How hot are the Cairngorms?

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Synopsis

Heat flow measured over the East Grampians batholith in the 1980s was found to be unexpectedly low and at odds with high radiogenic heat production within the outcropping granites and a very large volume of granite predicted from an interpretation of gravity data. Past climate variations perturb temperature gradients in the shallow sub-surface leading to erroneous estimates of heat flow. A reconstruction of the surface temperature history during the last glacial cycle has enabled a rigorous palaeoclimate correction to be applied to the heat flow that shows an increase of 25% over previously reported values; revised to 86 ± 7 mWm^{-2}. An interpretation of recent mapping reveals that the surface exposures of the East Grampians granites are the roof zones of a highly evolved magma system. Rock composition therefore is likely to become more mafic with depth and the heat production will decrease with depth. This petrological model can be reconciled with the gravity data if the shape of the batholith is tabular with deep seated feeder conduits. The increased heat flow value leads to revised predictions of sub-surface temperatures of 129 ºC at 5 km depth and 176 ºC at 7 km depth, increases of 40% and 49% respectively compared to previous estimates. These temperatures are at the lower end of those currently required for power generation with Engineered Geothermal Systems, but could potentially be exploited as a direct heat use resource in the Cairngorm region by targeting permeable fractures with deep boreholes.

Introduction

Engineered Geothermal Systems (EGS) are reservoirs that have been created to extract economical amounts of heat from low permeability and/or porosity geothermal resources (MIT 2006). In regions of the world with average continental heat flows, EGS is often associated with granites that have elevated concentrations of the naturally occurring radioelements of uranium (U), thorium (Th) and potassium (K). Where large volumes of such rocks occur, the radioactive decay of these elements produces heat anomalies at depth; these intrusions are therefore known as high-heat producing (HHP) granites. The geothermal

energy they contain can in theory be exploited by pumping cold water down a borehole into a zone of hot rocks where it is heated as it travels through fractures of an engineered reservoir to a second borehole, from which it is extracted. The heat is then transferred to a binary fluid (that has a lower boiling point than water) via a heat exchanger which then turns a turbine to generate electricity. The highest reported heat flow in the UK of ~130 mW m^{-2} was measured (Wheildon *et al*. 1981) in the Permian granite intrusions of Cornwall and Devon (surface expressions of the Cornubian batholith) and these intrusions have been extensively investigated as potential EGS reservoirs (e.g. Downing & Gray 1986a, b; Batchelor 1987; Richards *et al*. 1994). The potential for EGS in Scotland was assessed during the Geothermal Energy programme (Rollin 1982, 1984; Lee 1984; Webb & Brown 1984; Wheildon *et al*. 1984; Lee *et al*. 1984, 1987). There are no major late Carboniferous to Permian granite intrusions in Scotland, and therefore no direct analogues of the south-west England intrusions. The East Grampians batholith (EGB) underlies an east-west trending zone extending inland from Aberdeen. Many large Siluro-Devonian granite intrusions crop out within this zone and, from geochemical determinations of U, Th and K a number were found to have the highest heat production (HP) values in the UK (Webb & Brown, 1984) (see Table 1 and Figure 1). Subsequent heat flow measurements in shallow boreholes (~300 m deep) at Cairngorm, Mount Battock, Ballater and Bennachie of 70, 59, 71 and 76 mWm^{-2} respectively were much lower than anticipated from the heat production data (Wheildon *et al*. 1984) and were therefore disappointing.

The East Grampians batholith is associated with an extensive Bouguer gravity anomaly low that has a minimum magnitude of -53 mGal (see Figure 2). Modelling of this gravity anomaly (Rollin 1984, 2009) suggested that the granite intrusions may extend to between 9 and 13 km depth as one large intrusive mass with an approximate volume of granite of 25000 km^3. In order to reconcile the disparity between high heat production and low heat flow, Wheildon *et al*. (1984) modelled the heat flow at each of the heat flow boreholes. It was concluded that heat production must decline rapidly with depth within the granite and that the background regional heat flow must be relatively low. The rapid decrease in heat production was ascribed to strong vertical fractionation of the radiothermal elements; in other words, the concentrations of U, Th and K diminish rapidly with depth, so that the HHP character of the intrusions is just a near-surface feature. This interpretation was based, to a large extent, on a theoretical understanding of granite magma evolution, the geochemical data derived from samples from the relatively narrow vertical range spanned by the boreholes (~300 m) and

surface exposures (Webb & Brown 1984; Webb *et al*. 1985). The heat flow modelling therefore predicted a sub-surface temperature at 5 km depth of 92ºC. When considered against predicted temperatures of 182ºC at 5 km depth for parts of the Cornubian Batholith (Downing & Gray 1986a) the East Grampians were judged as geothermally unprospective.

It is known that past climate change can perturb sub-surface temperature gradients from which heat flow is calculated (e.g. Benfield 1939; Birch 1948; Crain 1968; Jessop 1971; Beck 1977). In Britain, warming since the last glaciation would result in a positive correction to heat flow which Younger *et al*. (2012) and Westaway & Younger (2013) suggested to be of the order of ~20 mW m^{-2}. Corrections to heat flow for palaeoclimate were not originally applied to the East Grampians heat flow boreholes (Downing & Gray 1986a). The reason stated was that it was unnecessary for comparative regional studies, although this would then preclude using heat flow for predicting temperatures at depth. Westaway & Younger (2013) have recently published a climate corrected heat flow value for the Ballater borehole of 89.5 mWm^{-2}, a 26% increase over the original value. Hence, it is quite likely that a lack of consideration of palaeoclimate has resulted in an underestimate of heat flow, and by implication geothermal potential, of the East Grampians.

This paper presents a rigorous palaeoclimate correction to East Grampians heat flow and, with more recent petrological data on the intrusions, considers the implications for the geothermal resource.

The East Grampians heat flow boreholes

As part of the UK Geothermal Energy Programme (Downing & Gray 1986a) heat flow boreholes were drilled into the Cairngorm, Mount Battock, Ballater and Bennachie intrusions. The Monadhliath intrusion, which is also of HHP character, was not included due to poor accessibility. In each case a single vertical borehole was sunk to around 300 metres and core was recovered in three short (<7 metre) sections at approximately 100, 200 and 300 metres (amounting to ~5% of the total drilled depth). HP values for surface samples were affected by uranium mobility in the surface and near-surface environment, so a second set of 'preferred' HP values were calculated from unweathered rock recovered in core discs and chippings. The four intrusions consist of granite *sensu stricto* with subordinate proportions of coarser (pegmatitic) and finer (microgranitic and aplitic) granitic rock. Variations in grain-size and in the degree to which phenocrysts of feldspar are developed are characteristic features of all the intrusions, and this textural heterogeneity is the main basis for recognising and mapping

internal divisions. Zones of hydrothermally altered rock, which probably formed shortly after emplacement, are common. The passage of hot water through these zones has produced a range of secondary minerals (notably hematite, epidote and chlorite), quartz veining and joints, which act to locally weaken the rock mechanically, lower its overall thermal conductivity and raise its permeability.

Downhole temperatures were measured with a thermistor probe suspended on a cable that was calibrated against a platinum resistance thermometer and was capable of measuring in-hole temperatures to ± 0.01ºC. Due to the transient disturbance of downhole temperatures by the drilling, borehole temperatures were monitored for several months until no change was observed before an equilibrium temperature log was run. Thermal conductivities of recovered borehole samples were measured with the divided bar technique using discs cut from the cored sections and chippings for the rest of the boreholes. Samples were flooded with water under vacuum and subjected to axial stress up to 7 MPa in the divided bar in order to simulate natural conditions (Wheildon *et al*. 1984).

Calculation of heat flow

There are a number of techniques for calculating heat flow. The heat flow Q_d at depth d is given by

$$Q_d = \lambda_d \times \left(\frac{\delta T}{\delta z}\right)_d \quad (1)$$

where $(\delta T/\delta z)_d$ is the temperature gradient over the interval of thermal conductivity λ_d. A technique that combines all the observations from the borehole is the step-integrated heat flow equation of Bullard (1939). The relationship between the thermal resistance R and the temperature T is linear for conductive, steady-state vertical heat flow with no internal heat production, i.e.

$$T_z = T_o + Q \sum_i \left(\frac{\Delta z_i}{\lambda_i}\right) \quad (2)$$

Where $R = \sum_i \left(\frac{\Delta z_i}{\lambda_i}\right)$, λ_i is the thermal conductivity of the ith layer of thickness Δz_i, T_o is the mean ground surface temperature and Q is the heat flow. Wheildon *et al*. (1984) used equation (2) when calculating the original heat flow values for the East Grampians intrusions. Errors can be introduced when using the step integrated heat flow equation if any sections of the borehole are subjected to convective heat transport; an indication of this is shown by

irregular temperature gradients. Hence, for this study, heat flow in each borehole has been re-calculated using equation (1) over several 20-30 m thick intervals, at or below 100 m, that are associated with uniform temperature gradients. The quoted, uncorrected, heat flow for each borehole is the average of the interval measurements and these new values are shown in Table 1. Two heat flow values are shown for Bennachie. This is because there is an increase in measured thermal conductivity in the depth interval 210-280 m that is not associated with a decrease in the temperature gradient. This implies that there may be an error in the thermal conductivities from the lower section of the borehole, although Wheildon *et al*. (1984) did not discuss these higher thermal conductivities. Hence for Bennachie one heat flow measurement is based on an analysis of the whole borehole (90-280 m), whilst a second is calculated from measurements in the upper section (90-200 m) of the borehole.

