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Selection of Deep Borehole from South and Central Australia to Reconstruct Last Glacial Maximum Temperature History

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ABSTRACT

We analysed six deep boreholes temperature data from southern and central Australia to understand downhole temperature characteristics for inversion and to reconstruct Last Glacial Maximum (LGM) temperature histories. Analysis shows, most of the deep boreholes are not suitable for inversion to reconstruct long term temperature history. Variation in the sub-surface lithology is the main driver for not picking up climate signal from these boreholes. However, borehole is drilled in homogeneous lithology shows promise to reconstruct long term temperature history. Blanche 1 borehole from central Australia was identified as being of high quality, with a very low area misfit of ~0.001 m^2/m, thus enabling for inversion to reconstruct temperature history since about LGM. Drill a deep borehole is a costly operation, thus it is recommended to select a deep borehole site carefully in homogeneous rock based on details survey in the sub-surface lithology.

Keywords : Boreholes, Lithology, Thermal conductivity, Central Australia

I. INTRODUCTION

The climate of the last glacial cycle (~100,000 years) contains periods of major natural variability, such as the intense cold of the Last Glacial Maximum (LGM), major fluctuations during subsequent deglaciation and the relative stability of the Holocene (Clark et al., 2009; Petherick et al., 2013; Reeves et al., 2013; Williams et al., 2009). Records of past climate help us to understand how the landscape, people and biotic inhabitants have come to be in their current state. Paleoclimate records are also important for understanding how global climate forcing, such as greenhouse gases are translated into the regional climates. Thus, any advancements in our knowledge of climate variability during this time period are important for understanding our past environment and for improving the accuracy of future projections by climate models.

Studies of past climate variability in Australia and the Southern Hemisphere have received considerable attention, especially the period during and since the LGM (Petherick et al., 2013; Reeves et al., 2013; Turney et al., 2006; Williams et al., 2009). Australasian long-term climate records are reconstructed using data from a wide range of different proxies, e.g. pollen (Fletcher and Thomas, 2010; Mackenzie and Moss, 2014; Williams et al., 2009), marine records (Barrows et al., 2007; Reeves et al., 2013; Turney et al., 2006), lake sediments (Rees et al., 2008; Rees and Cwynar, 2010), as well as, syntheses of proxies (Petherick et al., 2013). Such proxy records provide confident estimates of the timing of the LGM (Barrows et al., 2002; Yokoyama et al., 2000) in the Australian region. However, there is less confidence in the magnitude of the temperature change between the LGM and the Holocene, and whether spatial variations in temperature changes match those recorded elsewhere across the globe (Otto-Bliesner et al., 2006).

Semi-arid and arid central Australia covers about 40% of mainland Australia and has long been a focus of research attention. There are limited records of long term temperature history in central Australia, as a result of the poor preservation of typical paleoclimate proxies, for example, pollen (Miller et al., 1997). Our understanding of paleoclimate in central Australia is dependent upon amino acid racemization rates in emu eggshells (Johnson et al., 1999; Miller et al., 1997), dune deposits (Fitzsimmons et al., 2007a; Fitzsimmons et al., 2007b; Rhodes et al., 2005), dust flux (Hesse et al., 2004; Williams et al., 2001), and lake records (Croke et al., 1996; Magee and Miller, 1998). Most of these records indicate that central Australia was dryer and cooler during the LGM than at present. However, numerical estimation of temperature change in the region is very limited during this time period.

Temperature reconstructions of the last 500 years in Australia have been generated from the south-west of western Australia (Appleyard 2005), Eastern Tasmania (Suman & White 2017; Suman et al. 2017), Australian continental average (Pollack et al. 2006) and for the last 2,000 years from east Australia (this thesis Chapter- IV). However, despite early attempts (Cull, 1980) temperature reconstructions during the LGM using borehole temperature data have not widely been applied in Australia, despite success in other parts of the world (Chouinard and Mareschal, 2009; Pickler et al., 2015). In this study, we analyze deep borehole temperature data from southern and central Australia, to understand the magnitude of temperature change between the LGM and Holocene, and the timing of these changes.

