Hot rocks in a cold place: high sub-glacial heat flow in East Antarctica

Chris J. Carson[1*], Sandra McLaren[2], Jason L. Roberts[3, 4], Steven D. Boger[2], Don D. Blankenship[5]

[1]Geoscience Australia, GPO Box 378, Canberra, ACT, 2601, Australia.

[2]School of Earth Sciences, University of Melbourne, VIC, 3010, Australia.

[3]Australian Antarctic Division, Channel Hwy, Kingston, TAS, 7005, Australia.

[4]Antarctic Climate and Ecosystem Co-operative Research Centre, University of Tasmania, Private Bag 80, Hobart, TAS, 7001, Australia.

[5]University of Texas, School of Geosciences, Austin, TX, 78758-4445, USA.

*Corresponding author (e-mail: chris.carson@ga.gov.au)

Words (including title, abstract, authors, addresses, references and fig captions) = 3494

Tables = 1, **Figures** = 2, **references** =29.

Abbreviated title “**Geothermal heat flow in East Antarctica”**

Abstract: Numerical models are the primary predictive tools for understanding the dynamic behavior of the Antarctic ice sheet. But a key boundary parameter –sub-glacial heat flow – remains poorly constrained. We show that variations in abundance and distribution of heat-producing elements within the Antarctic continental crust result in greater and more variable regional sub-glacial heat flows than currently assumed in ice modeling studies. Such elevated heat flows would fundamentally impact on ice sheet behaviour and highlight that geological controls on heat flow must be considered to obtain more accurate and refined predictions of ice mass balance and sea level change.

Keywords: heat flow, heat production, Antarctica, Prydz Bay, South Australian Heat Flow Anomaly, Mawson Craton.

The Antarctic ice sheet plays a fundamental role in controlling ocean circulation, sea level and global climate (Alley *et al.* 2005). As such, significant effort has been directed to understanding ice sheet behavior and ice mass balance, particularly in the context of anthropogenic global climate change. Major physical parameters that influence ice sheet behavior include ice sheet margin-ocean interaction, bedrock topography, long-term climate variability and basal ice-bed interface conditions, such as bed roughness, melt water availability, water-saturated soft sediment deformation and hydrology networks (e.g. Winborrow *et al.* 2010).

Another critical yet poorly constrained parameter is the heat flow supplied to the base of the ice sheet (e.g. Waddington 1987; Greve 2005; Näslund *et al.* 2005; Pollard *et al.* 2005). This sub-glacial heat flow is from geothermal sources and is the sum of the amount of heat supplied to the conductive lithosphere from the convective mantle and the heat generated within the lithosphere from the radiogenic decay of the heat-producing elements (HPEs) – primarily U, Th and K (Turcotte and Schubert 2002). The HPEs are incompatible in mantle rocks and are preferentially fractionated, by various geological processes, into dominantly felsic rocks of the upper continental crust (e.g. Sandiford & McLaren 2002). The distribution of HPEs varies spatially and temporally within the crust meaning there are local and regional scale geological controls on sub-glacial heat flow.

Elevated sub-glacial heat flow can: (1) affect ice rheology and viscosity; (2) facilitate local pressure melting of the basal ice resulting in mechanical decoupling of the basal ice-rock interface, the formation of sub-glacial meltwater, basal hydrological networks and sub-glacial lakes and; (3) promote development of easily-deformed water-saturated basal till and other unconsolidated sediments (e.g. Greve & Hutter 1995; Siegert 2000). These factors can facilitate ice surging and ice stream flow (e.g. Greve 2005; Pollard *et al.* 2005; Llubes *et al.* 2006). For example, Näslund *et al.* (2005) showed that a modest 17% increase in average sub-glacial heat flow beneath the Fennoscandian ice sheet would facilitate local ice sheet mobilization and ice streaming from a 40% increase in basal melt production.

