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Tectonic and climatic considerations for deep geological disposal of radioactive waste: A UK perspective

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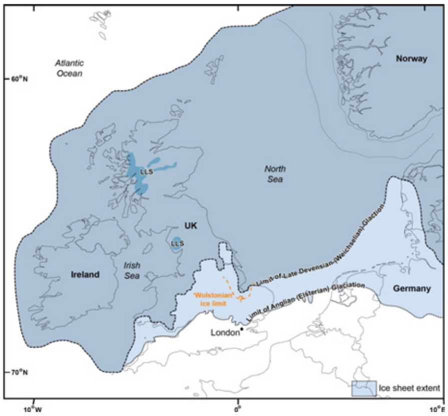
HIGHLIGHTS

- Natural processes are key to developing a safety case for geological disposal.
- Key factors include plate tectonic and climate-mediated processes.
- Process variability is a challenge to predicting the natural environment.
- We highlight the challenges for geological disposal programs using the example of the UK.

GRAPHICAL ABSTRACT



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ABSTRACT

Identifying and evaluating the factors that might impact on the long-term integrity of a deep Geological Disposal Facility (GDF) and its surrounding geological and surface environment is central to developing a safety case for underground disposal of radioactive waste. The geological environment should be relatively stable and its behaviour adequately predictable so that scientifically sound evaluations of the long-term radiological safety of a GDF can be made. In considering this, it is necessary to take into account natural processes that could affect a GDF or modify its geological environment up to 1 million years into the future. Key processes considered in this paper include those which result from plate tectonics, such as seismicity and volcanism, as well as climate-related processes, such as erosion, uplift and the effects of glaciation. Understanding the inherent variability of process rates, critical thresholds and likely potential influence of unpredictable perturbations represent significant challenges to predicting the natural environment. From a plate-tectonic perspective, a one million year time frame represents a very short segment of geological time and is largely below the current resolution of observation of past processes. Similarly, predicting climate system evolution on such time-scales, particularly beyond 200 ka AP is highly uncertain, relying on estimating the extremes within which climate and related processes may vary with reasonable confidence. The paper highlights some of the challenges facing a deep geological disposal program in the UK to review understanding of the natural changes that may affect siting and design of a GDF.

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1. Introduction

The disposal of radioactive waste represents a significant challenge for those countries that have utilised nuclear materials for defence, power generation and medicinal purposes. Many countries with developed nuclear industries, including the UK, have opted for deep geological disposal to address this problem. However, geological disposal of radioactive waste differs from other sub-surface exploitation in that it requires significant assessment, to understand the impact of potential fugitive radionuclides, for up to 1 million years into the future. This timescale reflects the length of time for the radioactivity of typical waste materials to reach an acceptable risk level solely by natural decay (NDA, 2010). A key component of deep geological disposal is the emplacement of wastes within an engineered facility (termed a Geological Disposal Facility, GDF), constructed at depths of hundreds of meters below the surface, making use of the surrounding geological environment as one of the containment barriers (NDA, 2010). A fundamental requirement of the geological environment is that it should be relatively stable and its behaviour adequately predictable (IAEA, 2011). The need for predictability arises from the requirement to make scientifically sound evaluations of the long-term radiological safety of a disposal facility.

In considering the long-term safety functionality of a GDF, it is necessary to take into account natural processes that could affect it or modify its geological environment. However, understanding the inherent variability of geological process rates, critical thresholds, and the influence of unpredictable perturbations, represents a significant challenge to predicting these changes. For instance, when considering the processes that may have an impact on the geological environment surrounding a GDF, a one million year time frame represents a very short segment of geological time that is largely below the resolution of observation of past plate-tectonic processes. Similarly, predicting climate system evolution on such time-scales is also very challenging, relying on estimating the extremes within which climate and related processes may vary with reasonable confidence (Näslund et al., 2013).

In regions of the world with active tectonism and/or recent glaciation these considerations are typically assessed on the basis of deterministic evaluation informed by direct observation of their effects (e.g. Stephens et al., 2015). However, the intraplate setting of the UK, with its weak tectonic activity (e.g. Ambraseys and Jackson, 1985; Musson and Sargeant, 2007) and largely glacier-free environment for the last 11.5 kyr (Sutherland, 1993), assessment is necessarily based on developing consensus amongst the research community based on more circumstantial evidence, modelling and probabilistic evaluation.

As a pioneer in the development and use of nuclear technology, the UK has accumulated a substantial legacy of radioactive waste since the 1940s. It will continue to do so for decades to come, in light of the UK Government's expectation that nuclear power will play a role in the country's future energy mix, helping to meet the challenge of decarbonising our energy supply (DECC, 2011). By the end of this century, it is forecasted that 1.1 million m^3 (2.6 million tonnes) of high level waste will need to be safely managed (NDA, 2014).

The UK has not yet identified a site to host a GDF, however a new program to implement geological disposal was launched in 2014 (DECC, 2014) Other radioactive waste disposal programs in northern latitudes such as Sweden, Finland and Canada, have undertaken assessments of future natural processes as part of their site investigation programs all of which have some relevance to some situations in the UK's (for example, SKB, 2011; SKB, 2014; Posiva, 2012). However, the UK's geographical situation on the north western margin of Europe, combined with its highly varied geology and topography means that is has distinctive factors that are likely to influence potential future natural change when compared to these other assessments. The purpose of this paper is to highlight some of the challenges facing deep geological disposal programs in such intraplate settings to review understanding of the natural changes that may affect siting and design of a GDF in the UK.

2. Earth system processes: rates and feedbacks

In order to gain an appreciation of the challenges around forecasting the impact of natural processes, it needs to be understood that the Earth is a dynamic, evolving system with many complex processes interacting at all scales, from global to local, often in a non-linear way. Many of the processes that impose change on the Earth's system are understood to be closely interlinked with dynamic feedbacks (Steffen et al., 2004). For example, secular chemical evolution of the geosphere over geological time scales, in part facilitated by mantle convection, has largely controlled the compositional evolution of the atmosphere as well as driving the major crustal evolution mechanism of plate tectonics (e.g. Kearey et al., 2013; Schubert et al., 2004). Atmospheric processes, including climate, have a strong influence on surface processes, such as rates of erosion and composition of sedimentary deposits, modifying the topography and redistributing very significant volumes of sedimentary material. These may be sufficient to exert dynamic loading or unloading of the lithosphere which may in-turn drive displacement of the underlying asthenosphere and influence rates of plate and mantle processes (e.g. Burov and Toussaint, 2007; Koons et al., 2013; Raymo and Ruddiman, 1992). At the same time, tectonically-induced topographic contrasts are a necessity for driving erosion and sedimentation processes and have been proposed to have a strong control on climate (Gray and Pysklywec, 2012; Raymo and Ruddiman, 1992). Consequently, there is a positive feedback loop whereby tectonics have a clear control over surface processes and surface processes are a forcing factor of tectonics (e.g. Burov and Toussaint, 2007; Kiraly et al., 2015).

As well as feedbacks within the earth system, there are external processes that have a strong influence, in particular those associated with the Earth's orbit, and its patterns of distance and angle to the sun. This so called ‘orbital forcing’ causes changes in the global mean temperature and has a dramatic impact on the Earth system (Hays et al., 1976; Huybers, 2011; Huybers and Wunsch, 2005; Lisiecki and Raymo, 2007).

The pattern of interaction is further complicated by highly variable rates of process. For instance, over the past 65 Myr the Earth's climate has undergone a significant and complex evolution. This includes gradual trends of warming and cooling driven by tectonic processes on time scales of 10^5 to 10^7 years, rhythmic or periodic cycles driven by orbital processes with 10^4- to 10^6-years, and rare rapid climatic aberrations (for example, catastrophic methane release) with durations of 10^3 to 10^5 years (Zachos et al., 2001).

2.1. Plate tectonic processes and the impact of seismicity and volcanism

The response of the Earth's lithosphere to convection in the underlying asthenosphere is described by plate tectonic theory (e.g. Wilson, 1966) wherein strong lithospheric ‘plates’ establish relative motions with respect to each other, riding on a weaker asthenosphere. Many of the geological and topographic features evident at the Earth's surface stem from the resulting interactions and high stresses at plate boundaries.

