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Evidence for shear heating, Musgrave Block, central Australia

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Abstract

The phenomenon of shear-heating is generally difficult to recognise from petrologic evidence alone. Establishing that shear zones attain higher temperatures than the surrounding country rocks requires independent evidence for temperature gradients. In the Musgrave Block, central Australia, there is a clear spatial association between shear zones and interpreted elevated temperatures. Eclogite facies shear zones that formed at ~550 Ma record temperatures of ~650–700°C. Outside the high-pressure shear zones, minerals with low closure temperatures such as biotite (~450°C in the ^{40}Ar–^{39}Ar and Rb–Sr systems), preserve ages >800 Ma, suggesting that these rocks did not experience temperatures greater than about 450°C at ~550 Ma for any extended period. Thus, the shear zones record temperatures that are ~200°C higher than the surrounding country rocks. Simple calculations show that the combination of relatively high shear stresses (~100 MPa) and high strain rates (~10^{-11} s^{-1}) for short durations (<1 Ma) can account for the observed apparent temperature variations. The evidence indicates that shear heating is the dominant mechanism for localised temperature increases in the shear zones, while the country rock remained at relatively lower temperatures.

1. Introduction

Shear heating refers to the transformation of mechanical work into heat during progressive deformation. Along brittle faults, at shallow crustal levels, heat is produced by friction in shear zones (as evidenced by pseudotachylytes), whereas at deeper crustal levels heat produced by mechanical energy generally is dissipated during viscous flow. Considerable uncertainty exists regarding the amount of heat which can be generated via shear heating for geologically realistic rheologies and strain rates. Consequently, the role of shear heating as a heat source for metamorphism and anatexis remains controversial (Barton and England, 1979; Molnar et al., 1983).

Several studies have investigated the thermal effects of shear heating based on theoretical considerations (Molnar and England, 1990; Peacock, 1992; Stüwe, 1998), with most attention being focused on systems involving differential vertical movement. Thus, shear heating has been invoked to explain inverted isograds (England and Molnar, 1993) and to explain partial melting of the subducting slab in subduction zones (England and Molnar, 1990; Peacock et al., 1994; Harrison et al., 1997). However, Leloup and Kienast (1993) suggested that shear-heating may also be important in strike-slip systems.

It is difficult to recognise the effects of shear-heating, because it requires that the shear zone attains a higher temperature than the surrounding country rocks for sufficiently long periods for solid-state phase transformations to occur. The evidence for shear heating is commonly indirect. For example, the presence of inverted isograds across major fault zones has been suggested by some as evidence for the dissipation of heat during shearing (Scholz, 1980). Here we present petrological and isotopic evidence for shear heating at eclogite facies conditions in the Musgrave Block, central Australia, involving a clear spatial association between the shear zones and interpreted elevated temperatures.

2. Regional setting

The Musgrave Block consists of the Meso-Neoproterozoic granulite-facies Fregon and amphibolite-facies Mulga Park subdomains. An episode of granulite and amphibolite-facies metamorphism is constrained by U-Pb SHRIMP zircon ages at ~1180 Ma and occurred at pressures of ~8 and ~5 kbar, respectively (Camacho and Fanning, 1995). The two subdomains were juxtaposed during the Petermann Orogeny around 550 Ma, with the granulites thrust over the amphibolite facies gneisses on the gently south-dipping