Correction for palaeoclimate

It is necessary to apply a correction for the effects of past climate variations as these will perturb temperature gradients in the ground from which heat flow is calculated. For simplified modelling purposes palaeoclimate can be considered as a series of one-off surface temperature changes that will affect sub-surface temperatures depending on the magnitude of the change in surface temperature and the time that has elapsed since the change. A surface temperature history for the Quaternary consists of a series of cyclical (e.g. glacial–interglacial cycles) to pseudo-cyclical (e.g. Dansgaard-Oeschger events) changes in temperature between warmer and colder conditions. Each cycle can last from a few hundred to several thousand years. The change in surface temperature will propagate into the ground, but the amplitude of the change will decrease exponentially with depth and there is a time lag between the temperature perturbation at the surface and at depth. The rate of the exponential decrease and the time lag are both dependent on the thermal diffusivity of the geological strata. Representing the surface temperature history as a series of step changes in temperature, Carslaw & Jaeger (1959) have shown that

$$T_\theta = T_0 \times \mathrm{erfc}\left[z/2\sqrt{\kappa t}\right] \quad (3)$$

where T_θ is the departure from original equilibrium temperature at depth z and time t after an instantaneous change in surface temperature of T_0; κ is the average thermal diffusivity of the geological strata down to depth z and erfc(x) is the complementary error function. Noting that the change in surface temperature is the difference in temperature between successive steps, the effect of more than one temperature step is found by addition of all the steps, i.e.

$$T_\theta = \sum T_{\theta i} \quad (4)$$

Where $T_{\theta i}$ is the temperature deviation due to the ith event (Beck 1977; Beardsmore & Cull 2001). An account of the theory for palaeoclimate correction from first principles is given by Westaway & Younger (2013). This temperature deviation is subtracted from the measured temperature to generate the undisturbed temperature distribution in the ground from which a palaeoclimate corrected heat flow is calculated.

Surface temperature history

For the East Grampians region the magnitude of the climate correction to heat flow depends on the surface thermal history during the last glacial-interglacial cycle, considered to extend back to 126 kyr BP (thousand years before present) and in particular the extent of warming since the coldest period (often referred to as the Last Glacial Maximum or LGM, ~20 kyr BP). There are several proxies for past land surface temperature, which include fossil pollen and beetle assemblages, and although each has its uncertainties, multiple proxy data used together can provide reasonably robust reconstructions. Some generalised surface temperature histories have been published; Beck (1977) generated a thermal history for the northern hemisphere at three different latitudes and Westaway & Younger (2013) attempted a reconstruction for the southern and northern UK over the last 150 kyr based on a combination of climate proxy records including sea surface temperature (SST) and ice core temperature data. The approach here has been to produce a surface temperature history specific to the Cairngorms region, rather than to use a regionalised temperature history (c.f. Westaway & Younger 2013). We attempt to capture the localised advance and retreat of glacier ice and the temperature beneath the ice, which can vary rapidly over relatively short distances (Hall & Glasser 2003). This has been achieved by reconstructing the shape of the last glacial-interglacial cycle temperature history for the UK from nearby mean annual air temperature (MAAT) reconstructions, scaling the curve for the Cairngorms latitude and modifying the surface temperature for periods of ice cover. This is detailed below.

Time interval 0–12 kyr BP

For this interval pollen records are available across Europe, including the UK, which have been quantitatively analysed by Davis *et al*. (2003). Based on this large dataset (500 sites), these authors produced MAAT records for six different regions of Europe. The ‘central west’ MAAT curve has been followed for the last 12 kyr (Figure 3), as this is the region in closest proximity to the UK. In this reconstruction the temperature anomaly (relative to present day temperature) for the Younger Dryas (11-12 kyr BP) is -4^{o}C.

Time interval 12–22 kyr BP

This important interval encompasses the LGM and the complicated, subsequent, deglaciation (transition from the LGM to the onset of the current, Holocene, interglacial). The most comprehensive analysis of the MAAT history for this interval is provided by the study of Shakun *et al*. (2012) which summarises 80 records of both sea surface and land surface proxies to reconstruct global latitudinal temperature curves. Their temperature curve corresponding to 30–60^{o}N is used here (Figure 3).

Time interval 22–40 kyr BP

For this interval there are no available regional time-series compilations of MAAT, and therefore proximal NE Atlantic SST records have been used to estimate the shape of the UK MAAT curve. For 22–40 kyr the proximal SST record from ocean core BOFS (Biogeochemical Ocean Flux Study) 5K (Figure 3) was referenced; this site is located west of the Porcupine Seabight at a similar latitude to the southern UK (Maslin *et al*. 1995). This is believed to be a reasonably accurate estimate due to the proximity of the site, and similarity to the Davis *et al*. (2003) and Shakun *et al*. (2012) compilation curves from the 0–22 kyr interval (Figure 3). For BOFS 5K, both summer and winter absolute temperatures are reconstructed by using planktonic foraminiferal assemblage data and different transfer functions which all show similar trends (Figure 3).

Time interval 40–140 kyr BP

Finally, for the longer oldest time interval, the NE Atlantic SST reconstruction from ocean core ODP 980 has been used (Figure 3), which is located in the Rockall Trough at a similar latitude to the central UK (McManus *et al*. 1999). This record has some similarities to BOFS 5K, but is at a far lower temporal resolution and is therefore only applied to the older interval.

Scaling the MAAT curve

In order to scale the idealised MAAT curve (Figure 4 middle panel) modern MAAT is applied as the Holocene average (maximum temperature), and the Annan and Hargreaves (2013) global estimate of MAAT during the LGM (19–23 kyr BP) is used as a guide for the minimum temperature, with a linear scaling of temperature between. The Annan & Hargreaves (2013) dataset is based on a combination of computer modelling and pollen MAAT proxies, where northern England and Scotland localities are 12–20^{o}C below present. Therefore, the minimum MAAT for the Cairngorms during the LGM has been estimated as 17^{o}C below modern (present day) temperatures. This estimated temperature anomaly of -17^{o}C below present day temperatures for the Cairngorm region can be compared against

regional estimates. The average global estimate for the LGM fits reasonably well with the NE Atlantic SST records, which show ~11^{o}C offset between Holocene and LGM values at BOFS 5K (Maslin *et al*. 1995), and ~8^{o}C offset at ODP 980 (McManus *et al*. 1999). The anomaly is slightly greater than the SST estimates of the oceans surrounding the UK published by MARGO *et al*. (2009), which were based on a synthesis of global integrated fossil and geochemical proxies. It also fits well with pollen based reconstructions at 21 kyr BP from central Europe (Bartlein *et al*. 2011) and NE France (Busschers *et al*. 2007), showing MAAT ~10^{o}C below present, and the pollen-based European regional reconstructions for the Younger Dryas (12-11 kyr) at ~4^{o}C below present (Davis *et al*. 2003).

Effect of ice cover

Due to the insulating capacity of ice sheets, the final land surface temperature estimates will differ from the estimated MAAT during periods of glacier ice cover. Hence, it is necessary to reconstruct the times at which the East Grampians were covered by glacier ice. This has been modelled by several studies (e.g. Siegert & Dowdeswell 2004; Hubbard *et al*. 2009; Evans *et al*. 2009; Clark *et al*. 2012). The British Ice Sheet reconstructions of Hubbard *et al*. (2009) provide a series of time-slices with reconstructed ice sheet extent since 35 kyr BP. To reconstruct the presence of an ice sheet in the older part of the record two scenarios have been modelled. A number of authors have presented evidence for glaciations during this older period (e.g. Clapperton 1997; Stoker & Bradwell 2005; Stewart & Lonergan 2011), so in the first scenario glacier ice is assumed in the period 35–120 kyr BP whenever the reconstructed temperature is at or below that during the period 12–35 kyr BP where Hubbard *et al*. (2009) modelled the presence of glacier ice in the East Grampians region. Thus, ice cover is assumed continuously from 110 kyr to 12 kyr BP. However, some authors dispute the presence of older ice cover (e.g. Westaway & Younger, 2013) and so in the second scenario it is assumed the Cairngorm region is only covered by glacier ice during the period 37 to 12 kyr BP.