The Antarctic ice sheet is divided into the West Antarctic ice sheet (WAIS) and the East Antarctic ice sheet (EAIS) along the axis of the Transantarctic Mountains (TAMS, Fig. 1A). Sub-glacial heat flow beneath the WAIS is elevated due to active rifting and volcanism; direct borehole heat flow measurements from McMurdo Sound and western Ross Sea are between 60 and 164 mWm^{-2} (e.g. Schröder *et al.* 2011). In contrast, sub-glacial heat flow beneath the EAIS has not been measured directly and 'global average' values for stable continental crust, typically between c. 42 and 65 mWm^{-2}, have been assumed (e.g., Sclater *et al.* 1980; Pollard *et al.* 2005; Llubes *et al.* 2006). Alternatively, sub-glacial heat flow has been estimated using low-resolution remotely sensed data such as global seismic tomography (Shapiro & Ritzwoller 2004) or satellite-based geomagnetic observations (Fox Maule *et al.* 2005). These methods also yield similar estimates c. 50-60 mWm^{-2} but explicitly assume a thermally homogenous crust in which the primary control on heat flow is the variation in the mantle contribution as a function of crustal thickness. These approaches do not account for any possible thermal effect of crustal rocks enriched in heat-producing elements.

We show, using two geologically unrelated examples from (1) George V Land-Terre Adélie region and (2) eastern Prydz Bay, East Antarctica (Fig. 1a), that heat flow in East Antarctica is highly heterogeneous and profoundly influenced by the presence and variable distribution of crustal rocks enriched in heat-producing elements. Furthermore, we suggest that for numerical ice sheet modelling simplified sub-glacial heat flow estimates that ignore the crustal contribution to surface heat flow, and its variability, may be inappropriate.

THE MAWSON CONTINENT AND THE SOUTH AUSTRALIAN HEAT FLOW ANOMALY

Prior to the breakup of Gondwana, the Gawler and Curnamona cratons of South Australia and Terre Adélie and George V Land of East Antarctica are thought to have been contiguous, forming a crustal entity known as the Mawson Craton (Fig. 1b; Fanning *et al.* 1996; Boger 2011; Gibson *et al.* 2012). Despite recognition of the striking geological similarities between outcrops along the Terre Adélie and George V Land coast and the Gawler Craton (e.g. Peucat *et al.* 2002) the full sub-glacial extent of the Mawson Craton remains unknown, although available geophysical data indicate that the craton may extend as much as 800 km into the interior of the Antarctic (Finn *et al.* 2006).

Recognizing this connection is important for understanding the thermal conditions beneath the EAIS because the Australian component of the Mawson Craton is characterized by domains of high modern-day surface heat flow (for heat flow and heat production definitions see supplementary material). Such high heat flow domains include the regional South Australian Heat Flow Anomaly (SAHFA; Fig. 1c) and the broader continental-scale Central Australian Heat Flow Province (Sass & Lachenbruch 1979). The SAHFA has an average modern surface heat flow of 92 ± 10 mWm^{-2} (Neumann *et al.* 2000), 2-3 times that of average global continental crust of similar age (e.g., Nyblade & Pollack 1993), with 60-75 mWm^{-2} from the contribution of HPEs within the crust (Neumann *et al.* 2000). Such a contribution from crustal sources is highly anomalous as typical continental crust contributes only 18-48 mWm^{-2} (McLaren *et al.* 2003). The high heat-producing (HHP) rocks within the Gawler Craton component of the SAHFA are largely Palaeo- to Mesoproterozoic aged granites (Fig. 1d) which have an average heat production of 5-9 μWm^{-3} (c.f. the global average granitic heat production of 2.5 μWm^{-3}; e.g. Rybach 1976; see supplementary Table A1); this average includes the voluminous and areally extensive Mesoproterozoic Gawler Range Volcanics and granites of the Hiltaba Suite (Fig. 1b). Heat production values as high as 62 μWm^{-3} are reported for granitic bodies in the Curnamona Craton (Neumann *et al.* 2000; Mount Painter Province; Fig. 1b), in the northeast of the SAHFA.

