# High radiogenic heat–producing granites and metamorphism—An example from the western Mount Isa inlier, Australia

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## ABSTRACT

**The origins of metamorphism (~600 °C and 3–4 kbar) in the western Mount Isa inlier, Australia, remain controversial for a number of reasons. (1) No synmetamorphic intrusive bodies can be recognized; (2) high temperatures appear to be sustained for periods >100 m.y.; and (3) metamorphism follows an extended phase of thermal subsidence. We show that the burial of granite batholiths enriched in radiogenic elements beneath the thick insulating sedimentary succession of the Mount Isa Group (deposited in response to repeated rift-sag cycles) was capable of generating steep upper crustal thermal gradients immediately prior to the Isan orogeny. These gradients are appropriate to peak metamorphic conditions, such that the ensuing Isan orogeny required no significant additional heat input. This result is significant in that it may provide a mechanism for understanding the origins of high-temperature metamorphism in other terranes where the involvement of transient heating is not obvious.**

## INTRODUCTION

The processes driving high-temperature metamorphism at low to intermediate pressure have been the subjects of many studies, and are fundamental to our understanding of crustal behavior. Because crustal heat generation rates are normally considered to be too low to promote heating, such metamorphism is generally regarded as a consequence of the transient advection of heat from depth during magma ascent (De Yoreo et al., 1991; Karlstrom and Williams, 1995). However, it has become increasingly clear that such metamorphism is not always transient (Hodges et al., 1994; Williams et al., 1995). A notable example is in the vicinity of the Sybella batholith, western Mount Isa inlier, Australia (Fig. 1), where Mesoproterozoic metamorphism culminated in peak conditions of ~600 °C and ~4 kbar (Rubenach, 1992), reflecting average upper crustal thermal gradients of ~40 °C/km. Despite an apparent spatial association between metamorphic grade and the Sybella batholith, there is an ~130 m.y. delay between granite intrusion and peak regional metamorphism (Connors and Page, 1995). Moreover, Ar-Ar mineral closure ages suggest that elevated geothermal gradients were sustained for >100 m.y. (Perkins et al., 1999). These data prohibit a primary role for advective heat transfer during granite emplacement and raise concerns about (1) what source provided thermal energy to drive metamorphism and (2) why there is a spatial association between the batholith and the metamorphic isograds (Fig. 1).

We show that the generation of steep upper crustal thermal gradients can be attributed to burial of high heat–producing granites beneath an insulating cover sequence during a prolonged period of rift-related subsidence. We begin with an analysis of the setting and nature of metamorphism and then present a compilation of heat flow, heat production, and thermal conductivity data in order to constrain thermal regimes at the onset of the Isan orogeny. This analysis forms the basis for a discussion of the origins of high-temperature metamorphism in this and other Proterozoic terranes.

## GEOLOGY OF THE WESTERN MOUNT ISA INLIER

The Mount Isa inlier is a Paleoproterozoic-Mesoproterozoic metamorphic and igneous complex in northwest Queensland (Fig. 1) consisting of the Western, Kalkadoon-Leichhardt, and Eastern fold belts (Blake and Stewart, 1992). The Western fold belt records contractional and extensional events involving 1840–1660 Ma basement and 1660–1630 Ma cover sequences. The Paleoproterozoic history records both rift- and sag-phase sedimentation, in five major periods of extension (O'Dea et al., 1997). The Sybella batholith, currently ~3 km thick (Drummond et al., 1998), was emplaced into the Leichhardt River fault trough, a tectonic subdivision of the Western fold belt, at a depth of only a few kilometers during a 1660 Ma rifting event (O'Dea et al., 1997). It was subsequently buried beneath the Isa basin, a sedimentary succession ~13 km thick (Scott et al., 1999) (Fig. 2). Although only ~5 km of this sedimentary cover is preserved in the Leichhardt River fault trough, correlative sections south of the

