Impact of maximum borehole depths on inverted temperature histories in borehole paleoclimatology

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Abstract. A quantitative assessment is presented for the impact of the maximum depth of a temperature-depth profile on the estimate of the climatic transient and the resultant ground surface temperature (GST) reconstruction used in borehole paleoclimatology. The depth of the profile is important because the downwelling climatic signal must be separated from the quasi-steady state thermal regime established by the energy in the Earth's interior. This component of the signal is estimated as a linear increase in temperature with depth from the lower section of a borehole temperature profile, which is assumed to be unperturbed by recent changes in climate at the surface. The validity of this assumption is dependent on both the subsurface thermophysical properties and the character of the downwelling climatic signal. Such uncertainties can significantly impact the determination of the quasi-steady state thermal regime, and consequently the magnitude of the temperature anomaly interpreted as a climatic signal. The quantitative effects and uncertainties that arise from the analysis of temperature-depth profiles of different depths are presented. Results demonstrate that widely different GST histories can be derived from a single temperature profile truncated at different depths. Borehole temperature measurements approaching 500-600 m depths are shown to provide the most robust GST reconstructions spanning 500 to 1000 ypb. It is further shown that the bias introduced by a temperature profile of depths shallower than 500-600 m remains even if the time span of the reconstruction target is shortened.

1 Introduction

The last several decades have witnessed increasing research efforts to quantify and explain the variability of the climate system during the Common Era (2000 ybp) (e.g. Jones et al., 2009). These

efforts have been motivated in part by observed increases in mean global temperatures during the 20th century and projected future increases in global temperatures during the 21st century (Bindoff et al., 2007; Jansen et al., 2007; Randall et al., 2007). Placing these modern observations and projections in context is thus an important means of evaluating the magnitude, extent and impacts

25 of the projected warming. Such context can only be achieved by characterizing climatic conditions prior to the advent of the instrumental record, which has been done on myriad spatial and temporal scales using climatic proxies. The Common Era has become an important paleoclimatic interval of focus because the widespread availability and high temporal resolution of proxy records during this time period offer the potential for large-scale reconstructions on seasonal and annual timescales.

30 Nevertheless, many uncertainties also exist in the interpretation of paleoclimatic proxies, and it is therefore important to better understand the sources, character and magnitude of these uncertainties so that paleoclimatic reconstructions of the Common Era can be properly interpreted. The purpose of this study is to evaluate a source of uncertainty in the interpretation of one type of paleoclimatic indicator, namely temperature-depth profiles measured in terrestrial boreholes.

35 Borehole temperature-depth profiles are used as paleoclimatic indicators by inverting the profiles to yield a temperature time series at the ground surface. These inversions assume that long-term changes in the energy balance at the ground surface propagate conductively into the terrestrial subsurface where they are recorded as anomalies on the background signal associated with the outward flow of heat from the Earth's interior. The estimated changes in ground surface temperatures (GSTs)

40 from borehole temperature inversions have been shown to agree well with surface air temperatures (SATs) during their period of overlap (Beltrami et al., 1992; Huang et al., 2000; Harris and Chapman, 2001; Pollack and Smerdon, 2004). This agreement, when combined with results from modeling and observational studies of air and ground temperature coupling, has supported the assumption that multidecadal to centennial changes in SAT are coupled to equivalent changes in GST and hence

45 motivate the interpretation of GST reconstructions as indicators of long-term changes in SATs (see Pollack and Huang, 2000; Bodri and Cermak, 2008; González-Rouco et al., 2009, for reviews and related references).