Further support for the presence of elevated sub-glacial heat flow beneath Terre Adélie and George V Land is provided by the study of sub-glacial lakes by Siegert & Downswell (1996). They conclude that to induce local basal ice pressure melting and form the observed sub-glacial lakes in Terre Adélie and George V Land (Siegert & Downswell 1996, p. 502, fig. 1), 25-50 mWm^{-2} of geothermal heat, in addition to the assumed basal heat flow of c. 55 mWm^{-2}, is required. This implies a sub-glacial heat flow of c. 79-104 mWm^{-2} – a value that closely matches that of the SAHFA. Although Siegert & Downswell (1996) conclude that the additional heat required for basal melting is derived from internal ice deformation and shearing, they also acknowledge the possibility of an elevated geothermal heat flow. We suggest that given the likely extension of HHP rocks of the SAHFA into the Terre Adélie and George V Land region, this possibility is highly likely and one that has not previously been considered for estimates of sub-glacial heat flow there (e.g. Pollard *et al.* 2005)

Recognizing that the HHP crustal rocks and elevated heat flow characteristics of the SAHFA extend into the Antarctic continent emphasizes the inherent thermal heterogeneity of continental crust; this must be acknowledged if realistic and useful estimates of heat flow within Antarctica are to be developed. It also illustrates the importance of understanding the sub-glacial basement geology and potential impact on the cryosphere and the valuable insights that can be gained from examination of adjacent Gondwana crustal fragments.

2D THERMAL MODELLING OF PRYDZ BAY AND THE EFFECT OF CAMBRIAN GRANITES

In our second example, the eastern shore of Prydz Bay, East Antarctica, is characterized by a number of ice-free bedrock exposures along ~ 300 km of coastline including the Vestfold Hills, Rauer Islands, Larsemann Hills, and other small peninsulas and offshore islands (Fig. 2a). Prior to the breakup of Gondwana, the Prydz Bay area is thought to have been juxtaposed along the eastern coastline of India (e.g. Boger 2011) and is unrelated to the previous example. The Vestfold Hills comprises mostly Neoarchaean orthogneisses and paragneisses (e.g. Sheraton *et al.* 1984) while south of the Sørsdal Glacier (Fig. 2a), the Prydz Bay coastline comprises Palaeo- to Mesoarchaean and Palaeoproterozoic rocks (e.g. Kinny *et al.* 1993), which, unlike the Vestfold Hills, were profoundly affected by both Neoproterozoic and Cambrian granulite-facies tectonothermal events, and intruded by felsic Cambrian granites.

Table 1 is a summary of heat production data calculated using measured U, Th and K_2O contents of outcrop samples (Carson & Pittard 2012) along the Prydz Bay transect (Fig. 2a). The data illustrate the generally low heat production of Vestfold Hills rocks (c. 0.4 μWm^{-3}) and of the Proterozoic and Archaean rocks exposed in the Rauer Islands (c. 1.5 μWm^{-3}) and in southern Prydz Bay (c. 2.4 μWm^{-3}). In contrast, Cambrian-aged granites have significantly elevated (median c. 13 μWm^{-3}) and variable, heat production values (c. 4-66 μWm^{-3}), principally due to elevated Th concentrations. We note that Cambrian granites and pegmatites elsewhere in East Antarctica, such as the Denman Glacier region, also have elevated heat production (Carson & Pittard 2012).

To explore the implications of the presence of these HHP Cambrian intrusives on regional heat flow, we constructed a 2-D model of the gross geometry of the continental lithosphere for a section through Prydz Bay (Fig. 2a; supplementary data). As detailed seismic data is not yet available, our section is necessarily simplified but includes all key geological components (see supplementary material for additional model details). The distribution of HHP granites is based on their known outcrop distribution and heat production values are from Carson & Pittard (2012). The resultant surface heat flow distribution was calculated using the finite element analysis modeling software COMSOL Multiphysics (v4.2).

