Regional modelling of permafrost thicknesses over the past 130 ka: implications for permafrost development in Great Britain

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The greatest thicknesses of permafrost in Great Britain most likely occurred during the last glacial-interglacial cycle, since this is when some of the coldest conditions occurred during the last 1 M years. The regional development of permafrost across Great Britain during the last glacial-interglacial cycle has been modelled from a ground surface temperature history based on mean annual temperatures and the presence of glacier ice. To quantify the growth and decay of permafrost, modelling was undertaken at six locations across Great Britain that represents upland glaciated, lowland glaciated, upland unglaciated and lowland unglaciated conditions. Maximum predicted permafrost depths derived in this academic study range between several tens of metres to over a 100 m depending on various factors including elevation, glacier ice cover, geothermal heat flux and air temperature. In general, the greatest maximum permafrost thicknesses occur at upland glaciated locations with minimum thickness at lowland sites. Current direct geological evidence for permafrost is from surface or shallow processes, mainly associated with the active layer. Further research is recommended to identify the imprint of freeze/thaw conditions in permanently frozen porous rocks from beneath the active layer.

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Modern permafrost has been recognised in several mid-high latitude regions that are subjected to High Arctic (Smith *et al.* 2007), Continental (Halsey *et al.* 1995; Bockheim & Hall 2002) and High-altitude (Gorbunov 1978; Guodong & Shaoling 1982) climatic regimes. It has also been widely interpreted from the geological record within mid- to high-latitude areas where it developed repeatedly during successive Quaternary cold stages (Ballantyne & Harris 1994; Rozenbaum & Shpolyanskaya 1998; Clayton *et al.* 2001; French *et al.* 2007; French 2008; Candy *et al.* 2011; French & Millar 2014; Vandenberghe *et al*. 2014).

Preserved evidence for past permafrost development typically relates to phenomenon produced by 'seasonal' frost action (French 2008). Recognising evidence for 'perennial' permafrost is by contrast more challenging. This is because 'perennial' permafrost is likely to have occurred largely at depth and the potential subtlety and ambiguity of the geological evidence. Specific challenges relate to the identification of geological evidence for the growth of ice within various materials, the effects of groundwater chemistry upon freezing at depth and the recognition of materials that have remained dry, but were 'thermally-frozen'. Recent studies from deep mines and boreholes have demonstrated modern 'thermally-frozen' permafrost thicknesses of 500-600 m in northern Canada (Ruskeeniemi *et al.* 2002; Ruskeeniemi *et al.* 2004), 1500 m in central Siberia (Fotiev 1997) and nearly 100 m of permafrost buried at depth in Poland (Szewczyk & Nawrocki 2011). What is less clear are the thicknesses of 'perennial' permafrost that developed during the Quaternary.

Understanding past permafrost thicknesses is important from several geological and applied angles. Firstly, it provides a direct insight into the depth to which cold climate processes have operated and this has major implications for weathering rates and the development of regolith/saprolite. From an applied perspective, the depth to which permafrost may have developed is directly relevant to establishing a safety case for a geological disposal facility (GDF) for radioactive waste (McEwen & de Marsily 1991;

Ershov *et al.* 2003; Chapman & Hooper 2012). The safety case for a GDF relies on complementary natural and engineered barriers to provide the necessary level of containment in the post-closure period. Post-closure safety case studies typically consider natural changes over the first one million years following GDF closure.

There are no definitive indicators of the maximum depth of permafrost development in Great Britain during the Quaternary. Within this paper, we utilise a numerical modelling approach linked to the past climate, thermal conductivity and geothermal heat flux to reconstruct permafrost thicknesses for six localities in Great Britain during the last 130 ka. Each locality was carefully chosen to exhibit variations in inferred glacier cover during the Late Devensian, latitude, elevation and geology.

Background

Definition of permafrost

Historically, several definitions of the term *permafrost* exist. The term was originally employed as an abbreviated form of 'permanently frozen' (Muller 1945). However, this definition is somewhat restrictive because it relies upon the availability of water within the substrate for the ground to freeze. Within modern literature, *permafrost* is widely defined as ground which remains at or below 0 °C for at least two consecutive years and perennially frozen ground as ground that keeps frozen for at least two consecutive years (French 2007). Hence, permafrost is solely based on temperature, thus disregarding the texture, degree of compaction, water content, and lithologic character of the material, whereas perennially frozen ground is defined on the basis of freezing of water. The freezing of water is itself dependent on pressure, salinity and by the adsorptive and capillary properties of the ground matter. In the study here *permafrost* (i.e. ground which remains at or below the 0 °C (32 °F) isotherm) has been predicted by one dimensional heat conduction modelling that does not take into account the freezing of water, the effect of groundwater movement or the change in ground properties due to freezing. Therefore this modelling identifies the potential for ice formation.

The Quaternary record of permafrost within Great Britain

Mid-latitude regions including Great Britain have proven particularly sensitive to global-scale climatic change during the Quaternary with marked climatic variability recognised at both Milankovitch (Bridgland 2000; Bridgland 2006; Bates *et al.* 2010; White *et al.* 2010; Penkman *et al.* 2011) and sub-Milankovitch time-scales (Lewis *et al.* 2001; McDermott *et al.* 2001; Walker *et al.* 2003; Briant *et al.* 2005; Candy & Schreve 2007; Gao *et al.* 2007).

Evidence demonstrates the cyclical occurrence of cold and temperate (interglacial) climatic conditions in Great Britain during the Quaternary although the geological record is highly-fragmented and far from complete. Based upon the marine oxygen isotope record, Great Britain has experienced at least 50 major cold climatic stages (Lisiecki & Raymo 2005) and at least 30 distinct episodes of glaciation of varying scale and extent during the Quaternary (Lee *et al.* 2011; Böse *et al.* 2012; Lee *et al.* 2012; Thierens *et al.* 2012). Likewise, multiple episodes of permafrost development have been recognised during the Early-Middle (Rose & Allen 1977; West 1980; Kemp *et al.* 1993; Murton *et al.* 1995; Lee *et al.* 2003; Candy *et al.* 2011) and Late Pleistocene (Watson & Morgan 1977; Seddon & Holyoak 1985; Allen 1987; Ballantyne & Harris 1994; Bateman 1995; Murton *et al.* 2003; Boardman 2011; Bateman *et al.* 2014). Palaeontological evidence from the last two cold periods – the Younger Dryas (12.9-11.7 ka BP) and Late Devensian glaciation (30-18 ka BP), reveal that mean winter air temperatures were at least -25 °C (Atkinson *et al.* 1987; Huijzer &

Vandenberghe 1998). From this climate record it might be expected that depths of periglacial disturbance might extend to 10s, or even 100s, of metres. However, despite evidence for permafrost being both temporally and spatially common, there is no currently known geological evidence that refers to thicknesses of it beyond several tens of metres.

Permafrost modelling approach

The modelling is based on the periodic heating at the surface of a column of infinite depth and the propagation of the heat into the ground in the vertical (depth) dimension. Only the variation of thermal properties in the vertical (z) dimension is considered. In situations where the geology is horizontally layered this 1D assumption is reasonable but it will lead to a more approximate solution if the geology varies substantially in the horizontal (x, y) plane. For the purposes of a regional investigation to assess the potential for permafrost development this, static, 1D modelling approach is appropriate, but it does not lend itself to a full sensitivity analysis whereby all the input modelling parameters are varied across their permissible limits.

A surface temperature history consists of a series of cyclical swings in temperature between warm and cold conditions. Each cycle can last from a few hundred to several thousand years. An example of a surface temperature history for Prudhoe Bay, Alaska, based on an East Siberia model, is shown in Fig. 1a (Osterkamp & Gosink 1991). The change in surface temperature will be propagated into the ground, but the amplitude of the change will decay exponentially with depth and there is a time-lag between the temperature perturbation at the surface and at depth. The rate of the exponential decay and the time-lag are both dependent on the thermal diffusivity of the geological strata. A surface temperature history can also be represented as a series of step changes in temperature. The surface temperature history for Prudhoe Bay, shown in Fig. 1a, is shown as a series of step changes in Fig. 1b.