An understanding of the UK's position with respect to plate boundaries is clearly fundamental to identifying those processes that may impact on the long-term safety of a GDF. Also, understanding the rates of tectonic processes will provide limits to the potential impact on a GDF site in the time frame considered. A comprehensive seismic hazard assessment, such as that done by SKB for the Forsmark site in Sweden (SKB, 2011), is a detailed, site specific, assessment that would have to be carried out for any site in the UK that is considered for the construction of a GDF in future.

A variety of interactions at active plate boundaries generate distinct geological processes, structures and landforms. These include zones of subduction of dense oceanic lithosphere or collision of continental lithosphere, both these types of plate boundaries are marked by linear belts of deformation (major fault zones, crustal thickening or thinning) and are typically the focus of more frequent, higher magnitude earthquakes and development of volcanoes and igneous intrusions. At present, the UK sits in a stable continental setting on the passive continental margin of the Atlantic Ocean and is not close to a margin where active tectonic processes are happening (Fig. 1). However, in the future, the Atlantic Ocean will start to contract, subduction will expand along the passive continental margins and the UK will eventually become closer to an active plate margin. The timing of the onset of this process and the rate at which it progresses is clearly the important factor in determining the impact of tectonic process on a UK GDF. Because ocean closures occur over 10's Myr timescales, and only limited or nascent subduction is currently occurring in the Atlantic (Duarte et al., 2013), the 1 Myr period of interest to UK GDF safety is probably a highly conservative estimate of when tectonic change is likely to affect the UK, however at the time of writing this is not backed up by quantitative forward modelling of Atlantic Ocean closure.

The effects of plate tectonics, in particular earthquakes, igneous intrusion and volcanoes, present a number of potential hazards for radioactive waste disposal and for the long-term safety performance of a GDF. Fault displacement (rupture) hazard caused by reactivation and movement along pre-existing fractures in response to plate stresses has the potential to affect a GDF. Earthquakes (seismicity), the result of instantaneous fault movements, may give rise to vibratory hazard where possible strong shaking may, depending on the GDF concept and design, cause damage to a GDF.

Hazards associated with a nearby volcanic eruption or igneous intrusion include melting or heating of a GDF and secondary disruption of groundwater patterns in response to alteration of fracture networks. The presence of a heat source would drive hydrothermal circulation. This process would modify the mechanical and chemical properties of the host rock and surrounding rocks, heat the groundwater and modify its hydrochemistry, potentially increasing the rate of corrosion of the engineered part of a GDF and impacting on its containment function.

The last volcanic episode to affect the UK ended at around 55 Ma and was related to the opening of the Atlantic Ocean. This episode was responsible for forming the basalt lava flows of Antrim and the volcanic centres of the Hebrides (Preston, 2009). The onset of volcanic activity in the future is expected to occur as the Atlantic contracts and subduction systems expand.

In the UK, the geological record preserves evidence for complex tectonic history. Overprinting of multiple plate tectonic cycles, where the UK has been formerly located at active plate margins and in continental collision zones, has left a legacy of heterogeneous crust including permeation by faults and fractures and preservation of regions of complex strain that will have an impact of the design of a GDF.

Although currently located in a stable intracontinental setting, the UK is still affected by weak tectonic stresses that can be attributed to the far-field present day relative movements of tectonic plates. Other factors that locally modify the stress field include uplift and subsidence in response to mantle plumes and mantle underplating, glacial isostatic adjustment and denudational isostasy and are considered later in this section (e.g. Arrowsmith et al., 2005; Bott and Bott, 2004; Main et al., 1999). Evidence for the current tectonic stress regime is provided from focal mechanisms derived from instrumental measurements of earthquakes and fault-plane solutions. Other stress tensor estimates, based on well-bore breakouts, drilling-induced fractures and in-situ stress measurements, can be influenced by additional near surface processes. Evidence from earthquake focal mechanisms shows that the modern UK lies with a broadly northwest-southeast compressive stress regime (σ_1) with southwest-northeast minimum stress (σ_3) (Baptie, 2010). This stress field is attributed to plate forces exerted by both separation of Europe from North America as well as the roughly northerly movement of Africa relative to Eurasia (Brereton and Müller, 1991).

Although recent sedimentary basins are not preserved onshore in the UK, post-Miocene strata (younger than c. 10 million years) preserved in the North Sea do not record a history of basin inversion,

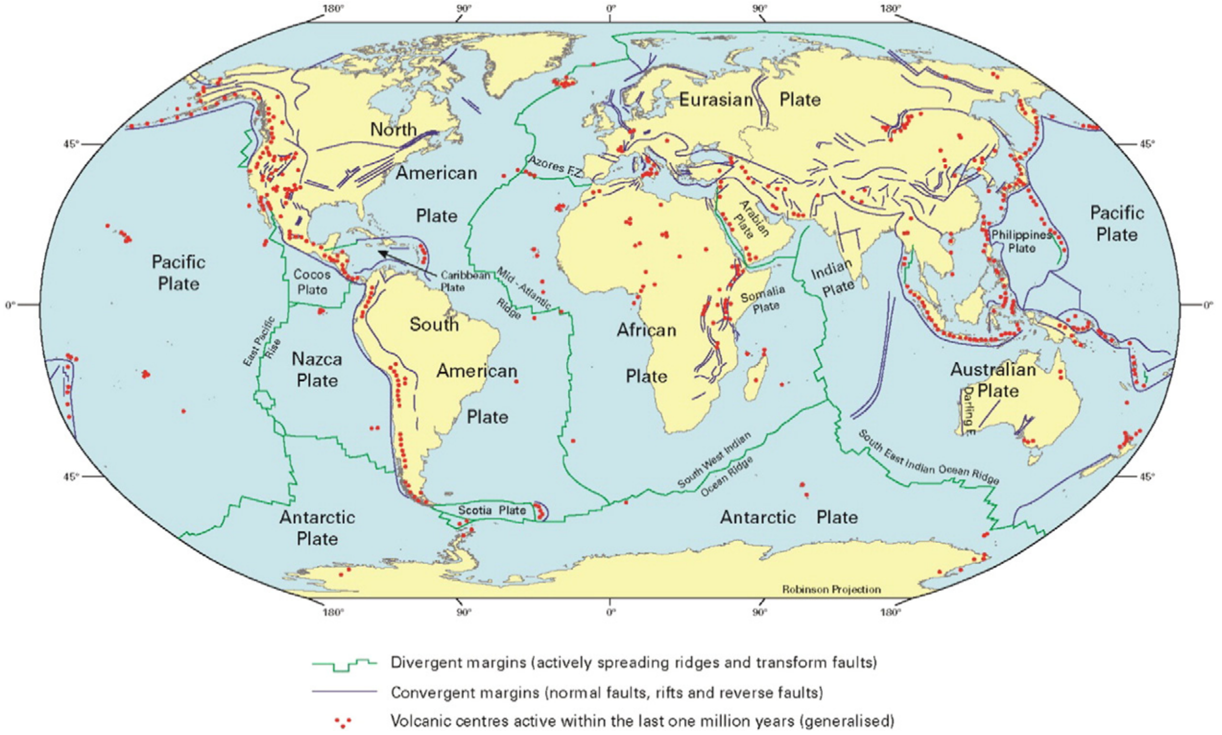

Fig. 1. Map showing global plate boundary, volcanic activity and earthquake activity (modified after Lowman, 1997).

indicating that shortening strain associated with the current stress field is relatively low. However, earthquakes are still felt in the UK as the result of distributed strain deeper in the crust (Fig. 2).

The seismic hazards related to a GDF are largely controlled by the alignment of existing fault planes within the current stress field and their propensity to reactivate. Current good practice in assessing seismic hazard in stable continental regions utilises a probabilistic approach in which the likelihood of exceeding peak ground acceleration recorded over a specified earthquake return period is calculated. This approach considers the spatial distribution of earthquakes in a given region, the magnitude and recurrence relationship for those earthquakes and the likely ground motions as a function of distance from the seismic source. The first probabilistic seismic hazard map for the UK was produced by Musson and Winter (1997). The UK was also included in the Global Seismic Hazard Assessment Program (GSHAP, Grünthal et al., 1996) and the Seismotectonics and Seismic Hazard Assessment of the Mediterranean Basin (SESAME) (Jiménez et al., 2001). Musson and Sargeant (2007) published seismic hazard maps for the UK for seismic zoning in relation to Eurocode 8 (Fig. 3). These studies, however, considered ground acceleration at surface, not at GDF depths.