II. METHODS

Ground surface temperature (GST) variations during the last glacial cycle are recorded by the Earth's subsurface (depth ≥1500 m, Pickler et al., 2015) as perturbations to the 'steady-state' temperature profile (Chouinard and Mareschal, 2009; Mareschal and Beltrami, 1992). If there was no change in GST, then temperature increases with depth in the sub-surface thermal regime would govern only by the outflow of heat from Earth's interior. However, during the LGM and Holocene when GST changed significantly, downward temperature diffusion is recorded as perturbations in the semi-equilibrium thermal regime.

Theoretically the length of the past temperature history obtainable from borehole records is primarily dependent on the depth of borehole temperature record. This is because of the nature of the diffusive propagation of surface temperature changes into the crust (Beltrami et al., 1992; Beltrami and Mareschal, 1995; Chouinard and Mareschal, 2009; Mareschal and Vasseur, 1992). For periodic oscillation of GST, the amplitude of the temperature fluctuation decreases exponentially with depth over a length scale δ (skin depth) proportional to the square root of the period ($\delta = \sqrt{kT/\pi}$), where k is the thermal diffusivity of rock, $\approx 10^{-6}$ m^2s^{-1}. This damping eliminates the high-frequency variability that is seen in meteorological records and contains long-term climatic trends in the ground temperature signal (Beltrami and Mareschal, 1995; Pickler et al., 2016).

To calculate the temperature-depth profile, we assume that heat is only transported by vertical conduction and perturbation of the temperature profile is the time varying surface boundary condition only. For a homogenous half-space with horizontally uniform variations in the surface temperature, the temperature at depth can be written as (Mareschal and Jaupart, 2011):

$$T(z) = T_0 + Q_0 R(z) - \int_0^z \frac{dz'}{\lambda(z')} \int_0^{z'} H(Z'')dz'' + T_t(z) \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where T_0 is the reference GST (steady-state temperature), Q_0 is the reference heat flux (steady-state heat flux), λ(z) is the thermal conductivity, Z is the depth, H is the heat generation and $T_t(z)$ is the temperature perturbation at depth Z as a result of time-varying changes to the surface boundary condition and R(z) is the thermal resistance to depth Z.

Temperature perturbations $T_t(z)$ were calculated for each depth where borehole temperature measurements were available. By using the information of temperature perturbation throughout the borehole, we were able to reconstruct past GST history. We used a Matlab program that applies SVD methods (Clauser and Mareschal, 1995; Menke, 1989) to reconstruct past GST history, as described in Suman et al., (2017) and Suman et al., in review (this thesis Chapter IV). This method is well established and for further details we refer the reader to Beltrami and Mareschal (1995); Chouinard and Mareschal (2007); Chouinard and Mareschal (2009); and Mareschal and Beltrami (1992).

We assessed the reliability of each borehole temperature inversion using a range of criteria. These include the potential for non-climatic perturbation, i.e. horizontal ground water flow, high variation in sub-surface thermal conductivity (TC) that affect the temperature profiles and thus reconstruction of past GST history. We also applied a technique to assess borehole temperature data quality based on model misfit between measured and modelled data, which is described in Suman et al., (2017) (this thesis Chapter-III).

Data Description and Study Area

To reconstruct temperature history during the last 50,000 years, high resolution borehole temperature data are needed from boreholes >1500 m deep (Pickler et al., 2015). Deep boreholes have been logged across the country, mainly for the exploration of gas, oil, water and geothermal resources. However, continuous and equilibrated temperature data have only been collected from geothermal boreholes and occasionally from gas exploration boreholes. Temperature data collected from other types of boreholes tends to be coarse, and limited to the bottom of holes and is of insufficient resolution to be used for past temperature reconstruction. We looked for deep geothermal borehole temperature data across eastern Australia and found only five deep geothermal boreholes from southern and central Australia with continuous temperature data, appropriate for reconstructing late Pleistocene temperature history. One further deep borehole, Wombat4 drilled for the exploration of gas resources, was found to have continuous temperature data available. These six deep boreholes (Fig. 1 and Table 1) were analysed to determine the temperature variation between LGM and Holocene and the timing of these variations. Detailed borehole temperature and TC data is given in Appendix XII and XIII.