Heat flow modeling (Fig. 2b) predicts that the Vestfold Hills Block and the Rauer Islands have relatively low and uniform surface heat flows of c. 31 mWm^{-2} and c. 44 mWm^{-2} respectively (average heat flow across individual crustal blocks). In contrast, significantly higher and more variable heat flow is predicted for southern Prydz Bay. The model predicts a background heat flow of c. 60-70 mWm^{-2} in southern Prydz Bay, however occurrence of HHP Cambrian granites have a profound impact on heat flow with local 'hot-spots' of heat flow c. 80-90 mWm^{-2} and much as120 mWm^{-2} (Fig. 2b) We emphasize that our heat flow estimates for Prydz Bay probably represent *minimum* values as we conservatively use only the known surface extent of the HHP Cambrian granites. We speculate that the HHP granites may be more widespread beneath the modern ice cover as aeromagnetic data (e.g. 'Amery Lineament' of Golynsky *et al.* 2002) in southern Prydz Bay, shows rounded high response magnetic anomalies coincident with surface outcrops of the HHP granites and which may represent large, unexposed, HHP intrusive provinces. The approximate boundaries of these anomalies are indicated in Figure 2A.

Importantly, the local high heat flow associated with volumetrically small HHP Cambrian intrusives and the higher heat flow in granite-dominated domains are both significantly higher than values normally assumed for the East Antarctic continental crust.

Notably, both the magnitude and, in particular, thevariability of the sub-glacial heat flow calculated here for sections of the Prydz Bay coast are not predicted by the low-resolution continent-scale heat flow estimates of Fox Maule *et al.* (2005) and Shapiro & Ritzwoller (2004) which show uniform values of heat flow of c. 60 mWm^{-2} over much of East Antarctica. Our calculations predict marked regional thermal variability of the continental crust and highlight the likelihood of heterogeneity of sub-glacial heat flow in East Antarctica. Furthermore, the heat flow modeling presented here highlights the need for geophysical delineation of the location and distribution of sub-glacial Cambrian-aged orogenic terrains, associated HHP granites and potential elevated regional heat flow. This information will be critical to develop a better understanding of the regional heat flow characteristics of the Antarctic crust and the potential impact on numerical ice sheet models of the Antarctic Ice Sheet.

CONCLUSIONS

The East Antarctic continental crust is characterized by elevated geothermal heat flow that varies spatially on local and regional scales. Tectonic reconstructions provide a valid connection with documented high heat flow domains in southern Australia. In additionheat flow modeling in Prydz Bay indicate that local crustal heat flow in East Antarctica can be as much as 2-3 times higher than the ‘normal’ stable continental values used in ice dynamics modeling. Our study has demonstrated that there are significant variations in heat production of surface rocks, which imply remarkable variation in heat flow (>150%) over comparatively short horizontal length scales (10-100 km).

Although detailed assessment of the sub-glacial heat flow field also requires an understanding of crustal thermal conductivity variations and the vertical and lateral extent of

HHP rocks, the assumption that the crust is thermally homogeneous—as used by remotely-sensed continental-scale heat flow mapping techniques—is clearly inappropriate and a critical reminder that both local and regional geology must be considered in ice modeling studies.

Acknowledgements

N. Neumann, D. Champion (both GA) and R. Powell (University of Melbourne) commented on earlier drafts. This is a contribution to Stream 1.1; *The Antarctic Ice Sheet*, under the Australian Antarctic Science Strategic Plan (2011-12 to 2020-21). SM acknowledges support from Australian Research Council DP0987765. This research was also supported by the Australian Government's Cooperative Research Centres Programme via the Antarctic Climate and Ecosystems Cooperative Research Centre. CJC publishes with permission from the CEO, Geoscience Australia. GeoCat 75002.

REFERENCES

Alley, R. B., Clark, P. U., Huybrechts, P. & Joughin, I. 2005. Ice-Sheet and Sea-Level Changes. *Science*, **310**, 456-460.

Boger, S. D. 2011. Antarctica — Before and after Gondwana. *Gondwana Research*, **19**, 335-371.

Carson, C.J. & Pittard, M. 2012. A reconnaissance crustal heat production assessment of the Australian Antarctic Territory (AAT). Geoscience Australia Record 2012-63, p.57.