Assuming present day seismicity rates, average hazard values of peak ground acceleration for a return period of 10,000 years are in the range 0.1–0.15 g (Musson and Winter, 1997), implying that seismic hazard in the UK is low.

The maximum magnitude earthquake that is likely to occur has a strong influence on both vibratory hazard and is proportional to the amount of fault displacement, and therefore likelihood of a rupture intersecting GDF structures, and as such has important implications for GDF design. However, estimating the largest earthquake that can be expected in the British Isles in the current tectonic regime is difficult because of the low seismicity rates and the limited history of observation. Predictions from a range of studies provide maximum values ranging between 5.5 Mw and 6.5 Mw (Ambraseys and Jackson, 1985; Main et al., 1999; Musson and Sargeant, 2007) and there are only a few global records of intraplate earthquakes with magnitudes in excess of 7 Mw (e.g. Hough et al., 2000).

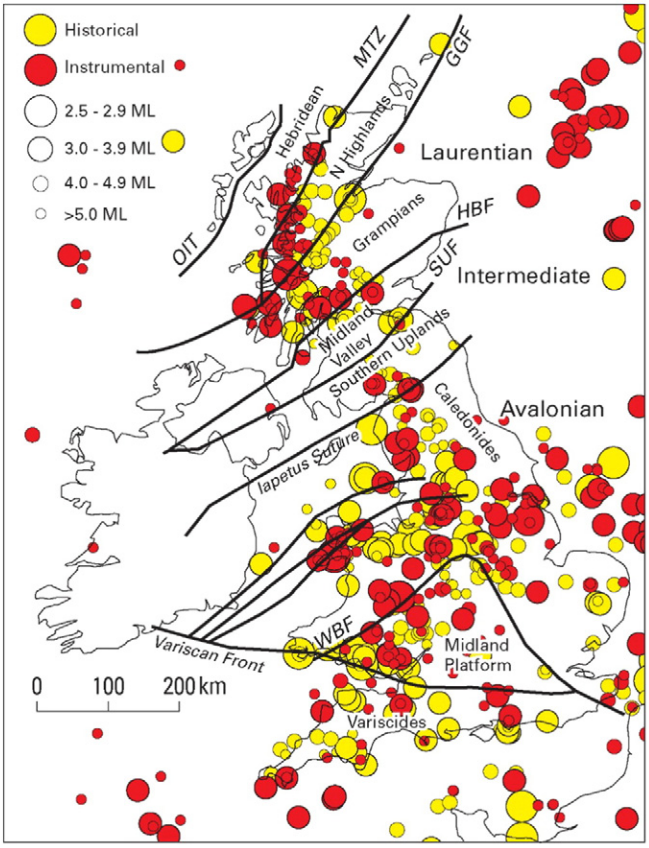

Fig. 2. Instrumental (red) and historical (yellow) seismicity of the British Isles from the British Geological Survey earthquake catalogue (Musson, 1996). Earthquake symbols are scaled by magnitude.

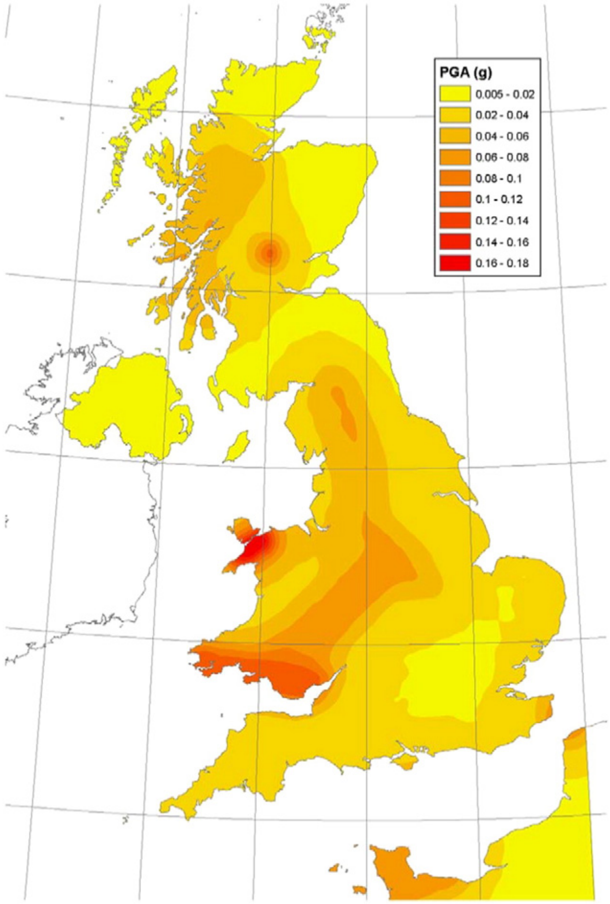

Fig. 3. Hazard map showing peak ground accelerations (g) with a 10% probability of being exceeded for a 2500 year return period (Musson and Sargeant, 2007).

The rupture hazard for a GDF developed at between 200 and 1000 m depth in a low seismicity intraplate region such as the British Isles is very low (Musson and Sargeant, 2007). Published data for larger UK earthquakes suggest that most events with magnitudes of 4.5 Mw or greater tend to nucleate at depths of at least 10 km (Musson and Sargeant, 2007). Fault rupture plane dimensions for the largest recorded earthquakes in the UK are typically of a few kilometres, so that, although a rupture that nucleates at depths of at 10 km may propagate upward, the potential for it to reach the surface is limited. No UK earthquake recorded either historically or instrumentally is known to have produced a surface rupture although a detailed study of potential surface rupture is likely to be undertaken at any proposed GDF site (Musson, 1996).

Several studies documenting earthquake damage to underground structures such as tunnels (e.g. Hashash et al., 2001; Pitilakis and Tsinidis, 2014) conclude that they suffer appreciably less damage than surface structures. This evidence suggests that the shaking hazard for a buried GDF is likely to be less severe than for a structure at surface. For the Yucca Mountain site in Nevada, USA, located within a more seismically active area, it is considered that direct damage from earthquake shaking to the engineered facility and the packages of waste emplaced within it is an insignificant probability (Smistad et al., 2001).

Earthquakes are also known to alter hydrogeological systems. Effects such as changes to water table levels in response to moderate to large earthquakes are largely transient and unlikely to impact on the long-term safety of a GDF (e.g. Brodsky et al., 2003; Manga and Wang, 2007). Similarly, expulsion of small volumes of deeper formation water, attributed to fracture dilation and contraction, is thought to have little overall impact on the safety function of a GDF (Rojstaczer et al., 1995). In contrast, permanent changes to fracture networks could present a hazard to the safety function of a GDF. Emerging good practice in Europe favours GDF development in a low groundwater transmissivity geological environment, effectively providing a high level of attenuation for emitted radionuclides between a GDF and the overlying biosphere. Propagation of new, permanent fracture systems is response to earthquakes has the potential to create high transmissivity pathways with that could reduce radionuclide attenuation (Ingebritsen and Sanford, 1999).

The generation of tsunami when fault movements rupture the seafloor would have negligible impact on the post-closure safety of a GDF once sealed and protected from water ingress and are not considered further in this paper.

2.2. Uplift, subsidence and erosion

All points in the lithosphere are subjected to processes that cause vertical movement and which result in either uplift or subsidence at surface. These vertical movements of Earth's surface can vary considerably in scale, distribution and rate. Although they are often controlled by plate tectonics, subsidence and uplift are also linked to other non-exclusive processes affecting the Earth's surface, such as mantle plumes and mantle underplating, glacial isostatic adjustment and denudational isostasy. Critical to the North Atlantic region, erosion can also be driven by glacial loading, and depending on ice mass, can over-deepen sub-glacial valleys and depressions to depths significantly below sea level (Evans, 2014). Uplift and accompanying erosion and subsidence are important considerations for GDF design. Subsidence and sedimentary burial would result in increased isolation of the waste in a GDF, enhancing its capacity to isolate the waste from the biosphere for the long-term. Conversely, uplift and erosion, including sub-glacial erosion, have the potential to degrade GDF isolation barriers, that could ultimately result in exposure of the waste as well as substantially alter the direction of flow in any over- and underlying aquifers and new pathways formed that could potentially transport radionuclides rapidly to the surface (e.g. McKinley and Chapman, 2009).

