravestock, P.S. Moore & G.M. Pitt), *Geol. Soc. Aust. Spec. Publ.*, **12**, 203–220.
- DEIGHTON, I., DRAPER, J.J., HILL, A.J. & BOREHAM, C.J. (2003) A hydrocarbon generation model for the Cooper and Eromanga Basins. *APPEA J.*, **43**, 433–451.
- DREXEL, J.F. & PREISS, W.V. Eds. (1995) *The Geology of South Australia, Vol. 2, The Phanerozoic*. *South Austral. Geol. Survey Bull.*, **54**.
- DRAPER, J.J. (2002) *Geology of the Cooper and Eromanga Basins, Queensland. Queensland Minerals and Energy Review Series*. Queensland Department of Minerals and Energy, Brisbane, Australia.
- DODSON, M.H. (1973) Closure temperature in cooling geochronological and petrological systems. *Contrib. Mineral. Petrol.*, **40**, 259–274.
- DUDDY, I.R. & MOORE, M.E. (1999) Thermal history reconstruction in Cooper–Eromanga Basin wells using Apatite and Zircon Fission Track analysis and vitrinite reflectance. Geotrack Report # 668, Primary Industries and Resources South Australia Open File Envelope 8426.
- DUNLAP, W.J. (2000) Natures diffusion experiment: the cooling-rate cooling-age correlation. *Geology*, **28**, 139–142.
- DUNLAP, W.J. & FOSSEN, H. (1998) Early Paleozoic orogenic collapse, tectonic stability, and late Paleozoic continental rifting revealed through thermochronology of K-feldspars, Southern Norway. *Tectonics*, **17**, 604–620.
- DUNLAP, W.J. & TEYSSIER, C. (1995) Paleozoic deformation and isotopic disturbance in the southeastern Arunta Block, central Australia. *Precambrian Res.*, **71**, 229–250.
- FITZGERALD, J.D. & HARRISON, T.M. (1993) Argon diffusion domains in K-feldspar I: microstructures in MH-10. *Contrib. Mineral. Petrol.*, **113**, 367–380.
- GALLAGHER, K. (1988) The subsidence history and thermal state of the Eromanga and Cooper Basins. PhD Thesis, Australian National University, Canberra, unpublished.
- GATEHOUSE, C.G., FANNING, C.M. & FLINT, R.B. (1995) Geochronology of the Big Lake Suite, Warburton Basin, northeastern South Australia. *Q. Geol. Notes Geol. Survey South Austral.*, **128**, 8–16.
- GRAVESTOCK, D.I., HIBBURT, J.E. & DREXEL, J.F. Eds. (1998) The petroleum geology of South Australia. *Cooper Basin*, Vol. 4. South Australian Department of Primary Industries and Resources, Report Book 98/09.
- HARRISON, T.M., HEIZLER, M.T., LOVERA, O.M., CHEN, W. & GROVE, M. (1994) A chlorine-disinfectant for excess argon released from K-feldspar during step-heating. *Earth Planet. Sci. Lett.*, **123**, 95–104.
- HARRISON, T.M. & BÉ, K. (1983) $A^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum analysis of detrital microclines from the southern San Joaquin Basin, California: an approach to determining the thermal evolution of sedimentary basins. *Earth Planet. Sci. Lett.*, **64**, 244–256.
- HE, S., MIDDLETON, M., KAIKO, A., JIANG, C. & LI, M. (2002) Two case studies of thermal maturity and thermal modelling within the overpressured Jurassic rocks of the Barrow Sub-basin, North-West Shelf of Australia. *Mar. Petrol. Geol.*, **19**, 143–159.
- HILL, A.J. & GRAVESTOCK, D.I. (1995) Late Palaeozoic: Cooper Basin. In: *The Geology of South Australia, Vol. 2 (The Phanerozoic)* (Ed by J.F. Drexel & W.V. Preiss), *South Austr. Geol. Survey Bull.*, **54**, 78–87.
- KANTSLE, A.J., COOK, A.C. & ZWIGULIS, M. (1986) Organic maturation in the Eromanga Basin. In: *Contributions to the Geology and Hydrocarbon Potential of the Eromanga Basin* (Ed by D.I. Gravestock, P.S. Moore & G.M. Pitt), *Geol. Soc. Aust. Spec. Publ.*, **12**, 305–322.
- LOVERA, O.M., GROVE, M. & HARRISON, T.M. (2002) Systematic analysis of K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating results; II, Relevance of laboratory argon diffusion properties to nature. *Geochim. Cosmochim. Acta*, **66**, 1237–1255.
- LOVERA, O.M., RICHTER, F.M. & HARRISON, T.M. (1989) The $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronometry for slowly cooled samples having a distribution of diffusion domain sizes. *J. Geophys. Res.*, **94**, 17917–17935.
- LOVERA, O.M., RICHTER, F.M. & HARRISON, T.M. (1991) Diffusion domains determined from ^{39}Ar released during step-heating. *J. Geophys. Res.*, **96**, 2057–2069.
- MCDUGALL, I. & HARRISON, T.M. (1999) *Geochronology and Thermochronology by the $^{40}\text{Ar}/^{39}\text{Ar}$ Method*, 2nd edn, 269pp. Oxford University Press, New York.
- MCDUGALL, I. & ROKSANDIC, Z. (1974) Total fusion $^{40}\text{Ar}/^{39}\text{Ar}$ ages using HIFAR reactor. *J. Geol. Soc. Aust.*, **21**, 81–89.
- MCLAREN, S., DUNLAP, W.J., SANDIFORD, M. & MCDUGALL, I. (2002) Thermochronology of high heat-producing crust at Mount Painter, South Australia: implications for tectonic reactivation of continental interiors. *Tectonics*, **21**, doi: 2000TC001275.
- MIDDLETON, M.F. (1979) Heat flow in the Moomba, Big lake gas fields of the Cooper Basin and implications for hydrocarbon maturation. *Bulletin of the Australian Society of Exploration Geophysics*, **10**, 149–155.
- MOORE, P.S. & PITT, G.M. (1984) Cretaceous of the Eromanga Basin-implications for hydrocarbon exploration. *APPEA J.*, **24**, 358–376.
- NEUMANN, N., SANDIFORD, M. & FODEN, J. (2000) Regional geochemistry and continental heat flow: implications for the origin of the South Australian heat flow anomaly. *Earth Planet. Sci. Lett.*, **183**, 107–120.
- PANKHURST, R.J., MOORBATH, S., REX, D.C. & TURNER, G. (1973) Mineral age patterns in ca. 3700 my old rocks from West Greenland. *Earth Planet. Sci. Lett.*, **20**, 157–170.
- PARSONS, I., BROWN, W.L. & SMITH, J.V. (1999) $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology using alkali feldspars: real thermal history or mathematical mirage of microtexture? *Contrib. Mineral. Petrol.*, **136**, 92–110.
- PERIERA, E.B., HAMZA, V.M., FURTADO, V. & ADAMS, J.A.S. (1986) U, Th and K content, heat production and thermal con-