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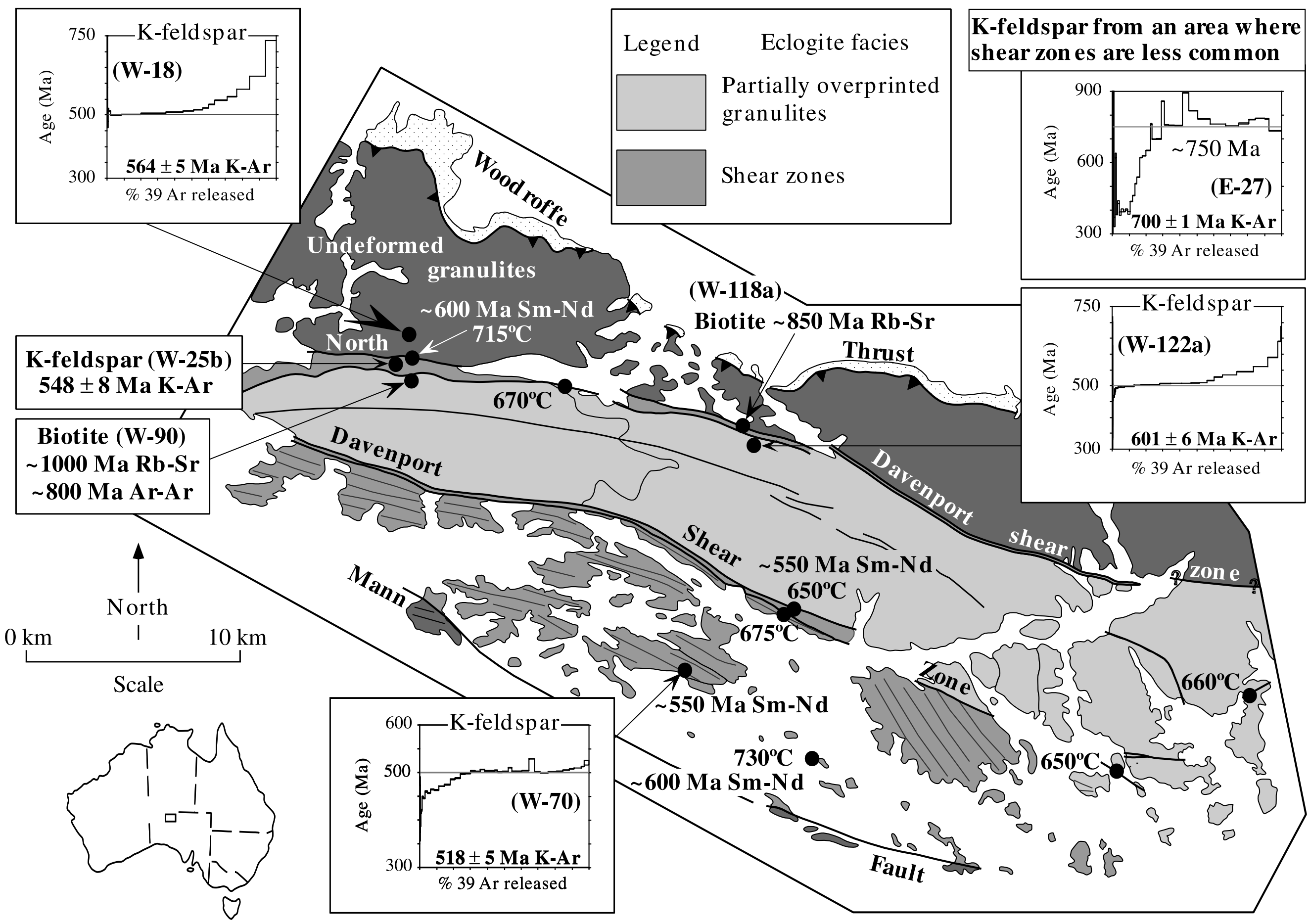

Fig. 1. Geological map of the Mount Woodroffe area showing temperature estimates and mineral ages for the block between the Woodroffe Thrust and the Mann Fault. Modified after Major (1973).

Woodroffe Thrust (Collerson et al., 1972; Maboko et al., 1992). The Fregon Subdomain is dominantly quartzofeldspathic gneiss, whereas the Mulga Park Subdomain mainly consists of granite with a few screens of amphibolite and metasediment.

The Musgrave Block was heterogeneously overprinted during the Petermann Orogeny, with zones of high-strain concentrated along broadly east–west striking shear zones. These high-strain zones formed under eclogite-to-greenschist facies conditions and have strike-slip and reverse movement. The major shear zones (Fig. 1) are: (1) the Woodroffe Thrust, (2) the North Davenport shear zone, and (3) the Davenport Shear Zone. Farther south is the poorly exposed Mann Fault.

These shear zones form part of a strike-slip related, crustal-scale, flower structure (Camacho and McDougall, 2000), of the kind postulated for the Alps and Pyrenees in Europe (e.g., Choukroune et al., 1990). This kind of model can account for the rapid burial and exhumation of the granulite facies gneisses during the Petermann Orogeny. Oblique convergence caused part of the Musgrave Block (mainly the Fregon Subdomain) to be buried in a transpressional environment. These strike-slip shear zones penetrate into the mantle, causing the observed gravity anomalies (Lambeck and Burgess, 1992). The burial to deeper crustal levels produced the observed high-pressure mylonites. These early shear zones locked up and movement was then transferred northwards to form new shear zones that began to bring these early shear zones to shallower crustal levels.