Temperatures at the base of the Scottish ice sheet were discussed by Glasser & Siegert (2002) and Hall & Glasser (2003). Wet-based ice that is often found under thick ice in topographical troughs is warmer than dry-based ice frozen to its bed. Temperatures at the base of the ice will also be affected by the mean annual air temperature. Sliding at the base of ice sheets may be due to the pressure being close to the pressure melting point; a sufficiently high pressure that the ice melts even though its temperature is below 0ºC. Hall & Glasser (2003) have shown that during basal freezing conditions, basal temperatures can range from -12ºC to -6ºC (absolute). However, when basal melting occurs, basal temperatures are more likely to be in

the range of -1ºC to +1ºC (absolute). The results of Hall & Glasser (2003) have been used to assign basal ice temperatures for the four heat flow borehole localities considered here. For the period 110-37 kyr BP a pre-glacial topography is assumed, whilst present-day topography is used for the period 37-12 kyr BP. The Mount Battock, Bennachie and Ballater boreholes are all in valleys, hence a basal ice temperature of 0ºC is assumed for the period 110-37 kyr BP and +1ºC (absolute) for 37-12 kyr BP. The Cairngorm borehole is situated at a higher elevation (616 m compared to ~220 m for the other boreholes) and is on the upper slope of a valley. Assumed basal ice temperatures are therefore -3ºC (absolute) for the period 110-37 kyr BP and -2ºC (absolute) for 37-12 kyr BP. These surface temperature histories are shown in Figure 5.

Heat flow from each of the boreholes has been corrected for the surface temperature histories. There are two alternative corrections reflecting the two scenarios of continuous ice cover from 110-12 kyr BP (scenario 1) and ice cover only for the period 37-12 kyr BP (scenario 2). These corrections are listed in Table 1 and demonstrate that the palaeoclimate correction is large, approximately 24-28% of the raw (uncorrected) heat flow.

Corrections for topography

Heat flow is also affected by topography as heat will preferentially diffuse into valleys resulting in an over estimate of heat flow in valleys, but an underestimate on hills and mountains. As the heat flow boreholes in the East Grampians region were all in valley locations heat flow will have been over estimated. Wheildon *et al*. (1984) applied a topographic correction using an analytical three-dimensional treatment of topography, described by Bullard (1940), and the heat flow values quoted in the Introduction above include this correction. Westaway & Younger (2013) also discussed topographic corrections and adapted a method by Lees (1910) for mountain ranges so that it could be applied to valley locations. In this method a 2D topographic profile perpendicular to the valley axis is fitted according to a mathematical form, referred to as a Lees Valley. From the fit, a series of parameters are obtained from which the temperature perturbation arising from the valley is easily calculated at any depth and location along the profile. From knowledge of thermal conductivity this can be converted to a perturbation to heat flow via equation (1). For the depth range 100-290 m Westaway & Younger (2013) calculated a topographic heat flow correction of -5.7 mWm^{-2} for the Ballater borehole. The Lees Valley method has been applied here to Ballater for each of the intervals over which heat flow was calculated and the average for the depth range 140-280 m is -5.8 mWm^{-2}. The value quoted by Wheildon *et al*. (1984)

for Ballater is -4.2 mWm^{-2}, which is in close agreement with those derived using the Lees Valley method. Therefore heat flow topographic corrections for the Cairngorm, Mount Battock and Bennachie boreholes have not been repeated using the Lees Valley method and the corrections of Wheildon *et al*. (1984) are used. These are shown in Table 1 along with a final corrected heat flow for each borehole.

New insights into the geology and petrogenesis of the East Grampians Batholith

All of the East Grampians intrusions have been re-mapped since the mid-1980s (British Geological Survey 1989; 1992; 1993a,b; 1995a,b,c; 1996a,b; Harrison 1987; Thomas *et al*. 2004). The new maps and descriptions reveal aspects of their character and emplacement history in considerably more detail than was known previously. A feature of all the intrusions (and of the nearby Monadhliath intrusion, which is similar lithologically and also has HHP character), is the sense of a complicated emplacement history. The two larger intrusions (Cairngorm and Mount Battock) in particular display patterns indicating multi-phase emplacement of magma batches that over time became smaller and increasingly scattered within the confines of the intrusion. Two-phase texture, caused when magma is emplaced forcefully into a nearly-solidified rock causing it to brecciate, is another relatively common feature of the East Grampians intrusions, providing further support for a complicated, multi-phase emplacement history. This character may in part reflect the compositional similarity of the various batches of magma, which probably lacked the contrasts in density and viscosity that are believed to yield more ordered arrangements, such as concentric zoning, in some intrusions. However, the large number of discrete mappable units and their lack of spatial order contrast markedly with other well-characterised granite intrusions of broadly the same age in Scotland, which display simple, concentrically zoned patterns at outcrop; these include the Ben Rinnes, Lochnagar, and Peterhead plutons (Stephenson & Gould 1995), the Fleet pluton (Stephens 1999) and the Ross of Mull pluton (Highton 1999).

It seems likely that HHP character, highly evolved magma compositions, disordered emplacement patterns, and fluid enrichment are related features in the four studied East Grampians intrusions. The presently exposed surface through each one probably lies near to (<2 km below) the former intrusion roof (Thomas *et al*. 2004), in a zone situated at the top of the evolving magma system. Within this zone, multiple batches of highly fractionated, radiothermal granite magma were emplaced in rapid succession. Much of the magma fractionation may have occurred prior to emplacement, at deeper levels in the system, and there was probably little additional fractionation following emplacement. The radiothermal

elements therefore may not be vertically fractionated within the zone exposed at outcrop. This zone is likely to be of limited vertical extent - perhaps 1-2 km - and a vertical diminution in the concentration of radiothermal elements may only become apparent over a depth range of this size. Fluid exsolving from the magma (and perhaps also entering the system from adjacent country rocks) initially caused pervasive alteration of crystallised minerals (mainly feldspars), but became increasingly partitioned into discrete zones as the magma solidified.

The Hill of Fare, Lochnagar, Glen Gairn and Peterhead intrusions crop out in the same E-W trending zone as the four intrusions studied in the Geothermal Energy programme, and a shared set of geochemical and petrological attributes (and similar age) led Stephens & Halliday (1984) to propose that they all share a genetic relationship and therefore constitute a suite - the 'Cairngorm Suite'. Stephens & Halliday (1984) did not include intrusions north of the Great Glen Fault in their study, but the Helmsdale intrusion and possibly one or two others in this region appear to share the same set of attributes and may be related genetically to the East Grampians intrusions. These other intrusions of the Cairngorm Suite have HP values in the range 2.2-4.1 μWm^{-3} (Brown *et al*. 1982) and therefore lack the very high HP values of the four studied intrusions. They also lack evidence for fluid enrichment, and they have more organised emplacement patterns - the Lochnagar, Peterhead and Ben Rinnes intrusions are concentrically zoned at outcrop (Stephenson & Gould 1995). These intrusions may therefore give an indication of what the Cairngorm, Mt Battock, Ballater and Bennachie intrusions are like at levels a few kilometres below their present outcrop.

Webb & Brown (1984) showed that HP values calculated from surface samples were around 20-30% lower than those in equivalent rocks collected from borehole cores, because uranium is easily leached in near-surface bedrock. The range of HP values for these other intrusions of the Cairngorm Suite rises to 2.6-4.9 μWm^{-3} after a correction of 20% is applied to allow for inferred uranium leaching. The East Grampians granite intrusions have such highly evolved compositions that the nature of their source rocks has not been deduced with certainty. They display I-type characteristics (formed mainly from melted igneous rock), but were considered by Stephens & Halliday (1984) to be transitional between I-type and A-type (formed from melted high-grade metamorphic rocks). If they are I-type, the intrusions may be vertically stratified, with granite at outcrop and progressively less evolved compositions (e.g. granodiorite, diorite and cumulate mafic rocks) at deeper levels.