Fanning, C. M., Moore, D.H., Bennet, V. C. & Daly, S.J. 1996. The "Mawson Continent"; Archean to Proterozoic crust in the East Antarctic Shield and Gawler Craton, Australia; a cornerstone in Rodinia and Gondwanaland. *In:* Kennard J.M. (ed)

Geoscience for the community. Abstracts - Geological Society of Australia. **41**,135.

Finn, C.A., Goodge, J.W., Damaske, D. & Fanning, C.M. 2006. Scouting Craton's Edge in Paleo-Pacific Gondwana. *In:* Fütterer, D.K. (ed) *Antarctica: Contributions to global earth sciences*. Springer-Verlag, Berlin Heidelberg New York, p165–174.

Gibson, G.M., Totterdell, J. M., White, L.T., Mitchell, C.H., Stacey, A.R., Morse, M.P. & Whitaker, A. 2012. Pre-existing basement structure and its influence on continental rifting and fracture zone development along Australia's southern rifted margin. *Journal of the Geological Society*, in press.

Golynsky, A.V., Alyavdin, V.N., Masolov, A.S., Tscherinov, A.S. & Volnukhin, V.S. 2002. The composite magnetic anomaly map of the east Antarctic. *Tectonophysics*, **347**, 109-120.

Greve, R. 2005. Relation of measured basal temperatures and the spatial distribution of the geothermal heat flux for the Greenland ice sheet. *Annals of Glaciology*, **42**, 424-432.

Kinny, P.D., Black, L.P. & Sheraton, J.W. 1993. Zircon ages and the distribution of Archaean and Proterozoic rocks in the Rauer Islands. *Antarctic Science*, **5**, 193-206.

Llubes, M., Lanseau, C. & Rémy, F. 2006. Relations between basal condition, subglacial hydrological networks and geothermal flux in Antarctica. *Earth and Planetary Sciences*, **241**, 655-662.

Fox Maule, C., Purucker, M. E., Olsen, N. & Mosegaard, K. 2005. Heat flux anomalies in Antarctica revealed by satellite magnetic data: *Science*, **309**, 464-467.

McLaren, S., Sandiford, M., Hand, M., Neumann, N., Wyborn, L. & Bastrakova, I. 2003. The hot southern continent: Heat flow and heat-production in Australian Proterozoic terranes. *Geological Society of America Special Paper,* **372**, 157–167.

Näslund, J-O., Jansson, P., Fastook, J.L., Johnson, J. & Andersson, L. 2005. Detailed spatially distributed geothermal heat-flow data for modeling basal temperatures and meltwater production beneath the Fennoscandian ice sheet. *Annals of Glaciology*, **40**, 95-101.

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 and Planetary Science Letters*, **183**, 107-120.

Nyblade, A.A. & Pollack, H.N. 1993. A Global Analysis of Heat Flow from Precambrian Terrains: Implications for the Thermal Structure of Archean and Proterozoic Lithosphere. *Journal of Geophysical Research*, **98**, 12207-12218.

Peucat, J.J., Capdevila, R., Fanning, C.M., Ménot, R.P., Pécora, L. & Testut, L. 2002. 1.60 Ga felsic volcanic blocks in the moraines of the Terre Adélie Craton, Antarctica: comparisons with the Gawler Range Volcanics, South Australia. *Australian Journal of Earth Sciences*, **49**, 831-845.

Pollard, D., DeConto, R. M. & Nyblade, A. A. 2005. Sensitivity of Cenozoic Antarctic ice sheet variations to geothermal heat flux. *Global and Planetary Change*, **49**, 63-74.

Rybach, L. 1976. Radioactive heat production in rocks and its relation to other petrophysical parameters. *Pure and Applied Geophysics*, **114**, 309-317.

Sandiford, M., & McLaren, S. 2002. Tectonic feedback and the ordering of heat producing elements within the continental lithosphere. *Earth and Planetary Science Letters*, 204, 133-150.

Sass, J.S. & Lachenbruch, A.H. 1979. Thermal regime of the Australian continental crust. *In:* McElhinny, M.W. (ed) *The Earth: its origin, structure and evolution*. Academic Press, London, New York, 301-351.