The depth to which the effect is noticeable depends on the magnitude of the temperature step, the time since the event and the thermal diffusivity of the geological strata. Carslaw & Jaeger (1959) have shown that:

$$T_\theta = T_0 \times \operatorname{erfc}\left[z/2\sqrt{\kappa t}\right], \tag{1}$$

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.

$$T_\theta = \sum T_{\theta i}, \tag{2}$$

where $T_{\theta i}$ is the temperature deviation due to the ith event.

Therefore to model the evolution of sub-surface temperatures through time, an initial sub-surface temperature profile is perturbed by any step changes in surface temperature that have occurred from the initial time up to the time being considered. The initial time has been taken as 126 ka BP and sub-surface temperatures have been calculated at 5 m depth intervals to 1 km every 250 years up to present day. The derivation of the step changes in surface temperature, i.e. the palaeoclimate of the last glacial-interglacial cycle and its variations across Great Britain, are discussed below.

Temperature and ice sheet evolution over the last glacial-interglacial cycle

For the permafrost modelling a surface temperature history is required for each locality considered. This has been achieved by constructing a generic record of past mean annual air temperature (MAAT) over the last glacial-interglacial cycle (0-130 ka BP) which has then been modified for latitude and periods of ice cover.

There are several proxies for past land-surface temperature, which include fossil pollen and beetle assemblages, and although each has its uncertainties, using multi-proxy data can provide reasonably robust reconstructions. Estimating cold winter temperatures from fossil beetle assemblages is thought to be particularly problematic. This is due to a lack of proxy data in the calibration curve (Coope *et al.* 1998); the lack of abundance data in the transfer function used (Bray *et al.* 2006); plus the ability of beetles to bury themselves in the ground during winter months – beetles therefore may only respond to summer temperatures (Westaway & Younger 2013), which is not suitable for MAAT reconstruction.

Last Glacial-Interglacial cycle MAAT curve

Westaway & Younger (2013) attempted to reproduce the MAAT curve for southern and northern UK over the last 150 ka, based on a combination of climate proxy records including sea-surface temperature (SST), derived from planktonic foraminifera, and ice-core temperature data. Here, we produce a different MAAT record by utilising NE Atlantic SST records (Fig. 2B-D), and pollen-based MAAT records (Fig. 2A), to reconstruct an idealized curve (Fig. 3A) which looks different from Greenland ice core temperature records (Fig. 3C). This approach is necessary as there are no land-surface MAAT pollen records from the UK during the Last Glacial (c. 30-19 ka BP) (Davis *et al.* 2003; Bartlein *et al.* 2011).

Time interval 12–0 ka BP. **-** For this interval, which spans the Younger Dryas and current Holocene interglacial, pollen records are available across Europe, including the UK, which have been quantitatively analysed in Davis *et al.* (2003). Based on this large dataset (500 sites), these authors produced MAAT records for 6 different regions of Europe. The 'central west' (which is the approximate region, N-S, from northern Scotland to northern Spain and W-E from western Ireland to Poland) MAAT curve has been followed for the last 12 ka (Fig. 2A), as this is the proximity region that includes Great Britain. In this reconstruction the temperature anomaly (relative to present day temperature) for the Younger Dryas is –4 °C.

Time interval 22–12 ka BP. **-** This important period encompasses the progressive break-up of the Last British-Irish Ice Sheet, encompassing the global climatic minimum (c. 21 ka), the complicated phase of climatic amelioration commonly referred to as the Lateglacial, and the onset of the Younger Dryas stadial. The most comprehensive analysis of the MAAT history for this interval is provided by the study of Shakun *et al*. (2012) that summarizes 80 proxy records of both sea surface and land surface proxies to reconstruct global latitudinal temperature curves. Their temperature curve corresponding to 30–60°N (Fig. 2B) is used here.

Time interval 40–22 ka BP. **-** The time interval between 40-22 ka BP includes the build-up of the Last British-Irish Ice Sheet to its maximum-known extent at approximately 27 ka BP and then its gradual decline (Clark *et al.* 2012). For the time interval before 22 ka ago 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 ka the proximal SST record from BOFS (Biogeochemical Oceanic Flux Study) ocean core 5K was referenced (Fig. 2C), which is located west of the Porcupine Seabight at a similar latitude to southern Britain (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 ka interval (Fig. 2). 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 (Fig. 2).

Time interval 140–40 ka BP. - The final time-interval spans the Last Interglacial (Ipswichian/Eemian/MIS 5e) and the complex transition into the Last Glaciation (Late Devensian). For the longer, oldest time interval the NE Atlantic SST reconstruction from ODP (Ocean Drilling Program) ocean core 980 (Fig. 2D) has been used, which is located in the Rockall Trough at a similar latitude to central Great Britain (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 for the older section.

Last Glaciation – absolute temperature

In order to scale the idealised MAAT curve (Fig. 3B) to each of the six Great British localities, modern MAAT is applied as the Holocene average (maximum temperature), and the Annan & Hargreaves (2013) global estimate of MAAT during the global peak of the last glaciation (19–23 ka BP) as a guide for the minimum temperature at each locality, 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 the southern England and Wales localities are estimated to be 8–12 °C below present, and the northern England and Scotland sites 12–20 °C below present. Therefore the estimated climate range for the last glacial-interglacial cycle is 12 to 17 °C below modern, between southern English and northern Scottish sites respectively.

The average global estimate for the climatic peak of the last glaciation fits reasonably well with the NE Atlantic SST records, which show ~11 °C difference between Holocene and global climatic minimum values at BOFS 5K (Maslin *et al.* 1995), and ~8 °C difference at ODP 980 (McManus *et al.* 1999). These values are slightly greater than the SST estimates of the oceans surrounding the British Isles by Waelbroeck *et al.* (2009), which was based on a synthesis of global integrated fossil and geochemical proxies. It also fits well with pollen based reconstructions at 21 ka BP from central Europe (Bartlein *et al.* 2011) and NE France (Busschers *et al.* 2007), showing MAAT ~10 °C below present, and the pollen-based European regional reconstructions for the Younger Dryas (12.9-11.7 ka) at ~4 °C below present (Davis *et al.* 2003).

Insulating effect of ice cover

Due to the insulating capacity of ice sheets and glaciers, for the final land-surface temperature estimates, it is necessary to reconstruct the time-intervals that each location was covered by ice and the temperature at the base of the ice. Ice sheet dynamics in Great Britain have been modelled by several studies (Siegert & Dowdeswell 2004; Boulton & Hagdorn 2006; Evans *et al.* 2009; Hubbard *et al.* 2009; Clark *et al.* 2012; Patton *et al.* 2013) with the reconstructions of Hubbard *et al*. (2009) providing a series of time-slices with reconstructed ice sheet extent from 0-35 ka ago and these have been used here for the period >35 ka BP. To reconstruct the presence of ice cover in the older part of the record, the sensitivity of the ice sheet or glacier presence at each location for the 0–35 ka BP record, derived from Hubbard *et al*. (2009), is used to extend back using the reconstructed temperature record; i.e. for each locality, when the temperature in the older part of the record falls below that in the recent record (<35 ka BP) when ice is predicted, ice is assumed in that part of the older record. The modelled reconstructions of Hubbard *et al.* (2009) appear to correlate well with the proxy data, and hence the ice cover presence/absence data over the interval 0–35 ka BP are far less uncertain than those from the interval 35–130 ka BP. Periods of ice cover at each of the six localities are given in the description of the localities in Table 1.

The theory behind the reconstruction of temperatures beneath glaciers in Scotland has been discussed by Glasser & Siegert (2002) and Hall & Glasser (2003). Warm-based ice that is often found under thick ice in topographical troughs is warmer than cold-based ice frozen to its bed. Temperatures at the base of the ice will also be affected by the mean annual air temperature and ice thickness. Sliding ice may be due to the pressure at the base of the ice being close to the pressure melting point; a sufficiently high pressure that the ice melts even though its temperature is below 0 ºC. Hall & Glasser (2003) have shown that during basal freezing conditions, basal temperatures can range from -12 to -6 ºC (absolute). However, when basal melting occurs, basal temperatures are more likely to be in the range of -1 to +1 ºC (absolute).

