

Modelling the potential for permafrost development on a radioactive waste geological disposal facility in Great Britain

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Abstract

The safety case for a geological disposal facility (GDF) for radioactive waste based in Great Britain must consider the potential impact on the repository environment of permafrost during the 1M yrs following GDF closure. The depth of penetration of permafrost, defined as ground which remains at or below 0°C for at least two consecutive years, has been modelled for a future climate that uses the climate of the last glacial-interglacial cycle as an analogue. Two future climates are considered; an average estimate case considered to be the best estimate of ground surface temperatures during the last glacial-interglacial cycle, and a cold estimate case considered to be an extreme cold, but plausible future climate. Maximum modelled permafrost thicknesses across Great Britain range from 20-180 m for the average estimate climate and 180-305 m for the cold estimate climate. The presence of ice cover is an important determinant on permafrost development. Thick permafrost evolves during long periods of cold-based ice cover and during periods of ice retreat that results in ground exposure to very cold air temperatures. Conversely, warm-based ice has an insulating effect, shielding the ground from cold air temperatures that retards permafrost development. For a GDF at a depth greater than that predicted to be directly affected by permafrost, phenomena associated with permafrost, e.g., enhanced groundwater salinity at depth, will need to be taken into account when considering the impact on the engineered and natural barriers associated with a GDF.

1. Introduction

A geological disposal facility (GDF) for radioactive waste is based upon a multi-barrier system that combines a series of engineered and natural barriers to isolate the wastes and contain the radionuclides associated with the wastes (Chapman and Hooper, 2011). The depth of the GDF is dependent on minimising the impact of external environmental processes, such as those associated with climate change. Post-closure safety case studies typically consider such natural changes over the first one million years following GDF closure. Perennially frozen ground has been identified as one of a number of natural processes that could affect a GDF over such a time scale (e.g. Chapman and Hooper, 2011; Shaw et al., 2012). It is still uncertain as to the significance and impact of frozen ground on the long-term physical and chemical stability of the repository environment (EC, 2008; Loew et al., 2008; Miller, 2012). There may be a number of geophysical and geochemical changes to the geological barrier induced by freezing, including: (1) the thermo-hydro-mechanical impact on the host rock stress induced by freeze/thaw conditions; (2) a change in the regional and local groundwater flow paths; (3) the formation of taliks (unfrozen ground beneath lakes) that could act as points for radionuclide releases to the surface; (4) increased groundwater salinity due to salt exclusion in freezing that may also give rise to density-driven flow at depth; (5) intrusion of freshwater during melting; (6) formation and destabilisation of gas hydrates that could form

1 beneath the frozen layer. In-turn, the hydromechanical and geochemical properties of the
2 engineered barrier system (which could contain significant amounts of bentonite and/or
3 concrete/cement) may be impacted by freezing in several different ways such as: (1) long-
4 term performance during transient periods with high hydraulic, thermal or chemical
5 gradients, which could influence the evolution of repository components; (2) highly-saline
6 residual brine, produced during the formation of frozen ground, that may affect the swelling
7 characteristics of bentonite and the stability of cement. The development of frozen ground
8 could affect the properties of rocks above a GDF leading to the possible development of new
9 fracture pathways affecting groundwater recharge and discharge. Frozen ground will create a
10 barrier to groundwater flow, but once the ground has thawed its permeability may be
11 increased leading to temporary or permanent changes to groundwater flow paths.
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14 This paper investigates the potential for permafrost development across Great Britain under
15 possible future climate scenarios. It follows a previous modelling study on permafrost
16 thickness during the last glacial-interglacial cycle (Busby et al., in press). It is non site
17 specific, but a series of locations have been selected in order that a range of geographical and
18 geological settings can be considered. The modelling is at the regional scale with a focus on
19 the maximum depth extent to which permafrost might develop in an average future climate
20 and in an extreme (cold) climate up to three hundred thousand years into the future.
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24 **2. Permafrost modelling approach**

25 The definition of permafrost applied here is ground which remains at or below 0°C for at
26 least two consecutive years (French, 2007) as opposed to perennially frozen ground that
27 keeps frozen for at least two consecutive years. Hence, permafrost is defined on the basis of
28 temperature, thus disregarding the texture, degree of compaction, water content, and
29 lithologic character of the material, whereas perennially frozen ground is defined on the basis
30 of the freezing of water. The freezing of water is itself dependent on pressure, salinity and the
31 adsorptive and capillary properties of the ground matter.
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34 The modelling is based on the periodic heating at the surface of a column of infinite depth
35 and the propagation of the heat into the ground in the vertical (depth) dimension. This one
36 dimensional heat conduction approach does not take into account the freezing of water, the
37 effect of groundwater movement or the change in ground properties due to freezing. Carslaw
38 and Jaeger (1959) have shown that
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$$42 \quad T_{\theta} = T_0 \times \operatorname{erfc} \left[z / 2\sqrt{\kappa t} \right], \quad (1)$$

43 where T_{θ} is the departure from original equilibrium temperature at depth z and time t after an
44 instantaneous change in surface temperature of T_0 ; κ is the average thermal diffusivity of the
45 geological strata down to depth z and $\operatorname{erfc}(x)$ is the complementary error function. Noting that
46 the change in surface temperature is the difference in temperature between successive steps,
47 the effect of more than one temperature step is found by addition of all the steps, i.e.
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$$51 \quad T_{\theta} = \sum T_{\theta i}, \quad (2)$$

52 where $T_{\theta i}$ is the temperature deviation due to the i th event.
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55 The approach here has been to use the last glacial-interglacial cycle as an analogue for future
56 climate and therefore to model permafrost evolution over the period of the last glacial-
57 interglacial cycle. To model the evolution of ground sub-surface temperatures through time,
58 an initial sub-surface temperature profile is perturbed by any step changes in surface
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1 temperature that have occurred from the initial time up to the time being considered. The
2 initial time has been taken at 126 kyr BP (Before Present) and sub-surface temperatures have
3 been calculated at 5 m depth intervals to 1 km every 250 yrs up to present day.
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6 **3. Future climate**

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8 When we consider future climate, one approach is to consider what has happened in the past,
9 on the assumption that it will repeat in the future. The climate over the last ~1 million years
10 in northern Europe has experienced a series of cold spells, broadly every 100 kyr.
11 Superimposed upon these large-scale glacial cycles are more medium-term climatic events
12 occurring with a ~40 kyr periodicity (Lisiecki & Raymo 2005). The last glacial stage, called
13 the Devensian Glaciation, was one of the most intense glacial events to affect Great Britain
14 and hence can be used as a suitable analogue for modelling the development of permafrost
15 during a similar-scale cold-event over the next ~300 kyrs. Since the beginning of the
16 Industrial Revolution this natural climate system has been modified by increased greenhouse
17 gas emissions, which are set to cause significant warming of the climate in the relatively near
18 future (IPCC, 2013). However, over the long term (>10s to 100s kyr) modelling studies
19 suggest that the climate will return to past glacial-interglacial background conditions
20 (BIOCLIM, 2001). This conclusion is supported by palaeoclimate proxy data over past
21 'hyperthermal' episodes (e.g. at the Palaeocene–Eocene Thermal Maximum), which show
22 that Earth's climate returned to background temperature levels within ~200 kyr after
23 significant atmospheric CO₂ release and global warming (DeConto et al. 2012).
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27 The mean annual air temperature (MAAT) for Great Britain over the last glacial-interglacial
28 cycle (0–130 kyr ago) has been constructed from multiple proxy data comprising NE Atlantic
29 sea surface temperature (SST) and pollen-based MAAT proxies to reconstruct an idealized
30 temperature curve. The detail of this procedure was presented in Busby et al. (in press) and is
31 not repeated here. The result is an idealised MAAT profile that is shown in Figure 1. It is
32 necessary to scale this profile to account for the variation in latitude between southern and
33 northern Britain. Present day MAAT is the maximum temperature and is taken as the
34 Holocene average, whilst the minimum MAAT is from the Annan and Hargreaves (2013)
35 global estimate of MAAT during the global peak of the last glaciation (19–23 kyr BP).
36 Therefore the minimum MAAT for southern England and Wales localities are estimated to be
37 8–12°C below present, and the northern England and Scotland sites 12–20°C below present.
38 Two climate models have been applied; the first is an average estimate (AE) case considered
39 to be the best estimate of ground surface temperatures during the last glacial-interglacial
40 cycle where the climate range is 12°C to 17°C below modern, between southern English and
41 northern Scottish sites respectively. The second climate is a cold estimate (CE) case
42 considered to be an extreme cold, but plausible future climate. The cold estimate climate is
43 towards the cold extreme of the error range reported by Annan and Hargreaves (2013) and
44 ranges between 18°C and 27°C below modern, between southern English and northern
45 Scottish sites respectively.
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51 The temperature at the ground surface will also be affected by ice sheet and glacier ice cover.
52 Ice extent during the Late Devensian has been modelled by several studies (e.g. Siegert and
53 Dowdeswell, 2004; Hubbard et al., 2009; Evans et al, 2009; Clark et al., 2012). The model
54 reconstructions of Hubbard et al. (2009) provide a series of time-slices that document the
55 growth and decay of the Last British-Irish Ice Sheet extending back to 35 kyr BP. For the
56 period prior to 35 kyr BP, ice cover is assumed whenever the MAAT falls below the
57 temperature where ice cover is predicted for the period since 35 kyr BP. The temperature at
58 the base of the ice is warmer for warm-based ice, which is often found under thick ice in
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topographical troughs, than cold-based ice frozen to its bed. Hall and Glasser (2003) have shown that during basal-freezing conditions, basal temperatures can range from -12°C to -6°C (absolute). However, when basal melting occurs, basal temperatures are more likely to be in the range of -1°C to $+1^{\circ}\text{C}$ (absolute). The procedure for assigning basal ice temperatures is the same as that used by Busby et al. (in press) whereby the British-Irish Ice Sheet modelling of Hubbard et al. (2009) is used to predict if cold-based or warm-based conditions are more likely. Basal absolute temperatures for cold-based frozen conditions are therefore estimated as -3°C for the average estimate surface temperature history and -4°C for the cold estimate case. For warm-based ice conditions, absolute temperatures are assumed to be $+1^{\circ}\text{C}$ for the average estimate surface temperature history and -1°C for the cold estimate case. Application of this concept to two examples within the modelling exercise for the average estimate climate (see Figure 2) reveals that for the Weald (which has never been glaciated), a minimum surface temperature of 12°C below present occurred during the climatic minimum between, approximately, 19 and 30 kyr BP. Alternatively, within the Southern Uplands example, the land-surface is modelled to have been insulated from the minimum MAAT of 17°C below present by extensive phases of ice-sheet cover. These occur between 110-102, 76-37 and 34-14.5 kyr BP and the temperature is constant at -3°C absolute (10.8°C below present). The minimum surface temperature of 11.9°C below present occurred between 13-12 kyr BP after the ice had retreated.