Sclater, J.G., Jaupart, C. & Galson, D. 1980. The heat flow through oceanic and continental crust and the heat loss of the Earth. *Reviews of Geophysics and Space Physics*, **18**, 269-311.

Schröder, H., Paulsen, T., & Wonik, T. 2011. Thermal properties of the AND-2A borehole in the southern Victoria Land Basin, McMurdo Sound, Antarctica. *Geosphere*, *7*, 1324-1330.

Sheraton, J.W. & Black, L.P. 1984. Regional geochemical and isotopic characteristics of high-grade metamorphics of the Prydz Bay area: the extent of Proterozoic reworking of Archaean continental crust in east Antarctica. *Precambrian Research*, **26**, 169-198.

Shapiro, N. M. & Ritzwoller, M. H. 2004. Inferring surface heat flux distributions guided by a global seismic model: particular application to Antarctica. *Earth and Planetary Science Letters*, **223**, 213-224.

Siegert, M. J. & Dowdeswell, J. A. 1996. Spatial variations in heat at the base of the Antarctic Ice Sheet from analysing of thermal regime above subglacial lakes. *Journal of Glaciology*, **42**, 501-509.

Siegert, M.J. 2000. Antarctic subglacial lakes. *Earth-Science Reviews*, **50**, 29-50.

Turcotte, D. L. & Schubert, G. 2002. Geodynamics. Cambridge University Press, New York, 458pp.

Waddington, E. D. 1987. Geothermal heat flux beneath ice sheets. *In:* Waddington, E.D. & Walder, J.S. (eds) *The physical basis of Ice Sheet Modelling*. International Association of Hydrological Sciences, **170**, 217-226.

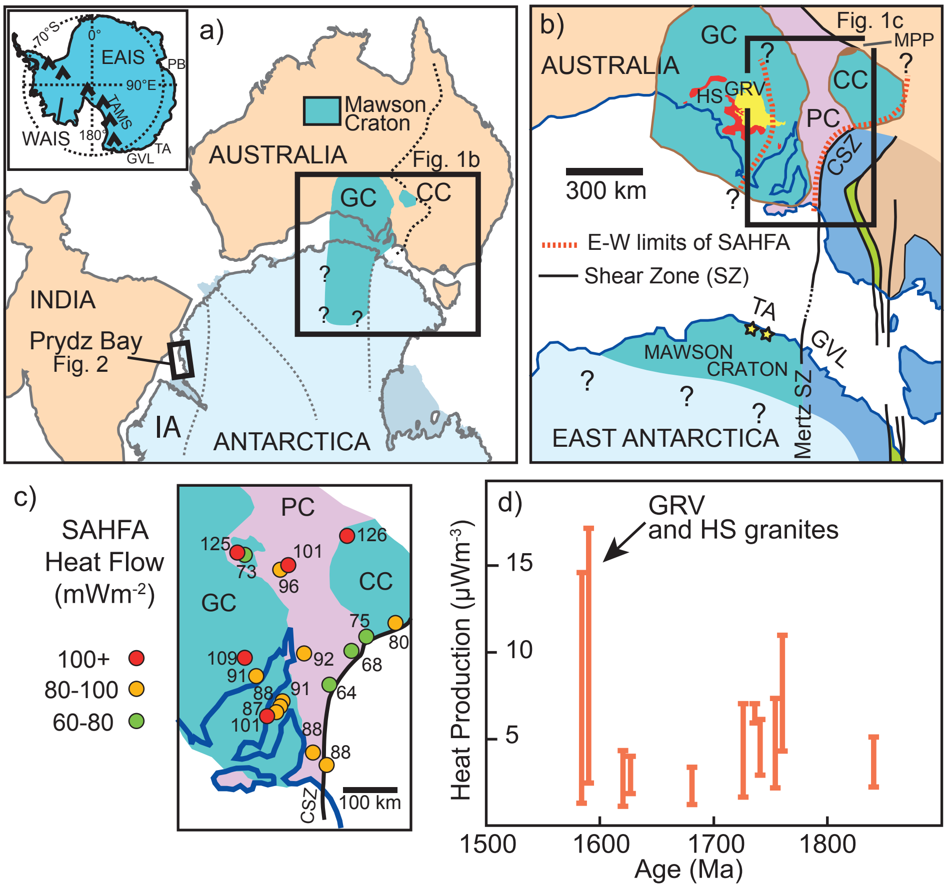
Winsborrow, M. C. M., Clark, C. D., & Stokes, C. R. 2010. What controls the location of ice streams. *Earth-Science Reviews*, **103**, 45-59.