A large collection of work has inferred GST variations during the last five centuries to a millennium (Lewis, 1992; Huang et al., 2000; Beltrami and Harris, 2001; Pollack and Huang, 2000; Harris

50 and Chapman, 2001; Beltrami, 2002a; Beltrami and Bourlon, 2004; Pollack and Smerdon, 2004; Bodri and Cermak, 2008; Rath and Smerdon, 2008; González-Rouco et al., 2009) and estimated GST histories as long-term (centennial) trends that are generally consistent with meteorological and other paleoclimatic records (e.g Pollack and Smerdon, 2004; Pollack et al, 2006). Indeed, a wide range of research around the general subject of interpreting geothermal climate signals has developed over

55 the last two decades (see Pollack and Huang, 2000; Bodri and Cermak, 2008; González-Rouco et al., 2009, for reviews and related references), including recent efforts to estimate heat storage in the terrestrial subsurface (Beltrami, 2001a; Baker and Baker, 2002; Beltrami et al., 2002; Beltrami, 2002a;

Beltrami et al., 2006a; Huang, 2006) and assessments of the long-term behavior of GCMs and the suitability of their component soil models (Lynch-Stieglitz, 1994; Sun and Zhang, 2004; Smerdon and Stieglitz, 2006; Beltrami et al., 2006; González-Rouco et al., 2009, 2003, 2006; Stevens et al., 2007; MacDougall et al., 2008; Lawrence et al., 2008; Stevens et al., 2008; MacDougall et al., 2010).

One advantage of GST reconstructions is that they are derived from a direct measure of temperature. In this sense, they are not a proxy for past temperatures inasmuch as they are indicative of a direct temperature response to the integrated changes in the energy balance at the Earth's continental surface. Temperature reconstructions from geothermal data are thus independent of meteorological records – a characteristic unique within the collection of paleoclimatic proxies used to reconstruct the climate of the Common Era. Similar to all paleoclimatic methods, however, the borehole method has advantages and disadvantages. One disadvantage is that borehole reconstructions suffer from reduced resolution back in time, and can only resolve multidecadal to centennial temperature changes (e.g. Clow, 1992; Harris and Chapman, 1998). There are also a number of uncertainties associated with interpretations of borehole reconstructions that require further investigation. One such example that has received a considerable amount of attention is assessments of the relationship between GST and SAT signals at various timescales, which can be altered by surface conditions such as variations in the onset, duration and depth of snow cover, land use changes, vegetation evolution and change, and long-term increases or decreases in soil moisture. (e.g. Baker and Ruschy, 1993; Putnam and Chapman, 1996; Zhang et al., 2001; Lin et al., 2003; Stieglitz et al., 2003; Beltrami and Kellman, 2003; Bartlett et al., 2004, 2005; Pollack et al., 2005; Zhang, 2005; Bense and Kooi, 2004; Bense and Beltrami, 2007; Hu and Feng, 2005; Ferguson and Beltrami, 2006; Ferguson et al., 2006; Smerdon et al., 2003, 2004, 2006, 2009; Sushama et al., 2006, 2007; Demetrescu et al., 2007; Cey, 2009).

One uncertainty that is widely recognized in interpretations of borehole temperature profiles, but has not been quantitatively characterized in terms of the impact on derived GST reconstructions, is the degree to which these reconstructions are impacted by the maximum depth of the profile. Because the vast majority of measured temperature profiles are acquired from boreholes of opportunity, the maximum measurement depth varies considerably (beginning at depths as shallow as 100-150 m and extending to depths of more than 1 km). The principal reason why the depth of the borehole is important stems from the fact that the downwelling climatic signal must be separated from the quasi-steady state signal associated with the upwelling of heat from the Earth's interior. This latter component of the signal is estimated as a linear increase in temperature with depth from the lower section of a borehole temperature profile, which is assumed to be unperturbed by the downwelling component of the surface signal. The validity of this assumption is dependent on both the thermophysical properties of the subsurface and the character of the downwelling climatic signal, giving rise to multiple sources of uncertainty associated with the determination of the steady-state signal. Such uncertainties can significantly impact the determination of the quasi-steady-state thermal regime, and consequently the magnitude of the temperature anomaly interpreted as a climatically induced

95 signal.