Eclogite-facies ($T = 650$°C and $P = 12$ kbar; Ellis and Maboko, 1992), high-strain, deformation is confined to the granulite-facies Fregon Subdomain (Fig. 1; Camacho et al., 1997). The granulites between the North Davenport and Davenport shear zones are variably overprinted by the eclogite-facies deformation, with high-strain bands, up to 50 m thick, truncating and deflecting the granulite foliation.

The Davenport shear zone is a strike-slip system up to 10 km wide that formed at eclogite facies conditions. The lineation in the shear zone is subhorizontal and shear sense indicators suggest that movement was sinistral and dextral. Sm–Nd mineral isochrons obtained from high-pressure assemblages, as well as ^{40}Ar–^{39}Ar data, show that the eclogite facies high-strain overprint occurred $\sim$550 Ma (Camacho et al., 1997).

The eclogite facies North Davenport shear zone, the focus of this study, is up to 500 m wide and consists of mylonitised and ultramylonitised granulite facies gneiss, charnockite and dolerite. It dips about 50° to the south and has a strong rodding lineation that plunges around 10–40° to the southeast. Asymmetrical folds and folded feldspar grains all suggest dextral reverse movement. Along the margins of the North Davenport shear zone, the trend of the granulites and ~800 Ma dolerite dykes (Zhao and McCulloch, 1993) rotate into parallelism with the mylonitic foliation until it eventually becomes parallel with the shear zone. These dykes become partially-to-completely recrystallised into high-pressure assemblages in the vicinity of the mylonitic zones. Significantly, granulite facies pressure estimates of ~8 kbar on either side of the North Davenport shear zone are within error (±1 kbar), which limits the vertical displacement between the two blocks to less than ~3 km.

3. Evidence for shear heating

3.1. Thermometry

The degree of re-equilibration in shear zones depends on a number of parameters such as strain rate, grain size, fluid activity and composition (e.g., Austrheim and Griffin, 1985). Gneisses within the North Davenport shear zone preserve most of the original granulite facies mineralogy, with the exception of the finer grained dolerites, which are completely recrystallised. Consequently, these dolerites were investigated for pressure and temperature evaluation. The mylonitised dolerites have the overprinting assemblage of garnet + clinopyroxene + albite + rutile + quartz. The minerals are fine grained (~50 μm in diameter), unzoned and yield temperature estimates from ~650 to ~700°C (Table 1) using garnet–clinopyroxene Fe–Mg exchange thermometers (Ellis and Green, 1979; Powell, 1985; Krogh, 1988). Because garnet and clinopyroxene grew during the high-strain deformation, the temperature estimates of around 650–700°C (Fig. 1) are considered to reflect the conditions of growth.

3.2. K-feldspar deformation microstructures

The deformation behaviour of K-feldspar (and any other mineral) is a strong function of pressure and temperature and thus varies with metamorphic conditions (Tullis, 1983; Pryer, 1993). Consequently, K-feldspar-bearing mylonites from the eclogite facies shear zones were examined to determine approximate temperature conditions during high-strain deformation. K-feldspar grains in the North Davenport shear zone commonly show subgrain development and pass into zones of small, uniformly-sized recrystallised grains of quartz and K-feldspar. These domains of small strain-free recrystallised grains are zones of dynamic recrystallisation (Fitz Gerald and Stünitz, 1993). Grain boundary sliding, rather than dislocation creep may have occurred in areas where the grain size is small (i.e. recrystallised domains). Some K-feldspar grains are elongate, folded and show strong undulatory extinction. Overall, these deformation textures indicate that the quartz–feldspar mylonites in the North Davenport shear zone, primarily deformed by dislocation creep accompanied by dynamic recrystallisation, which is characteristic of temperatures of around 500°C or greater (Tullis and Yund, 1991). Recrystallisation and dislocation creep in K-feldspar at temperatures of ~650°C requires relatively high strain rates of $\sim 10^{-12}\ s^{-1}$ (Tullis and Yund, 1991).

In contrast to the material in the eclogite-facies shear zones, the country rocks were not extensively deformed or metamorphosed at the time the shear zones formed. They have no newly grown minerals or deformation textures. Therefore, the evidence for the country rocks being at lower temperatures than the shear zones is based primarily on isotopic information.