Discussion

The palaeoclimate corrections clearly indicate that a substantial underestimation of heat flow has occurred by not considering the effect of past climate. The two scenarios of continuous ice cover from 110-12 kyr BP (scenario 1) and ice cover only for the period 37-12 kyr BP (scenario 2) have produced a very similar result. This is because at the shallow depths of the East Grampian boreholes, the main palaeoclimate influence is the warming that has taken place since the LGM during the last 18 kyr. The difference in the two climate scenarios occurs for the period prior to 37 kyr, which would have a greater influence on the palaeoclimate correction for heat flows calculated from greater depths. The palaeoclimate correction for each borehole has been taken as the mean of the two climate scenarios and these range from 20.7 to 17.9 mWm^{-2}. The Bennachie borehole yields the highest value, but also has the largest error due to the discrepancy in thermal conductivities between the upper and lower sections of the borehole. For the analysis at Bennachie three heat flow determinations were made in the interval 90-200 m and three in the interval 200-280 m. Hence, the upper part of the borehole generates a lower value of corrected heat flow (89.9 ± 2.1 mW m^{-2}) compared to the lower part (111.9 ± 1.4 mW m^{-2}).There is no discussion in Wheildon *et al*. (1984) as to the change in thermal conductivity, but the high values in the lower part of the borehole appear suspect. In Table 1 heat flows are listed for the average of the whole borehole and the average for the upper section. Overall, the measured heat flow from the four boreholes of the East Grampians shows a substantial increase over that previously reported as a result of correction for palaeoclimate. The percentage increases are 27%, 29%, 24% and 18% for the Cairngorm, Mount Battock, Ballater and Bennachie (upper section) boreholes respectively. Combining these borehole heat flows gives a mean revised heat flow for the East Grampians batholith of 86 ± 7 mWm^{-2}, an increase of 25% over the previously reported values of Wheildon *et al*. (1984).

The gravity modelling of Rollin (1984; 2009) represented the granites as large volumes with steeply outward-dipping straight (or slightly convex) sides extending to considerable depth (9-13 km) with either a flat or curved base, modelled with a mean granite density of 2.62 Mg m^{-3}. This can be considered as the traditional view of how granites are intruded into the upper crust. This gravity modelling is at odds with the revised petrological evidence where it is expected that the East Grampians intrusions become increasingly mafic, and therefore denser, with depth. More recent published work (e.g. Cruden 1998; Petford *et al*. 2000; Taylor 2007) indicates that granites more commonly have a tabular form reflecting upward travel of magma through one or several near-vertical, narrow (1 – 50 m wide) conduits. Spreading-out

of the magma at higher crustal levels results in thinner granite (a few kms thick) with potentially very thick granite over the feeder conduits. The Bouguer gravity anomaly at the Cairngorm and Ballater borehole sites is -46 mGal and is -28 and -38 mGal at the Bennachie and Mount Battock borehole sites respectively. Assuming a tabular space form for the East Grampians batholith this may indicate a central, west-east orientated conduit (beneath Cairngorm and Ballater) and thinner tabular lobes to the north and south (beneath Bennachie and Mount Battock). The revised heat flow value for Mount Battock is the lowest, possibly reflecting thinner granite, although the heat flow values for Cairngorm, Ballater and Bennachie are virtually the same.

Sub-surface temperature profiles, based on the revised heat flow determinations, and taking into consideration the nature of the East Grampians batholith, have been made. It is assumed that the Cairngorm, Mount Battock, Ballater and Bennachie intrusions are part of the roof zone of the evolved magma system and, due to vertical fractionation, the concentration of radiothermal elements diminishes with depth. Other intrusions of the Cairngorm suite may give an indication of reduced HP values at depth within the East Grampians batholith. From studies of continental heat flow it has been observed that there is a linear relationship between the heat production at the surface, A_0 ($\mu W\ m^{-3}$), and the surface heat flow, q_0 (mWm^{-2}) (Birch et al, 1968; Roy et al, 1968) i.e.

$$q_0 = q^* + A_0 D \tag{5}$$

where q* is the basal or lower crust/mantle heat flow (mWm^{-2}) and D, which has a dimension of length, represents a depth of radioactive enrichment within the upper crust. Solutions for calculating the subsurface temperature are given by Wheildon *et al*. (1981) and Wheildon & Rollin (1986). These take into account the decrease of thermal conductivity with increasing temperature, which will occur with increasing depth, i.e.

$$\lambda_z = \frac{\lambda_0 a\prime}{(b\prime + T_z)} \tag{6}$$

where λ_z ($W\ m^{-1}\ K^{-1}$) is the thermal conductivity at depth z (km), λ_0 ($W\ m^{-1}\ K^{-1}$) is the surface thermal conductivity, T_z (ºC) is temperature at depth z, b´ is an empirical constant, with units of ºC, quoted by Wheildon & Rollin (1986) as 823.33 and á = b´+ T_0 (where T_0 is the surface temperature in ºC). The vertical temperature distribution is given by Wheildon & Rollin, (1986) as,

$$T_z = a' e^{\frac{(q_0 z - f(z))}{a' \lambda_0}} - b' \tag{7}$$

Where for an exponential decrease of heat production with depth, f(z) in equation (7) has the form,

$$f(z) = A_0 D \left[z - D \left(1 - e^{\frac{-z}{D}} \right) \right] \quad (8)$$

In this case D is the range of depth over which the heat production decreases to 1/e (0.37) of its surface value and has been assigned a value of 4 km. Predicted sub-surface temperatures incorporating the revised heat flows are tabulated in Table 2 along with λ_0 and T_0 for each borehole (note that heat production data, A_0, are given in Table 1). A graphical representation of the sub-surface temperatures is shown in Figure 6. Two predictions are shown for Bennachie, the first (small dashed line) is based on the heat flow of 100.9 mWm^{-2} calculated from the whole depth of the borehole and the second (large dashed line) on the heat flow of 89.9 mWm^{-2} calculated from the upper section of the borehole. For the East Grampians batholith as a whole the predicted temperature at 5 km depth is 129 ºC and at 7 km depth it is 176 ºC, where these mean temperatures have excluded the heat flow calculated from the lower section of the Bennachie borehole where the thermal conductivities appear suspect. The predicted temperatures are dependent on the depth value D. For instance, if D = 7 km then the equivalent mean temperatures at 5 km and 7 km depth are 126 ºC and 168 ºC respectively. A value of D = 4 km is preferred based on the geological mapping evidence presented above that the HHP character of the granite is likely to be confined to a relatively narrow upper zone of the intrusions.

Westaway (2009) and Westaway & Bridgland (2014) also present a solution to the temperature distribution with depth assuming heat production decreases exponentially with depth, but with constant thermal conductivity, i.e.

$$T_z = T_0 + \frac{q^* z}{\lambda_0} + \frac{A_0 D^2}{\lambda_0} \left(1 - e^{\frac{-z}{D}} \right) \quad (9)$$

With a value of D = 4 km and with the same parameters as used above, sub-surface temperature predictions based on equation (9) are also tabulated in Table 2 and shown in Figure 7. The result is a set of slightly reduced geotherms (-8 ºC at 5 km and -15 ºC at 7 km depth) that illustrates the importance of considering the effect of increasing temperature on thermal conductivity.

The revised temperatures of 129 ºC and 176 ºC at 5 km and 7 km respectively, compare to temperatures of 92 ºC at 5 km depth and 118 ºC at 7 km depth predicted by Wheildon *et al.* 1984, corresponding to percentage increases of 40% at 5 km depth and 49% at 7 km depth.

These temperatures are lower than expected at similar depths in the Cornubian batholith of Cornwall where temperatures of 182 ºC at 5 km depth and 258 ºC at 7 km depth were predicted by Downing & Gray (1986a). However, they do indicate a substantially increased resource over that originally predicted for the East Grampians batholith and suggest that power generation could be possible from boreholes drilled to depths greater than 5 km. In addition, the geothermal resource may be accessible as hot water (direct use geothermal). Calcite-cemented breccia, quartz-calcite veins and calcite veins were all described from the cores taken in the heat flow boreholes (Webb & Brown 1984; Webb *et al*. 1985) raising the possibility that there are networks of transmissive fractures at depth from where the calcite has dissolved. Manning *et al*. (2007) measured a fracture permeability of 1.68 x 10^{-10} m^2 within the North Pennine Batholith (Weardale granite) which is the highest measured permeability for a granite within the UK. Although there is no evidence to indicate a fracture permeability of this magnitude within the East Grampians, with predicted temperatures of 58 ºC at 2 km depth a borehole targeted to intersect a fracture zone could provide a direct use resource for communities within the Cairngorm region.

Conclusions

A rigorous correction for the effects of palaeoclimate on heat flow has been applied to the East Grampians batholith. This has resulted in an increase of 25% over previously reported values to 86 ± 7 mWm^{-2}. Two scenarios have been followed for the surface temperature history in the Cairngorm region during the last glacial-interglacial

cycle due to uncertainty in the extent of ice cover for the period prior to 37 kyr BP. These two scenarios made little difference to the correction demonstrating that in the depth range 100-300 m it is warming since the LGM that has been the major influence on perturbing sub-surface temperatures. Recent mapping suggests that the outcropping granites of the East Grampians batholith lie near the surface of a highly evolved magma system. Evidence from other outcropping granites that are probably representative of the Cairngorm, Mount Battock, Ballater and Bennachie intrusions at a few kilometres depth supports the hypothesis that heat production decreases with depth as the rock becomes progressively less siliceous. The coincident, large Bouguer gravity anomaly low has been previously modelled as granite extending to great depth. More recent work on granite emplacement suggests that granite intrusions are more likely to be tabular in form with deep seated, semi-vertical feeder conduits. Such a shape presents more options for creating a model of evolved granite at

outcrop with more mafic (and hence denser) rocks at depth. It is recommended that a new 3D gravity model of the East Grampians batholith should be produced.