Plate tectonic uplift and subsidence are caused by plate-scale forces of compression and extension. At its most extreme, uplift associated with collision of continental lithospheric plates gives rise to the development of mountain belts, such as the Himalayas, and broader regions of landscape uplift such as the adjacent Tibetan Plateau. Stretching continental lithospheric plates at its most extreme leads to thinning of the crust and subsidence, rifting and, ultimately, the creation of new ocean basins.

Denudational isostasy encompasses both erosion of uplifted surfaces as well as subsidence driven by complementary sedimentary loading. Erosion is driven largely by gravity and the rates are dependent on the mechanical and chemical properties of the rocks, climate, altitude and uplift rate. High uplift rates generally correlate with high erosion rates. Equally, subsidence is generally accompanied or driven by loading of sediments onto the sinking surface, supplied by material eroded from the adjacent, relatively uplifted basin flanks (McKinley and Chapman, 2009). Both the processes of deposition and erosion can drive crustal flexure and are often driven themselves by other uplift/subsidence mechanisms (e.g. Watts, 2001). In extreme cases, such as in parts of the Himalayas, some authors have argued that coincidence of high rainfall, erosion and uplift rates exerts a control over the location of tectonic deformation (Whipple, 2014). A compilation of denudation rates of bedrocks from four climate regions around the world (Table 1) including Mediterranean type climate (warm temperate), temperate (current UK type climate), sub-arctic (boreal, periglacial, forest tundra) and polar (periglacial, permafrost and glacial) shows shat the greatest denudation rates occur in orogenic environments such as the European Alps (Vernon et al., 2008) or the San Bernadino Mountains where bedrock lowering rates of 200 to 700 m Myr^{-1} and 70 to 1200 m Myr^{-1} have been estimated respectively (Binnie et al., 2008). Typically, bedrock erosion rates in non-orogenic settings, such as the UK, are much less than 50 m Myr^{-1} (Table 1).

In higher latitude regions, much of the relatively recent uplift and subsidence has been attributed to glacial isostasy. This describes the relatively short-term uplift and subsidence which are typical lithospheric responses to loading and unloading during glacial advance and retreat. The effects of which are increasingly recognised as providing significant uplift (in some regions of the North Atlantic margin and adjacent continental hinterland (Ekman, 1991). For example, the maximum amount of glacial rebound that has occurred because of the decay of the Fennoscandian ice sheet is approximately 800 m (Mörner, 1979).

Over the last 23 Ma, the UK has seen considerable uplift, in particular an estimated 1 km of exhumation during Neogene times (Blundell, 2002; Hillis et al., 2008; Holford et al., 2008). This has been attributed to a variety of non-exclusive processes including uplift above mantle plumes or underplating by mafic magmas associated with Atlantic extension (Al-Kindi et al., 2003; Bott and Bott, 2004; Brodie and White, 1994; Cope, 2004; Tiley et al., 2004;), late Alpine collisional effects and 'ridge-push' from the Atlantic which was spreading at this time, as well as deglaciation (Cloetingh et al., 2005).

There is an emerging consensus amongst the scientific community that the present day pattern of uplift in the north of the UK and complementary subsidence in the south is driven largely by glacio-isostasy (e.g. Cloetingh et al., 2005; Davenport et al., 1989; Firth and Stewart, 2000; Lambeck, 1995; Musson, 1996; Peltier et al., 2002). Although other processes including lithospheric stretching beneath the North Sea (Barton and Wood, 1984) and continuation of an Atlantic thermal anomaly (e.g. Arrowsmith et al., 2005; Bott and Bott, 2004) have also been proposed, some recent earthquake studies have corroborated glacio-isostatic uplift by observing that contemporary seismicity in the Scottish Highlands is concentrated in the area of expected maximum glacio-isostatic uplift (e.g. Davenport et al., 1989; De Luca et al., 1998).

Drivers for uplift during the future 1 Myr period in consideration for GDF safety function include changes in tectonic stress regime. Although major changes in the tectonic regime are likely to lie beyond the period of interest, given the current tectonic configuration in the North Atlantic it is possible to speculate that transient Atlantic ridge push or an increased rate of Africa-Eurasia convergence could propagate an increase in horizontal compressive stress in the UK and in turn lead to increased uplift. Because of a paucity of forward tectonic modelling available for the North Atlantic region it is not possible to provide estimates of timing and rates of these processes and their potential impact. However, in contrast, future climate models predict that cycles of glacial advance and retreat are likely to affect the UK within the next 1 Myr which are likely to drive glacial isostatic adjustment and climate-linked denudational isostacy depending on the location and extent of the resulting ice sheets.

2.3. Climate evolution and potential impacts

Even with consideration of anthropogenically-forced climate change, longer-term projections of climate forecast that the Northern Hemisphere will experience further cycling between glacial and interglacial periods over the next 100,000 to one million years (see reviews by Huybrechts, 2010; Fischer et al., 2014; Näslund and Brandefelt, 2014), Therefore, a GDF in the UK is likely to experience glaciation and or permafrost conditions several times over its life time and hence, predictions of the duration, thickness and extent of future ice cover are important for assessing the post-closure safety of a UK GDF. This includes the impact of permafrost and frozen ground, glacial isostasy and associated seismic and erosional hazards and eustatic changes in sea-level.

Most climate models use understanding of climate variation in recent geological time, including the extent, duration and interval of

Table 1
Bedrock denudation rates.

Location	Climate	Setting/geology	Authors	Method	Rate m Myr^{-1}
Dry Valleys, Antarctica	Polar	Crystalline	Summerfield et al. (1999)	^{21}Ne	0.26–1.02
Antarctica	Polar	Sandstone (hyper-arid)	Nishiizumi et al. (1991)	^{10}Be and ^{26}Al	0.1–1.0
S. Norway	Sub-arctic	Elev. Plain gneiss schist	Nicholson (2008)	Quartz veins, weathering rinds	0.5–2.2
Eyre Peninsula, Australia	Mediterranean	Granite (semi-arid)	Bierman and Turner (1995)		0.5–1.0
Pajarito Plateau (NM)	Temperate	Tuff (temperate)	Albrecht et al. (1993)	^{10}Be and ^{26}Al	1–10
N. Sweden	Sub-arctic	Plain Crystalline	Stroeven et al. (2002)	^{10}Be and ^{26}Al	1.6
Canada	Polar	Plain crystalline	Peulvast et al. (2009)	Palaeo-surface reconstruction	2–8
Masanutten Ttn, USA	Temperate	Sandstone, Shale	Afifi and Bricker (1983)	Mass Balance	2–10
S. Piedmont, USA	Temperate	Piedmont, granite	Pavich (1986)	Mass Balance	4
Brubaker Mts, USA	Sub-arctic	Low relief Schist, gneiss	Price et al. (2008)	Mass Balance	4.5–6.5
Rheinsh Massif, Germany	Temperate	Sedimentary	Meyer and Stets (1998)	^{10}Be	4.7–6.5
Iceland	Sub-arctic	Basalt	Geirsdóttir et al. (2007)	Sediment record	5
Namib desert, S. Africa	Mediterranean	Granite Inselbergs	Cockburn et al. (1999)	^{10}Be and ^{26}Al	5–16
Haleakala and Mauna Loa (HW)	Temperate	Basalt (various 0-3 km elevation)	Kurz (1986)		7–11
Mt Evans (CO)	Sub-Arctic	Granite erosion of bare surface	Nishiizumi et al. (1993)	^{10}Be and ^{26}Al	8
S. Piedmont, USA	Temperate	Piedmont granite	Pavich (1989)	^{10}Be and residence time	20
Pacific NW, USA	Temperate	Orogenic	Dethier, 1986	Mass Balance	33
Smokey Mts, USA	Temperate	Schist, gneiss	Velbel, 1986	Mass Balance	38
Boso Peninsula Japan[a]	Humid-temperate	Sst/mudst. High rates of glacio/eustatic change	Matsushi et al. (2006)	^{10}Be, ^{26}Al	90–720
European Alps[a]	Sub-arctic	Orogenic	Vernon et al. (2008)	AFT	200–700
India[a]	Mediterranean	Escarpment	Gunnell (1998)	Functional Relationship model	205–275
San Bernadino Mts, California, USA	Temperate	Orogenic, qtz-monzonite and granodiorite, sst, granite	Binnie et al. (2008)	^{10}Be, Apatite (U-Th/He) thermochronometry	70–1200