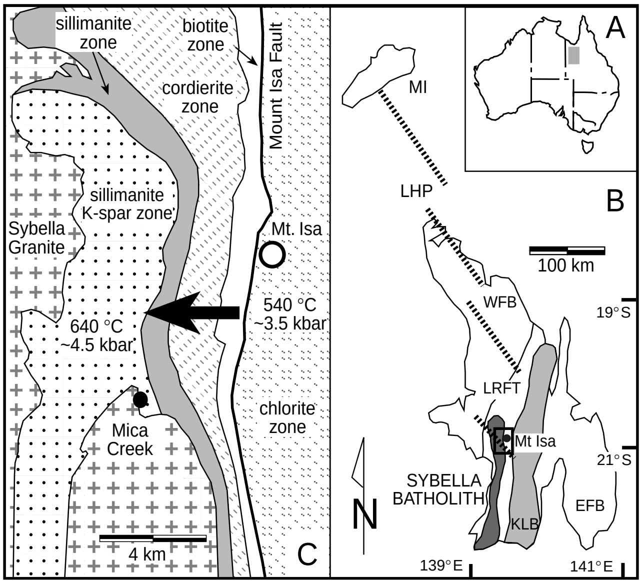

**Figure 1. A: Location of Mount Isa inlier in northwest Queensland, Australia. B: Structural domains of Mount Isa area (after Blake and Stewart, 1992) and section lines used for construction of Figure 2. WFB—Western fold belt (including Leichhardt River fault trough [LRFT]), KLB—Kalkadoon-Leichhardt fold belt, EFB—Eastern fold belt, MI—Murphy inlier, and LHP—Lawn Hill platform. C: Isograd structure around northeastern Sybella batholith, immediately west of Mount Isa city (area is indicated by small square in B) (after Rubenach, 1992).**

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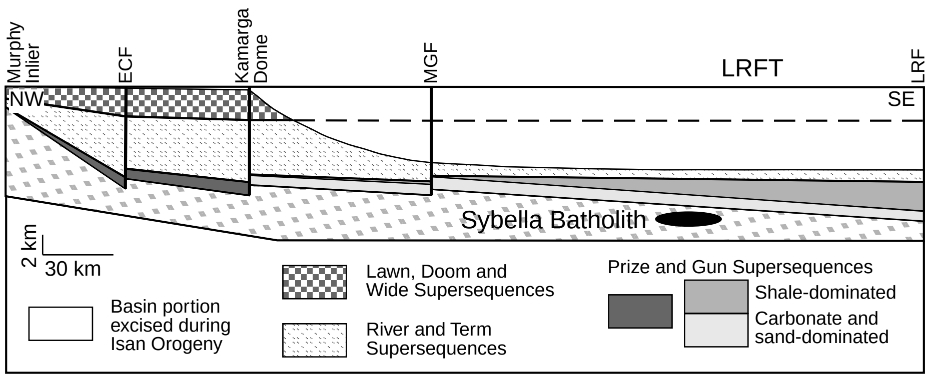

**Figure 2. Composite geometry of Isa basin immediately prior to Isan orogeny (ca. 1530 Ma) compiled using seismic and outcrop data of Deborah Scott. Section constructed oblique to strike, northwest-southeast from Murphy inlier to Western fold belt–Kalkadoon-Leichhardt fold belt boundary; individual section localities are shown in Figure 1. Supersequence terminology is from Scott et al. (1999). Thicknesses at Mount Gordon (MGF) and in Leichhardt River fault trough (LRFT) are minimum estimates, based on preserved thicknesses at Kamarga dome. Basin width includes estimate of subsequent orogenic shortening. Sequences deepen and fine to south and east and, in Leichhardt River fault trough, River, Term, Lawn, Doom, and Wide supersequences are inferred to be 70%–80% fine-grained clastic material. Most dramatic basin inversion, and consequently most eroded part of basin, is area in easternmost Leichhardt River fault trough. ECF—Elizabeth Creek fault, LRF—Leichhardt River fault.**

Murphy inlier (Fig. 1) and in the Eastern fold belt imply continuity of an extensive preorogenic basin (Peter Southgate, 1998, personal commun.) throughout the Western fold belt. The subsidence history was terminated by the Isan orogeny (Blake and Stewart, 1992), during which contractional deformation was partitioned strongly into the Leichhardt River fault trough, the deepest portion of the preorogenic basin.

Isan orogeny metamorphism in this region is defined by regionally extensive intermediate- to high-temperature and low- to intermediate-pressure assemblages and elevated field gradients (Rubenach, 1992). Counterclockwise pressure-temperature paths show prograde heating through the andalusite field. Peak metamorphism is dated, by U-Pb zircon methods on a locally derived partial melt, as 1532 ± 7 Ma (Connors and Page, 1995). Mineral textures, including retrograde kyanite, indicate an isobaric or slightly decompressional cooling history (Rubenach, 1992). The absence of pressure-sensitive assemblages does not allow a precise cooling path to be constrained; however, $^{40}$Ar-$^{39}$Ar muscovite ages at Mica Creek (Fig. 1) suggest cooling rates of ~1.5 °C/m.y. in the period from peak metamorphism to ca. 1400 Ma (Perkins et al., 1999).