The basal ice thermal regime may also change with time and space as the ice mass thins or thickens. However, for simplicity and for each surface temperature history, a single basal ice temperature has been assigned for periods of ice cover. Hubbard *et al*. (2009) have modelled the development of the Last British-Irish Ice Sheet and have predicted the cumulative time that the ice sheet bed was at pressure melting point. At each of the localities, if Hubbard *et al*. (2009) predict predominantly persistent frozen basal conditions then cold-based ice is assumed, however, if predominantly pressure melting conditions are predicted then warm-based ice is assumed, for the entire period from 0-130 ka BP. Basal absolute temperatures for cold-based frozen conditions are therefore estimated as -3 ºC (absolute). This temperature is not as low as modelled by Hall & Glasser (2003) as it is assumed that warm-based conditions would have also occurred as the ice sheet grew and declined. For warm-based ice conditions, absolute temperatures are assumed to be +1 ºC.

Two examples of surface temperature histories are shown in Fig. 4. Central East Anglia was ice-free during the Late Devensian (Clark *et al.* 2004; Bateman *et al.* 2014). Therefore, the land surface temperature estimates infer a minimum temperature of 12 ºC below present, which occurred at the global peak of the last glaciation (19-23 ka BP) (Annan & Hargreaves 2013). By contrast, within the Stainmore Trough, the land-surface was insulated from the minimum MAAT of 14 ºC below present by the extensive periods of ice cover (Livingstone *et al.* 2012). These occur between 110-102, 76-37 and 34-14.5 ka BP and the temperature during these periods is constant at +1 ºC absolute (8.2 ºC below present). The minimum temperature of 9.8 ºC below present occurred between 13-12 ka BP after the ice had retreated.

Modelling results

Permafrost modelling

In order to assess how permafrost development may vary across Great Britain, six locations have been selected which present a variety of latitude, elevation, substrate geology and periods of ice cover. These are shown in Fig. 5. For each location, the vertical geological bedrock section, at the 1:625 000 scale, has been extracted to 1 km depth from the BGS GB3D national geological model (Mathers *et al.* 2014). In summary these locations comprise;

Upland glaciated

Mid-Wales	Silurian mudstone, sandstone, siltstone and conglomerate
Northwest Highlands	Precambrian psammite

Lowland glaciated

Stainmore Trough	Carboniferous sedimentary rocks of mixed lithologies

Midland Valley	Carboniferous Coal Measures and Clackmannan Group limestone, sandstone and mudstone
Upland unglaciated	
Dartmoor	Permian granite pluton
Lowland unglaciated	
East Anglia	Chalk and Mesozoic argillaceous rocks overlying Lower Palaeozoic basement

Each geological unit has been assigned a thermal conductivity after (Rollin 2002), which is required for the calculation of thermal diffusivity that is used in equation (1). (Note that specific heat and density that are also required for the calculation of thermal diffusivity, were taken as standard values for the geological lithologies.) Sketch diagrams of the geological succession at each of the glaciated locations are shown in Fig. 6 and the unglaciated locations in Fig. 7. In addition, for each location, a mean annual present day surface temperature and heat flow (Downing & Gray 1986; Lee *et al.* 1987; Rollin 1995; Rollin *et al.* 1995; Barker *et al.* 2000) were assigned, which are required for the estimation of the initial vertical sub-surface temperature profile (see below). All of these parameters are presented in Table 1.

Permafrost models have been run with the repeated application of equation (1) with the surface temperature histories. The initial temperature profile at 130 ka BP has been estimated by application of Fourier's Law

$$\text{grad } T_z = -\frac{q}{\lambda_z}, \qquad (3)$$

where grad T_z is the temperature gradient (K m^{-1}) between depths z_i and z_{i+1}, q is heat flow (W m^{-2}) and λ_z is thermal conductivity (W m^{-1} K^{-1}) between depths z_i and z_{i+1}. This is applied from the ground surface downwards where, from the derivation of the surface temperature histories discussed above, at 130 ka BP the ground surface temperatures have been taken to be 5 ºC less than present day surface temperature at all locations (see Fig. 4).

The evolution of sub-surface temperatures at the six localities as a result of the surface temperature histories has been modelled with sub-surface temperatures generated every 250 years from 126 ka BP to present day. Classed plots of the sub-surface temperatures for each locality are shown in Figs. 8 to 10 where permafrost (T ≤ 0 ºC) is shown as shades of blue/cyan. For the upland glaciated sites periods of ice cover are associated with cold based ice leading to extensive permafrost development with maximum depths of 105 and 180 m for mid-Wales and the Northwest Highlands respectively. Within the Northwest Highlands, permafrost is modelled as continuous from 110 to 12 ka BP due to the sub-zero temperatures imposed by the cold-based glacial ice. Permafrost development is very different between the lowland glaciated sites. For the Midland Valley where cold-based ice has been assumed, the maximum permafrost depth is 110 m, similar to the upland sites. For the Stainmore Trough, despite three periods of ice cover, permafrost only develops within the model after the ice has retreated and then to a maximum depth of only 20 m. Dartmoor has been classified as an upland unglaciated locality although there is an ongoing debate regarding the presence of localised glaciers during the Quaternary (Evans *et al.* 2012; Straw 2013; Evans *et al.* 2014; Straw 2014). However, the small localised glaciers advocated by Evans *et al.* (2012) are unlikely to exert a major influence on the regional permafrost development. Within the model, permafrost develops on Dartmoor whenever the MAAT is less than 9.0 ºC below present day (0 ºC absolute). This occurs in intervals from 62 to 14.5 ka BP. The maximum permafrost thickness of 80 m occurs during the peak of the Late Devensian cold stage. At the lowland unglaciated location, East Anglia, the pattern of permafrost development is similar to Dartmoor except there is no permafrost development until after 40 ka BP and the maximum permafrost thickness is 65 m. In this case, the lowland location results in a 1 ºC rise in MAAT. Maximum thicknesses of permafrost at the six locations are summarised in Table 2.

Discussion

Controls on permafrost development

In the current modelling, maximum predicted permafrost depths in Great Britain range between several tens of metres to over a 100 m depending on various factors including elevation, glacier ice cover, geothermal heat flux and air temperature. The results comprise 1D heat conduction models that have not considered the effects of freezing or groundwater flow. In addition, due to the static modelling approach, our best estimate for each input parameter (e.g. thermal conductivity, periods of ice cover etc.) has been applied rather than considering the full permissible range for each parameter. The evolution through time of sub-surface temperatures has been modelled when the surface temperature has been allowed to vary based on the climate from the last glacial-interglacial cycle. It is not possible to make any statements about ice formation or the depth to which partially or completely frozen ground might penetrate. However, as shown in other studies, perennially frozen ground is likely to correlate with the extent of the 0 ºC isotherm (Hartikainen *et al.* 2010; Govaerts *et al.* 2011). Freezing will depend upon other factors such as the porosity of the geological strata and salinity of the groundwater (French 2007; Stotler *et al.* 2009).

The subglacial thermal regime plays an important role in permafrost development and specifically the speed and depth to which permafrost can penetrate. The deepest permafrost development was modelled in the Northwest Highlands where extensive, but thin cold-based ice cover has been assumed for much of the last 110 ka up to the beginning of the Holocene. The predominantly frozen basal conditions would have led to colder basal-ice, assumed to be -3 ºC (absolute) enabling propagation of sub-zero temperatures into the substrate for an extensive period of time. However, cold basal-ice still had an insulating effect on the substrate because without ice cover, the MAAT during the last glaciation is predicted to have fallen to -9.8 ºC (absolute) which would have led to deeper and more rapid permafrost development. By contrast, the least and shallowest permafrost development corresponds to the Stainmore Trough which was a major zone of fast-flowing warm-based ice during the Late Devensian (Evans *et al.* 2009; Livingstone *et al.* 2012). A warm-based ice temperature of +1 ºC (absolute) has been assumed, limiting MAAT transfer into the substrate and restricting shallow permafrost development to a short period of ice-free conditions during deglaciation. At this northerly latitude the surface ground temperature could have fallen to -4.8 ºC (absolute) had there been no glacial ice cover. Hence, in both of these examples, ice cover has had a major insulating effect protecting the ground from the extremes of air temperature. In general, ice cover has an insulating effect because the temperature at the base of the ice, even for cold-based ice, is warmer than the extremes of the cold temperatures, especially during the peak of the Late Devensian.