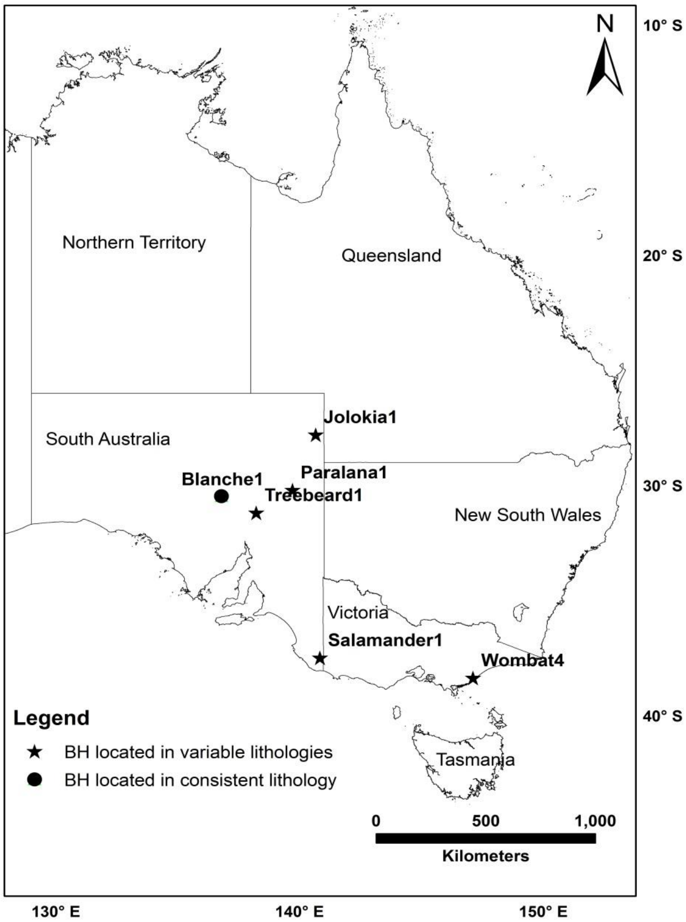

Fig 1. Study area showing deep borehole locations

Table 1. Geologic, geographic and topographic features of deep boreholes. SiS = Siltstone, SaS = Sandstone, and CS=Claystone

Well Name	Basin	Drilling company	Elevation (m)	Longitude	Latitude	Distance from Coast (km)	Total depth (m)	Average thermal Conductivity W/mK
Blanche1	Gawler Craton	Green Rock Energy Ltd	100	136.80	-30.47	300	1934	2.8±0.8
Paralana1	Arrowie	Petratherm Ltd	42	139.71	-30.21	350	1810	2.7±1.6
Treebeard1	Arrowie	Torrens Energy Ltd	65	138.23	-31.20	190	1807	2.3±0.5
Jolokia1	Cooper/Eromanga	Geodynamics	50	140.66	-27.80	633	4911	…
Salamander1	Otway	Panax Geothermal Ltd	65	140.83	-37.49	70	4025	…
Wombat4	Gippsland	Lakes Oil N.L.	27	147.12	-38.37	5	1714	1.6±0.5

III. RESULTS AND DISCUSSION

To reconstruct plausible GSTH, it is important to select appropriate borehole sites (Chouinard and Mareschal, 2007). In the following section, we discuss each of the borehole sites and explain the reason behind accepting or rejecting borehole sites for use in reconstructing the temperature history of the late Pleistocene.

We calculated reduced temperature profiles (Roy et al., 2002; Roy and Chapman, 2012; Suman and White, 2017) for each borehole. Reduced temperatures were calculated from the least square fit of the thermal gradient of the lowermost part in each borehole. In reduced temperature profiles, a higher positive or negative deviation from 0^{o}C is caused either by surface temperature change or variation in the TC. If these changes are caused by simple TC variation, then the borehole temperature profile can be corrected (Suman et al., 2017). However, in deep boreholes with complex lithology, we found that TC corrected boreholes do not yield plausible surface temperature history during inversion. This is probably caused by a lack of precise TC data throughout the borehole.

Blanche1

This hole was logged by Geoscience Associates (Australia) Pty Ltd using a normal temperature probe, a kuster geothermal temperature probe, natural gamma, density and acoustic scanner probe (Green Rock Energy Limited, 2006), and re-logged for integrated borehole temperature and other geophysical data, by the Department of State Development (DSD), South Australia.