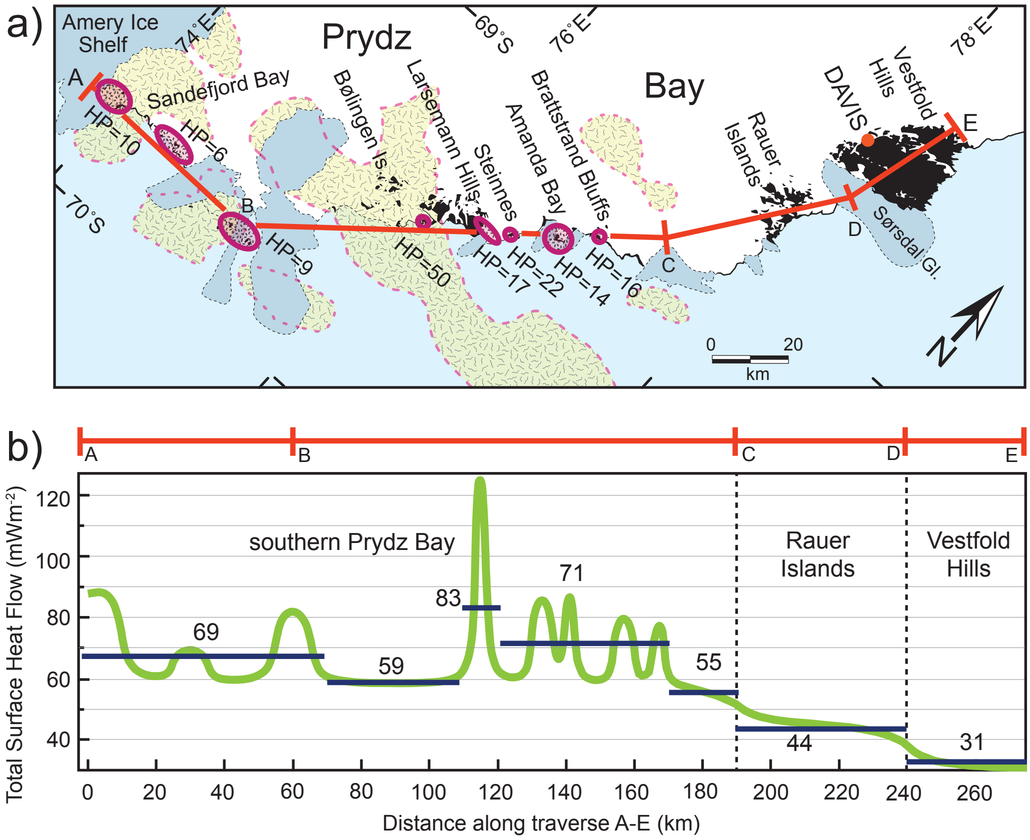
Figure Captions

Fig. 1. (**a**) Location of Australia, India and Antarctica in preEocene configuration showing,the interpreted extent of the Mawson Craton andlocation of Prydz Bay (PB; Fig. 2a). Prydz Bay is identified as having Indian affinities (IA = Indo-Antarctic Craton after Boger, 2011. Other dashed lines in Antarctica correspond to crustal elements defined by Boger, 2011.). Inset, map of Antarctica showing East and West Antarctic Ice Sheets (EAIS, WAIS respectively). (**b**) Major geological features of the Mawson Craton. Yellow stars show location of moraine samples that correlate with GRV in the Gawler Craton (Peucat *et al.* 2002). GRV = Gawler Range Volcanics and HS = Hiltaba Suite (both c. 1600-1585 Ma); TA = Terre Adelie; GVL = George V Land; GC = Gawler Craton; CC = Curnamona Craton; MPP = Mount Painter Province; CSZ = Coorong Shear Zone (Gibson *et al.* 2012); SAHFA = South Australian Heat Flow Anomaly; PC = Proterozoic Cover. (**c**) Heat flow measurements from the SAHFA (Neumann *et al.* 2000). (**d**) Range of heat production versus emplacement age for felsic intrusives from the Gawler Craton (n = 233); note elevated heat production range for Mesoproterozoic intrusives of the GRV and HS granites (arrowed).