The results obtained from the modelling can be compared to similar studies undertaken as part of international studies related to implementing geological disposal of radioactive waste. The geology at Mol (Belgium) comprises an alternating sedimentary succession of sandstones and mudstones. For a climate model with a minimum MAAT of -19 ºC compared to present day and length of cold periods comparable to those used here, maximum permafrost thicknesses (defined as the 0 °C isotherm combined with 50% frozen ground) of 160 m and 215 m for the climate models with and without surface cover respectively were modelled (Govaerts *et al.* 2011). The minimum MAAT applied here was -17 ºC compared to present day in the Northwest Highlands where the maximum depth of permafrost was 180 m, which is comparable to the results of Govaerts *et al*. (2011).

The Forsmark site in Sweden is located over crystalline bedrock and maximum modelled permafrost depths (0 ºC isotherm) were 260 m for the repetition of the last glacial-interglacial cycle and 390 m for a severe permafrost case (Hartikainen *et al.* 2010). The Dartmoor and Northwest Highlands sites here are analogous in terms of geology and the range in permafrost thicknesses between the three locations are compatible, given the differences in the surface temperature history resulting from the geographical location of Forsmark compared to Great Britain, and the extent and nature of glacial ice cover.

The principal factors that determine the depth of permafrost are the long-term surface temperature history, the thermal properties of the geological strata and the geothermal heat flux. Geological strata with high thermal conductivities will produce smaller temperature gradients and will therefore support thicker permafrost. Conversely, strata with low thermal conductivities act as insulators, creating a blanketing effect that leads to high temperature gradients and thinner permafrost. A geological sensitivity analysis was run where permafrost development was modelled at the six localities using the same surface temperature history and an initial temperature profile calculated with the same heat flow (0.065 W m^{-2}) and surface temperature (5 ºC), i.e. the only variable was the change in geology. This indicated a linear relationship between average thermal conductivity and permafrost depth where a 100% increase in thermal conductivity produced an 88% increase in permafrost depth. Of the two locations with the highest average thermal conductivities (Northwest Highlands and Dartmoor), Dartmoor is associated with the highest heat flow region in Great Britain, which will reduce permafrost thickness.

The surface temperature histories used in the modelling were derived from a review of recent literature. There is general agreement on the timing of major cold stages, but authors disagree on the minimum temperatures that may have been reached. For instance, Westaway & Younger (2013) have suggested that during the last glacial cycle temperatures in southern England reached -20 ºC (relative to present day) between 65-75 ka BP and at the peak of the last glaciation. Govaerts *et al*. (2011) in their 'realistic glacial cycle' indicated a minimum temperature in northern Belgium (which would be expected to be similar to southern England) of -19 ºC (relative to present day). The surface temperature history applied here for southern England has a minimum temperature of -12 ºC (relative to present day) during the last glaciation. Adoption of lower temperatures in the modelling would have led to the development of thicker permafrost, especially at the unglaciated locations.

Clearly, all the parameters in the modelling have a range of values that will influence permafrost depth and these could be tested with a full sensitivity analysis. The modelling has adopted a, static, 1D approach to defining the parameters and these have been chosen to be reasonable (and defendable) to produce a first pass assessment of permafrost thicknesses. The result therefore, provides an insight into regional differences across Great Britain of permafrost thicknesses, rather than a detailed analysis at each location of the range of potential permafrost depths.

Implications for major landscape change

Recent developments in the understanding of the scale and frequency of Quaternary climate change reveal that mid-latitude regions such as Great Britain have been subjected cyclically to cold stage conditions and presumably periglacial climatic regimes (Candy *et al.* 2011; Böse *et al.* 2012). Outputs from the modelling presented within this paper indicate the potential for permafrost to extend through the substrate to depths of between several tens of metres to, in-excess of, 100 m depending on location and a range of geological and climatic factors. This implies that over the duration of the Quaternary, surface and shallow sub-surface materials to considerable depths have been 'thermally stressed' by repeated cycles of permafrost development. Potential evidence for this 'thermal stressing' is the development of extensive weathered regolith (saprolite) capping interfluve areas, its downslope transportation via colluvium-mantled slopes (Booth *et al.* 2015) and transportation and deposition by rivers forming widespread aggradational river terrace sequences (Gibbard & Allen 1994; Rose 1994; Maddy *et al.* 1995; Rose *et al.* 1999; Westaway *et al.* 2006; Howard *et al.* 2007; Boreham *et al.* 2010; White *et al.* 2010). These deposits are particularly well-preserved beyond the southern-most limits of successive Quaternary glaciations, which acted to erode and remove the products of weathering (Booth *et al.* 2015).

Evolution of the modelling approach

The regional permafrost modelling presented here provides a valuable insight into the temporal and spatial controls of permafrost development. However, the approach is 1D in nature and could be enhanced by consideration of further variables. For instance, latent heat produced during freezing will result in thinner perennially frozen ground compared to permafrost. In addition groundwater flow and composition, groundwater recharge and discharge, porosity and saturation of the rock strata will all influence the development of frozen ground. Such modelling should also aim to explore the change in groundwater chemistry such as salinity and its vertical variability. The insulating effect of ice cover has been shown to be an important factor in shielding the ground surface from air temperature and limiting permafrost development. The temperature at the base of the ice can vary over a large temperature range and these temperatures will not be constant, but will change depending on ice thickness, prevailing climate (if the ice is thin enough) and glacier dynamics. Modelling schemes for estimating basal ice temperatures are available (Glasser & Siegert 2002; Forsström 2005), but they require the evolution of the ice sheet through time to be estimated. Hence it is recommended that further modelling studies of ice sheet evolution, particularly for the period prior to 35 ka BP should be undertaken.

Most experimental studies and direct geological evidence for permafrost is the result of surface or shallow processes, particularly those that occur within the active layer (Hallet *et al.* 1991; Murton *et al.* 2000; Murton *et al.* 2006; French 2008). By comparison, little evidence has been published relating to the geological signature of permanently frozen ground. Hutchinson & Thomas-Betts (1990) have reported depths of periglacial disturbance in southern England to be less than 20 m, except for one, unreferenced, site to 50 m depth. Some studies have been carried out for Finnish and Swedish programmes related to implementing geological disposal of radioactive waste by studying conditions at depth at Lupin in northern Canada (Ruskeeniemi *et al.* 2002; Ruskeeniemi *et al.* 2004; Stotler *et al.* 2009). However, these sites are all located on metamorphosed crystalline rocks and so differ significantly from those that underlie much of Great Britain. Therefore, there is a general lack of knowledge on the imprint that freeze/thaw conditions might have on saturated porous rocks in permanently frozen ground. Laboratory studies to simulate in-situ conditions of frozen ground might detect imprints such as damaged pore structures and changes to the geochemistry of pore fluids and associated precipitates. Such imprints could then be searched for from deep core material for evidence of permafrost during the last glacial-interglacial cycle.

Conclusions

- One-dimensional heat conduction modelling across Great Britain has demonstrated that permafrost development during the last glacial-interglacial cycle was likely at all locations and in some cases was extensive to over 100 m in depth.
- The surface temperature history at any location has been derived from a general reconstruction of the UK mean annual air temperature modified by latitude and

periods of ice cover. Simplifying assumptions have been made to temperatures beneath glacial ice but a distinction has been made between warm-based basal conditions and cold, frozen conditions.

- In general, the greatest maximum permafrost thicknesses occur at upland glaciated locations (cold-based ice) and localities that remained largely ice-free, with minimum thickness at insulated lowland sites.

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Figure 1. A) A surface temperature history for Prudhoe Bay, Alaska, based on an East Siberia model (after Osterkamp & Gosink 1991). B) The same surface temperature history represented as a series of step changes in temperature.

Figure 2. Selected temperature proxy records used to construct the average temperature trends over the UK during the past 140 ka. A) European pollen records from Davis *et al*. (2003). B) Sea surface temperature and land proxy records from Shakun *et al*. (2012). C) Sea surface temperature records from Maslin *et al.* (1995). D) Sea surface temperature records from McManus *et al.* (1999). Note that curves A, B and C are drawn against the top time axis and curve D against the bottom time axis. The dashed lines are to facilitate comparison between the curves, with the shaded area representing time greater than 40 ka BP.

Figure 3. The reconstructed temperature trend for Great Britain over the last 130 ka (B), aside the appended data used from several sources and regions to create the record (A; see also Fig. 2 where the four elements used to construct curve A are shown). Ice core temperature proxy shown for comparison (C). This reconstructed temperature trend was used as a basis for the surface temperature histories at each of the six localities, where the maximum and minimum MAAT were adjusted, along with the effect of ice sheet presence, at each location.