3.3. Mineral ages

The effective isotopic closure temperature of a mineral is affected by its composition, fluid circulation, grain size, deformation and the cooling rate (e.g., Harrison et al., 1985). Biotite is thought to close to volume diffusion at ~350 ± 50°C for both the Rb–Sr and K–Ar isotopic systems (Jäger, 1979; Harrison et al., 1985). However, Villa and Puxeddu (1994) placed the biotite closure temperature at ~450°C for the K–Ar system, in the absence of mineral transformation reactions (i.e., resetting is achieved only by volume diffusion). K-feldspar has a range of closure temperatures in the ^{40}Ar–^{39}Ar system from ~150 to ~350°C, depending on domain size (Harrison et al., 1991). The effect of pressure on closure temperature is small, and the consensus is that the closure temperature

Table 1
Summary of temperature estimates, using the garnet-clinopyroxene thermometer, for recrystallised mafic dykes in the North Davenport shear zone, Musgrave Block. Fe^{3+} in garnet was calculated by stoichiometry and charge balance. In clinopyroxene, Fe has been partitioned using the recommended procedures in Morimoto et al. (1988). If all Fe is assumed to be Fe^{2+}, the temperature estimates increase by ~100°C

Sample no.		Ellis and Green (1979)	Powell (1985)	Krogh (1988)
W-20	Average	725	715	705
	Range	690–760	670–780	650–760
W-107	Average	670	670	630
	Range	620–720	640–700	570–690

Table 2
Samarium–Neodymium analytical results for a mylonitised dolerite in the North Davenport shear zone (sample W-20), Musgrave Block, central Australia. Ratios were normalised to $^{146}Nd/^{144}Nd = 0.7219$. Errors are 0.2% and 0.01% at the 2σ level on the $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios, respectively

Sample type	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ (0)	Age (Ma)
TR	4.13	14.63	0.170854	0.512711	600 ± 20
Garnet	2.69	7.38	0.220091	0.512904	

does not change significantly with depth (Harrison et al., 1985).

The eclogite-facies shear zones record ages of around ~600 to ~500 Ma (Tables 2 and 3; Camacho et al., 1997) consistent with shearing having occurred at ~550 Ma ago. However, biotite from rocks only ~800 m away from the North Davenport shear zone preserve ages in the range 800–1000 Ma (e.g., biotite W-90; Fig. 1; Tables 3 and 4), similar to the age of granulite facies metamorphism, suggesting that the country rocks did not experience temperatures greater than ~450°C at this time. Calculations using a plane sheet geometry (Crank, 1975) for argon diffusion in biotite, using an activation energy and diffusivity of 250 kJ mol^{-1} and 3.81×10^{-25} m^2 s^{-1} (Villa and Puxeddu, 1994), respectively, show that a grain with a diameter of 1 cm (typical grain size ranges from ~1 mm to 1 cm) will lose ~40% of ^{40}Ar in 1 Ma at 600°C. For a temperature of 650°C, ~90% of ^{40}Ar will be lost in 1 Ma.

K-feldspar from the country rocks yield ^{40}Ar–^{39}Ar age spectra with an age component at ~500 Ma for the low temperature steps (Fig. 1). However, the high temperature steps preserve ages up to ~750 Ma, suggesting that they were only partially reset. Thus, the K-feldspar and biotite isotopic age information indicate that the rocks outside the shear zones did not experience temperatures greater than about 450°C during the Petermann Orogeny.

Overall, the data suggest that the temperature in the North Davenport shear zone was several hundred degrees hotter than the surrounding country rocks at the time of its formation (Fig. 2). This is consistent with a heat source localised in the shear zone. The localisation of heat in shear zones may potentially result from focusing of high-temperature fluid flow along them. However, the granulite facies rocks of the Musgrave Block are relatively dry and the mineral assemblages formed at eclogite facies in the shear zones are commonly anhydrous. Therefore, the advection of fluids does not appear to have been responsible for the localisation of heat in the North Davenport shear zone.