4. Permafrost modelling locations

In order to assess how permafrost development may vary across Great Britain, ten locations have been selected which present a variety of latitudes, elevations and geological sequences. These are shown in Figure 3. 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;

Dartmoor	Permian granite pluton
Weald	Mesozoic argillaceous, arenaceous and limestone rocks
East Anglia	Chalk and Mesozoic argillaceous rocks overlying Lower Palaeozoic basement
South Midlands	Argillaceous Jurassic and Triassic rocks overlying Lower Palaeozoic basement
Mid-Wales	Silurian mudstone, sandstone, siltstone and conglomerate
South Yorkshire	Carboniferous Coal Measures overlying Millstone Grit
Stainmore Trough	Carboniferous sedimentary rocks of mixed lithologies
Southern Uplands	Silurian greywacke
Midland Valley	Carboniferous Coal Measures and Clackmannan Group limestone, sandstone and mudstone
Northwest Highlands	Precambrian psammite

Table 1 details the geological succession at each locality and includes the thermal conductivity of the strata (Rollin 2002), the mean annual present day ground surface temperature, estimated heat flow (Busby et al. 2011) and assumed periods of ice cover during the last glacial-interglacial cycle.

5. Permafrost modelling results

1 Permafrost evolution over time has been modelled with the repeated application of equation
2 (1) utilising the location specific surface temperature histories. The initial temperature profile
3 at 130 kyr BP has been estimated by application of Fourier's Law;

$$4 \quad \text{grad } T_z = -\frac{q}{\lambda_z}, \quad (3)$$

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6 where $\text{grad } T_z$ is the temperature gradient (K m^{-1}) between depths z_i and z_{i+1} , q is the heat
7 flow (W m^{-2}) and λ_z is thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$) between depths z_i and z_{i+1} . This is
8 applied from the ground surface downwards where, from the derivation of the surface
9 temperature histories discussed above, the initial ground surface temperatures at 130 kyr BP
10 have been taken to be 5°C less than present day at all ten locations. The possibility that these
11 initial temperature profiles might be influenced by the previous glacial-interglacial cycle is
12 considered in section 5.3.
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15 5.1 Regional results

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17 The evolution of sub-surface temperatures (i.e. temperatures beneath the ground surface) as a
18 result of the surface temperature histories for both the AE and CE climates has been modelled
19 with sub-surface temperatures generated every 250 years from 126 kyr BP to present day.
20 Example plots of the sub-surface temperatures for the Weald and Southern Uplands are
21 shown in Figures 4 and 5 where permafrost ($T \leq 0^\circ\text{C}$) is shown as shades of blue/cyan. At the
22 southerly Weald location permafrost development in the AE climate was not extensive. An
23 absence of ice cover has resulted in maximum permafrost thicknesses, during the Late
24 Devensian climatic minimum, of 65 m for the AE climate and 245 m for the CE climate. At
25 the northerly Southern Uplands location, MAAT has been estimated to be 5°C and 9°C less
26 than at southern locations, for the AE and CE climates respectively. However, the land-
27 surface has been insulated from these coldest temperatures by extensive periods of ice-sheet
28 cover. It has been assumed that in the Southern Uplands this ice would have been cold-based
29 leading to extensive periods of permafrost, but the deepest permafrost development of 150 m
30 and 305 m for the AE and CE climates respectively, occurs at around 12.5 kyr BP after the
31 land-surface becomes ice free at 14.5 kyr BP. It should also be noted at the Southern Uplands
32 location that the relative permafrost evolution through time varies between the AE and CE
33 climates. For instance, between 76-94 kyr BP the permafrost is thicker during the unglaciated
34 period in the CE climate, but is thinner in the AE climate. This occurs because in the CE
35 climate the MAAT is colder than the basal ice temperature in contrast to the AE climate
36 where it is warmer. Maximum depths of permafrost at the ten locations are shown in Table 2.
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42 5.2 Short-term effects

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44 In the regional modelling a series of step changes in surface temperature have been taken to
45 represent cyclical events. For cyclical events, the development of glacier ice is likely to be
46 coincident with the onset of cold conditions and this is implicit in the modelled sampling
47 period of 250 years. However, there is strong evidence that the onset of glaciations can be
48 very rapid and of the order of tens to hundreds of years, often linked to abrupt changes in
49 oceanic (thermohaline) circulation (Prueher and Rea, 1998; Rahmstorf, 2002). Hence, given
50 the lag-time between the onset of very cold conditions and ice-sheet expansion, the land-
51 surface may be exposed to the cold extremes of the MAAT that could lead to the
52 development of short-lived, but thick permafrost. This has been explored in a theoretical
53 situation for one location only, the Southern Uplands, where under these conditions the
54 deepest permafrost development would be expected as it has been assumed that it was
55 exposed to the coldest MAAT and the thermal conductivity of the geological succession is
56 high at this location.
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1 In the surface temperature history for the Southern Uplands (Figure 2b) there is an ice-free
2 period between 37-34 kyr BP. At the onset of glaciation, a revised temperature history
3 assumes that at 34 kyr BP the land-surface is exposed to the coldest MAAT (-17°C relative to
4 modern; -9.2°C absolute for the AE climate and -27°C relative to modern; -19.2°C absolute
5 for the CE climate) for 50, 100, 200 and 500 years before the development of glacier ice. This
6 is a theoretical situation to explore maximum possible permafrost depths as during the last
7 glacial cycle at the Southern Uplands the temperature step at 34 kyr BP would have reduced
8 surface temperatures to -12.9°C relative to modern for the AE climate and -20.5°C relative to
9 modern for the CE climate. The modelling has been run from 40-31 kyr BP at 10 year
10 intervals and for increasing exposure (50-500 years) of the land-surface to ice-free
11 conditions, resulting in maximum permafrost thicknesses of 100, 125, 150 and 190 m for the
12 AE climate and 220, 240, 265 and 315 m for the CE climate (Figure 6).
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15 5.3 Impact of the last two glacial-interglacial cycles

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17 The permafrost modelling at the ten locations has been based on a surface temperature history
18 from the last glacial-interglacial cycle. The coldest temperatures experienced in Great Britain
19 during the last glaciation occurred at the Late Devensian climatic minimum and the deepest
20 permafrost modelled corresponds to this period unless insulated by ice cover. Previous
21 glacial-interglacial cycles, although not as cold as the Late Devensian climatic minimum, will
22 have imposed a thermal imprint into the sub-surface that may alter the modelled permafrost
23 depths if only the last glacial-interglacial cycle is considered.
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26 A permafrost evolution model has been run for the Dartmoor location with a surface
27 temperature history from 212 kyr BP to present that is shown in Figure 7. The extension to
28 212 kyr BP incorporates the last two glacial-interglacial cycles. It utilises the SST
29 reconstruction from ODP (Ocean Drilling Program) ocean core 980 (McManus et al., 1999).
30 Two cases have again been considered, the average estimate case with a minimum MAAT of
31 -12°C (relative to present day) and a cold estimate case with a minimum MAAT of -18°C
32 (relative to present day). From the palaeoclimate reconstruction the surface temperature at
33 212 kyr BP has been estimated to be equivalent to present day and hence the initial sub-
34 surface temperature profile has been estimated assuming a surface temperature of 9°C, the
35 present day value for Dartmoor. The heat flow has been assumed to be constant at 0.105 W
36 m⁻².
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40 The modelling has been performed every 250 years and the results are shown in Figures 8a
41 and b with temperatures plotted to 1000 m depth. It can be seen that there is no influence of
42 the previous glacial cycle on the last glacial cycle and maximum depths of permafrost during
43 the last glaciation are 75 m and 220 m for the average and cold estimate surface temperature
44 histories respectively, which is in agreement with depths modelled when only considering the
45 last glacial-interglacial cycle.
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48 5.4 Impact of anthropogenic warming

49 The models run have used the last glacial-interglacial cycle(s) as an analogue for future
50 climate. However, future climate will be affected by present day anthropogenic warming.
51 Shaw et al. (2012) report that glacial cyclicity will return to dominate global climate, but not
52 until the effects of anthropogenic warming have receded. One plausible model (BIOCLIM,
53 2001) comprises rapid (century scale) warming of 3°C after which the climate returns to
54 present day temperatures by 90 kyr AP (After Present) with the onset of the first Northern
55 Hemisphere glaciations between about 170 and 180 kyr AP. A surface temperature prediction
56 based on this model is shown in Figure 9, where a 3°C rise of temperature over present day
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1 decays back to present day temperatures in equal 0.5°C increments by 90 kyr AP, until the
2 last glacial-interglacial cycle repeats from 170 kyr AP.