Figure 4. Surface temperature histories for A) East Anglia which was ice free and the minimum temperature of 12 ºC below present occurred at the peak of the last glaciation. B) The Stainmore Trough, where ice cover between 110-102, 76-37 and 34-14.5 ka BP insulated the land surface from the extremes of air temperature. Hence, despite a minimum MAAT of 14 ºC below present, the minimum temperature of 9.8 ºC below present occurred after the ice had retreated. Periods of ice cover are indicated by the blue bars.

Figure 5. The six selected locations across Great Britain for permafrost modelling overlaid on the 1:625 000 scale bedrock geology. The geological key for this map can be viewed at http://mapapps.bgs.ac.uk/geologyofbritain/home.html.

Figure 6. Sketch diagrams (not to scale) of the geological succession at each of the glaciated locations. A) Mid-Wales. B) The Northwest Highlands. C) The Stainmore Trough. D) The Midland Valley. Depths (m), relative to Ordnance Datum (+ve above sea level), are shown to the left of each sketch and the geology (with, in brackets, the thermal conductivity in W m^{-1} K^{-1}) on the sketch. The rock unit name (left part of geology code) can be found at http://www.bgs.ac.uk/lexicon/ and the rock description (right part of geology code) can be found at http://www.bgs.ac.uk/data/vocabularies/dictionary.cfm?name=DIC_ROCK_SIGMA.

Figure 7. Sketch diagrams (not to scale) of the geological succession at each of the unglaciated locations. A) Dartmoor. B) East Anglia. Depths (m), relative to Ordnance Datum (+ve above sea level), are shown to the left of each sketch and the geology (with, in brackets, the thermal conductivity in W m^{-1} K^{-1}) on or to the right of the sketch. The rock unit name (left part of geology code) can be found at http://www.bgs.ac.uk/lexicon/ and the rock description (right part of geology code) can be found at

http://www.bgs.ac.uk/data/vocabularies/dictionary.cfm?name=DIC_ROCK_SIGMA.

Figure 8. Permafrost evolution modelling for the upland glaciated locations presented as classed plots of ground temperatures from 126 ka BP to the present. Mid-Wales is shown in the top panel and the Northwest Highlands in the lower panel.

Figure 9. Permafrost evolution modelling for the lowland glaciated locations presented as classed plots of ground temperatures from 126 ka BP to the present. The Stainmore Trough is shown in the top panel and the Midland Valley in the lower panel.

Figure 10. Permafrost evolution modelling for the unglaciated locations presented as classed plots of ground temperatures from 126 ka BP to the present. Dartmoor, which is an upland unglaciated location, is shown in the top panel and East Anglia, which is a lowland unglaciated location, in the lower panel.

Table 1. Descriptions of the permafrost modelling locations. Coordinates are British National Grid and elevation is relative to Ordnance Datum (OD, +ve above mean sea level). The minimum mean annual air temperature (MAAT) relative to the present, predicted by the surface temperature histories, is shown along with periods of ice cover and assumed temperatures at the base of the ice (relative temperature, and in brackets, the absolute temperature).

Table 2. Maximum regional, modelled thicknesses of permafrost at the six locations.