The purpose of this study is to illustrate how the maximum depth of a temperature-depth profile impacts the estimation of the downwelling climate signal, and consequently the derived GST reconstruction. In particular, we quantitatively illustrate the effects and uncertainties that arise from the analysis of borehole temperature logs of different depths. Our results demonstrate that different

100 GST histories can be derived from temperature profiles truncated at different depths, even when the profiles are generated from the identical surface and subsurface conditions.

2   Theoretical framework

Temperatures in the first several hundred meters beneath the terrestrial surface – the depth range in which climatic signals of the past several centuries reside – are governed principally by two

105 processes: the outward flow of heat from the planetary interior and the downward propagating temperature perturbations arising from time-varying temperatures at the land-atmosphere boundary. Changes in the outward heat flux from the planetary interior occur on time scales of millions of years; thus in the context of decadal, centennial or millennial climatic changes, the outward heat flux and its subsurface temperature signature can be considered to be in steady-state. For the regions

110 of the subsurface relevant to GST reconstructions, this steady-state signal is approximated as a linearly increasing temperature signal with depth. If robustly identified, the steady-state temperature signal can therefore be separated from the more rapidly changing subsurface temperatures driven by climate-related fluctuations at the surface. Nevertheless, in some cases the downwelling surface signal can impact the estimate of the background thermal regime if the lower depth range of an

115 available temperature profile – the region over which the background thermal regime is estimated – is significantly perturbed by the downwelling signal. Hence, it is widely acknowledged within the borehole paleoclimatic literature that deeper boreholes are preferable, but this preference has been balanced against the practical limitation of available borehole depths.

Various studies discuss the maximum borehole depth and in some cases have explicitly consid-

120 ered means of inferring whether or not the lower depths of a borehole are significantly affected by downwelling surface signals. As a general rule, the Global Database of Borehole Temperatures and Climate Reconstructions applies 200 m as a minimum depth criterion (Pollack and Huang, 2000), and comprises the database used by many of the global borehole reconstruction analyses (e.g. Pollack et al., 1998; Huang et al., 2000; Beltrami, 2002a; Harris and Chapman, 2001; Pollack and

125 Smerdon, 2004). Chisholm and Chapman (1992) discuss the fact that borehole temperatures between the depths 100-160 m can be affected by past climatic perturbations and that only boreholes deeper than 500 m can typically avoid this problem. Harris and Chapman (2001) estimate the background thermal regime in all analyzed boreholes using data below 160 m, a depth that is argued to be "sufficient to avoid more recent climate change effects but that retains enough data in the deeper

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130 subsurface to obtain robust estimates" of the background regime. Similarly, Majorowicz et al. (2002)

perform synthetic experiments that tested inversions for different maximum borehole depths. They

report depths below 150-200 m to be sufficient for their analyses of boreholes in Canada. It is im-

portant to note, however, that the numerical experiments on which this conclusion was based used

synthetic borehole profiles generated with a surface temperature history comprising a linear increase

135 in temperature over 150 years. Given the realistic thermophysical properties used by Majorowicz et

al. (2002) to model their subsurface profiles, such a surface temperature history would never yield

perturbations below about 100-150 m. As we show in this study, temperature fluctuations that occur

prior to the advent of the instrumental record can impact borehole profiles well below such depths,

and therefore require much deeper maximum borehole depths to adequately identify an unperturbed

140 background steady-state signal. Such considerations make the Majorowicz et al. (2002) study dif-

ficult to interpret. Notably, Harris and Chapman (1995) and Roy et al. (2002) both propose means

of estimating the depth to which surface perturbations have significantly affected temperature pro-

files, below which they argue that the background thermal regime can be safely estimated. These

approaches nevertheless have not been adopted widely in the literature. Furthermore, despite these

145 discussions in the literature, the potential impact of borehole depths on the estimated background

thermal regime and the subsequent GST inversion have not been quantitatively characterized.