3 From an initial (present day) sub-surface temperature profile that comprises the climate
4 corrected estimated temperature (the modelled temperature from the last glacial-interglacial
5 cycle at present day), the future permafrost evolution at the Dartmoor location has been
6 modelled. Two cases have again been considered, the average estimate case with a minimum
7 MAAT of -12°C (relative to present day) and a cold estimate case with a minimum MAAT of
8 -18°C (relative to present day).
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10 The modelling has been performed every 500 years to 300 kyr AP and the results are shown
11 in Figures 10a and b. After an initial period of warmer sub-surface temperatures the onset of
12 glacial conditions leads to permafrost development as was observed in the models from the
13 last glacial-interglacial cycle. The maximum depths of permafrost are slightly greater at 90 m
14 and 255 m for the average and cold estimate surface temperature predictions respectively.
15 This slight increase in permafrost depth is a result of a different ground temperature profile at
16 the start of the glaciation.
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22 **6. Discussion**

23 When assessing the impact of permafrost on a GDF there are two primary considerations.
24 Firstly, is shallow permafrost development possible that may lead to changes in groundwater
25 movement and salinity levels? Secondly, is there a possibility that any permafrost might
26 extend to GDF depth and compromise both the engineered and natural barriers? The
27 permafrost modelling for the average estimate climate has indicated permafrost development
28 at all locations. Where the conditions are ice-free this occurs at the Late Devensian climatic
29 minimum. The location with the thinnest permafrost, of 20 m, for the average estimate
30 climate is the Stainmore Trough. Although this is at a northerly latitude, the ground was
31 insulated from the minimum air temperature by warm-based, fast-flowing, glacier ice during
32 the Late Devensian (Evans *et al.* 2009; Livingstone *et al.* 2012). The greatest thickness of
33 permafrost for the average estimate climate occurs at the Northwest Highlands location. An
34 extensive period of ice cover also insulated the ground from the coldest air temperatures, but
35 the frozen basal conditions of -3°C (absolute) resulted in a maximum depth of permafrost of
36 180 m. There is little published evidence relating to the geological signature of permanently
37 frozen ground with which to compare these modelled permafrost depths. However, Hutchison
38 (1991) reports deep periglacial disturbances of up to 62 m in the Derbyshire area and 47 m in
39 the Weald. These can be compared to modelled depths for the AE climate from South
40 Yorkshire (90 m) and the Weald (65 m). Given that permafrost ($T \leq 0^\circ\text{C}$) will be deeper than
41 perennally frozen ground (due to latent heat of freezing, salinity of groundwater etc.) there is
42 a fairly close correspondence between these reported and modelled permafrost depths.
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48 The cold estimate climate is also based on the climate of the last glacial cycle, but is
49 considered to be an extreme cold, but plausible, future climate. For this climate, extensive
50 permafrost development is seen at all localities. The shallowest development occurs in the
51 South Midlands and South Yorkshire and the deepest in the Southern Uplands. It might be
52 expected that the deepest development would be in the Northwest Highlands, but ice cover is
53 predicted until 12 kyr BP, whereas the Southern Uplands are assumed to be ice free by 14.5
54 kyr BP, exposing the land surface to extremely cold temperatures. Similarly, deep permafrost
55 is predicted at the Stainmore Trough locality, where minimal permafrost was modelled for
56 the average estimate climate case. Again, this locality is predicted to be ice free by 14.5 kyr
57 BP, exposing the ground surface to the very cold temperatures of the cold estimate climate.
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1 Exposing the land surface to the coldest conditions for short periods of time, as could occur
2 during rapid climate change before glacier formation, has indicated that maximum permafrost
3 thicknesses are similar to those observed in the regional modelling for the cold estimate
4 climate. However, this could occur anywhere across Britain as there is no insulation from ice
5 cover. This theoretical result is of relevance when considering maximum, future, permafrost
6 depths, assuming that the last glacial cycle can be taken as an analogue for future climate.
7 Two, further sensitivity models were run, one to test the influence of two glacial-interglacial
8 cycles and the second to examine, future, permafrost development in a climate comprising a
9 period of anthropogenic warming followed by a repeat of the last glacial-interglacial cycle.
10 These were only run for the Dartmoor location and in both cases the permafrost development
11 was as observed previously. Any anthropogenic warming from present day human activity is
12 likely to delay the onset of future glaciations, but it is beyond the scope of this paper to
13 speculate on how long that delay might be.
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16 Permafrost modelling has also been undertaken at the Belgian GDF site at Mol (Govaerts et
17 al., 2011). Their ‘realistic glacial cycle’ indicated a minimum temperature in northern
18 Belgium of -19°C (relative to present day), which is comparable to the cold estimate climate
19 used here. Maximum permafrost thicknesses (defined as the 0°C isotherm combined with
20 50% frozen ground) of 160 m and 215 m for the climate models with and without surface
21 cover respectively were obtained. The cold estimate climate applied here for the southern
22 England locations has a minimum MAAT of -18°C (relative to present day) and maximum
23 permafrost thicknesses of 180-245 m. Similarly, at Forsmark in Sweden, Hartikainen et al.
24 (2010) defined a repetition of the last glacial-interglacial cycle and a severe permafrost case
25 with maximum modelled permafrost depths (0°C isotherm) of 260 m and 390 m respectively.
26 It is not possible to compare these thicknesses directly to the modelling here due to different
27 MAAT and ice cover history, but maximum permafrost depths from the northern Britain
28 locations for the average and cold estimate climates were 110-180 m and 215-305 m
29 respectively.
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37 **Conclusions**

38 One dimensional heat conduction modelling has shown that by assuming past climate can be
39 taken as an analogue for future climate, permafrost development should be taken into
40 consideration when constructing the safety case for a GDF based in Great Britain. For a
41 future climate, considered to be an average representation of the last glacial-interglacial
42 cycle, permafrost developed at all localities with maximum thicknesses varying between 20-
43 180 m. For a climate, also based on the last glacial-interglacial cycle, but defined as an
44 extreme cold, plausible, future climate, maximum permafrost thickness varied between 180-
45 305 m. In general, the greatest maximum permafrost thicknesses occur in northern Britain.
46 This arises from colder northern air temperatures and long periods of ice cover associated
47 with cold, frozen basal conditions. As only ground temperature has been modelled, it is not
48 possible to make any statements about ice formation or the depth that partially or completely
49 frozen ground might penetrate to. However, as shown in other studies (e.g. Hartikainen et al.,
50 2010; Govaerts et al., 2011), perennially frozen ground is likely to correlate with the extent of
51 the ground below 0°C.
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57 A GDF based in Great Britain is being considered in the depth of 200-1000 m. Modelling has
58 demonstrated that were a GDF to be at relatively shallow depth, permafrost could have a
59 direct impact. Permafrost has the potential to affect the properties of rocks above a GDF,
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1 leading potentially to the development of new fracture pathways, affecting groundwater
2 recharge and discharge. Changes to groundwater chemistry, particularly salinity, could occur
3 that might result in changes to, e.g., geochemical conditions at GDF depth.

4 Predictions on permafrost depths and extent are far more uncertain for particular localities
5 than general statements referring to southern and northern Britain. This is due to uncertainties
6 in the minimum MAAT during the last glacial cycle, the extent and thickness of ice cover,
7 particularly in the period prior to 35 kyr BP, and the temperatures at the base of the ice over
8 time. For instance, Govaerts et al. (2011) in their ‘realistic glacial cycle’ indicated a
9 minimum temperature in northern Belgium (which would be expected to be similar to
10 southern England) of -19°C (relative to present day) and Westaway and Younger (2013) have
11 suggested that during the last glacial-interglacial cycle temperatures in southern England
12 reached -20°C (relative to present day). These are both colder than the climate reconstruction
13 used here and indicate that further research based on climate proxies from the British Isles is
14 needed to generate a more constrained estimate of MAAT for the last glacial-interglacial
15 cycle. Similarly, since ice cover has a major effect in determining permafrost thickness,
16 especially as an insulator against extremely cold MAAT, greater controls on ice cover and
17 thickness are needed for site specific permafrost determinations.
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23 **Acknowledgments**

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- Figure 1. The reconstructed mean annual air temperature trend for Great Britain over the last 126 kyr. This reconstructed temperature trend was used as a basis for the surface temperature histories at each of the 10 localities, where the maximum and minimum temperatures were adjusted, along with the effect of ice sheet presence.
- Figure 2. Ground surface temperature histories for the average estimate climate for a) the Weald, which was ice free and where the minimum temperature of 12°C below present occurred at the peak of the last glaciation; b) the Southern Uplands where ice cover between 110-102, 76-37 and 34-14.5 kyr BP insulated the land surface from the extremes of air temperature. Hence, despite a minimum MAAT of 17°C below present the minimum temperature of 11.9°C below present occurred after the ice had retreated.
- Figure 3. The ten selected locations across Great Britain for permafrost modelling, overlaid on the 1:625,000 scale bedrock geology. The geology key for this map can be viewed at <http://mapapps.bgs.ac.uk/geologyofbritain/home.html>.
- Figure 4. Permafrost evolution modelling for the Weald, a) derived with the average estimate surface temperature history, b) derived with the cold estimate surface temperature history.
- Figure 5. Permafrost evolution modelling for the Southern Uplands, a) derived with the average estimate surface temperature history, b) derived with the cold estimate surface temperature history.
- Figure 6. Permafrost evolution model for the Southern Uplands examining the theoretical case of exposure of the land surface to very cold conditions at the onset of a glacial advance before the formation of glacier ice, modelled here as an onset at 34 kyr BP and exposure for 200 years; a) the average estimate climate where the MAAT was -17°C relative to modern; b) the cold estimate climate where the MAAT was -27°C relative to modern.
- Figure 7. Surface temperature history for the average estimate climate for Dartmoor extending back to 212 kyr ago for the period of the last two glacial-interglacial cycles.
- Figure 8. Permafrost evolution modelling extending back over the last two glacial-interglacial cycles to 212 kyr BP for Dartmoor, a) derived with the average estimate surface temperature history, b) derived with the cold estimate surface temperature history. Permafrost thicknesses during the last glacial-interglacial cyclical are not affected by the previous cycle.
- Figure 9. Future surface temperature prediction for the average estimate climate for Dartmoor. After a period of anthropogenic warming that has receded by 90 kyr AP (BIOCLIM 2001), the climate assumes a repeat of the last glacial-interglacial cycle at 174 kyr AP.
- Figure 10. Modelled prediction of permafrost for Dartmoor in a future climate based on the surface temperature prediction in Figure 9, a) derived with the average estimate surface temperature history, b) derived with the cold estimate surface temperature history. Permafrost thicknesses are not significantly altered by the period of anthropogenic warming.
- Table 1a. Descriptions of the permafrost modelling locations in southern Britain. The minimum mean annual air temperature (MAAT) for both the average estimate

(AE) and cold estimate (CE) climates 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). A, not to scale diagram, illustrates the bedrock geology beneath the location with depth (m) relative to Ordnance Datum (+ve above sea level) shown on the left and geology (with, in brackets the thermal conductivity in $W m^{-1} K^{-1}$) on the right. 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.