On a regional scale, isograds cut across the north-plunging Sybella batholith with greenschist facies assemblages in the north and upper amphibolite assemblages in the south. In the Mica Creek area isograds are parallel to the Mount Isa fault and its equivalents and displacements of ~1.5 km (Drummond et al., 1998) across these faults contribute to extraordinary metamorphic field gradients of ~50 °C/km (Fig. 1). No significant synmetamorphic mafic or felsic bodies have been identified at depth (Drummond et al., 1998) or in outcrop, and peak metamorphism is thought to have occurred during regional shortening that followed an extended period of postrift subsidence, associated with deposition of the upper Mount Isa Group (O'Dea et al., 1997).

TABLE 1. GEOCHEMISTRY AND HEAT PRODUCTION, WESTERN MOUNT ISA INLIER

| Lithology | U (ppm) | Th (ppm) | $K_2O$ (wt%) | $Q$ (μWm$^{-3}$) | $Q^*$ (μWm$^{-3}$) |
|---|---|---|---|---|---|
| Sybella batholith | | | | | |
| Main phase (31) | 8 | 35 | 5.07 | 5.12 | 6.86 |
| Beta-qz phase (14) | 8 | 33 | 5.38 | 5.01 | 6.77 |
| Microgranite (12) | 12 | 54 | 5.81 | 7.62 | 10.00 |
| Big Toby Granite (4) | 5 | 19 | 3.61 | 3.03 | 4.16 |
| Sedimentary cover | | | | | |
| Sandstones and conglomerates (288) | 2 | 8 | 2.00 | 1.39 | 1.82 |
| Siltstones and shales (317) | 6 | 8 | 4.30 | 3.37 | 3.82 |
| Carbonates (1176) | 2 | 3 | 1.50 | 0.75 | 1.31 |

*Note:* $Q$ = present heat production; $Q^*$ = heat production at time of peak metamorphism (ca. 1550 Ma). The number in parentheses is the number of samples analyzed.

## MODERN HEAT-FLOW–HEAT-PRODUCTION RELATIONS IN THE WESTERN MOUNT ISA INLIER

Evaluation of the causes of metamorphism requires an assessment of the thermal structure of the lithosphere prior to metamorphism. This can be aided by analysis of modern-day heat-flow–heat-production relations and the thermal conductivity structure of the crust. The Mount Isa inlier is characterized by elevated heat flow of ~80 mWm$^{-2}$ (Hyndman and Sass, 1966). Although this is not unusual in the context of Australian Proterozoic terranes that average 85 mWm$^{-2}$ (Cull, 1982), it is when compared to equivalent-aged terranes elsewhere in the world (Cull, 1982). Seismic data indicate that the lithosphere beneath the Mount Isa inlier, along with other Australian Proterozoic terranes, is characterized by relatively high upper mantle velocities associated with an exceptionally thick lithosphere of ~250–300 km (Zielhaus and van der Hilst, 1996). Relatively high upper mantle velocities imply relatively low temperatures, and for such thick lithosphere we might expect mantle heat flows of 10–20 mWm$^{-2}$. For this to be consistent with the high surface heat flows, the crust must be exceptionally enriched in heat production, contributing as much as 60–70 mWm$^{-2}$. Calculated heat production values support the idea that the Mount Isa crust is exceptionally enriched in heat-producing elements, and that this enrichment is localized in discrete levels near the present surface. Average heat production in the Sybella batholith is ~5 μWm$^{-3}$ and in some individual stocks is as high as 10 μWm$^{-3}$ (Table 1; Fig. 3). Seismic data (Drummond et al., 1998) show that beneath the Sybella batholith the Big Toby granite forms a sheet ~5 km thick that has heat production of ~3.5 μWm$^{-3}$ (Table 1). The fundamental importance of these values is highlighted by the fact that, on the basis of thickness estimates, the Sybella and Big Toby granites contribute >30 mWm$^{-2}$ to the modern surface heat flow and that, in the Mesoproterozoic, this would have been ~30% greater (Table 1). Average heat production in the remaining ~30 km of crust of only 1 mWm$^{-3}$ would account for the observed surface heat flow.