Modelling of sub-surface temperatures that take account of the decrease of heat production and thermal conductivity with depth suggest a temperature of 129 ºC at 5 km depth and 176 ºC at 7 km depth for the East Grampians batholith, increases of 40% and 49% respectively compared to previous estimates. Although these temperatures are currently at the lower end of viability for EGS they indicate that there is a considerable geothermal resource within the batholith. Hydrothermal alteration within the granite indicates the possibility of transmissive fractures at depth that might be exploitable for direct geothermal heat use.

Acknowledgements

This paper is published by permission of the Executive Director of the British Geological Survey (NERC).

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Figure 1. Distribution of granite within the crust of Scotland based on surface exposure and interpretations of gravity data. Heat production (in units of μWm^{-3}) are shown for intrusions where values greater than 3.5 μWm^{-3} have been measured.

Figure 2. Shaded relief image, illuminated from the north, of the Bouguer gravity anomaly over the East Grampians batholith, based on gravity data from the British Geological Survey national gravity databank. The outlines of outcropping granites are shown in red and the locations of the four heat flow boreholes are indicated by white crosses.

Figure 3. Selected temperature proxy records used to construct the average temperature trends over the UK during the past 140 kyr. References from top to bottom: A) Davis et al. (2003); B) Shakun at el. (2012); C) Maslin et al. (1995); D) McManus et al. (1999). SST is sea surface temperature and G-IG range is glacial-interglacial range.

Figure 4. The reconstructed UK temperature trend for the last 120 kyr (B) scaled to the temperature at the Cairngorm latitude, aside the appended data used from several sources and regions to create the record (A; see also Figure 3). Ice core temperature proxy shown for comparison (C; North Greenland Ice Core Project members, 2004).

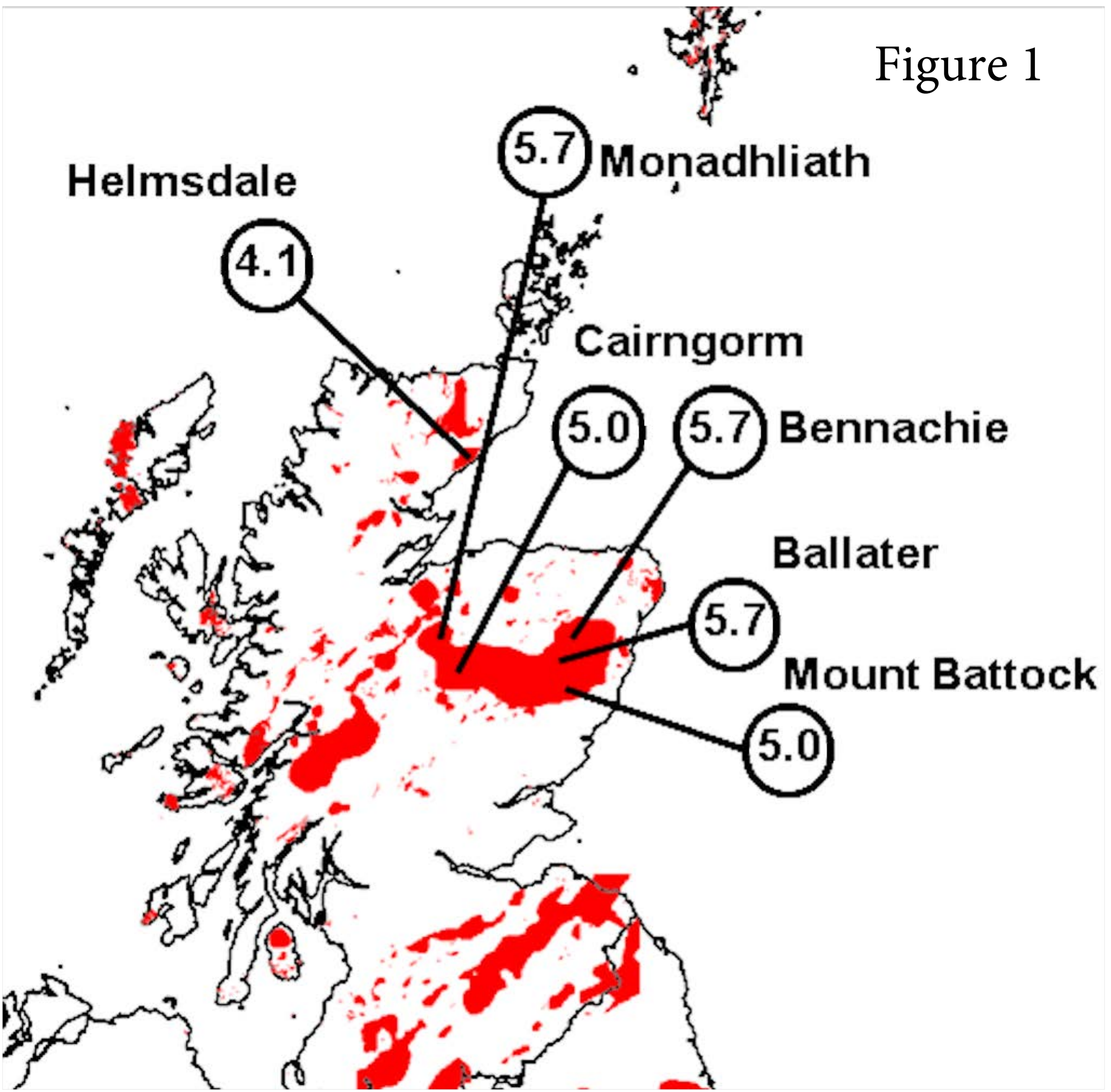
Figure 5. a) Surface temperature history for scenario 1 where continuous ice cover has been assumed for the period 110-12 kyr BP. The solid line is for Cairngorm and where this differs for Mount Battock, Bennachie and Ballater it is shown by the dashed line. b) Surface temperature history for scenario 2 where ice cover has been assumed for the period 37-12 kyr BP only. The solid line is for Cairngorm and where this differs for Mount Battock, Bennachie and Ballater it is shown by the dashed line.

Figure 6. Predicted sub-surface temperatures, based on the revised heat flow estimates, assuming heat production decreases exponentially with depth. A) Thermal conductivity decreases with temperature and B) thermal conductivity is assumed to be constant. In (A), the revised mean temperatures of 129 ºC at 5 km depth and 176 ºC at 7 km depth are displayed as stars. Note that two predictions are shown for Bennachie, where the solid line uses heat flow calculated from the whole borehole and the dashed line from the upper section only.

Table 1. Tabulated values of heat production, uncorrected heat flow and corrections to heat flow with a final value of corrected heat flow for the East Grampians heat flow boreholes. The palaeoclimate correction scenarios and the two Bennachie borehole options are explained in the text. Note that the heat production data are from Webb & Brown (1984) and the topographic correction is taken from Wheildon *et al*. (1984).

Table 2. Predicted temperatures at depth arising from the revised heat flow estimates. Heat production is assumed to decrease with depth exponentially for two cases. In the first, the temperature dependence of thermal conductivity is taken into account and in the second, it is assumed to be constant.