Table 1b. Descriptions of the permafrost modelling locations in northern Britain. Table contents are as described for Table 1a.

Table 2 Maximum regional, modelled thicknesses of permafrost at the ten locations resulting from the average and cold estimate climates.

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Table 1a

	Dartmoor		Weald		East Anglia		South Midlands		Mid-Wales	
Coordinates (m)	278000 (E)	84000 (N)	560800 (E)	133700 (N)	60300 (E)	287294 (N)	487479 (E)	240990 (N)	310453 (E)	292587 (N)
Elevation (m OD)	257		98		42		79		160	
Mean annual, present, surface temperature (°C)	9.0		10.0		10.0		9.9		8.8	
Heat flow (W m⁻²)	0.105		0.052		0.035		0.053		0.055	
Min MAAT relative to present (°C)	-12 AE	-18 CE	-12 AE	-18 CE	-12 AE	-18 CE	-12 AE	-18 CE	-12 AE	-18 CE
Periods of ice cover (kyr BP)	No ice cover		No ice cover		No ice cover		24-15.5		40-37; 29-26; 24-15.5	
Temp below ice relative to present (& absolute) (°C)							-8.9 AE (+1 AE)	-10.9 CE (-1 CE)	-11.8 AE (-3 AE)	-12.8 CE (-4 CE)
Geological sequence	<p>257.0 -2000.0 UIICP-FELSR (3.27)</p>		<p>98.0 -203.0 -325.0 -342.0 -835.0 -909.0 -1011.0 W-MDSS (2.18) PB-LSMD (1.3) PL-LMCS (2.1) KC-MDST (1.3) CR-LSSM (2.05) KLOX-MDSS (1.76)</p>		<p>42.0 29.0 -34.0 -100.0 -162.0 -216.0 -234.0 -259.0 -277.0 -295.0 -308.0 -315.0 -401.0 -1336.0 CCK-CHLK (1.56) NCK-CHLK (1.56) SECK-CHLK (1.56) LECH-CHLK (1.67) NPCH-CHLK (1.56) HCK-CHLK (1.58) ZZCH-CHLK (1.67) WMCH-CHLK (1.67) GUGS-MDSL (1.77) LGS-STMD (2.59) LI-MSLS (1.97) LDEV-MDSS (3.0) SILU-MDSS (3.0)</p>		<p>79.0 57.0 -58.0 -810.0 1894.0 KLOX-MDSS (1.76) LI-MSLS (1.97) CAOR-MDSS (2.8) AZRU-GD (3.27)</p>		<p>160.0 -630.0 -924.0 -1452.0 WEN-MDSS (2.4) WEN-SCON (3.4) LDVY-MDSS 2 (2.72)</p>	

Table 1b

	South Yorkshire		Stainmore Trough		Southern Uplands		Midland Valley		Northwest Highlands	
Coordinates (m)	434699 (E)	416565 (N)	444128 (E)	523367 (N)	343206 (E)	610104 (N)	290971 (E)	686182 (N)	230850 (E)	861650 (N)
Elevation (m OD)	54		28		247		66		165	
Mean annual, present, surface temperature (°C)	9.4		9.2		7.8		9.0		7.2	
Heat flow (W m⁻²)	0.071		0.067		0.071		0.069		0.058	
Min MAAT relative to present (°C)	-12 AE	-18 CE	-14 AE	-24 CE	-17 AE	-27 CE	-14 AE	-24 CE	-17 AE	-27 CE
Periods of ice cover (kyr BP)	40-37; 24-15.5		110-102; 76-37; 34-14.5		110-102; 76-37; 34-14.5		62-37; 34-14.5		110-12	
Temp below ice relative to present (& absolute) (°C)	-12.4 AE (-3 AE)	-13.4 CE (-4 CE)	-8.2 AE (+1 AE)	-10.2 CE (-1 CE)	-10.8 AE (-3 AE)	-11.8 CE (-4 CE)	-12.0 AE (-3 AE)	-13.0 CE (-4 CE)	-10.2 AE (-3 AE)	-11.2 CE (-4 CE)
Geological sequence										

Table 2

Location	Maximum thickness of permafrost (m) due to average estimate climate	Maximum thickness of permafrost (m) due to cold estimate climate
Dartmoor	80	220
Weald	65	245
East Anglia	65	245
South Midlands	30	180
Mid-Wales	105	215
South Yorkshire	90	180
Stainmore Trough	20	205
Southern Uplands	150	305
Midland Valley	110	215
Northwest Highlands	180	235

Table 2

Figure 1
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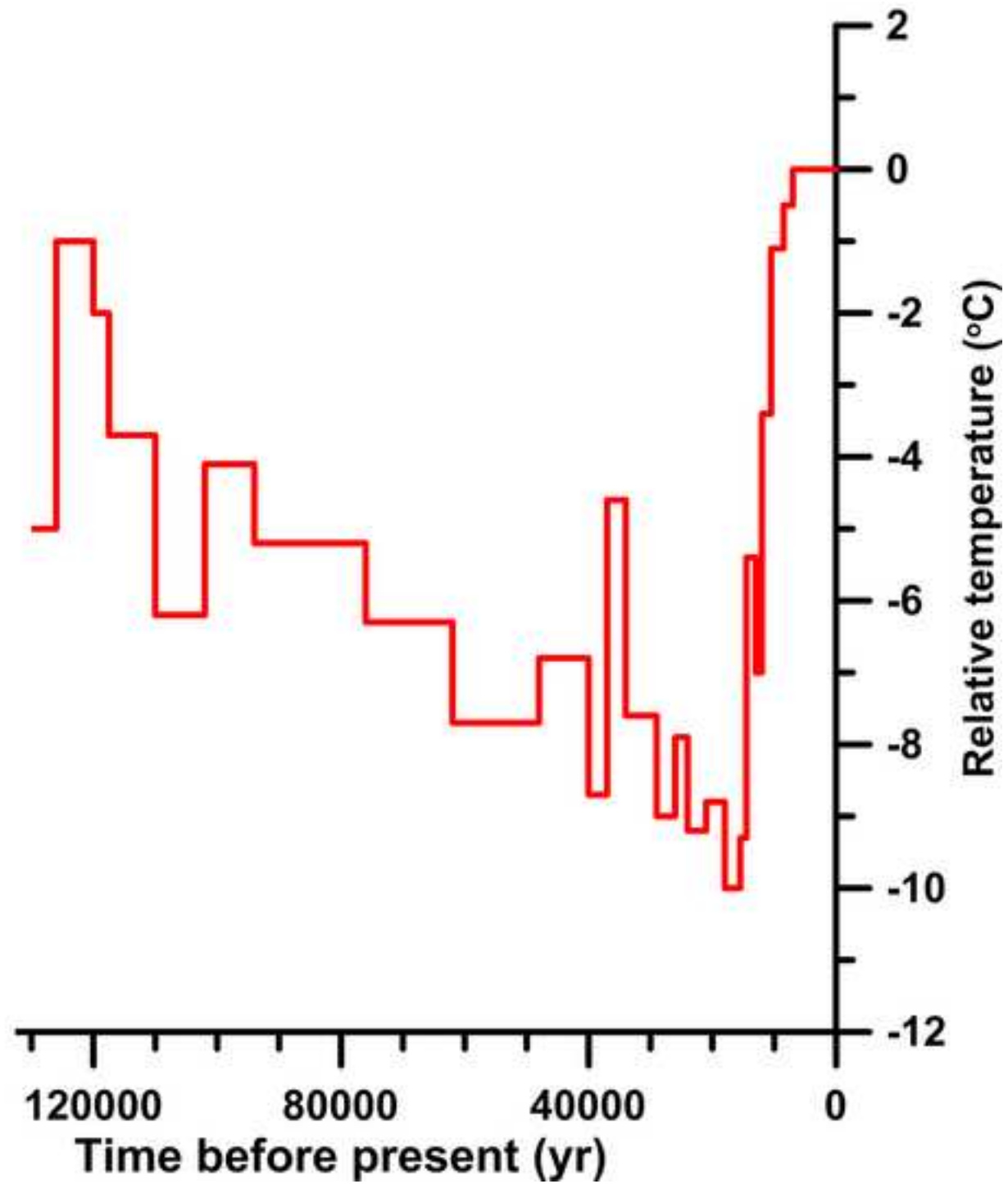