[a] Note that these are areas of active mountain building which consequently have much higher denudation rates than occur in mid-crustal locations such as the UK.

glacial periods, to make projections of future climate change. Evidence from the recent geological record indicates a progressive deterioration of global climate from greenhouse conditions in the early Cenozoic Era (c.55 Ma; e.g. Zachos et al., 2001). Indeed, since around 2.6 Ma, the geological record reveals evidence for multiple oscillations between short-term glacial and interglacial episodes, as well as the longer period 'Milankovitch' cycles influenced by shape of the Earth's orbit around the sun (Fig. 4, e.g. Grossman, 2012; Lisiecki and Raymo, 2007; Pillans and Gibbard, 2012; Shackleton, 1987). The Early Middle Pleistocene Transition (Berger and Jansen, 1994; Head et al., 2008) marks a prolonging and intensification of glacial-interglacial climate cycles from an average of 41,000 to 100,000 years (Zachos et al., 2001; Maslin and Brierley, 2015). This shift represented an increase in the amplitude of global ice volume variations (Elderfield et al., 2012; Rohling et al., 2014) with ice sheets surviving longer and becoming increasing vulnerable to catastrophic collapse and resultant rapid deglaciation (Maslin and Brierley, 2015; Ruddiman, 2003).

Mid-latitude regions, including the UK, have proven particularly sensitive to these global-scale climatic changes with marked variations in prevailing climate over comparatively short periods of geological time (tens of thousands of years; e.g. Candy et al., 2011; Rose, 2009) as a result of their position relative to southward moving cold polar air masses (Polar Front), and low latitude warm ocean currents (North Atlantic Current). It is currently thought that Britain has experienced over 30 episodes of glaciation, of varying scale, during the Quaternary (Böse et al., 2012; Lee et al., 2011; Lee et al., 2012; Thierens et al., 2012) with clear evidence preserved for a Younger Dryas glaciation (12.5–11.7 ka, Loch Lomond Stadial), preceded by a Weichselian (Late Devensian) glaciation which have left a strong imprint across the UK landscape, preceded by the less well recorded Elsterian (Anglian) glaciation (480–430 ka) which extended into southern Britain (Fig. 5; Clark et al., 2012; Gibbard and Clark, 2011).

2.3.1. Future climate projections

Over the past few decades, understanding of past climate change forcing processes have been brought together using a range of climate models and ensembles of model simulations for a range of future greenhouse-gas and aerosol emissions (see reviews by Fischer et al., 2014; Huybrechts, 2010; Näslund and Brandefelt, 2014). Longer-term simulations, up to 100 ka, use simple climate models and earth system models of intermediate complexity (EMIC) (for example, Archer and Ganopolski, 2005; Cochelin et al., 2006; Crucifix and Rougier, 2009; Loutre and Berger, 2000; Pimenoff et al., 2011; Texier et al., 2003). These models are forced to take account of known variations in orbital parameters and a range of future anthropogenic CO_2 concentrations. In the absence of human perturbations, the current interglacial is projected to last for the next 50,000 kyr (Ganopolski et al., 2016), however, the addition of moderate anthropogenic CO_2 emissions of 1000 to 1500 GtC are projected to delay the onset of the next glacial period by 50,000 years (Archer and Ganopolski, 2005; Berger and Loutre, 2002; Ganopolski et al., 2016; Paillard, 2006) with the next glacial inception projected to first occur at 100 ka AP (see review by Fischer et al., 2014).

Beyond timescales of 100 ka, model uncertainty becomes increasing large and model outputs become increasingly less robust. Future levels of atmospheric CO_2 beyond 100 ka are particularly uncertain, however, it is anticipated that effects of anthropogenic CO_2 will have diminished with a return 100 ka glacial-interglacial cycles (Fischer et al., 2014). Irrespective of the timing of inception, the broad pattern of glacial-interglacial cycles is likely to continue (Fischer et al., 2014).

Of direct relevance to a national to regional scale the assessment of a GDF in the UK, the BIOCLIM model (BIOCLIM, 2001) used the EMIC LLN 2-D NH climate model to simulate global climate change over the next 1 Ma for three atmospheric CO_2 scenarios: no CO_2 contribution, a low and high anthropogenic CO_2 contribution (210 ppmv and 280 ppmv respectively), corresponding to pre-industrial atmospheric CO_2

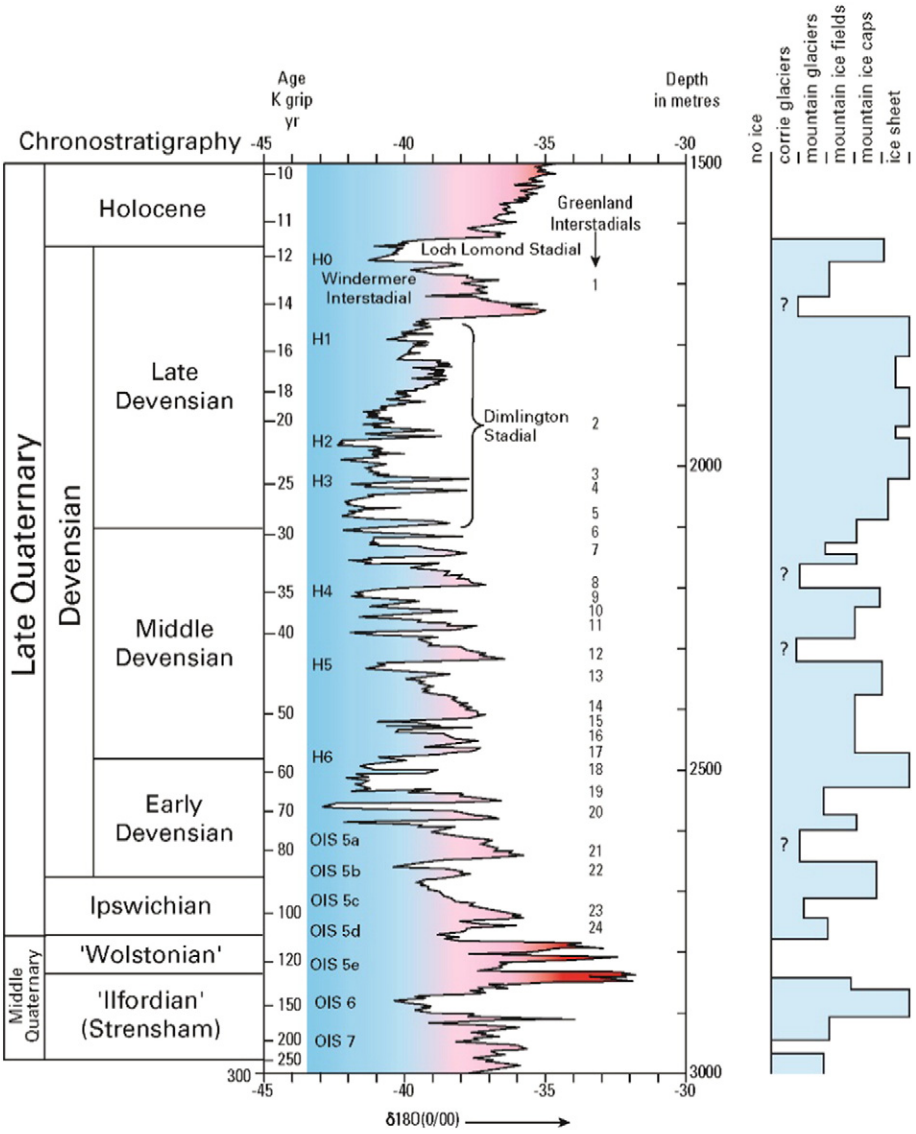

Fig. 4. British Quaternary chronostratigraphy (modified after Merritt et al., 2003) alongside the Greenland (GRIP Summit ice core) oxygen isotope record.

concentrations and 210 ppmv is typical of a glacial level (BIOCLIM, 2003, Fig. 6). These were downscaled to provide regional climate estimates for selected areas of Europe over the next 200 ka, one of which was central England.