Figure 1


Helmsdale
4.1
5.7
Moṇadhliath
Cairngorm
5.0
5.7
Bennachie
Ballater
5.7
Mount Battock
5.0

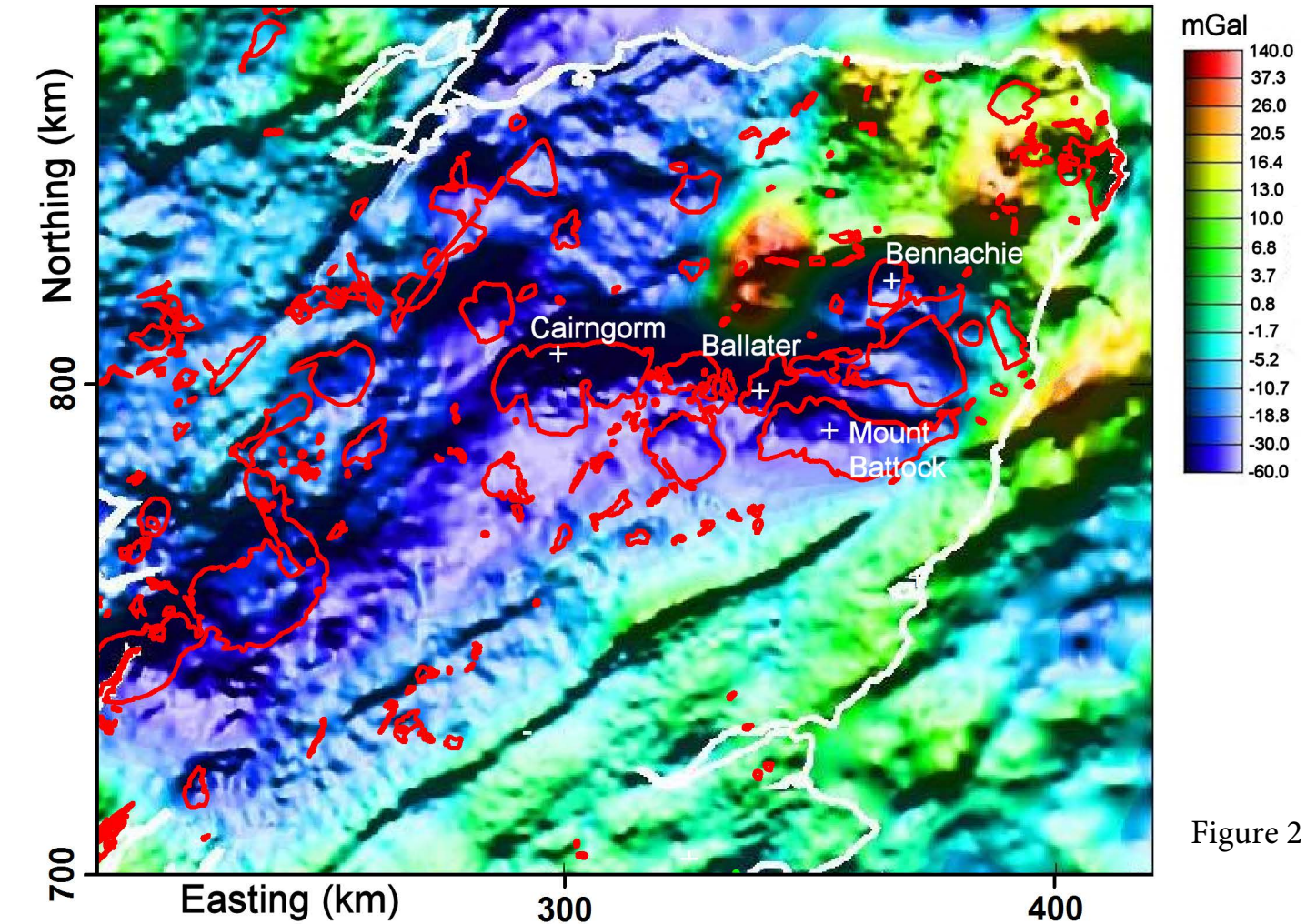

mGal
140.0
37.3
26.0
20.5
16.4
13.0
10.0
6.8
3.7
0.8
-1.7
-5.2
-10.7
-18.8
-30.0
-60.0
Bennachie
Cairngorm
Ballater
Mount Battock
Northing (km)
800
700
Easting (km)
300
400

Figure 2

Figure 3

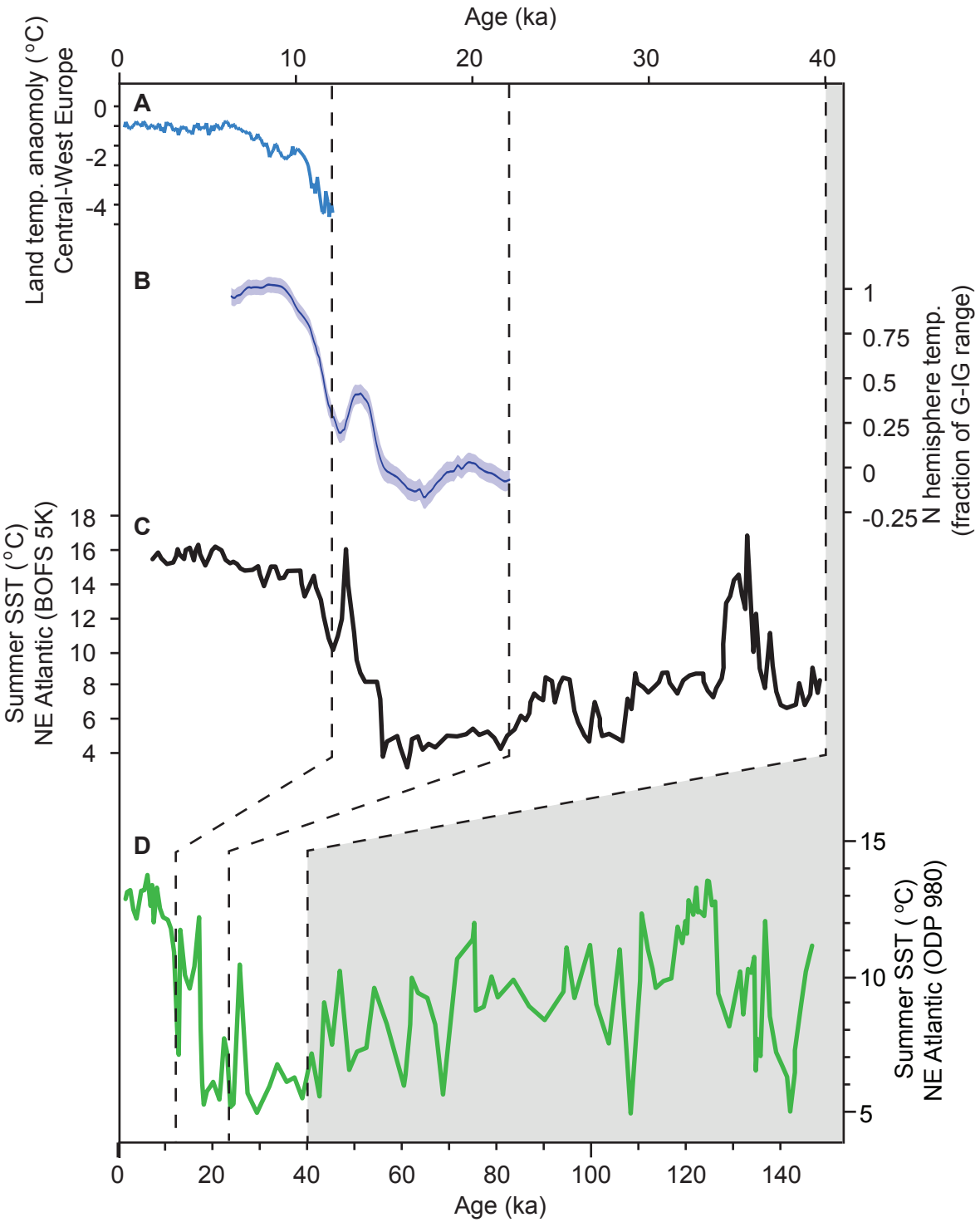

Age (ka)
0
10
20
30
40
A
Land temp. anaomoly (°C)
Central-West Europe
0
-2
-4
B
1
0.75
0.5
0.25
0
-0.25
N hemisphere temp.
(fraction of G-IG range)
C
Summer SST (°C)
NE Atlantic (BOFS 5K)
18
16
14
12
10
8
6
4
D
15
10
5
Summer SST (°C)
NE Atlantic (ODP 980)
0
20
40
60
80
100
120
140
Age (ka)