Figure 2a

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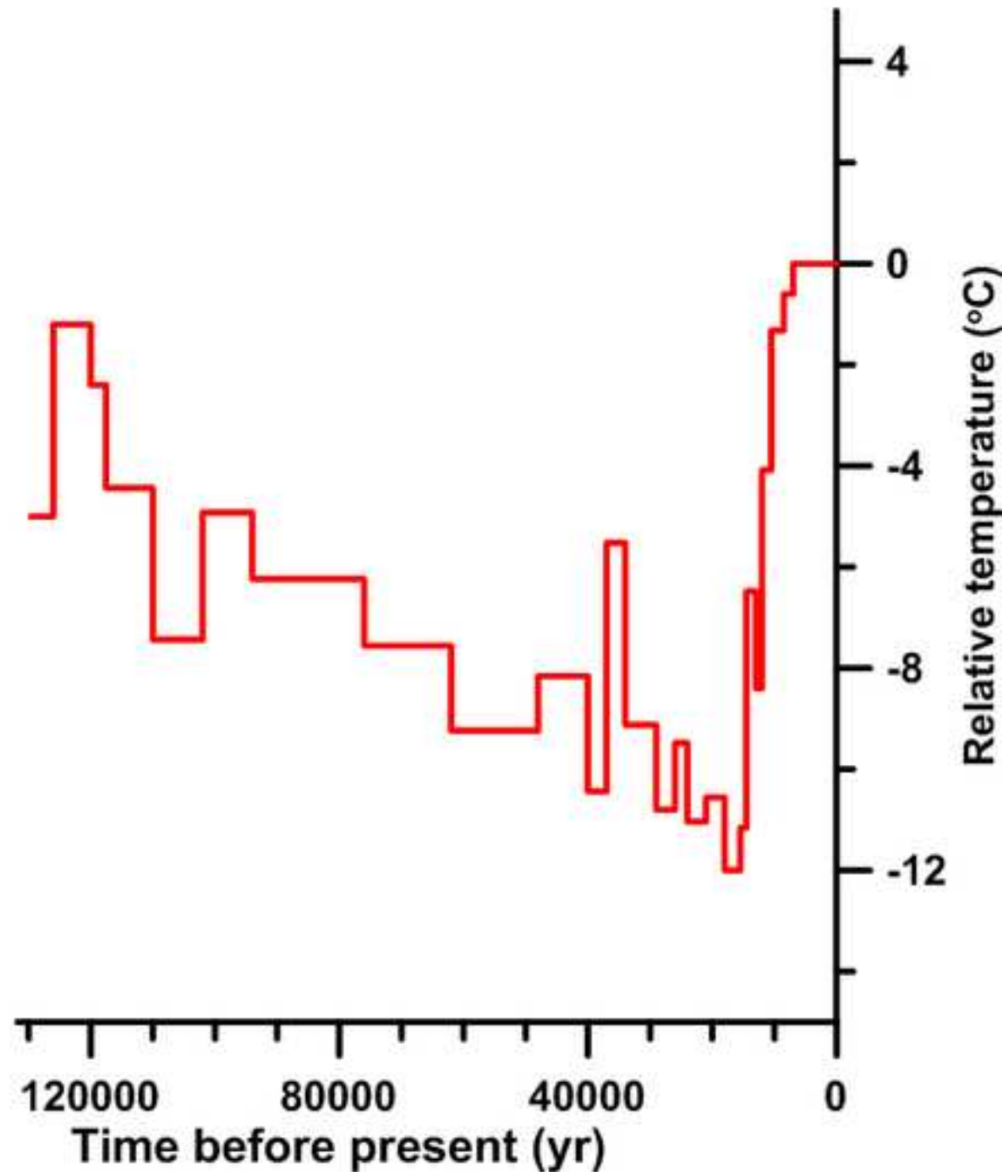


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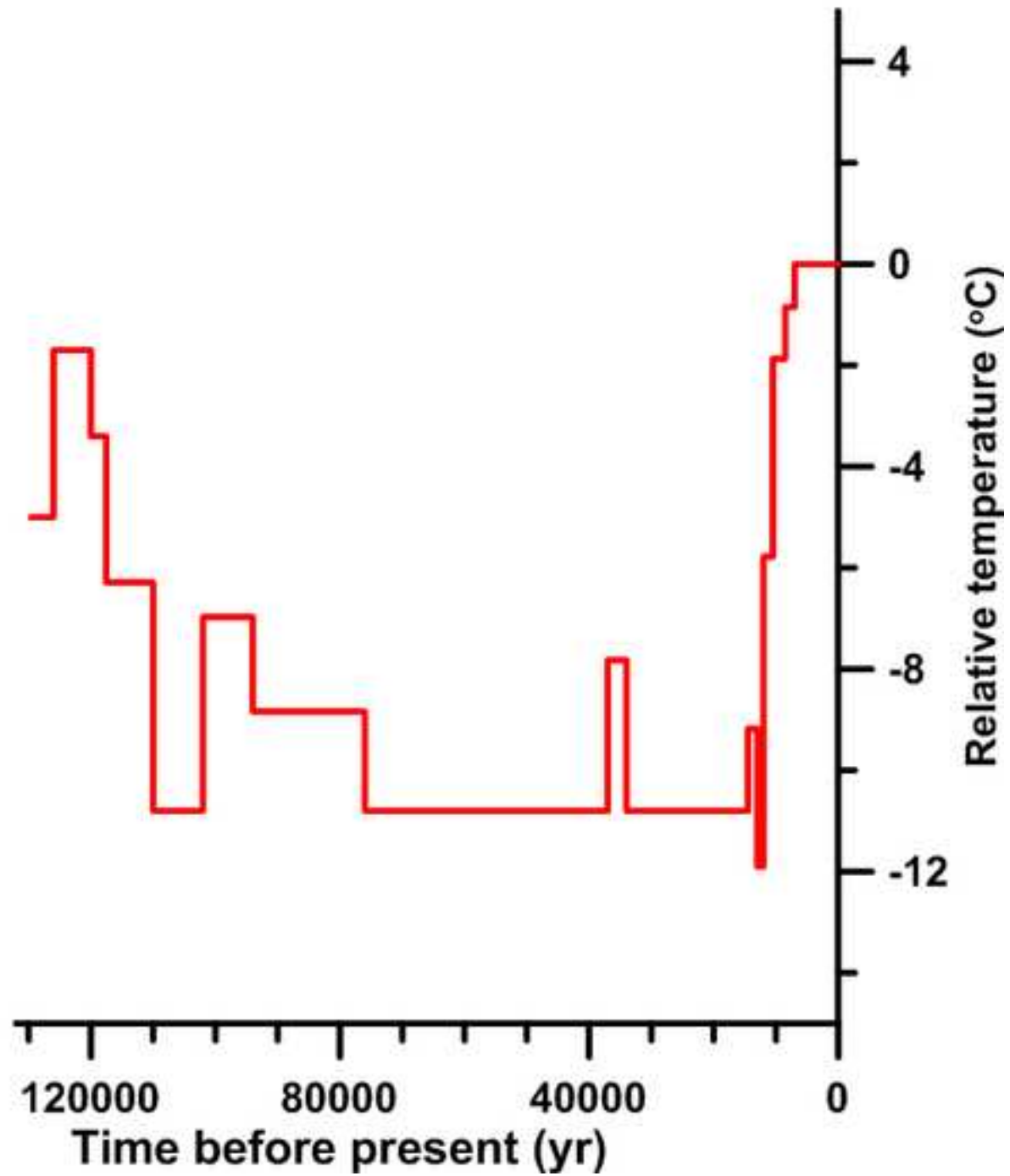


Figure 3

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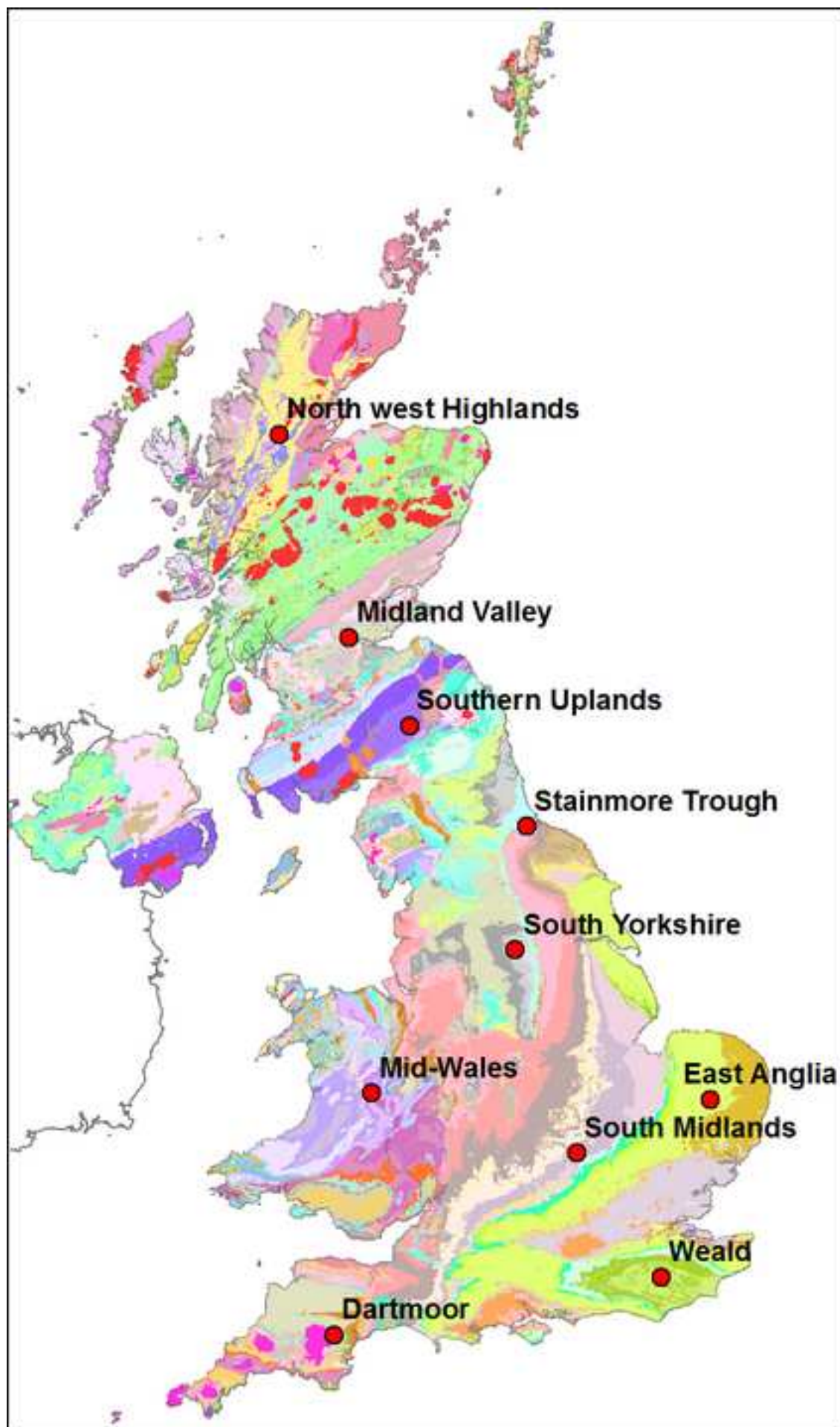