In both low and high anthropogenic CO_2 contributions, the Northern Hemisphere is projected to remain free of ice for most of the next 200 ka. From 167 ka AP, significant Northern Hemisphere ice sheets start to accumulate and are predicted to recover to present day equivalents by about 170 ka AP. Beyond 200 ka AP, the modelled effects of anthropogenic CO_2 were predicted to decline to negligible levels and from 200 ka AP to 1 Ma AP 'normal' glacial-interglacial cycling would return at 100 ka periodicities and persist throughout that time interval (Texier et al., 2003) (Fig. 7).

2.3.2. The impact of glacial isostatic adjustment

The mass applied and removed during growth and decay of large ice sheets have a loading effect on the lithosphere, driving changes in relative surface elevation. In response to this loading, lithospheric flexure forms a 'bowl' of depression below and proximal to the ice sheet, accommodated by asthenospheric flow radially outward from below the maximum ice load (e.g. Stewart et al., 2000; Peltier, 1998; Adams, 1989). Beyond the ice margin, lithospheric flexure is accommodated by radial vertical extension within a forebulge region (e.g.; Fjeldskaar, 1994; Lambeck, 1995; Mörner, 1977; Stewart et al., 2000) which may extend for several hundreds of kilometres beyond the ice margin (Lund and Näslund, 2009).

This process, known as Glacial Isostatic Adjustment (GIA) has been extensively studied from previously glaciated Northern Hemisphere regions. Much of the evidence that has been cited has been attributed to the gradual uplift of depressed lithosphere, subsidence of forebulges, denudation and landscape evolution that accompanies ice sheet denudation and lithospheric unloading (e.g. Clark et al., 2012). This lithospheric recovery is one aspect of GIA and is termed post-glacial rebound (PGR) and is considered by many researchers as the principal cause of uplift in former glaciated regions (e.g. Johansson et al., 2002; Sella et al., 2007, Fig. 8).

The three main lines of evidence for PGR are provided by geomorphological evidence for uplift, principally raised palaeo-marine and lacustrine shorelines, GPS monitoring data as well as faulting activity related to the emplacement or removal of large qualities of ice glaciers, ice caps or continental ice sheets, referred to as Glacially Induced Faulting (GIF) (Lund and Näslund, 2009).

In the Northern Hemisphere, the evidence for both these is most clearly preserved in Fennoscandia and northern North America where

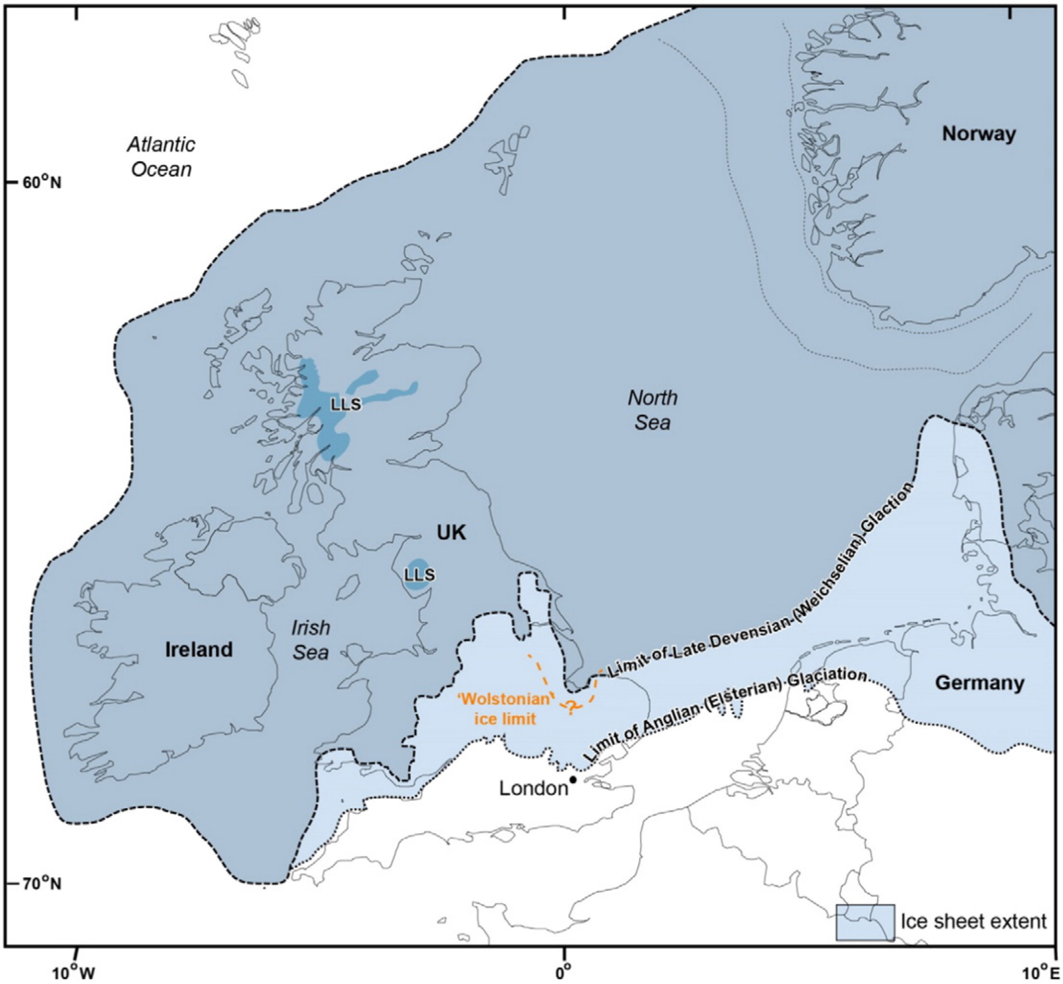

Fig. 5. Maximum extent of ice cover during the Elsterian (Anglian), Weichselian (Late Devensian) and Younger Dryas (Loch Lomond Stadial) glaciations of the British Isles and limit of Wolstonian glaciation in eastern England and the North Sea (Modified from Clark et al., 2004).

deglaciation has been most recent. In these regions, GIF is known from the occurrence of surface rupture of demonstrably post-glacial faults as well as a general co-location of these with areas of elevated seismicity (see review of Munier and Fenton, 2004).

Evidence for proposed PGR in the UK is largely based on height measurement of uplifted or subsided shorelines. Here, contrasting relative sea-level changes have been recorded at different locations with highest uplift of up to ca. 1.6 mm yr-1 (10 cm per century) centred around the area of central and northwest Scotland where it is estimated that the greatest thickness of ice was developed (Ballantyne et al., 1998; Shennan and Horton, 2002; Shennan et al., 2002). In contrast, relative land subsidence of up to 5 cm per century has been observed in the south and east of England (Shennan and Horton, 2002) (Fig. 9).

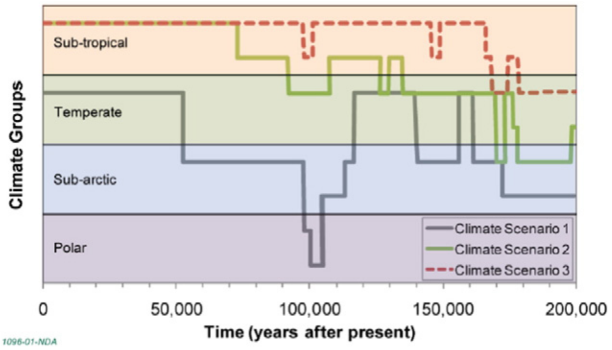

Fig. 6. Projected future climate states for central England under the different scenarios. Figure based on BIOCLIM (2003). Climate scenario 1: No anthropogenic CO_2 contribution. Climate Scenario 2: Low anthropogenic CO_2 contribution. Climate scenario 3: High anthropogenic CO_2 contribution.