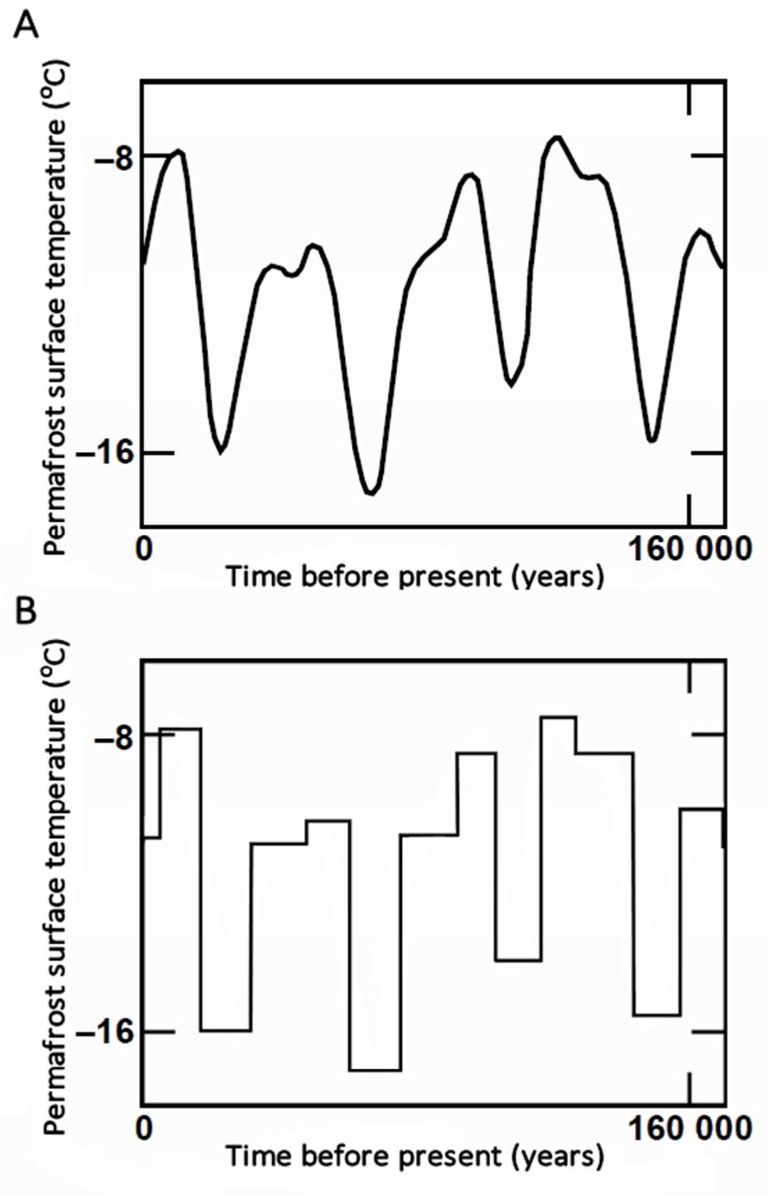
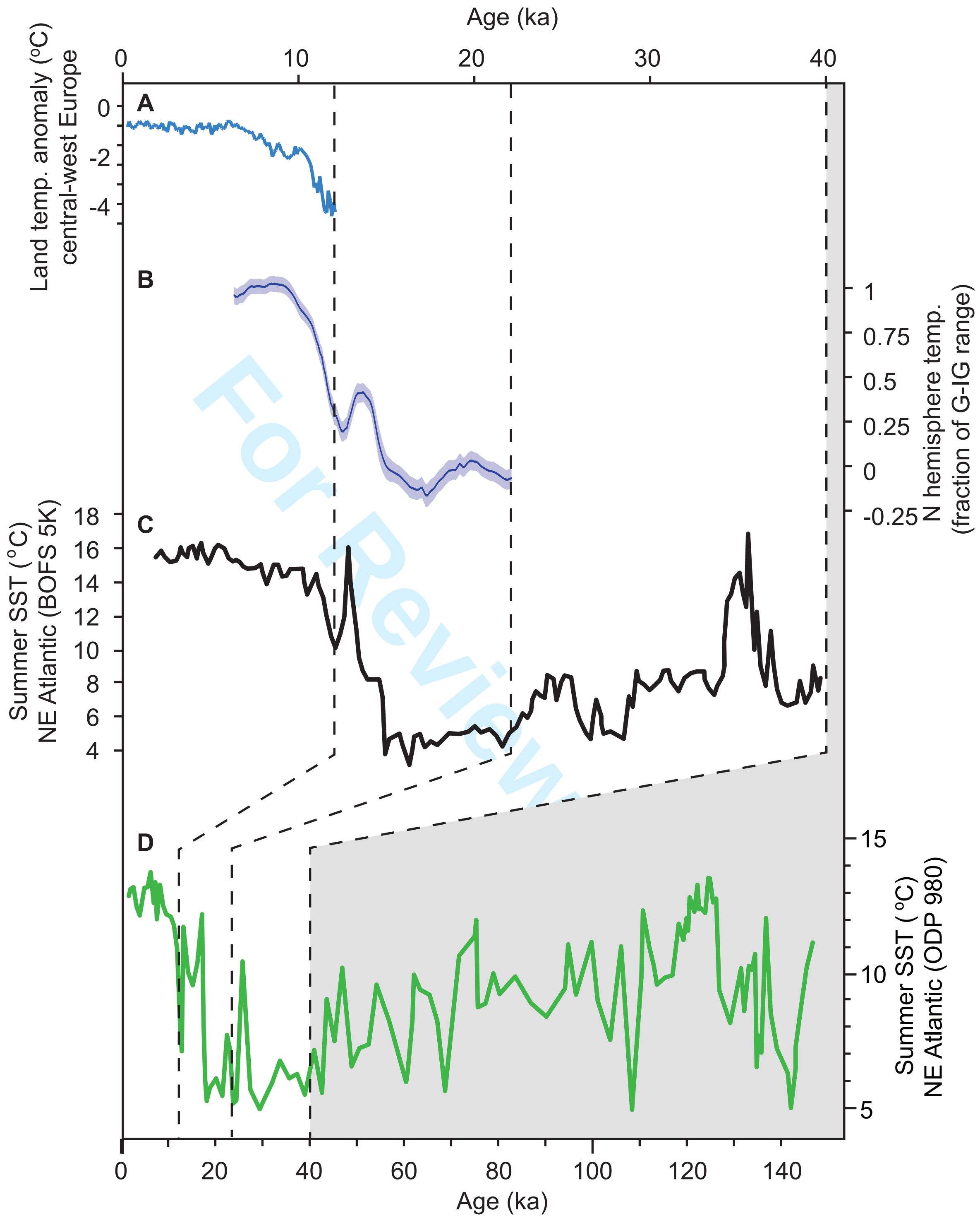
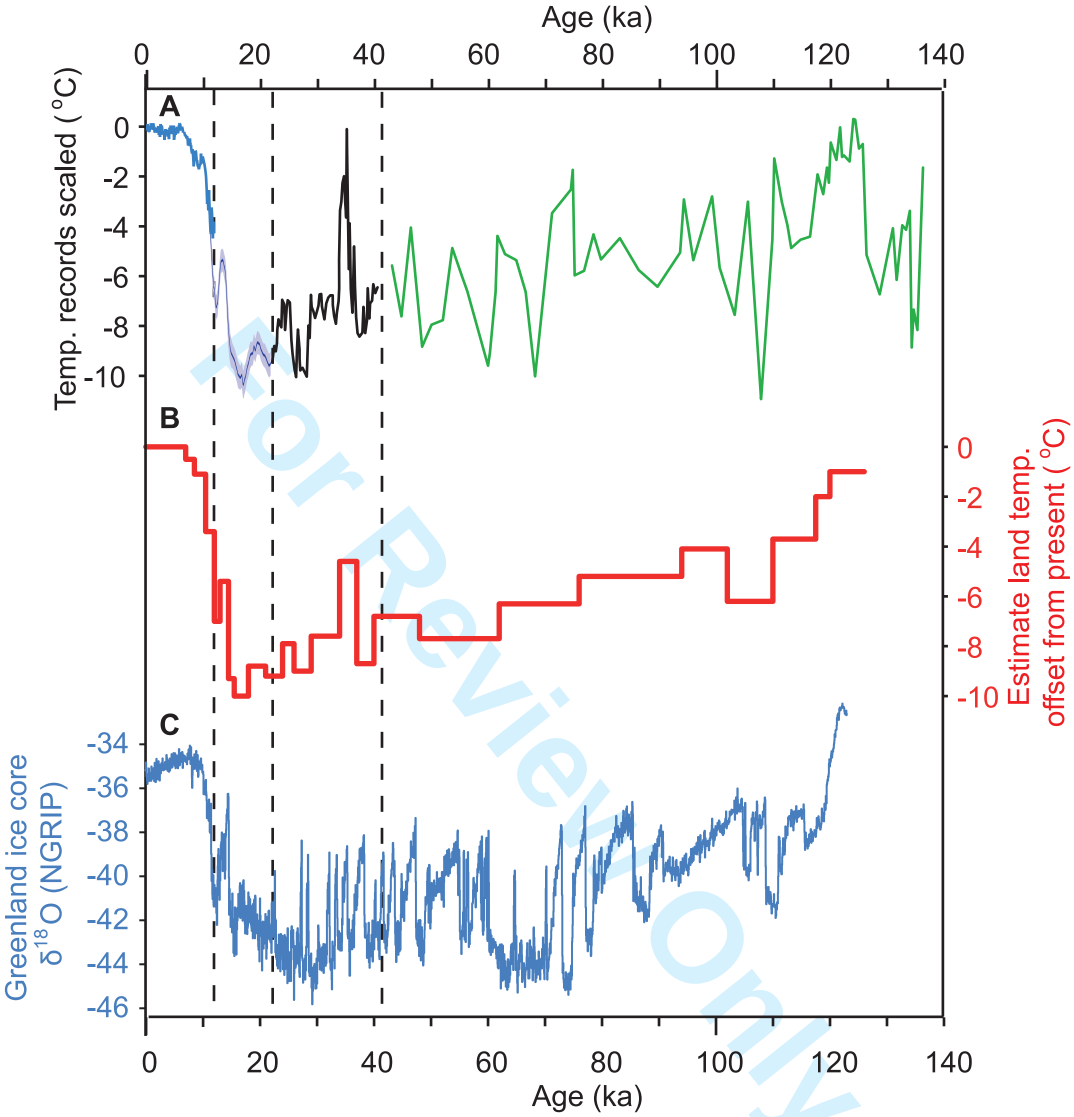


Figure 1
195x304mm (72 x 72 DPI)


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


Age (ka)
0
20
40
60
80
100
120
140
A
Temp. records scaled (°C)
0
-2
-4
-6
-8
-10
B
0
-2
-4
-6
-8
-10
Estimate land temp. offset from present (°C)
C
Greenland ice core δ^{18}O (NGRIP)
-34
-36
-38
-40
-42
-44
-46
0
20
40
60
80
100
120
140
Age (ka)

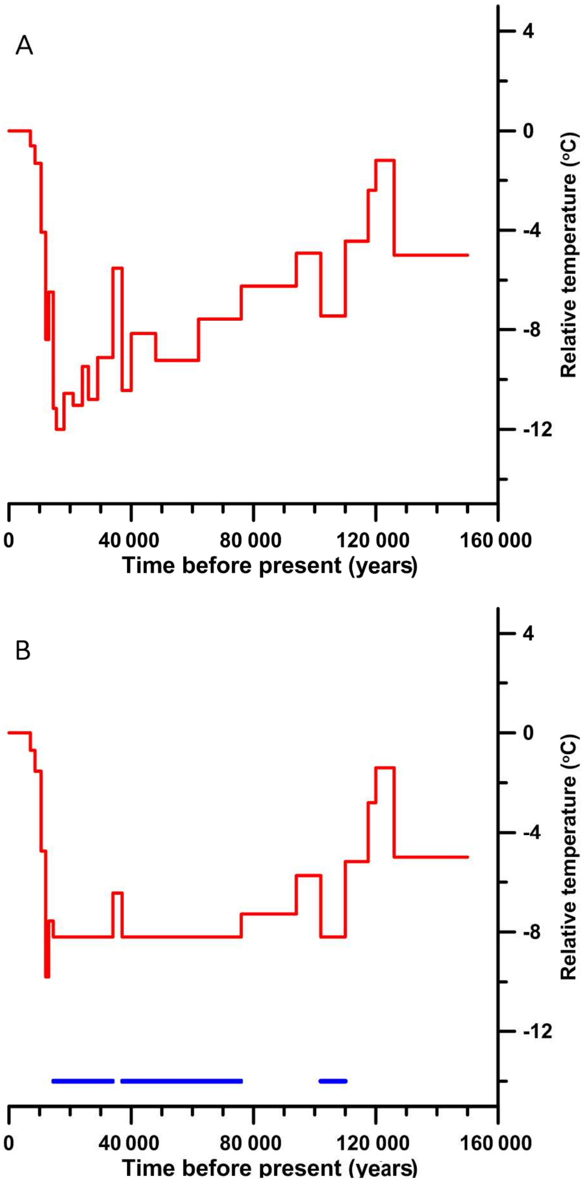


Figure 4
180x367mm (200 x 200 DPI)