Figure 4a

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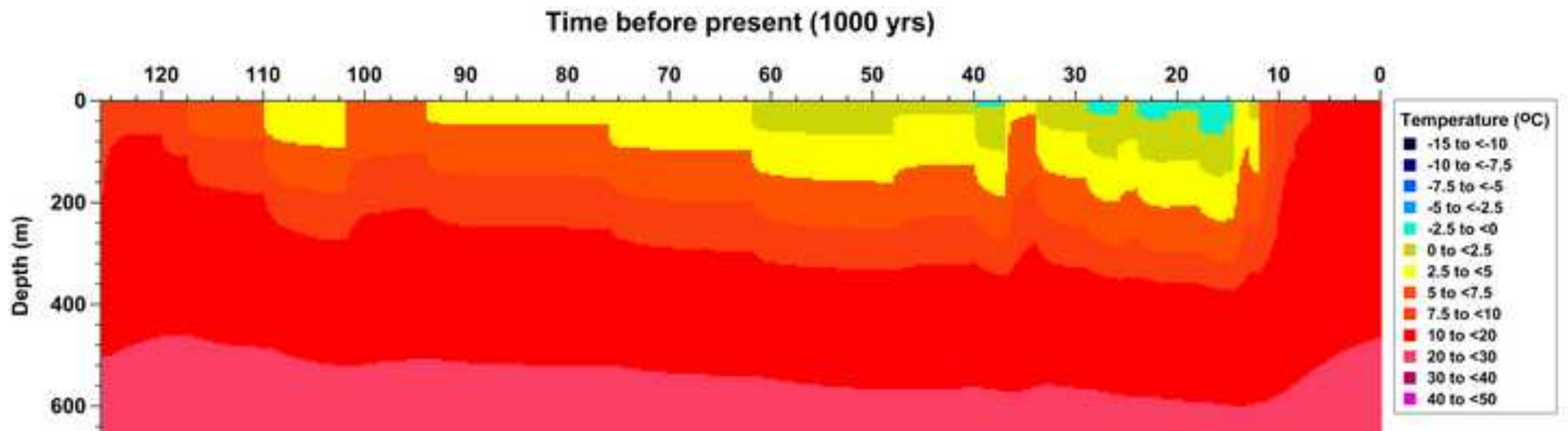


Figure 4b

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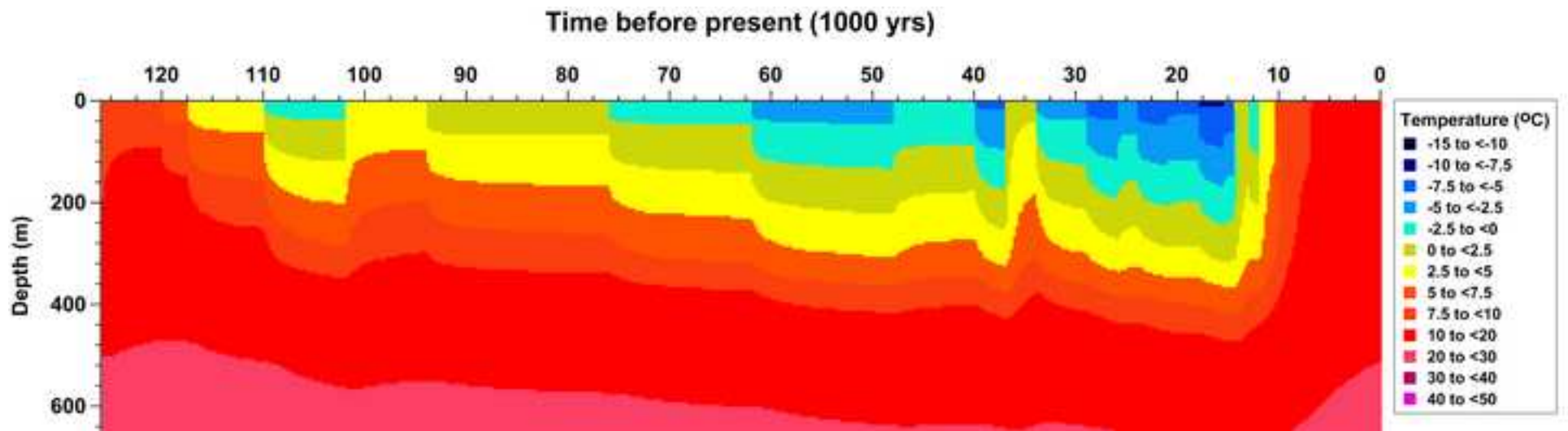


Figure 5a

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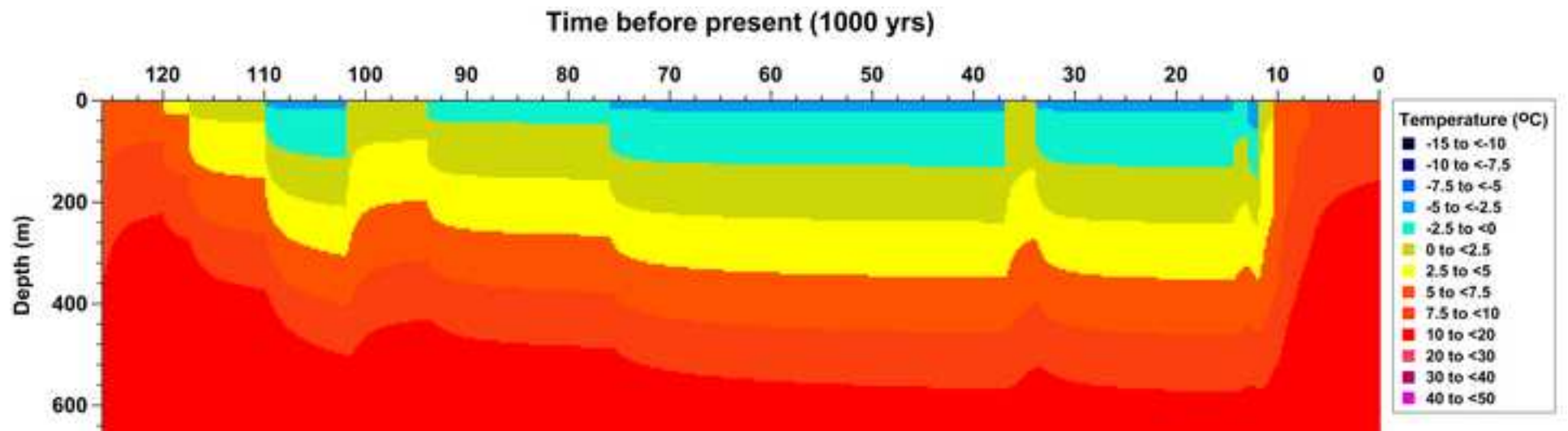


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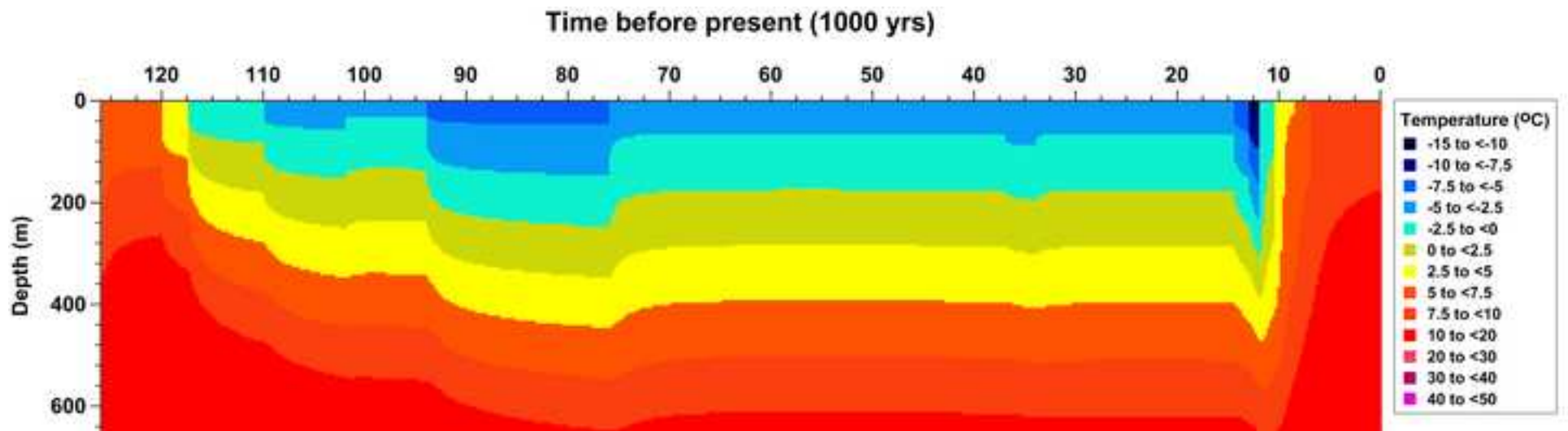


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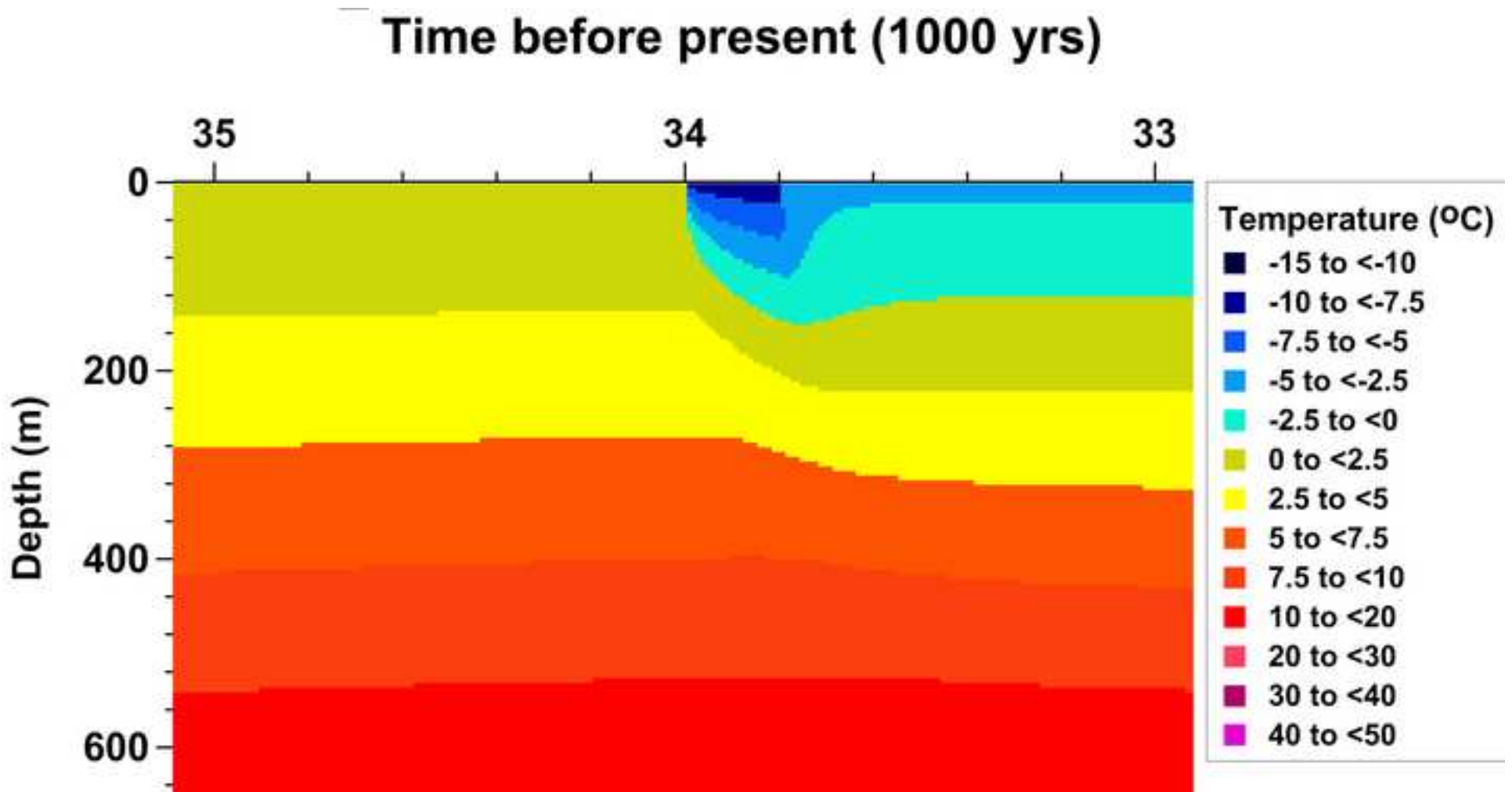