Fig. 2. (**a**) East Prydz Bay coastline, East Antarctica, showing the areas of outcrop (solid black) as discussed in the text. The 275 km transect (A-E) for 2-D heat flow modeling and the location and extent of known HHP Cambrian granites (purple ellipses; average heat production, HP, for each granite occurrence is shown in μWm^{-3}) are shown. Dashed outlines represent **possible** sub-glacial extents of HHP granites inferred from geomagnetic surveys (e.g. Golynsky *et al.* 2002). Dark blue areas represent coastal outlet glaciers and floating ice shelves, light blue represents continental East Antarctic ice sheet. (**b**) Calculated heat flow profile across the modeled section illustrating the significant impact of the HHP Cambrian granites of southern Prydz Bay region on the calculated sub-glacial heat flow; the red line marked A-E is the transect shown in Fig. 2a. The green line indicates modeled surface heat flow along transect A-E; the seven solid dark blue horizontal lines are average heat flow

values (in mWm^{-2}) for selected sections of traverse A-E.


a)
70°S
0°
EAIS
PB
90°E
TAMS
WAIS
180°
TA
GVL
Mawson Craton
AUSTRALIA
Fig. 1b
GC
CC
?
?
?
INDIA
Prydz Bay
Fig. 2
IA
ANTARCTICA
b)
GC
Fig. 1c
MPP
AUSTRALIA
?
?
HS
GRV
CC
PC
CSZ
300 km
?
E-W limits of SAHFA
Shear Zone (SZ)
TA
GVL
MAWSON CRATON
?
?
?
EAST ANTARCTICA
Mertz SZ
c)
SAHFA Heat Flow (mWm^{-2})
100+ ●
80-100 ●
60-80 ●
PC
125
73
101
96
126
CC
GC
75
80
109
92
68
91
88
91
64
87
101
88
88
CSZ
100 km
d)
GRV and HS granites
Heat Production (μWm^{-3})
15
10
5
1500
1600
1700
1800
Age (Ma)


a)
Amery Ice Shelf
74°E
Prydz
69°S
76°E
Bay
78°E
A
Sandefjord Bay
HP=10
HP=6
70°S
B
HP=9
Bølingen Is.
Larsemann Hills
HP=50
Steinnes
HP=17
Amanda Bay
HP=22
Brattstrand Bluffs
HP=14
HP=16
C
Rauer Islands
DAVIS
Vestfold Hills
E
D
Sørsdal Gl.
0
20
km
N
b)
A
B
C
D
E
Total Surface Heat Flow (mWm⁻²)
120
100
80
60
40
southern Prydz Bay
Rauer Islands
Vestfold Hills
69
83
71
59
55
44
31
0
20
40
60
80
100
120
140
160
180
200
220
240
260
Distance along traverse A-E (km)

Author/s:
Carson, CJ; McLaren, S; Roberts, JL; Boger, SD; Blankenship, DD

Title:
Hot rocks in a cold place: high sub-glacial heat flow in East Antarctica

Date:
2014-01-01

Citation:
Carson, C. J., McLaren, S., Roberts, J. L., Boger, S. D. & Blankenship, D. D. (2014). Hot rocks in a cold place: high sub-glacial heat flow in East Antarctica. JOURNAL OF THE GEOLOGICAL SOCIETY, 171 (1), pp.9-12. https://doi.org/10.1144/jgs2013-030.

Persistent Link:
http://hdl.handle.net/11343/112396