In the UK, evidence for GIF is based largely on recognition of a cluster of earthquakes located in northwestern Scotland that are coincident with the region of maximum expected uplift and thickest ice (Musson, 1996). The stress tensor interpreted from this group of earthquakes contrasts with the regional tectonic stress in that the interpreted principal compressive stress ($\sigma1$) is vertical and is close in value to the intermediate stress ($\sigma2$) with a near East-West extensional component ($\sigma3$) (Fig. 10). This stress field has been interpreted to reflect a modification of the normal regional tensor by the action of GIA (Baptie, 2010).

A number of studies (see Pascal et al., 2010) have suggested that earthquake activity levels are highest directly after the ice has retreated. Consequently, seismicity based on current rates may provide an inaccurate estimate of the possible levels of recurrence and magnitude that could occur during future glacial cycles. It should be noted that the largest stresses occur at the former ice margins, making these the most likely source region for seismicity (Lund, 2005). The implication for a GDF in such a region is that seismicity rates following any future glacial period may be significantly higher than at present. Given our current maximum magnitude earthquake in the UK of around 6 it is not unreasonable to expect an increase in the maximum possible magnitude to 7 following such an event. However, it should be noted that post-glacial fault stability is dependent on not only the thickness and extent of the ice sheet, but also on the initial

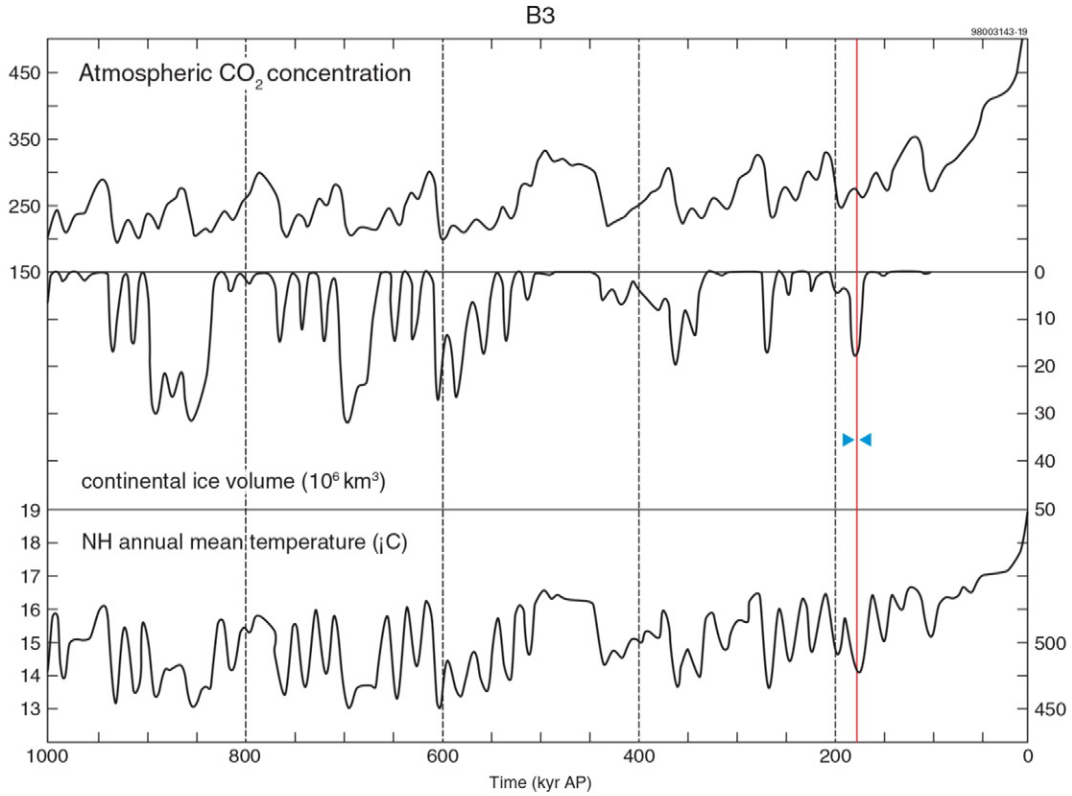

Fig. 7. Northern Hemisphere future model to 1 Ma AP with low CO_2 forcing (210 ppmv). The red line shows the first major glaciation at c. 170–180 ka AP (modified after BIOCLIM, 2001).

state of stress and the properties of the Earth itself, such as stiffness, viscosity and density (Lund, 2005).

2.3.3. The impact of sea-level change

Sea-level changes have occurred throughout the Earth's history and their magnitude and timing are extremely variable (e.g. Lambeck and Chappell, 2001). Global mean sea-level rise has increased ten-fold from a few centimetres per century over recent millennia to a few tens of centimetres per century in recent decades, attributed to climate change through the melting of land ice and the thermal expansion of ocean water (Milne et al., 2009). (This may be up to in total c 10 m for coastal sites in the Baltic, see e.g. analysis in SKB (2014).

Because the present warming trend is expected to continue, global mean sea level will continue to rise. In the time frame relevant to GDF safety case, forward climate modelling predicts that the most likely driver of sea level change will be thermosteric sea level rise during an initial period of global warming as well as the effects of melting ice sheets and glaciers (Milne et al., 2009).Typically, the global expansion of ice volume leads to a global marine regression as more of the Earth's water budget becomes locked up in comparatively buoyant ice, referred to as glacioeustatic regression. This is balanced against localised lowering of the land surface driven by GIA which is predicted to give rise to complex patterns of regional sea level variation, with local sea-level stands substantially above and below that observed at the present day (Lambeck and Chappell, 2001). In the UK Quaternary record, there is evidence for sea-levels that were locally 30 m higher than present following the Elsterian deglaciation (Shennan et al., 2006). Conversely, evidence for considerably lower sea levels during the Weichselian

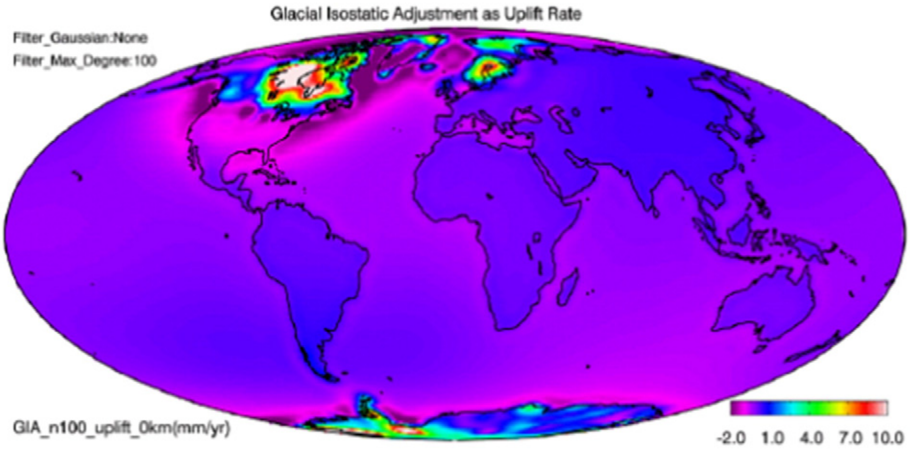

Fig. 8. Modelled rate of lithospheric uplift resulting from post-glacial rebound (Wahr and Zhong, 2013). Image from http://grace.jpl.nasa.gov