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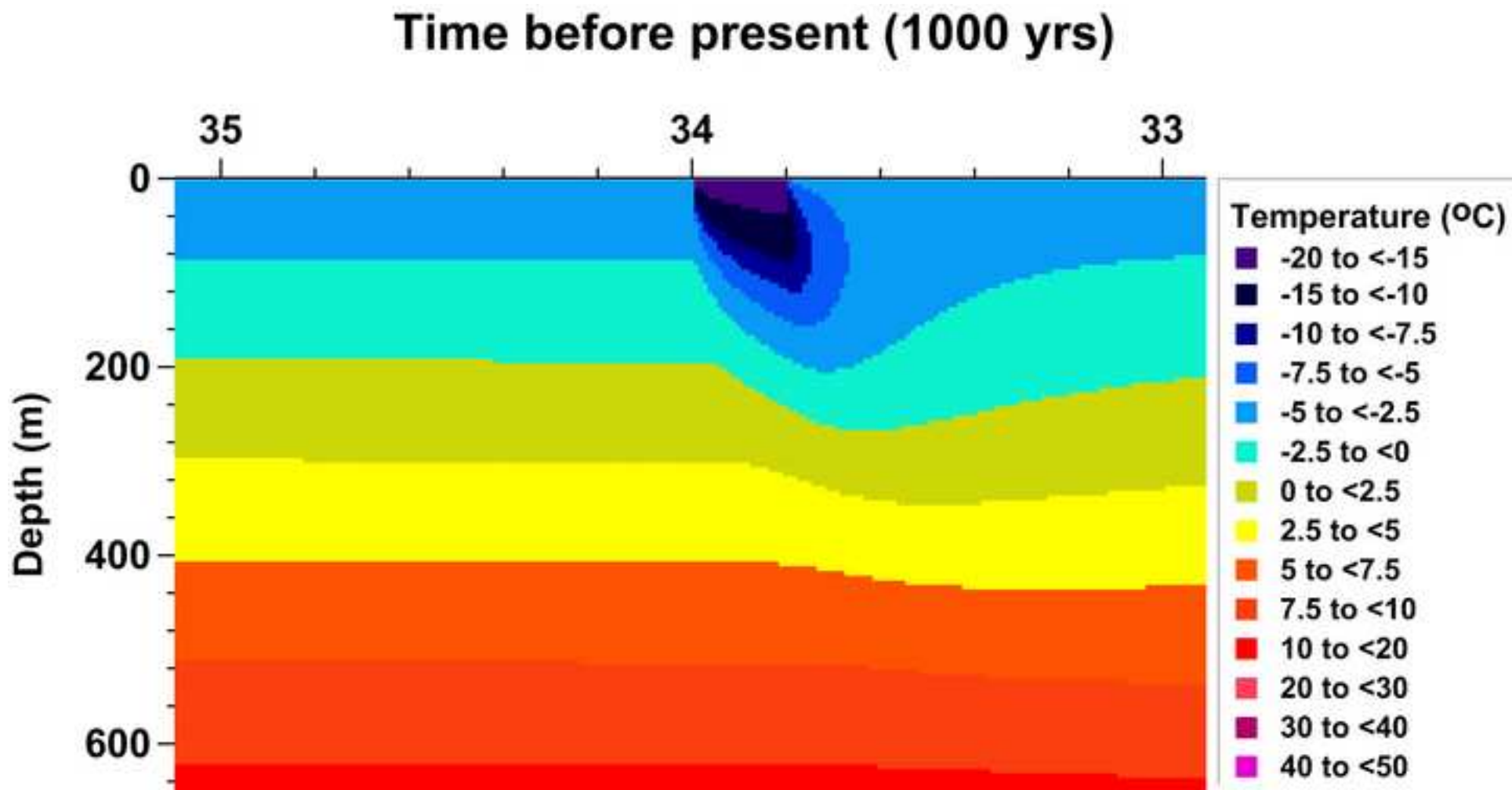


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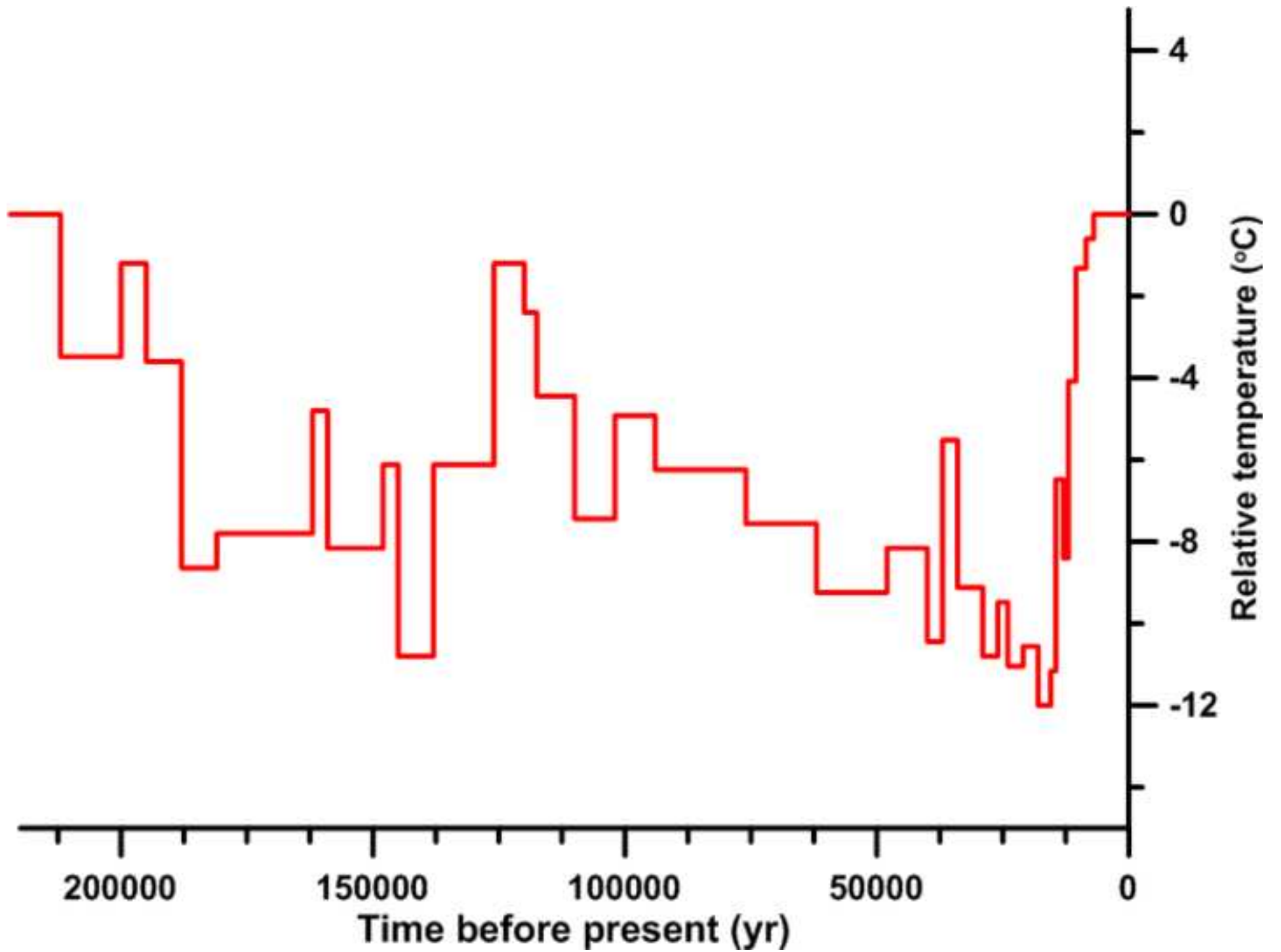