2.1 Model for Synthetic Temperature Profiles

Our synthetic analyses employ temperature profiles generated using a one-dimensional conductive

model that assumes uniform subsurface thermal diffusivity, no interior heat sources, a time vary-

150 ing surface boundary condition, and a lower boundary at infinity. We impose an upper boundary

condition comprising a series of step changes in temperature over uniform time intervals. For these

conditions, the temperature anomaly at depth z and time t, due to a step change in surface tempera-

ture T_0, is determined by the solution of the one-dimensional heat diffusion equation (Carslaw and

Jaeger, 1959):

155 $$T(z,t) = T_0 \mathrm{erfc}\left(\frac{z}{2\sqrt{\kappa t}}\right),$$ (1)

where erfc is the complementary error function and κ is the thermal diffusivity of the subsurface.

Generalizing this solution for a series of K step changes at the surface (Mareschal and Beltrami,

1992), the induced temperature anomalies at depth are given by:

$$T_t(z) = T_i(z) + \sum_{k=1}^{K} T_k[\mathrm{erfc}(\frac{z}{2\sqrt{\kappa t_k}}) - \mathrm{erfc}(\frac{z}{2\sqrt{\kappa t_{k-1}}})],$$ (2)

160 where $T_i(z)$ represents the initial temperature profile. Given a known upper boundary condition,

Eq. (2) allows the subsequent subsurface perturbations to be calculated as a function of time. We

thus use Eq. (2) later in our analysis to generate synthetic temperature profiles given an established

surface boundary condition.

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2.2 Inversion Method

165 Inversions of temperature-depth profiles seek to estimate the time-varying boundary condition that
has given rise to the measured profile at a specific moment in time (Cermak, 1971; Vasseur et al.,
1983; Shen and Beck, 1991; MacAyeal et al., 1991; Wang, 1992; Mareschal and Beltrami, 1992;
Bodri and Cermak, 1995; Cooper, 1998). The inverse problem requires the determination of the
equilibrium surface temperature, T_0, the geothermal gradient, Γ_0, the bottom boundary condition

170 and the time-varying upper boundary condition from the measured $T(z)$ data. Note that the surface
heat flux is formally required in the general inversion case, but an estimate of the geothermal gradient
can be used for inversions that assume uniform thermophysical properties in the subsurface, as we do
here. T_0 and Γ_0 can be estimated from the upward continuation of a linear trend estimated from the
deepest part of the temperature profile, assumed to be the depth range least affected by recent ground

175 surface temperature changes. The data, data geometry, a priori information, model and the physics
of the problem can be setup in matrix form (Mareschal and Beltrami, 1992) that will be solved here
using singular value decomposition (SVD) (Lanczos, 1961; Jackson, 1972; Menke, 1989), although
our results are also valid for other inversion techniques (Rath and Mottaghy, 2007; Shen and Beck,
1992; Beck et al., 1992; Wang, 1992; Hopcroft et al., 2007, 2009a,b). Details of the SVD method

180 are well documented and can be found in Mareschal and Beltrami (1992); Clauser and Mareschal
(1995); Beltrami and Mareschal (1995), and Beltrami et al. (1997).

3 Results

3.1 Synthetic temperature anomalies

In the following subsections we generate an artificial borehole temperature profile, truncate it to
185 simulate measurements down to different depths under the same climatic conditions, evaluate the
corresponding temperature anomalies and invert them using the SVD method to estimate the GST
history (i.e. the upper boundary condition). We then compare the results with the artificial forcing
function.

We chose an upper boundary condition to act as a time varying GST function based on typical
190 results obtained from previous analyses of geothermal data in Eastern Canada (Shen and Beck,
1992; Beltrami et al., 1992; Beltrami and Mareschal, 1992a; Beltrami et al., 1997). The chosen
function (Figure 1a) consists of a static temperature period from 1000 ypb to 500 ybp, at which
point a cooling period commences and reaches a minimum temperature of -1.4 K at about 250 ybp.
This cold minimum is followed by a warming period that reaches approximately 1 K at present day.