Figure 4

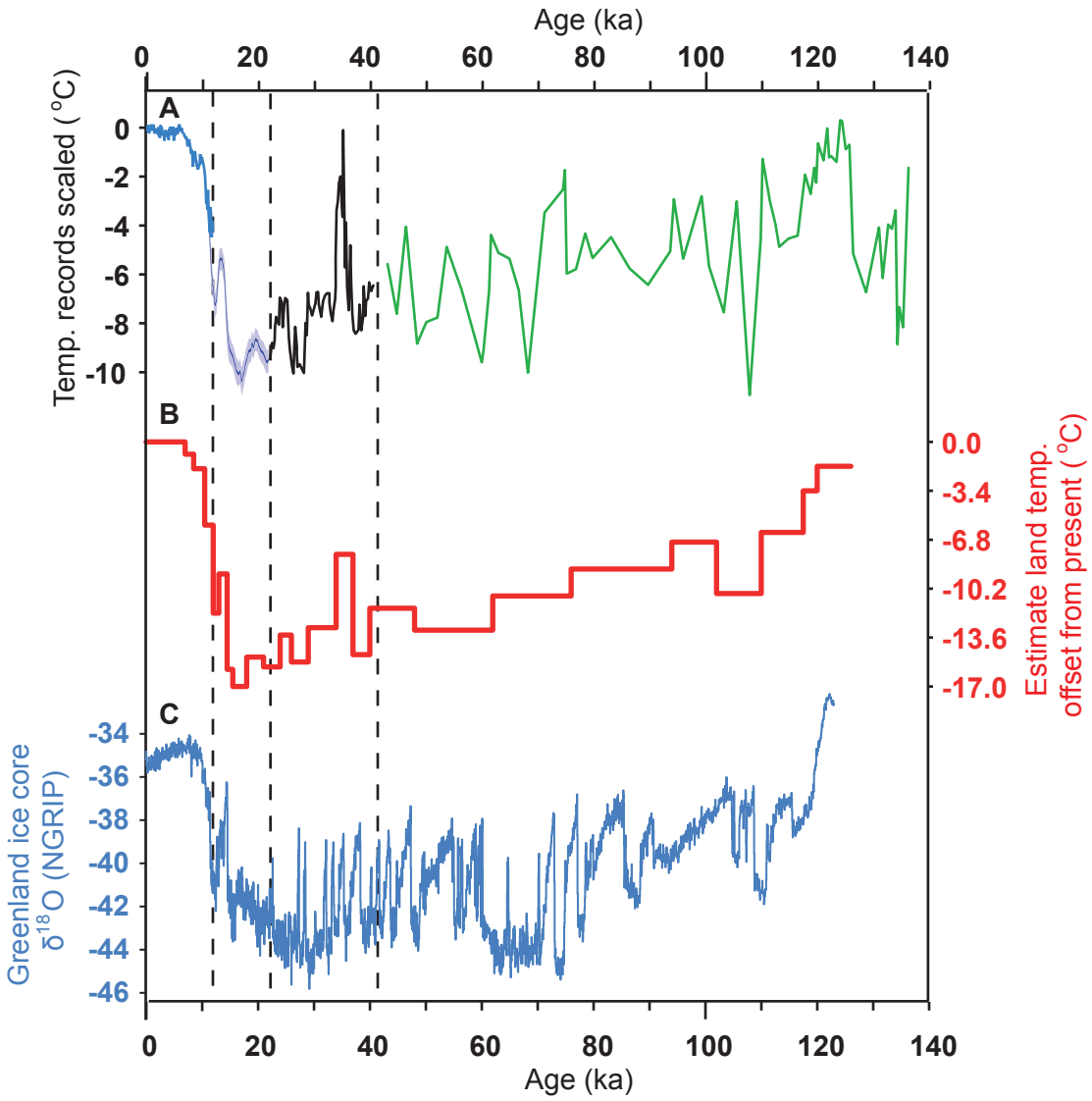

Age (ka)
0
20
40
60
80
100
120
140
A
B
C
Temp. records scaled (°C)
0
-2
-4
-6
-8
-10
0.0
-3.4
-6.8
-10.2
-13.6
-17.0
Estimate land temp.
offset from present (°C)
Greenland ice core
δ18O (NGRIP)
-34
-36
-38
-40
-42
-44
-46

Figure 5a

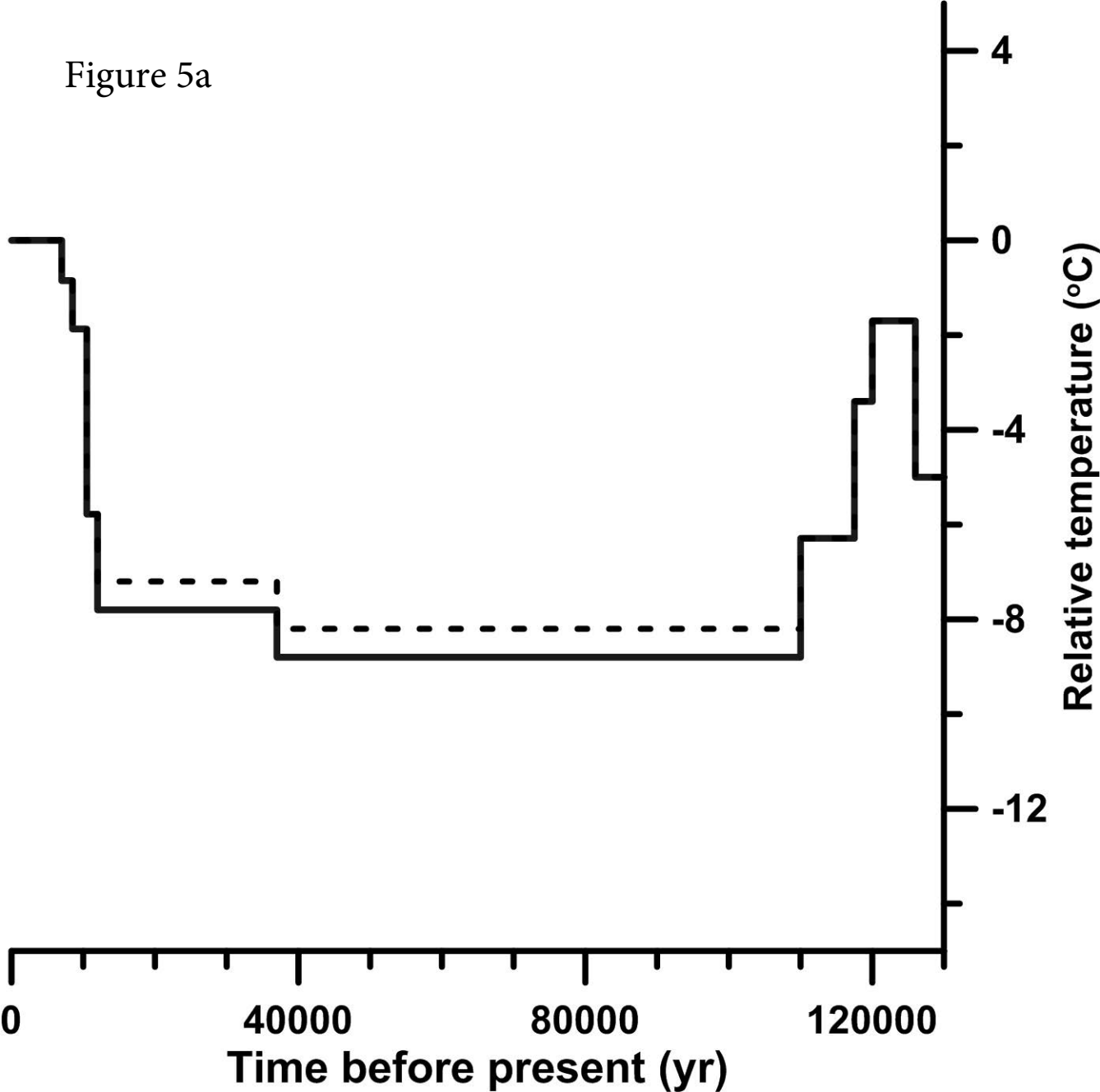

4
0
-4
-8
-12
Relative temperature (°C)
0
40000
80000
120000
Time before present (yr)