There is major lithologic variation at the top of the borehole; however, homogenous granite is present from a depth of ~650 m to the bottom of the borehole (1935m) (Fig. 2 a-c). In the granite portion, the average thermal gradient was 29.5^{o}C/km, the harmonic mean of TC was 3.0 W/mK and the conductive heat flow, 88.5 mW/m^2. Greater variability in TC towards the top of the borehole meant that reliable temperature inversion was not detectable for the last 3000 years. The presence of consistent Pandurra and Hiltaba Suite Granite formation between 650 m and 1935 m (Fig. 2c) with very low area misfit 0.001 m^2/m between measured and modelled data enabled a plausible estimate of the temperature variation between LGM and Holocene, to be determined.

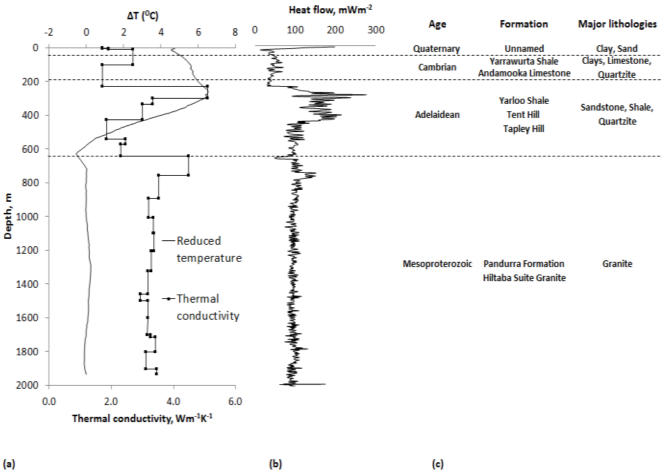

Fig. 2 (a) Reduced temperature and thermal conductivity (b) heat flow and (c) Stratigraphy at Blanche 1 borehole site. Figure shows significant variation in heat flow from the surface to about 650 m, and consistent lithology and heat flow from a depth of about 650 m to the bottom of the borehole

Paralana1

Stratigraphical analysis of Paralana1 borehole also shows frequently changing formation and lithology throughout the borehole (Fig. 3c). As a consequence, sub-surface TC is quite variable (Fig. 3 a,b). The Cambrian unit (depth 467-1554 m) (Fig. 3c) contains most of the LGM and Holocene temperature history, but TC varies from 1.80 to 7.03 W/mK in this interval. The highly variable TC means it is difficult to retrieve climate signal from this unit. Despite the relatively large number of TC measurements, the residual uncertainty in the TC means that corrections still result very uncertain heat flow. Thus, even TC correction (Suman et al., 2017) does not improve the thermal depth temperature profile (Chouinard and Mareschal, 2009) or the past surface temperature history. Therefore, Paralana1 borehole was not used in our reconstruction of the late Pleistocene temperature history.

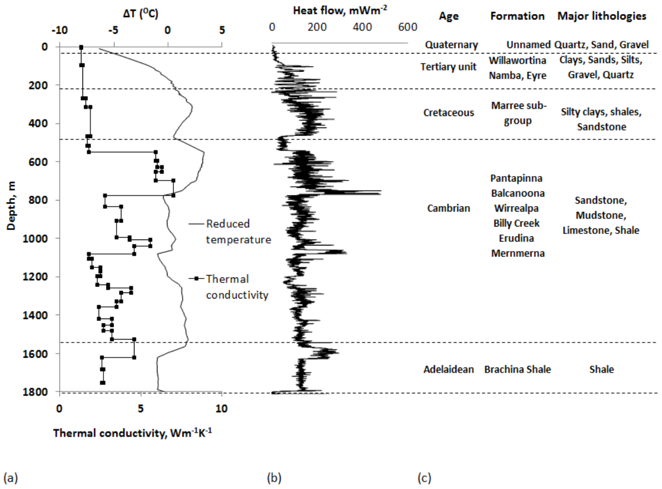

Fig. 3 (a) Reduced temperature and thermal conductivity (b) heat flow and (c) Stratigraphy at Paralana1 borehole site. Figure shows significant variation of lithology and heat flow throughout the borehole.