195 All temperature changes are expressed here as departures from the temperature at 1000 ybp. This
upper boundary condition is used to drive the forward model (Eq. 2) to generate the present-day
subsurface temperature anomaly profile shown in Fig. 1b, using the canonical thermal diffusivity

value of $10^{-6}m^2s^{-1}$ (Cermak and Rybach, 1982). To simulate field-acquired geothermal data, that is, temperature-depth profiles that include the thermal effects from the quasi-steady state geothermal regime, we add an equilibrium surface temperature and geothermal gradient to the anomaly profile generated above. The chosen values are 8 °C and 20 K km^{-1}, respectively, which are typical of some regions in Canada (Beltrami et al., 1992). The full synthetic temperature-depth profile is shown in Fig. 1c.

To mimic standard analyses in borehole climatology, we assume that our measured data are those of our synthetic temperature-depth profile in Fig. 1c. We generate a family of temperature profiles by truncating the full synthetic profile at varying depths. We estimate T_0 and Γ_0 for each sampling using a least-squares linear fit to the 100 m at the bottom of each of the truncated temperature profiles, as is typically done for real-world measurements (e.g. Bullard, 1939; Jaupart and Mareschal, 2011). Once the steady-state background components are estimated they are subtracted from the truncated profiles to generate the temperature anomalies associated with the estimated downwelling climatic components captured in each depth range. Figure 2 shows a set of the subsurface temperature anomalies generated from the a collection of temperature profiles truncated at the indicated depths. These anomalies represent the subsurface climate signal that would be estimated if the temperature log was in fact measured to these depths and indicates that the magnitude and shape of the signal is impacted strongly by the depth of the borehole.

The value of the thermal diffusivity controls the vertical extent of the downwelling climatic signal, and thus the depth of the borehole that is influenced by a given surface history. To illustrate the potential effect of spatially variable subsurface thermophyical properties on the temperature anomalies, we generate three sets of temperature profiles using a range of thermal diffusivity values, but identical surface temperature histories. Fig. 3 shows synthetic temperature anomalies simulated as previously described, for thermal diffusivities (κ) of 0.5, 1.0 and 1.5 $10^{-6}m^2s^{-1}$. This range of variability is excessive given that the thermal diffusivities of common crustal rocks typically vary within a range of $\pm10\%$ about the canonical value (e.g Cermak and Rybach, 1982; Carslaw and Jaeger, 1959). Nevertheless, Figure 3 serves to illustrate that different subsurface thermal properties could not realistically reconcile the depth range of the surface history penetration, given the specific history that we have adopted. Furthermore, while certain small characteristics are different, the gross impact of the maximum borehole depth on the estimated subsurface anomaly profie is clearly consistent across all three values of thermal diffusivity, as illustrated in Fig. 3 for the anomalies estimated from boreholes truncated at 200 and 600 m depths.

3.2 Inversion of synthetic subsurface anomalies

We use SVD to invert the set of subsurface temperature anomalies of Fig. 2 and derive estimates of the respective surface temperature changes. The model chosen for each individual SVD inversion (Mareschal and Beltrami, 1992) consists of a series of twenty 50-year step changes in ground surface

temperature. The value of the thermal diffusivity was set at 10^{-6} $m^2 s^{-1}$ for both the generation of the synthetic data and for the inversion. The eigenvalue cutoff was set at 0.025 for each GST history inversion, keeping five principal components for all of the temperature-depth profiles included in the the reconstruction (Beltrami, 2002a). Results from the inversion for each of the synthetic temperature anomalies and its corresponding maximum profile depth are shown in Figure 4. As expected, none of these inversions recover the GST function in full detail because of the resolution losses associated with thermal diffusion (Mareschal and Beltrami, 1992; Clow, 1992; Beltrami and Mareschal, 1995; Harris and Chapman, 1998). The temperature anomaly obtained from the deepest borehole, however, recovers the original function most faithfully. All inversions seem to recover the recent warming, but the overall solutions differ greatly as the minimum borehole depth decreases. We also observe in Fig. 4 a temporal shift in the minimum GST, as well as a change in its magnitude as the depth of the anomaly decreases.