4. Constraining the duration of the heating event

Simple calculations of heat dissipation by conduction (Carslaw and Jaeger, 1959, p. 80) from the shear zone into the country rock were used to assess the amount of heat required to increase the shear zone temperature by 200–300°C without increasing substantially the temperature of the country rock ~1 km away from the shear zone. The

Table 3
Potassium–argon analytical results and total fusion ^{40}Ar–^{39}Ar ages of K-feldspar and biotite separated from samples in the Musgrave Block, central Australia. Age in Ma and error on the age is 1 sigma. *Denotes the sample is a mylonite. ($\lambda e + e' = 0.581 \times 10^{-10}$ a^{-1}, $\lambda_\beta = 4.962 \times 10^{-10}$ a^{-1}, $^{40}K/K = 1.167 \times 10^{-4}$ mol mol^{-1})

Field no.	*K* (wt %)	Rad^{40}Ar (10^{-9} mol g^{-1})	$\frac{100\text{Rad}^{40}Ar}{\text{Total}^{40}Ar}$	K–Ar age	^{40}Ar–^{39}Ar age (total fusion)	Sample
K-feldspar						
E-27	10.45, 10.29	15.98	96.1	723 ± 10	719 ± 2	Granulite
W-18	10.70, 10.54	12.20	88.9	564 ± 5	548 ± 1	Granulite
W-25b	10.67, 10.52	11.86	92.9	548 ± 8	543 ± 3	Granitoid*
W-70	9.76, 9.70	10.12	70.9	518 ± 5	496 ± 1	Granitoid*
W-122a	10.86, 10.87	13.44	96.4	601 ± 6	525 ± 1	Granulite
Biotite						
W-90	7.50	14.44	99.1	864 ± 20	793 ± 2	Pegmatite

Table 4
Rubidium–strontium analytical results on mineral and total rock. Errors are 0.2 and 0.01% at the 2σ level on the $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios, respectively

Field no.	Sample type	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Age (Ma)	Rock type
W-118a	Total rock	48	288.0	0.488	0.72255		Granulite
	Biotite	598	25.1	75.204	1.61650	850	
W-90 (i)	Biotite	1139	18.3	245.224	4.39884	1053	Pegmatite
W-90 (ii)	Biotite	1173	16.4	291.576	4.84374	993	

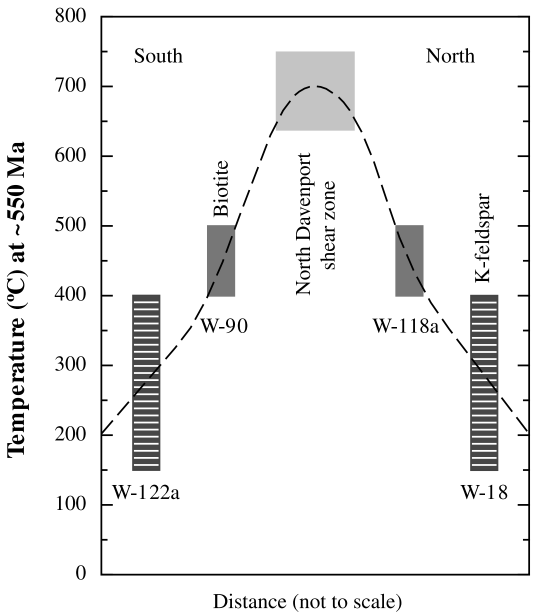

Fig. 2. Diagrammatic cross-section through the North Davenport shear zone illustrating the increase of temperature in the shear zone at ~550 Ma. Temperature estimates in the shear zone from Fe–Mg exchange thermometry. Temperature estimates in the country rock are from estimated isotopic closure temperatures for argon in biotite (~450°C) and K-feldspar (~150–350°C). Sample numbers are denoted with a W.