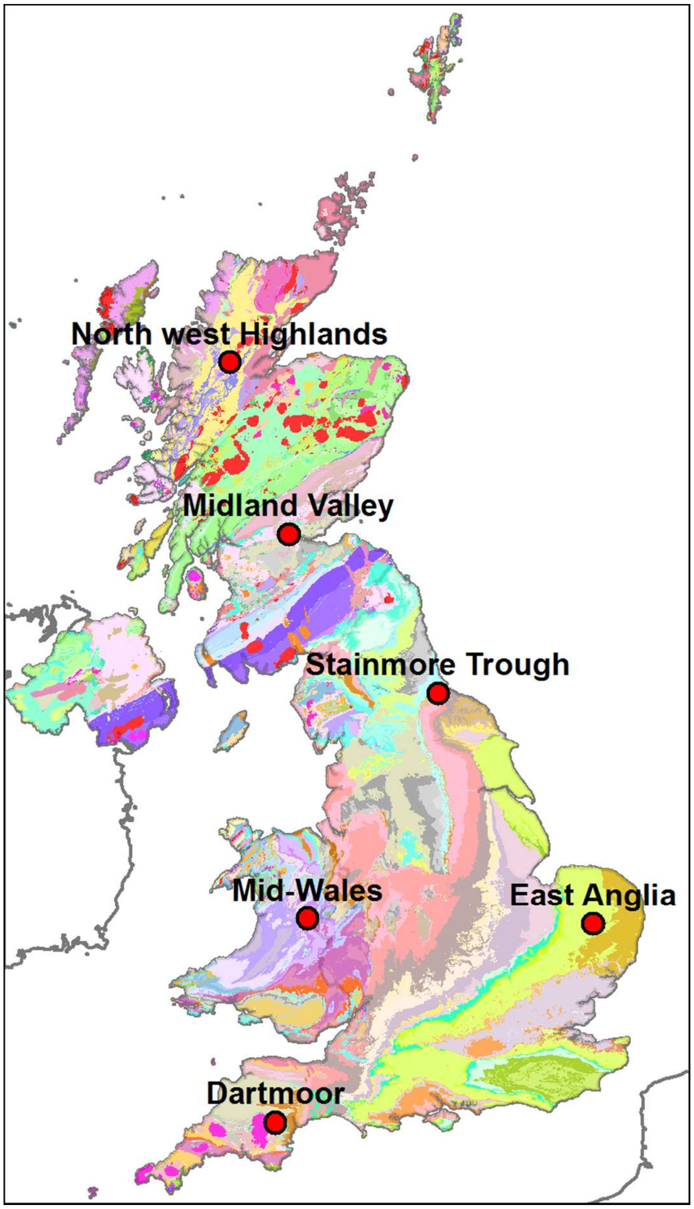


Figure 5
70x122mm (300 x 300 DPI)

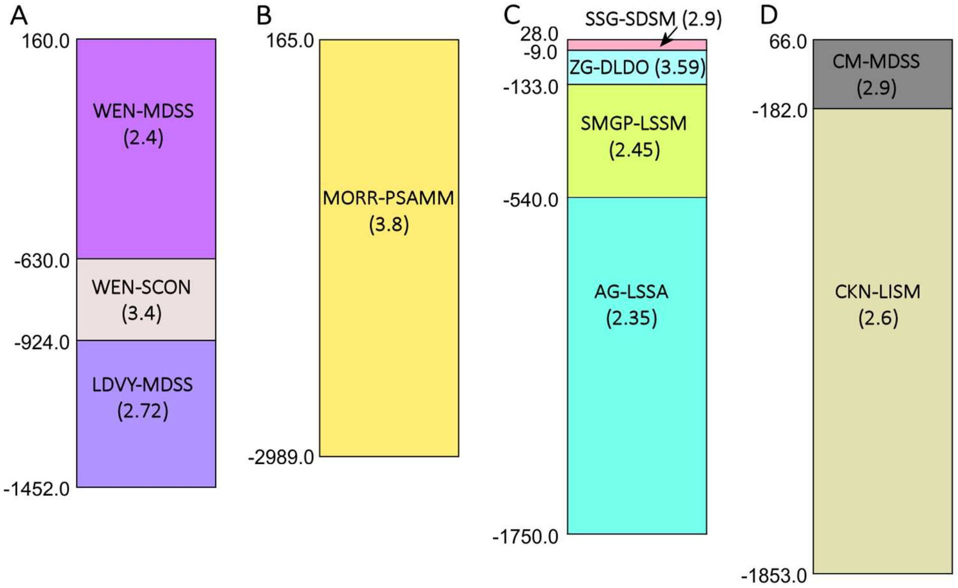

A
160.0
WEN-MDSS
(2.4)
-630.0
WEN-SCON
(3.4)
-924.0
LDVY-MDSS
(2.72)
-1452.0
B
165.0
MORR-PSAMM
(3.8)
-2989.0
C
SSG-SDSM (2.9)
28.0
-9.0
ZG-DLDO (3.59)
-133.0
SMGP-LSSM
(2.45)
-540.0
AG-LSSA
(2.35)
-1750.0
D
66.0
CM-MDSS
(2.9)
-182.0
CKN-LISM
(2.6)
-1853.0

Figure 6

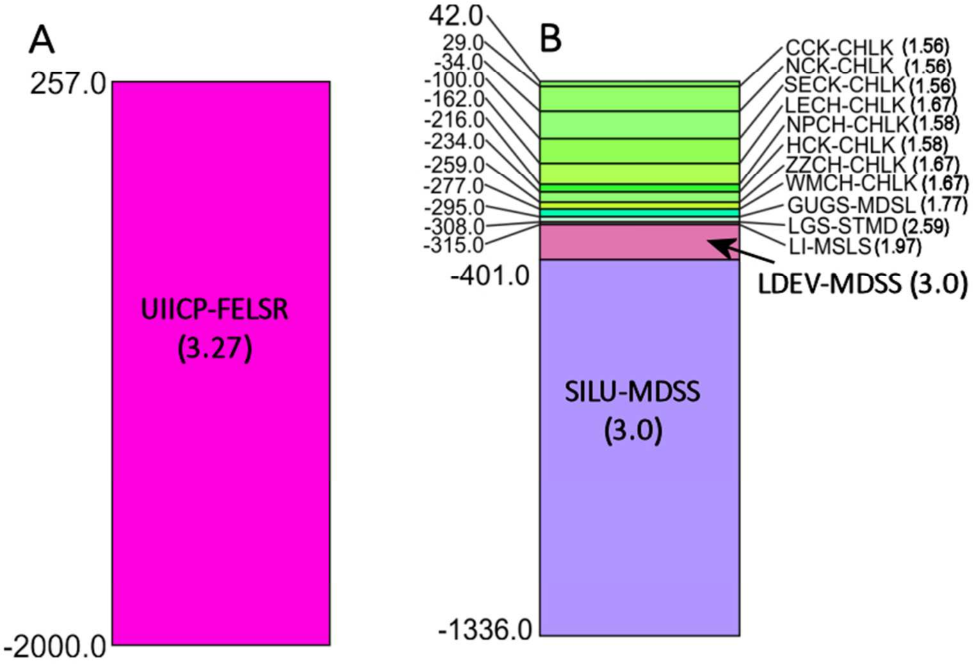


Figure 7
99x71mm (220 x 220 DPI)