As an additional test, we repeated the inversion of the family of temperature anomalies for the depths considered in Fig. 2, but only inverted for a surface temperature history that extends to 500 ybp (maintaining the same time step duration and eigenvalue cutoff). Figure 5a and 5b show the solutions for the 1000-year model of Fig. 4 but only back to 500 ybp and the results for the inversion employing the 500-year model. The solutions are very similar and show that the choice of the temporal length of the model has little influence on the GST history.

Fig. 6 shows the results for iterative estimates of the variation in the equilibrium surface temperature and geothermal gradient as functions of the maximum depth of the profile. The steady state parameters are estimated from the bottom 100 m of the profile, while the minimum depth of the profile is truncated iteratively by 1 m up to a depth of 100 m. Although this rate of truncation would rarely be possible with real-world data, it nevertheless illustrates well the apparent variability of the steady state geothermal regime as the depth is reduced. In this particular case using the chosen synthetic upper boundary condition, the correct parameters are best recovered from the deepest temperature log. Fig. 6 also helps illustrate that the forcing function itself (i.e. the true climatic history) can affect the identification of the required minimum depth of a temperature-depth profile. In other words, the depth to which a borehole should be measured to avoid erroneous estimates of the background thermal regime depends on the climate history at a given location.

3.3   Inversion of a measured temperature-depth profile

To compare the inversion results derived in the above synthetic test with results from observational data, we chose a measured temperature-depth profile from the Canadian data base. In keeping with previous work on method verification and benchmarking for borehole paleoclimatology, we chose CA-016 (Canadian Geothermal Database number for Minchin Lake) (Neilsen and Beck, 1989; Beck et al., 1992; Shen and Beck, 1992; Beltrami et al., 1997). This borehole has been measured three times, one of which involved continuous measurements with a sampling rate of approximately 2 cm

270 for a total of about 22,000 measurements over a depth range from 20 to 550 m; for our experiments
we used the continuous log shown in Figure 7. The mean value of the thermal conductivity is
$3W/mK$ and we use $\kappa = 10^{-6}$ for the inversion (IHFC, 2011). Figure 8 shows the resulting
temperature anomalies for approximately the same selected depths as in the synthetic test (Fig.
2). These were obtained by truncating the temperature-depth profile at the indicated depths and
275 estimating T_0 and Γ_0 from a least-squares linear fit to the bottom 100 m of each of the truncated
profiles (Bullard, 1939; Jaupart and Mareschal, 2011). Figure 9 shows the results from the inversion
of the temperature anomalies for the shown depths, and illustrates behavior similar to the results
from the synthetic case. Figure 10 shows the variation of the steady-state geothermal parameters as
a function of depth estimated from the same procedure used in the synthetic case above. Note that
280 the smaller-scale variations in Figure 10, such as those observed near the depth of 400 m, arise due
to lithological variations – not climatic changes – that are not included in the inversion procedure.

4   Discussion and Conclusions

We have demonstrated that the maximum depth of temperature-depth profiles used for borehole
paleoclimatology can have a large impact on the estimated climatic anomaly, and consequently on
285 the inverted GST history. The principal source of this effect is due to the impact of the downwelling
surface temperature signal on the estimate of the equilibrium surface temperature and geothermal
gradient. These values must be estimated from a portion of the temperature-depth profile that is not
significantly affected by downwelling surface perturbations in order to provide a robust estimate of
the historical climatic perturbation at the surface. Our results indicate that this effect is relevant over a
290 depth range commonly employed in borehole paleoclimatic studies. For instance, some studies have
used boreholes as shallow as 100-150 m (e.g. Majorowicz et al., 1999; Majorowicz and Safanda,
2001; Majorowicz et al., 2002; Hamza et al., 2007), while the many global analyses typically set the
minimum depth criterion at 200 m, thus employing boreholes 200 m or deeper (Huang et al., 2000;
Harris and Chapman, 2001; Beltrami, 2002a; Beltrami and Bourlon, 2004; Pollack and Smerdon,
295 2004). Our calculations suggest that these depths are likely too shallow, but several caveats are
necessary and discussed below.
    The results we have quantified are dependent on both the temporal character of the upper boundary
condition (i.e. the GST history) and on the thermophysical properties of the subsurface. Our analyses
suggest that the range of realistic subsurface thermophyiscal properties are not likely to significantly
300 change our conclusions. In both the synthetic and observational experiments performed in our anal-
ysis, however, the specific GST histories that gave rise to the subsurface temperature anomalies will
not be applicable at all locations. Nevertheless, in the absence of knowledge about the true climatic
history of a region, which is obviously the case in most paleoclimatic studies seeking to supplement
observational records, the most precautionary approach is to use the deepest possible borehole mea-

