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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 1 million years following GDF closure. The depth of penetration of permafrost, defined as ground which remains at or below 0 °C for at least 2 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 to 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, 2012). 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 1 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, 2012; 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 (European Commission, 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 beneath the frozen layer. In-turn, the hydromechanical and geochemical properties of the engineered barrier system (which could contain significant amounts of bentonite and/or concrete/cement) may be impacted by freezing in several different ways such as: (1) long-term performance during transient periods with high hydraulic, thermal or chemical gradients, which could influence the evolution of repository components; (2) highly saline residual brine, produced during the formation of frozen ground, that may affect the swelling characteristics of bentonite and the stability of cement. The development of frozen ground could affect the properties of rocks above a GDF leading to the possible development of new fracture pathways affecting groundwater recharge and discharge. Frozen ground will create a barrier to groundwater flow, but once the ground has thawed its permeability may be increased leading to temporary or permanent changes to groundwater flow paths.

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This paper investigates the potential for permafrost development across Great Britain under possible future climate scenarios. It follows a previous modelling study on permafrost thickness during the last glacial–interglacial cycle (Busby et al., in press). It is non-site specific, but a series of locations have been selected in order that a range of geographical and geological settings can be considered. The modelling is at the regional scale with a focus on the maximum depth extent to which permafrost might develop in an average future climate and in an extreme (cold) climate up to 300 k years into the future.

2. Permafrost modelling approach

The definition of permafrost applied here is ground which remains at or below 0 °C for at least 2 consecutive years (French, 2007) as opposed to perennially frozen ground that keeps frozen for at least 2 consecutive years. Hence, permafrost is defined on the basis of 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 the freezing of water. The freezing of water is itself dependent on pressure, salinity and the adsorptive and capillary properties of the ground matter.

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. This one dimensional heat conduction approach does not take into account the freezing of water, the effect of groundwater movement or the change in ground properties due to freezing. Carslaw and Jaeger (1959) have shown that

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

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.

The approach here has been to use the last glacial–interglacial cycle as an analogue for future climate and therefore to model permafrost evolution over the period of the last glacial–interglacial cycle. To model the evolution of ground 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 at 126 k years BP (before present) and sub-surface temperatures have been calculated at 5 m depth intervals to 1 km every 250 years up to present day.

3. Future climate

When we consider future climate, one approach is to consider what has happened in the past, on the assumption that it will repeat in the future. The climate over the last ~1 million years in northern Europe has experienced a series of cold spells, broadly every 100 k years. Superimposed upon these large-scale glacial cycles are more medium-term climatic events occurring with a ~40 k years periodicity (Lisiecki and Raymo, 2005). The last glacial stage, called the Devensian Glaciation, was one of the most intense glacial events to affect Great Britain and hence can be used as a suitable analogue for modelling the development of permafrost during a similar-scale cold-event over the next ~300 k years. Since the beginning of the industrial revolution this natural climate system has been modified by increased greenhouse gas emissions, which are set to cause significant warming of the climate in the relatively near future (IPCC, 2013). However, over the long term (>10 s to 100 s k years) modelling studies suggest that the climate will return to past glacial–interglacial background conditions (BIOCLIM, 2001). This conclusion is supported by palaeoclimate proxy data over past 'hyperthermal' episodes (e.g. at the Palaeocene–Eocene Thermal Maximum), which show that Earth's climate returned to background temperature levels within ~200 k years after significant atmospheric CO_2 release and global warming (DeConto et al., 2012).

The mean annual air temperature (MAAT) for Great Britain over the last glacial–interglacial cycle (0–130 k years ago) has been constructed from multiple proxy data comprising NE Atlantic sea surface temperature (SST) and pollen-based MAAT proxies to reconstruct an idealised temperature curve. The detail of this procedure was presented in Busby et al. (in press) and is not repeated here. The result is an idealised MAAT profile that is shown in Fig. 1. It is necessary to scale this profile to account for the variation in latitude between southern and northern Britain. Present day MAAT is the maximum temperature and is taken as the Holocene average, whilst the minimum MAAT is from the Annan and Hargreaves (2013) global estimate of MAAT during the global peak of the last glaciation (19–23 k years BP). Therefore the minimum MAAT for 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. Two climate models have been applied; the first is an average estimate (AE) case considered to be the best estimate of ground surface temperatures during the last glacial–interglacial cycle where the climate range is 12–17 °C below modern, between southern English and northern Scottish sites respectively. The second climate is a cold estimate (CE) case considered to be an extreme cold, but plausible future climate. The cold estimate climate is towards the cold extreme of the error range reported by Annan and Hargreaves (2013) and ranges between 18 °C and 27 °C below modern, between southern English and northern Scottish sites respectively.

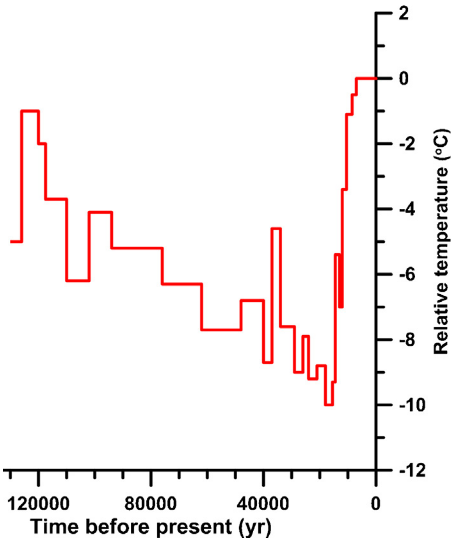

Fig. 1. The reconstructed mean annual air temperature trend for Great Britain over the last 126 k years. This reconstructed temperature trend was used as a basis for the surface temperature histories at each of the 10 localities, where the maximum and minimum temperatures were adjusted, along with the effect of ice sheet presence.