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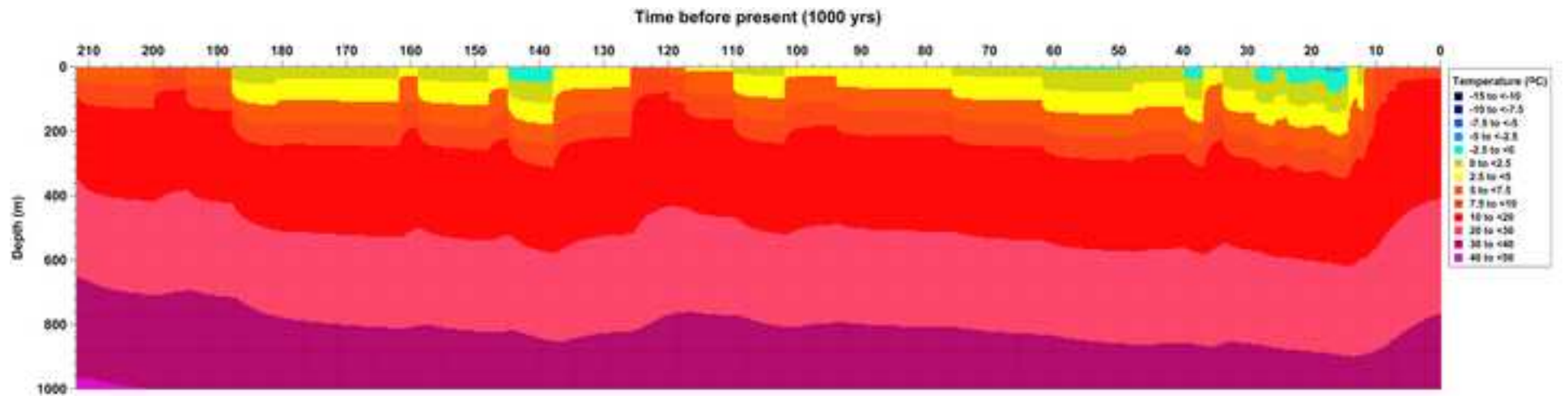


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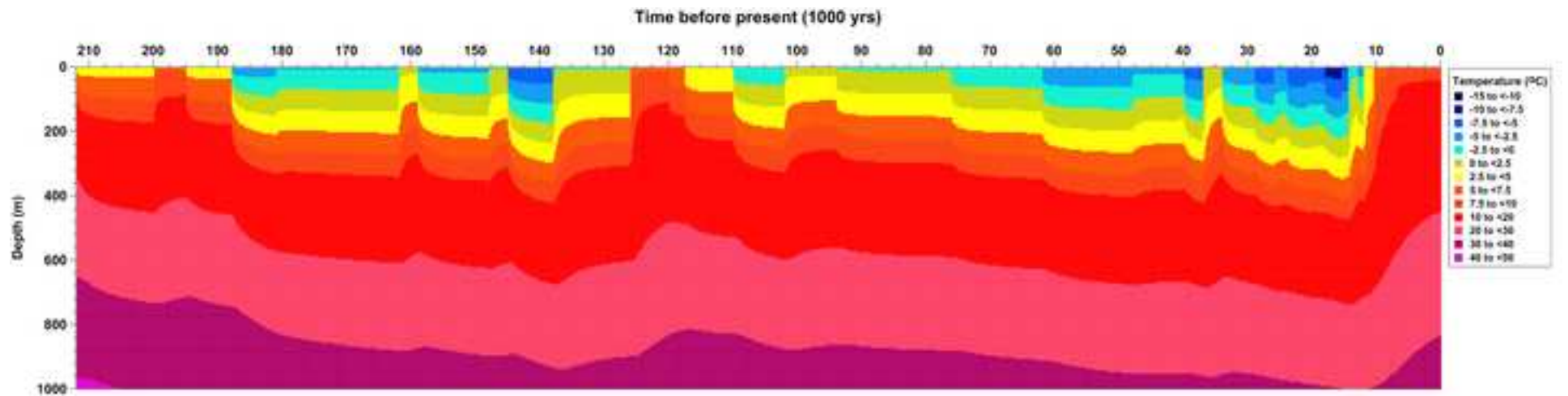


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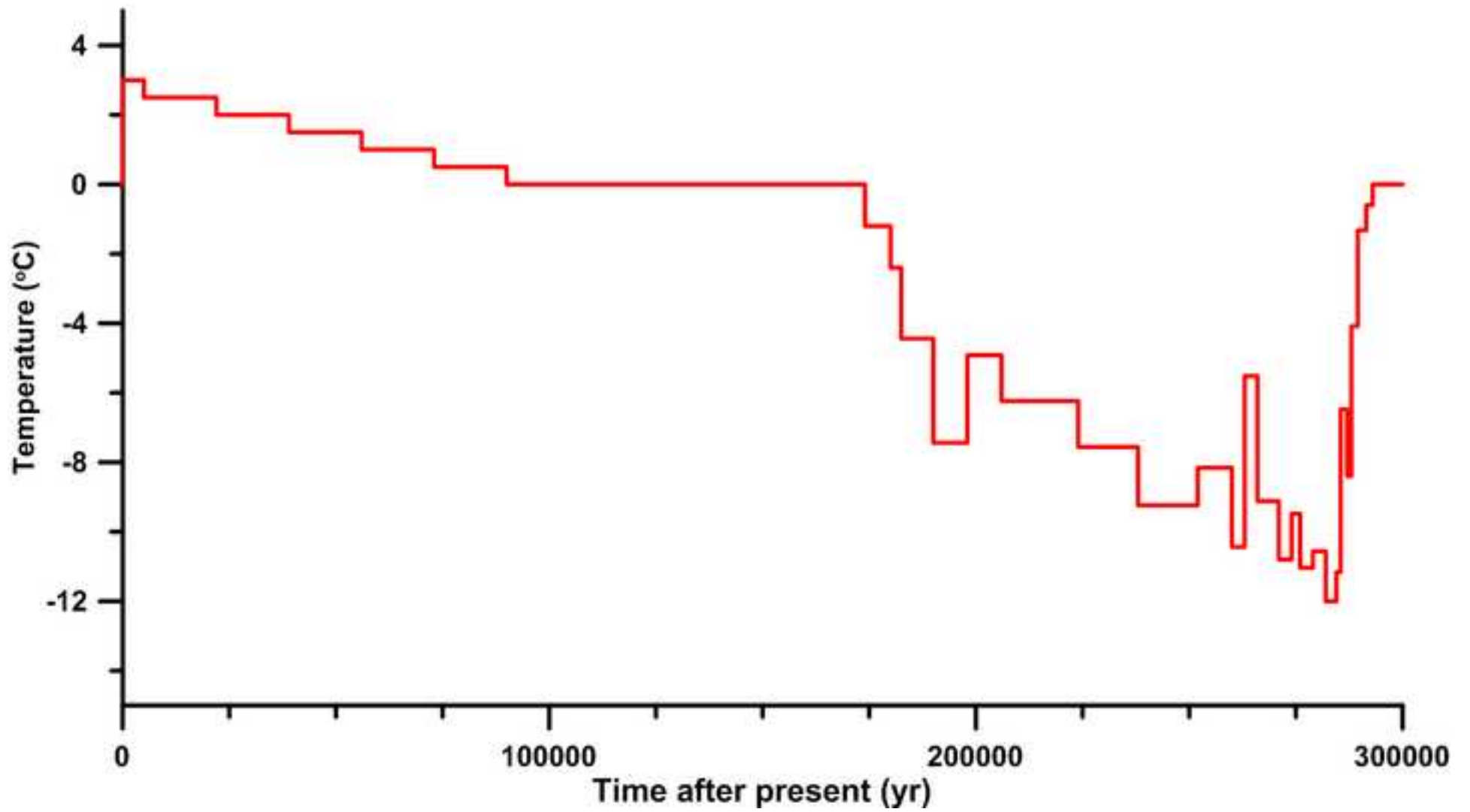


Figure 10a

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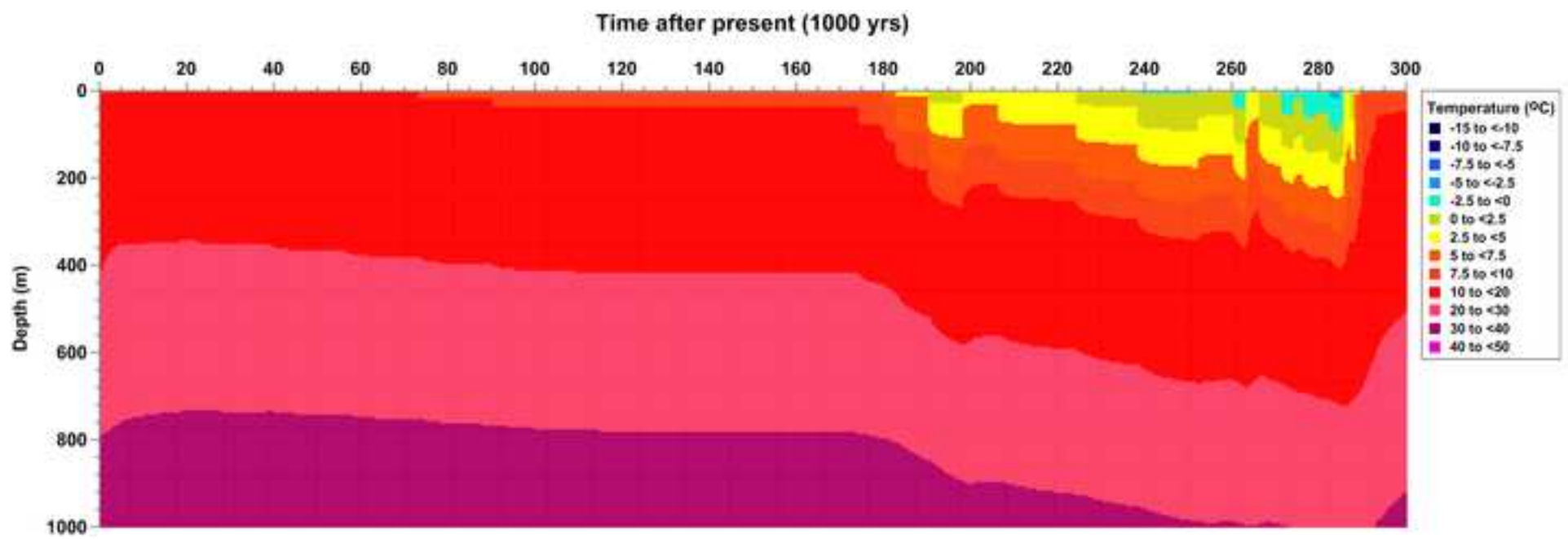


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