surements. Note also that the appearance of an unperturbed lower section of the temperature-depth profile is insufficient for impact assessments, as is clearly demonstrated from a quick inspection of the synthetic temperature log in Fig. 1c or the real log in Fig. 7. For those studies seeking to estimate GST histories between several hundred to a thousand years, our results thus suggest that the most conservative approach would be to target measurements that extend to at least 500 m. Furthermore, comparisons of regional GST reconstructions should, strictly speaking, only be carried out for sets of temperature-depth profiles that extend to the same depth. If subsurface thermophysical data are available, the analysis should be done for the same thermal depth incorporating in this manner the vertical variation of subsurface thermal properties.

Differences in maximum borehole depths can potentially introduce biases in the magnitude and shape of the subsurface temperature anomaly depending on the period of time considered. These biases consequently impact the estimated magnitude and temporal characteristics of recovered GST histories. Large scale analysis that involve comparisons of results from deep and very shallow borehole temperature logs (<200m) (Majorowicz et al., 1999; Majorowicz and Safanda, 2001; Majorowicz et al., 2002; Hamza et al., 2007), yield results that are difficult to evaluate because of potential biases due to preferential depth ranges within regions. This potential bias does not dissappear using simultaneous inversion since, as shown in Beltrami et al. (1997), the resulting GST histories are dominated by the deepest temperature log or those with larger sampling rates. Given these biases, it is important to realize that the comparison of reconstructed GST histories from temperature profiles with different maximum depths should be done with caution, as they likely do not contain climatic information for the same time interval, nor are the magnitudes of reconstructed temperatures referenced to the same initial conditions.

A final note is necessary regarding the implication of our results for hemispheric and global reconstructions derived from borehole data (e.g. Huang et al., 2000; Harris and Chapman, 2001; Beltrami, 2002a; Beltrami and Bourlon, 2004; Pollack and Smerdon, 2004). These reconstructions have largely been compiled from the Global Database of Borehole Temperatures and Climate Reconstructions, which has used 200 m as a minimum depth criterion. As stated above, whether or not the reconstruction estimates derived from this database are subject to the potential biases that we have described is dependent on the thermophysical properties of the subsurface at each borehole location and the character of unknown prior climatic variations. If inversions from individual boreholes are affected, the gross impact observed herein is one that mutes the estimated GST warming. Similarly, for boreholes that measure long-term cooling, the magnitude of the estimated cooling will also be muted. The overall impact of maximum borehole depths on large-scale averages of GST reconstructions would therefore also depend on the distribution of maximum depths in boreholes that measured cooling or warming. If more boreholes measuring warming were muted, for instance, the impact would be large-scale averages that estimate less warming than actually occured. The potential for these impacts therefore encourage more investigation. Studies that systematically eval-

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uate the character of large-scale reconstructions derived from different minimum depth criteria are highly warrented. This will be complicated by significant losses in the number of boreholes available as the minimum depth criterion becomes deeper. For instance, Beltrami and Bourlon (2004)

345 and González-Rouco et al. (2009) (in Fig. 1 and Fig. 6, respectively), as well as Chapman and Davis (2010) estimate that only about 10% of the boreholes in the global database extend to 600 m. These losses in data densities will therefore need to be property accounted for. We also suggest that uncertainty analyses may be possible based on the results that we have shown. Given the known maximum depth of a borehole and the estimated thermophysical properties, synthetic tests similar

350 to what we have shown here could be performed for a variety of temperature histories that vary, for instance, the magnitude of warming or cooling over the targeted interval. Such analyses would provide sensitivity estimates that characterize the potential for biases based on the depth of a borehole and its thermal properties. All of these approaches will ultimately help quantify the uncertainties in borehole reconstructions associated with the maximum depth of measured temperature profiles,

355 which we have shown to be an important element of borehole paleoclimatology requiring further consideration and characterization.