## THERMAL REGIMES AT THE ONSET OF THE ISAN OROGENY

From the point of view of the metamorphic evolution, it is useful to consider the thermal regimes that would result from such heat-production distributions at the onset of the Isan orogeny, following accumulation in the Isa basin. Given that the sediments of the Isa basin accumulated over an interval of about 130 m.y. preceding the Isan orogeny, it is likely that the lithosphere was close to conductive thermal equilibrium. Assuming that heat conduction is only in the vertical direction, the temperature at any depth, $z$, reflects the heat flow at that depth, $q_z$, contributed by deeper sources, as well as the thermal conductivity, $k_s$, and heat production, $H_s$, of the overlying sequence. Assuming that the thermal properties of the overlying sequence are largely independent of depth, then the temperature at depth $z$ can be approximated by:

$$T_{(z)} \sim \frac{z}{k_s}\left(q_z + \frac{H_s z}{2}\right). \qquad (1)$$

By the onset of the Isan orogeny the Sybella batholith was buried beneath ~13 km of Mount Isa Group sedimentary rocks and several kilometers of older sedimentary and volcanic rocks. This implies that the metamorphic pressures recorded in the vicinity of the Sybella batholith (~4 kbar) are largely explicable in terms of burial during sedimentation, with some additional contribution due to crustal thickening during deformation. The present-day surface heat flow provides insight into the magnitude of $q_z$, although it may differ because (1) radioactive decay has caused a reduction in the concentration of heat sources by ~30% since ca. 1500 Ma; (2) the heat flow contributed from the mantle, $q_m$, may have changed; and (3) the Isan orogeny increased the total heat production of the crustal columns due to crustal shortening of ~30%–40%. Points 1 and 3 cancel, at least to the first order, and it seems unlikely that at the onset of the Isan orogeny $q_m$ could have been much lower than the modern-day values. Therefore we consider that the present surface heat flow $q_s$ (~80 mWm$^{-2}$) provides a conservative estimate for $q_z$ ($z$ = 15 km) at the onset of the Isan Orogeny.

The temperature at depth $z$ is strongly dependent on the thermal properties of the overlying sequence. Table 2 shows thermal conductivity data for the main sequences of the Isa basin. The average thermal conductivity estimate of ~2.6 Wm$^{-1}$K$^{-1}$ was obtained by weighting the thermal conductivities of each sequence by relative thickness. This relatively low value reflects the dominance of fine-grained clastic sediments. The thermal conductivity of recent and diagenetic sediments is as much as 25%–50% lower than their lithified equivalents due to the effects of porosity, elevated temperature, and water saturation (Periera et al., 1986). Our samples of lithified sequences therefore provide an upper bound on the conductivity of the sediments following deposition. The weighted average using data from unlithified equivalents is 1.4 Wm$^{-1}$K$^{-1}$ (Table 2). Given that significant diagenetic alteration already occurred during progressive burial, the thermal conductivity at the onset of the Isan orogeny is likely to have been between the lithified and unlithified estimates. We adopt a likely range of thermal conductivities ~12%–25% lower than the weighted average lithified values (i.e., 2.0–2.3 Wm$^{-1}$K$^{-1}$). Geochemical data (Table 1) and calibrated airborne radiometric data (Fig. 3) constrain heat production for the preserved components of the sedimentary cover to be ~2–3 μWm$^{-3}$ at the time of metamorphism.