Treebeard1

Sub-surface lithology and TC are also quite variable at the Treebeard1 borehole site (Fig. 4 a,b). Climate signal during LGM and Holocene were expected within the Cambrian unit (depth 470-1807m) of this borehole (Fig. 4c). Although the total depth of Treebeard1 is 1807 m, the temperature log is available only to a depth of 948 m and this is not enough to detect climate signal during LGM. There was also significant variability in TC values within the Cambrian unit (1.1 to 6 W/mK) and so we did not use Treebeard1 borehole data in our reconstruction of the late Pleistocene temperature history.

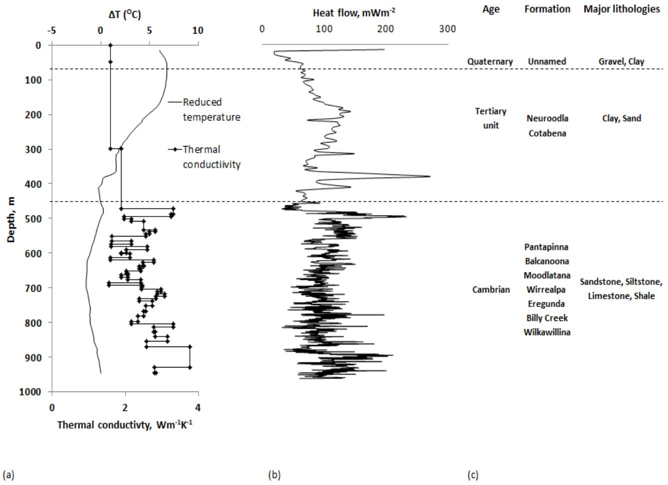

Fig. 4 (a) Reduced temperature and thermal conductivity (b) heat flow and (c) Stratigraphy at Treebeard1 borehole site. Figure shows significant variation of lithology and heat flow throughout the borehole.

Jolokia1 and Salamander1

Continuous temperature data are available to depths of 2870 m and 3000 m, for Jolokia1 (4911 m deep) and Salamander1 (4025 m deep) boreholes respectively, but TC data were not available. In both boreholes, coal is interbedded with other lithology which makes it difficult to calculate accurate TC values. Therefore, it is challenging to calculate thermal resistance temperature profiles (Chouinard and Mareschal, 2009) which are necessary for reconstructing reliable temperature history from the boreholes are located in variable lithologies. Stratigraphical analyses from drill chips shows subsurface lithologies are also highly variable at both sites (Fig. 5b and 6b). The reduced temperature of both holes shows significant variation from steady state geotherm (Fig. 5a and 6a). Consequently, it was not possible to reconstruct plausible temperature histories using Jolokia1 and Salamander1 borehole temperature data. Hence, neither of these boreholes was considered in our reconstruction of the late Pleistocene temperature history

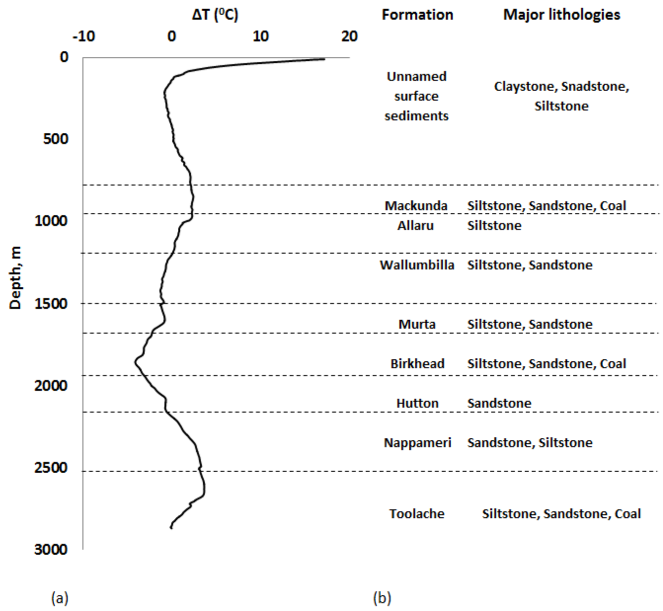

Fig. 5 (a) Reduced temperatures and (b) stratigraphy of Jolokia 1 shows significant variation in sub-surface lithology throughout the borehole