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Figure Captions

Fig. 1. (a) Synthetic ground surface temperature function used to generate the synthetic temperature-depth anomaly shown in (b). The simulated temperature log (c) was constructed by adding (b) to an equilibrium surface temperature of 8.0 °C, and a steady-state geothermal gradient of 20 K km^{-1}.

Fig. 2. Subsurface temperature anomalies estimated from the simulated temperature profile of Fig. 1c truncated at the depths indicated. The plotted temperature anomalies were derived by subtracting the equilibrium surface temperature and geothermal gradient, both of which were estimated by a least-squares linear regression on the bottom 100 m of each truncated profile.

Fig. 3. Temperature anomalies generated from the same artificial GSTH as in Fig. 1, but shown here for several values of subsurface thermal diffusivities (κ): (a) 0.5, (b) 1.0 and (c) 1.5 $10^{-6}m^2 s^{-1}$. Red lines correspond to the anomalies estimated from boreholes truncated at 600 m and blue lines for those estimated from boreholes truncated at 200 m.

Fig. 4. Ground surface temperature histories obtained from a SVD inversion of the synthetic subsurface temperature anomalies in Fig. 2. The GST models in all of the inversions consist of a series of twenty 50-year time steps, evenly spaced over the 1000-year period. The legend indicates the maximum depth of the temperature log for each inversion. The "true" synthetic GST history is shown in orange and is the same curve shown in Fig. 1a. A thermal diffusivity of $10^{-6}m^2 s^{-1}$ was assumed in all of the inversions.

Fig. 5. (a) Ground surface temperature histories using the 1000-year inversion model of Fig. 3, but only plotted back to 500 ybp. (b) GST histories for a 500-year inversion model consisting of ten 50-year surface temperature step changes. A thermal diffusivity of $10^{-6}m^2 s^{-1}$ was assumed in all of the inversions.

Fig. 6. Changes in the estimated equilibrium surface temperature, T_0, and geothermal gradient, Γ_0, as a function of borehole depth using the synthetic borehole log shown in Figure 1c. The known and equilibrium surface temperature (T_0) of 8.0 °C, and a steady-state geothermal gradient (Γ_0) of 20 K km^{-1} are recovered at depths approaching 500-600 m.

Fig. 7. Continuous temperature log for Minchin Lake (black dots). Note that only a subset of measurements have been included for clarity. The red line represents the quasi steady-state geothermal gradient estimated from a linear fit to the bottom 100 m of data. Inset: black dots and red lines represent the same as above, and the blue lines denote the error calculated in the slope and the intercept of the best fit line.

Fig. 8. Subsurface temperature anomalies estimated from the Minchin Lake temperature-depth profile after truncating the temperature log at different depths. The legend indicates the truncation depth of the profile used to calculate each of the temperature anomalies shown.

Fig. 9. Ground surface temperature histories estimated from inversions of the temperature anomalies shown in Fig. 7. Estimates of the error on the estimated parameters are not shown for clarity, but they are small because of the eigenvalue cutoff used to regularize the inversion.

Fig. 10. Changes in the estimated equilibrium surface temperature, T_0, and geothermal gradient, Γ_0, as a function of depth for the temperature data measured at Minchin Lake borehole. High frequency noise due to the variability of the thermal properties is apparent. The mean value of the thermal conductivity is $3W/mK$ (IHFC, 2011).Note that the true equilibrium surface temperature and geothermal gradient are unknown in the observational case.