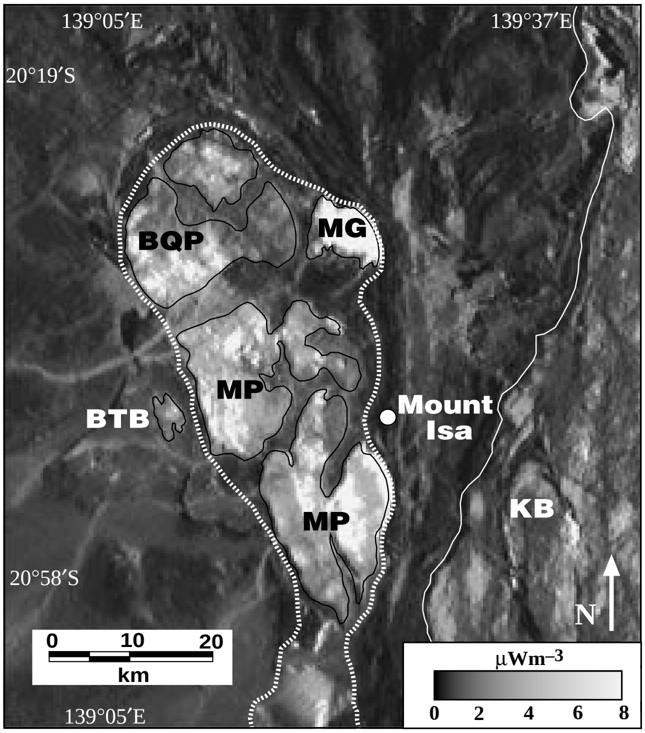

**Figure 3. Heat production of northern Sybella batholith (μWm$^{-3}$) around time of peak metamorphism. Heat-production values are calculated from calibrated radiometric data. All values above 8 μWm$^{-3}$ (to maximum of ~16 μWm$^{-3}$) are shown in white. Approximate outcrop extents of Sybella batholith are shown and include MG—microgranite phase, BQP—beta-quartz phase, MP—main phase, BTB—Big Toby Granite. Kalkadoon batholith (KB) to east also shows elevated heat production.**

Figure 4 shows predicted temperatures at 15 km as a function of $H_s$, $k_s$, and $q_z$. High temperatures and high geothermal gradients are favored by high $H_s$ and low $k_s$, and enhanced by crustal thickening during deformation. On the basis of the outlined constraints, plausible temperatures are in the range ~550–700 °C and imply that the accumulation of the Isa basin was sufficient to generate the thermal and baric conditions appropriate to the ensuing metamorphism.

## DISCUSSION

Thermal regimes developed beneath basins are dependent on the heat production of the basement as well as the thermal conductivity of the overlying sedimentary succession. For the western Mount Isa inlier, field gradients (when throw on known faults is considered) and recorded peak metamorphic conditions are compatible with the thermal gradients expected to result from the accumulation of thick insulating sequences of the

TABLE 2. AVERAGE THERMAL CONDUCTIVITY, ISA BASIN

| Sequence and Lithology | Estimated thickness (km) | Estimated thickness (%) | Conductivity (Wm$^{-1}$K$^{-1}$) Case 1* | Conductivity (Wm$^{-1}$K$^{-1}$) Case 2† | Heat production (μWm$^{-3}$) |
|---|---|---|---|---|---|
| P&G Shale | 2.8 | 21.6 | 2.3 | 1.20 | 3.37 |
| P&G Carbonate | 0.4 | 2.9 | 3.0 | 1.77 | 0.75 |
| P&G Sand | 0.6 | 4.3 | 3.5 | 2.00 | 1.39 |
| R&T Shale | 4.8 | 36.8 | 2.3 | 1.20 | 3.37 |
| R&T Sand | 1.2 | 9.2 | 3.5 | 2.00 | 1.39 |
| L,D&W Shale | 2.0 | 15.2 | 2.3 | 1.20 | 3.37 |
| L,D&W Sand | 1.3 | 10.1 | 3.5 | 2.00 | 1.39 |
| Total/Average | 13.05 | 100 | 2.6§ | 1.4§ | 2.8§ |

*Note*: Measured thermal conductivity data for Case 1 are from samples within the currently accepted lithological framework. Where a supersequence contains more than one type of each lithological unit, preference in calculating an approximate supersequence average is given to the freshest sample of each lithology. Supersequence terminology is from Scott et al. (1999). P&G, Prize and Gun, R&T, River and Term, and L,D&W, Lawn, Doom and Wide; see also Figure 2.

* Case 1—Measurements on lithified (and in some cases metamorphosed) outcrop or drillcore samples at 25 °C using a standard divided-bar apparatus; the maximum thermal conductivity of the preorogenic basin.

† Case 2 uses recent sedimentary thermal conductivities (Periera et al., 1986).

§ Average thermal conductivity and heat production values are weighted averages based on proportional vertical thickness by lithology. Heat production values are taken from Table 1.