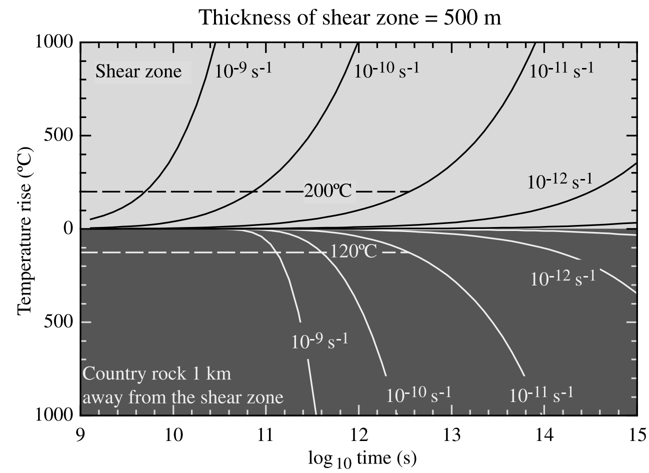

Fig. 3. Temperature versus $\log_{10}$ time diagram illustrating the results from mathematical calculations of shear heating for different strain rates in a shear zone 500 m thick. The light shaded area shows the temperature rise in the shear zone, whereas the dark shaded area shows the temperature rise in the country rock 1 km away. The temperatures calculated in these diagrams represent the heat generated by shear heating from a starting temperature of 20°C. To apply these results to realistic geological scenarios, the temperature predicted in these diagrams must be added to the ambient temperatures. The solid black lines show the temperature increase with time in the shear zone for a given strain rate, whereas the corresponding white lines show the temperature increase in the country rock.

shear zone is assumed to have a half thickness l of 250 m and to extend infinitely in the other two directions (Fig. 3). The shear zone and the country rock are assumed to be characterised by the same diffusivity of $10^{-6}\ m^2\ s^{-1}$ and conductivity of $3\ W m^{-1}\ K^{-1}$. Fig. 3 shows the temperature increase inside the shear zone ($x = 0$) and 1 km away from the shear zone as a function of time for a range of strain rates. We have assumed a shear stress of $\tau = 100$ MPa (Molnar and England, 1990; Stüwe, 1998) and converted the heat production values to characteristic strain rates ($\dot{\varepsilon}$), assuming that all mechanical energy ($\zeta = \dot{\varepsilon}\tau$) is transformed into heat. The results show that the heating must have been intense ($\dot{\varepsilon} \sim 10^{10} - 10^{-11}\ s^{-1}$) but of short duration ($<10^{11}$–10^{13} s; ~0.003–0.3 Ma) to lead to a substantial temperature increase (~300°C) in the shear zone, without an appreciable increase in the temperature of the country rock.

4.1. Evidence for high-strain rates in the Musgrave Block

For shear heating to be a viable mechanism for heat production in a shear zone, relatively high strain-rates (10^{-11}–$10^{-12}\ s^{-1}$) and shear stresses (~100 MPa) are required (Molnar and England, 1990). The greenschist to amphibolite facies shear zones of the Musgrave Block, active synchronously with the eclogite-facies shear zones, are characterised by the extensive development of pseudotachylyte and cataclasite. The Woodroffe Thrust contains a zone rich in pseudotachylyte, up to ~1 km thick (Bell, 1978; Camacho et al., 1995) probably caused by frictional heating (Philpotts 1964) during seismic faulting (McKenzie and Brune, 1972). Sibson (1977) estimated that strain rates as high as 10^{-10}–$10^{-11}\ s^{-1}$ were required to produce pseudotachylyte and cataclasite in the Outer Hebrides Thrust. Therefore, the extensive development of pseudotachylyte and cataclasite throughout the mid-crustal shear zones is evidence that strain-rates were locally high elsewhere in the Musgrave Block during the Petermann Orogeny. Pseudotachylyte production did not occur in eclogite facies shear zones, perhaps because shear heating weakened the rocks sufficiently to suppress brittle failure even at the highest strain-rates.

5. Summary and conclusions

Thermometry on overprinting assemblages from the high-pressure shear zones that formed during the Petermann Orogeny (~550 Ma) yield temperatures of ~650°C. Considering the distribution and extent of the high pressure shear zones together with evidence for limited vertical movement across the shear zones, the conventional wisdom would be to infer that the entire block experienced temperatures of ~650–700°C at ~550 Ma. However, outside the high-pressure shear zones, minerals with low closure temperatures such as biotite, preserve ages older than 550 Ma, suggesting that these rocks did not experience temperatures greater than about 450°C for any extended period at ~550 Ma.

These observations require the existence of a heat source localised to the shear zones sufficient to raise the temperature in the shear zones approximately 200°C above that in the surrounding country rocks. Petrological evidence argues against hot fluids as a heat source, leaving shear-heating as the most plausible explanation. Simple calculations show that the combination of relatively high shear stresses (~100 MPa) and high strain rates ($\sim 10^{-11}\ s^{-1}$) for short durations (<1 Ma) can account for the observed apparent temperature variations; otherwise, the isotopic mineral systems in the country rock would have been reset.

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