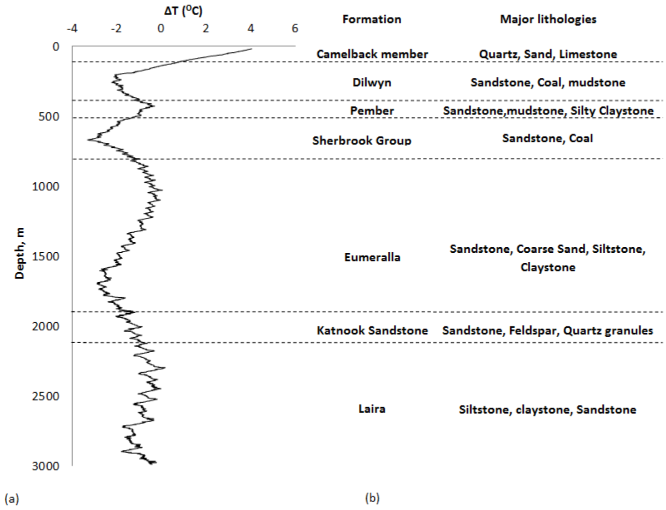

Fig. 6 (a) Reduced temperatures and (b) stratigraphy of Salamander1 shows significant variation in sub-surface lithology throughout the borehole.

Wombat4

There was only one borehole in Victoria that yielded enough temperature depth data to reconstruct the late Pleistocene temperature history. Wombat4 was drilled as part of a search for potential gas resources in the early Cretaceous Strzelecki group. Continuous temperature data are available from a depth of 1714 m down to 2500 m. Sub-surface lithologies and TC are highly variable at this borehole site (Fig. 7a,b). Further, the small number of TC measurements from this borehole limits accurate TC corrections, as indicated by the high variability in the calculated heat flows with depth. The resulting inversion of raw temperature profile does not yield plausible surface temperature history. Similar results are obtained with a range of TC corrections, such as TC correction with only formation average TC values. Therefore, Wombat4 also did not use in our reconstruction of the late Pleistocene temperature history.

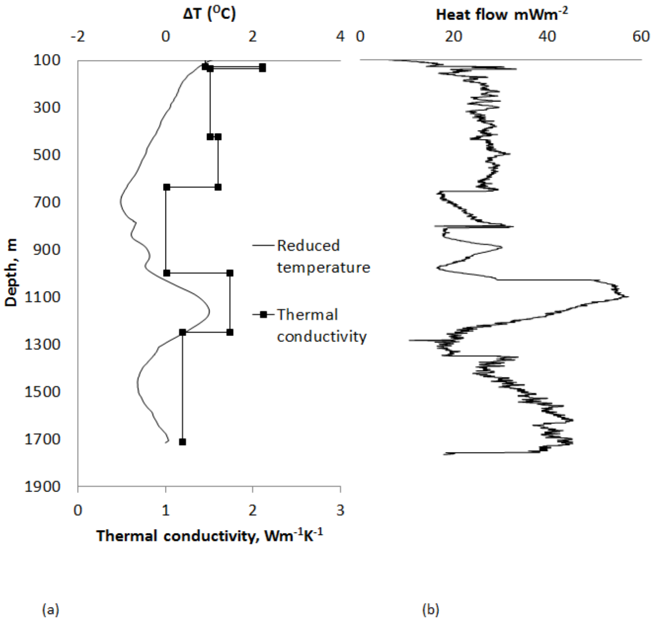

Fig. 7 (a) Reduced temperature and (b) heat flow at Wombat4 borehole site shows significant variation in sub-surface lithology as well as in heat flow

Detailed analysis of six deep borehole temperature depth profiles and respective lithologies shows most of the southern and central Australian deep boreholes are not suitable for reconstructing the long-term temperature history. Only deep borehole, Blanche1, can be potentially used to reconstruct the late Pleistocene temperature history.

IV. CONCLUSION

We analysed six deep boreholes from southern and central Australia to understand LGM and Holocene temperature variation. Unfortunately, it was found most of the deep boreholes are not suitable for inversion to reconstruct long term temperature history. This is because of high variation in the sub-surface lithology. However, borehole is drilled in homogeneous lithology shows promise to reconstruct long term temperature history. Blanche 1 borehole was identified as being of high quality, with a very low area misfit of ~0.001 m^2/m, thus enabling for inversion to reconstruct temperature history since about last glacial maximum. Drill a deep borehole is a costly operation, thus it is recommended to select a deep borehole site carefully in homogeneous rock based on details survey in the sub-surface lithology.

V. Acknowledgement

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