- ductivity of Sao Paulo, Brazil, continental shelf sediments: a reconnaissance work. *Chem. Geol.*, **58**, 217–226.
- POWELL, T.G., BOREHAM, C.J., MCKIRDY, D.M., MICHAELSEN, B.H. & SUMMONS, R.E. (1989) Petroleum geochemistry of the Murta Member, Mooga Formation, and associated oils, Eromanga Basin. *APPEA J.*, **29**, 114–129.
- QUIDELLEUR, X., GROVE, M., LOVERA, O.M., HARRISON, T.M., YIN, A. & RYERSON, F.J. (1997) The thermal evolution and slip history of the Renbu Zedong Thrust, southeastern Tibet. *J. Geophys. Res.*, **102**, 2659–2679.
- RENNE, P.R., SWISHER, C.C., DEINO, A.L., KARNER, D.B., OWENS, T.L. & DEPAOLO, D.J. (1998) Intercalibration of standards, absolute ages and uncertainties in $^{40}\text{Ar}/^{39}\text{Ar}$ dating. *Chem. Geol.*, **145**, 117–152.
- RICHTER, F.M., LOVERA, O.M., HARRISON, T.M. & COPELAND, P. (1991) Tibetan tectonics from $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of a single K-feldspar sample. *Earth Planet. Sci. Lett.*, **105**, 266–278.
- SANDIFORD, M. & HAND, M. (1998) Controls on the locus of Phanerozoic intraplate deformation in central Australia. *Earth Planet. Sci. Lett.*, **162**, 97–110.
- SANDIFORD, M. & McLAREN, S. (2002) Tectonic feedback and the ordering of heat producing elements within the continental lithosphere. *Earth Planet. Sci. Lett.*, **204**, 133–150.
- SANDIFORD, M., WALLACE, M. & COBLENTZ, D. (2004) Origin of the in situ stress field in south-eastern Australia. *Basin Res.*, **16**, 325–338.
- STEIGER, R. & JÄGER, E. (1977) Subcommittee on geochronology: convention on the use of decay constants in geo- and cosmochronology. *Earth Planet. Sci. Lett.*, **36**, 359–362.
- SUN, X. (1997) Structural style of the Warburton Basin and control in the Cooper and Eromanga Basins, South Australia. *Expl. Geophys.*, **28**, 333–339.
- TAYLOR, S.R. & McLENNAN, S.M. (1985) *The Continental Crust: Its Composition and Evolution*. Blackwell Scientific Publications, Oxford.
- TETLEY, N., McDOUGALL, I. & HEYDEGGER, H.R. (1980) Thermal neutron interferences in the $^{40}\text{Ar}/^{39}\text{Ar}$ dating technique. *J. Geophys. Res.*, **85**, 7201–7205.
- THORNTON, R.C.N. (1979) Regional stratigraphic analysis of the Cooper Basin, Australia. *South Austr. Geol. Survey Bull.*, **49**, 1–140.
- TINGATE, P.R. & DUDDY, I.R. (2002) The thermal history of the Eastern Officer Basin (South Australia); evidence from apatite fission track analysis and organic maturity data. *Tectonophysics*, **349**, 251–275.
- WARNOCK, A.C. & VAN DER KAMP, P.C. (1999) Hump-shaped $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra in K-feldspar and evidence for Cretaceous authigenesis in the Fountain Formation near Eldorado Springs, Colorado. *Earth Planet. Sci. Lett.*, **174**, 99–111.
- WARNOCK, A.C. & ZEITLER, P.K. (1998) $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronometry of K-feldspar from the KTB borehole, Germany. *Earth Planet. Sci. Lett.*, **158**, 67–79.

Manuscript received 20 June 2005; Manuscript accepted 29 March 2006.

SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article online:

Appendix S1 contains heating schedules, measured isotopic ratios and calculated ages for each step-heating experiment performed.

This material is available as part of the online article from <http://www.blackwell-synergy.com>