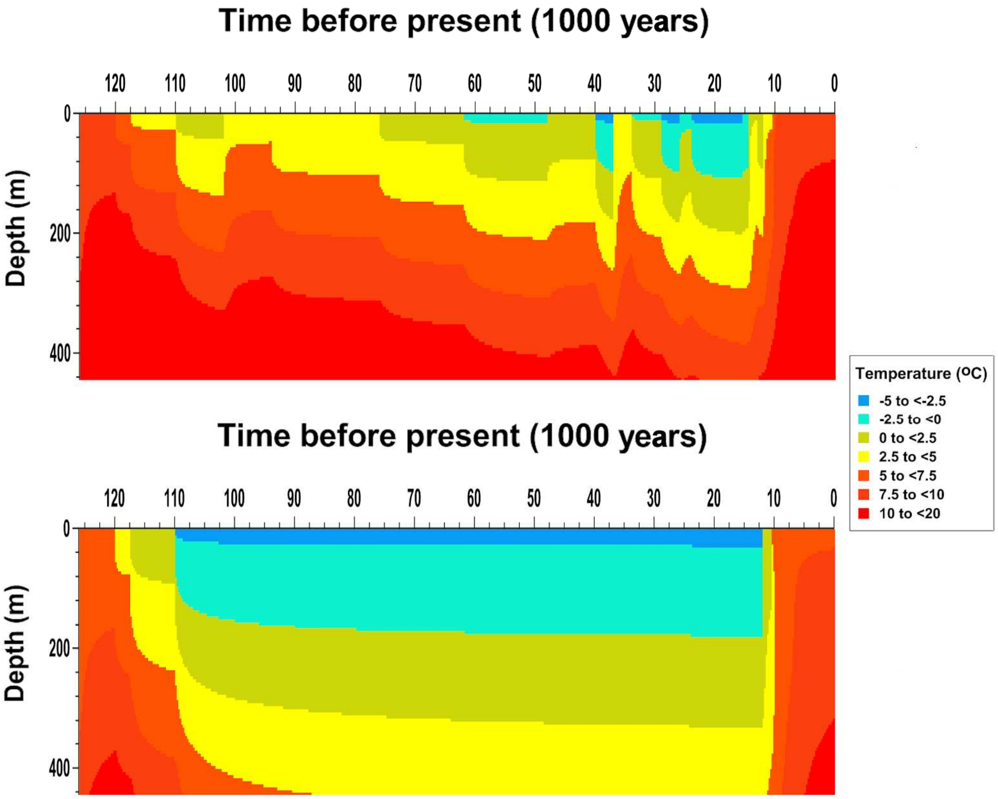


Figure 8
668x554mm (100 x 100 DPI)

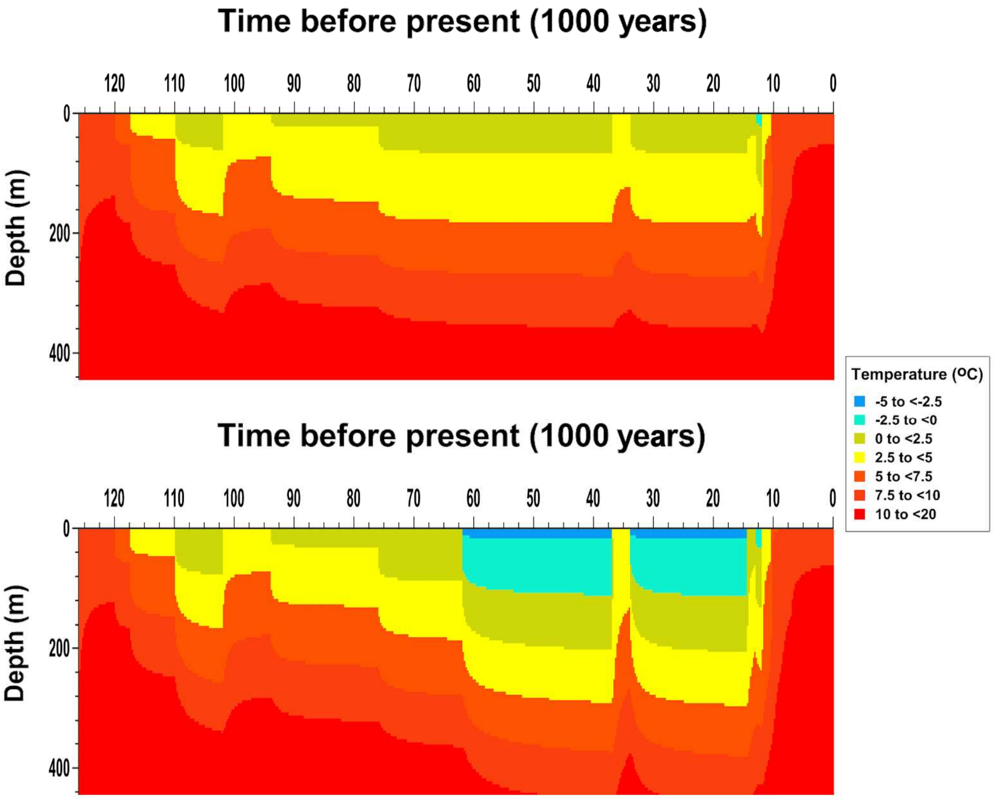


Figure 9
668x554mm (100 x 100 DPI)

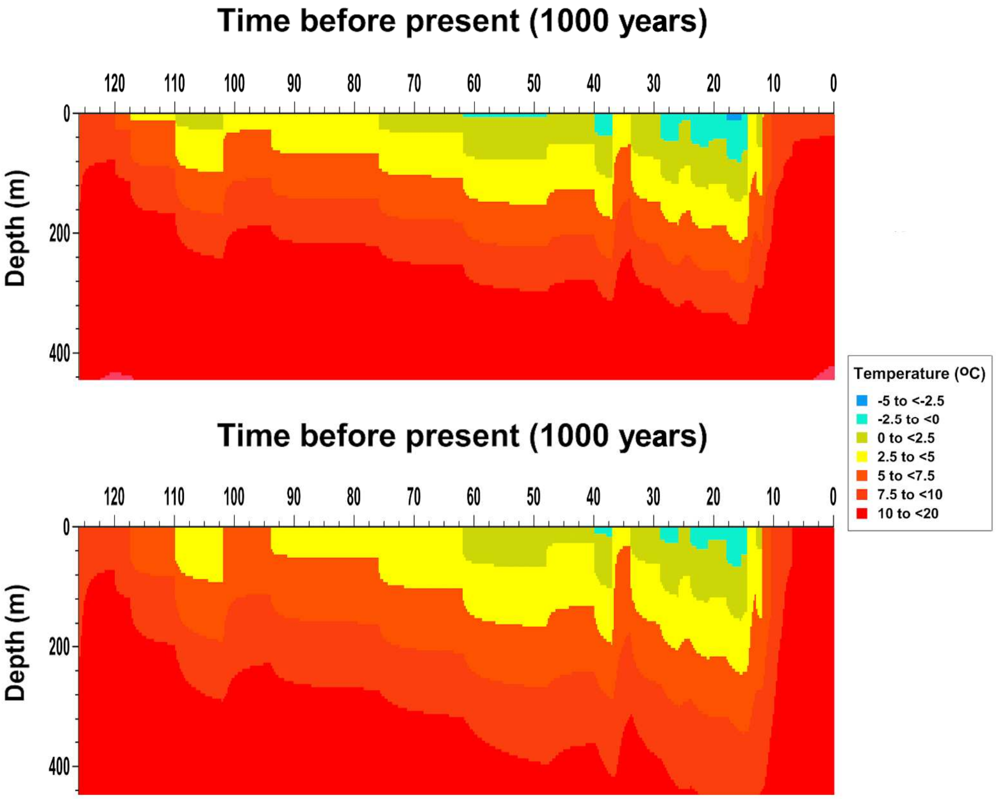


Figure 10
668x554mm (100 x 100 DPI)

	Mid-Wales	NW Highlands	Stainmore Trough	Midland Valley	Dartmoor	East Anglia
Easting (m)	310453	230850	444128	290971	278000	603000
Northing (m)	292587	861650	523367	686182	84000	287294
Elevation (m OD)	160	165	28	66	257	42
Present day MAAT (ºC)	8.8	7.2	9.2	9.0	9.0	10.0
Heat flow (W m^{-2})	0.055	0.058	0.067	0.069	0.105	0.035
Min MAAT relative to present (°C)	-12	-17	-14	-14	-12	-12
Periods of ice cover (ka BP)	40-37; 29-26; 24-15.5	110-12	110-102; 76-37; 34-14.5	62-37; 34-14.5	No ice cover	No ice cover
Temp. below ice relative to present (and absolute) (°C)	-11.8 (-3)	-10.2 (-3)	-8.2 (+1)	-12.0 (-3)		

Table 1

Location		Maximum thickness of permafrost (m)
Upland glaciated	Mid-Wales	105
	Northwest Highlands	180
Lowland glaciated	Stainmore Trough	20
	Midland Valley	110
Upland unglaciated	Dartmoor	80
Lowland unglaciated	East Anglia	65

Table 2