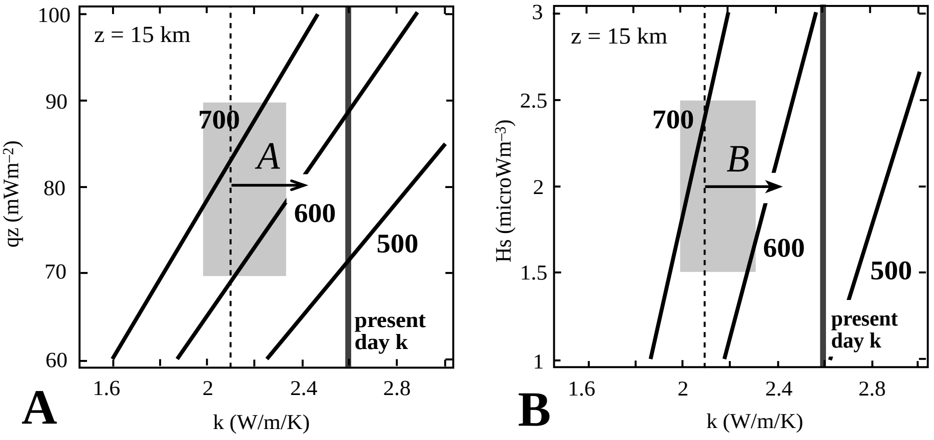

**Figure 4. Dependence of crustal temperatures at $z$ = 15 km on thermal conductivity of upper sedimentary sequence, $k$, and (A) integrated crustal heat flow, $q_z$, and (B) additional heat production in sedimentary pile, $H_s$. Shaded region is that area defined by known constraints on each parameter at time of metamorphism; present-day thermal conductivity is shown at 2.6 Wm$^{-1}$K$^{-1}$. Arrows *A* and *B* show temperature reduction due to 15% increase in average thermal conductivity of basin, from ~2.1 to 2.4 Wm$^{-1}$K$^{-1}$, illustrating possibility of mid-crustal cooling associated only with diagenesis of sedimentary cover.**

Isa basin above basement that contributes ~80 mWm$^{-2}$ (including $q_m$). Such high geothermal gradients are likely to occur wherever such conditions are met, and the data from Mount Isa imply that any understanding of the thermal energy budgets of high-temperature metamorphic terranes, regardless of tectonic setting, warrants detailed understanding of variations of heat production and thermal conductivity parameters at the crustal scale.

Our interpretation raises the important question of what terminated the metamorphism. At Mount Isa, metamorphic recrystallization is clearly associated with the Isan orogeny, which represents a major basin-inversion event, during which contractional deformation was localized in the deepest and hottest parts of the basin. We believe that the association between basin inversion and thermal regimes is not fortuitous, but reflects long-term thermal weakening of the lithosphere attendant with basin development on a radioactive basement. What causes the cooling that terminates metamorphism and, more particularly, the near-isobaric cooling that is interpreted to have occurred in the western Mount Isa inlier? Ultimately, basin inversion during the Isan orogeny lead to the unroofing of the high heat–producing granites from beneath the Isa basin. In a manner analogous to the mechanism we have proposed during basin accumulation, this unroofing must ultimately cause dramatic cooling. However, the origin of the near-isobaric cooling remains enigmatic. One intriguing possibility is suggested by the role played by the thermal conductivity of the overlying sediment. The conductivity of a thick sedimentary pile will show both depth and time dependence. The time dependence will inevitably lead to an increase in thermal conductivity (at a given temperature) as diagenesis proceeds, while the depth dependence means that the bulk conductivity of the sedimentary succession is sensitive to the shallowest and most insulating sections. Either the progressive diagenesis of this uppermost section or its removal during progressive basin inversion would be expected to lead to significant cooling of the deeper lithosphere with relatively minimal pressure changes. For the Isa basin, removal of 2 km of sediment with thermal conductivity significantly below the average basin value would lead to cooling of ~100 °C with a corresponding pressure decrease of only ~0.5 kbar, unresolvable using modern geobarometric techniques. Similarly, an increase in the bulk conductivity of the entire sedimentary column of 15% would induce cooling of ~80 °C (Fig. 4). In either case, cooling would be more than sufficient to account for the observed post-peak pressure-temperature record and suggests that the time scales of cooling recorded by the $^{40}$Ar-$^{39}$Ar data reflect either (1) the denudation that follows basin inversion or (2) the evolution of thermal conductivity in a deforming sedimentary basin.

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