Figure 5b

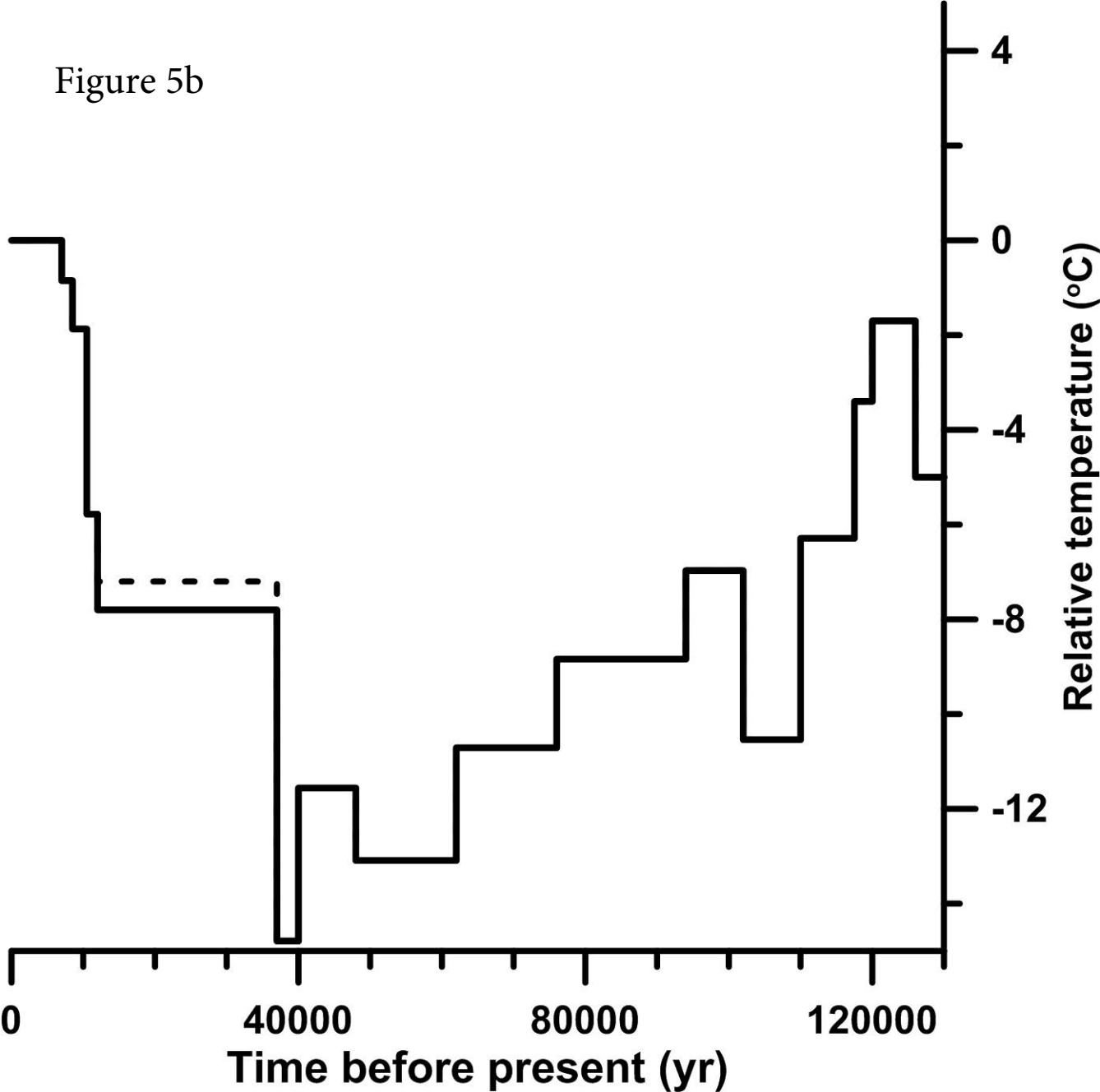

4
0
-4
-8
-12
Relative temperature (°C)
0
40000
80000
120000
Time before present (yr)

Figure 6

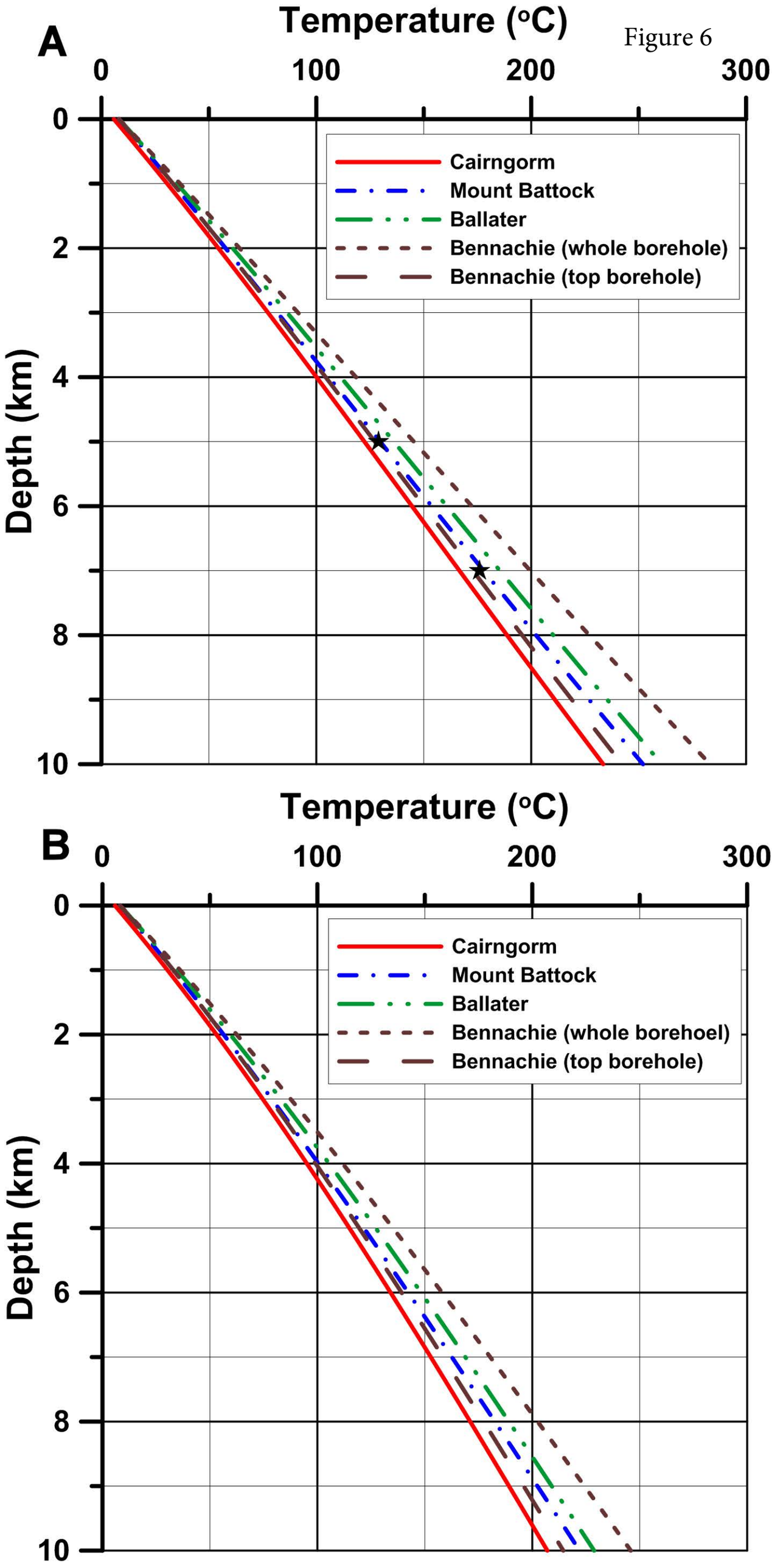

A
Temperature (°C)
0
100
200
300
0
2
4
6
8
10
Depth (km)
Cairngorm
Mount Battock
Ballater
Bennachie (whole borehole)
Bennachie (top borehole)
B
Temperature (°C)
0
100
200
300
0
2
4
6
8
10
Depth (km)
Cairngorm
Mount Battock
Ballater
Bennachie (whole borehoel)
Bennachie (top borehole)

Table 1

Borehole	Heat production, A_0 ($\mu W\ m^{-3}$)	Uncorrected heat flow ($mW\ m^{-2}$)	Palaeoclimate correction ($mW\ m^{-2}$)			Topographic correction ($mW\ m^{-2}$)	Corrected heat flow, q_0 ($mW\ m^{-2}$)
			Scenario 1	Scenario 2	Mean		
Cairngorm	7.3	71.3 ± 2.8	19.6 ± 0.5	21.0 ± 0.4	20.3 ± 0.5	-2.7	88.9 ± 2.8
Mount Battock	4.8	65.0 ± 2.2	17.4 ± 0.4	19.1 ± 0.4	18.2 ± 0.4	-6.9	76.3 ± 2.2
Ballater	6.8	74.1 ± 3.4	16.8 ± 1.3	19.0 ± 0.8	17.9 ± 1.1	-4.2	87.8 ± 3.6
Bennachie (whole borehole)	7.0	85.8 ± 13.2	19.6 ± 1.8	21.7 ± 1.7	20.7 ± 1.7	-5.6	100.9 ± 13.3
Bennachie (top borehole)	7.0	76.1 ± 2.1	18.3 ± 0.4	20.4 ± 0.4	19.4 ± 0.4	-5.6	89.9 ± 2.1

Table 2

Borehole	Surface temperature, T_0 (ºC)	Surface thermal conductivity, λ_0 ($W\ m^{-1}\ K^{-1}$)	Predicted temperature at 5 km depth (ºC)		Predicted temperature at 7 km depth (ºC)	
			Temperature dependent thermal conductivity	Constant thermal conductivity	Temperature dependent thermal conductivity	Constant thermal conductivity
Cairngorm	5.8	3.5	122	115	167	153
Mount Battock	8.2	3.0	130	122	178	163
Ballater	8.2	3.2	136	127	185	169
Bennachie (whole borehole)	8.2	3.5	145	135	200	180
Bennachie (top borehole)	8.2	3.5	127	119	173	158
Mean (excluding Bennachie whole borehole)			129	121	176	161