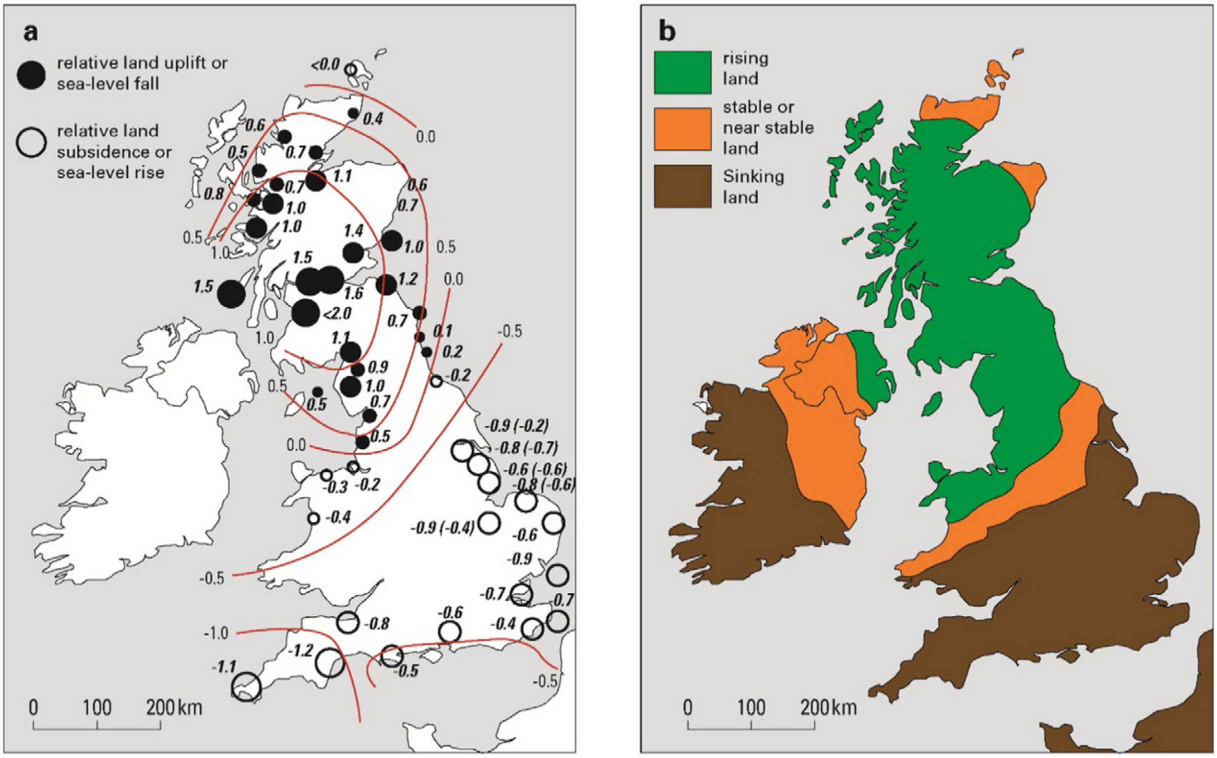

Fig. 9. Estimates of PGR and present day crustal deformation in Great Britain. (a) Late Holocene relative land-sea-level changes (mm yr^{-1}) in Great Britain. Figures in parentheses are the trends that take into account modelled changes in tidal range during the Holocene (after and based upon Shennan and Horton, 2002). (b) land which is rising as a result of post-glacial rebound, stable or near stable land conditions and land which is sinking.

glaciation is provided by imaging of terrestrial glacial landforms offshore from the present day coastline in the North Sea (e.g. Bradwell et al., 2008; Sutherland, 1993).

Future sea-level changes to 150 ka AP have been modelled by linear regression of past sea-levels and BIOCLIM simulated ice volume under a range of anthropogenic CO_2 contributions (Fig. 11, Goodess et al., 2004). For all of the CO_2 forcing scenarios, sea-level is envisaged to rise for about the next 50 ka, after which it drops sharply coinciding with the beginning of the modelled growth of Northern Hemisphere ice sheets with falls of global sea-level of between around 80–120 m at a glacial maximum between 110 and 125 ka AP. This is followed by a rapid sea-level rise associated with widespread deglaciation. For the highest modelled anthropogenic CO_2 levels, the rapid fall in sea-level is ameliorated and only begins shortly before the glacial maximum.

In regions where glaciation is likely to occur, such as northern and central parts of the UK, changes of relative sea-level could mean that a GDF site is further from or nearer to the coast, or even beneath the sea bed. This may lead to erosion or deposition around the surface or very shallow parts of a GDF and is likely to change the groundwater flow paths and reduce groundwater driving heads.

2.3.4. The impact of permafrost

Glacial advances affecting the UK over the next 1 Ma are likely to result in many areas experiencing permafrost conditions, that is ground that is 'permanently frozen, or that remains below freezing temperature for two or more consecutive years (Williams, 1970). The primary factors governing its development and depth are surface temperature, the thermal capacity of the geological strata and the local geothermal gradient (French, 2007; Williams and Smith, 1989).

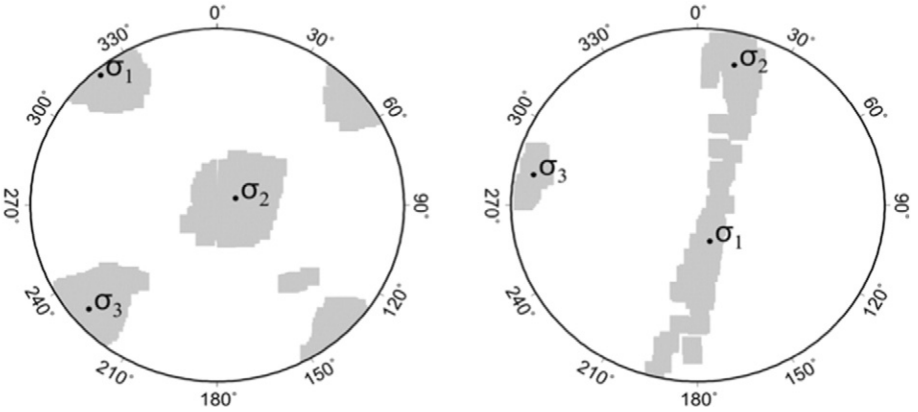

Fig. 10. Best-fitting stress tensors for two different subsets of the data, suggesting that there is a significant difference in the stress state in in England and Wales (left) and in northwest Scotland (right). The 95% confidence intervals are indicated by the shaded areas. From Baptie (2010).

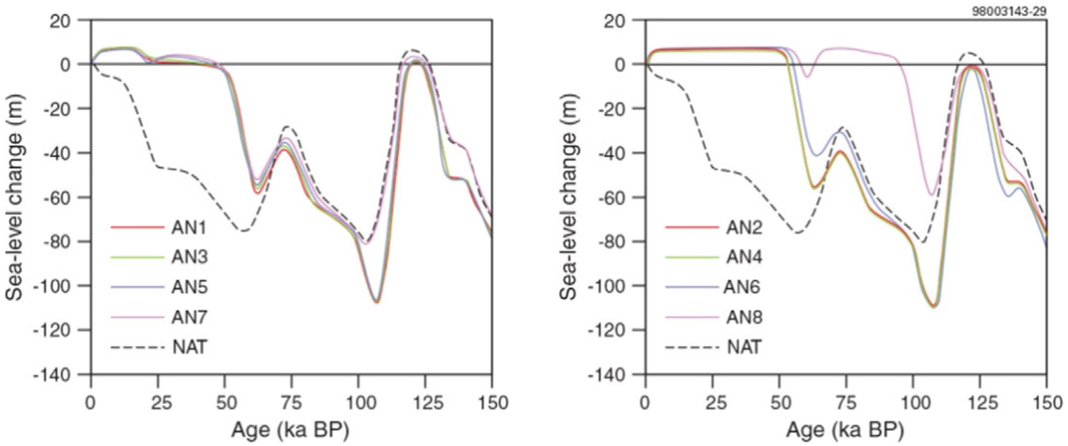

Fig. 11. Future eustatic sea-level change (m) for low (left) (AN1, 3, 5, 7) CO_2 forcing scenarios and the natural (NAT) simulation high (right) CO_2 forcing (AN 2, 4, 6, 8) (Goodess et al., 2004). "High" and "low" scenarios used were those of Sundquist (1990). The different scenarios assumed that the anthropogenic effects tailed off at 30 (AN1 & 2), 50 (AN3 & 4), 100 (AN5 & 6) and 150 ka AP (AN7 & 8). NAT assumes no anthropogenic effect.

Permafrost forms predominantly in periglacial and ice-marginal environments under sub-arctic to polar tundra climates (Rudlof, 1981). A wedge of permafrost is expected to exist beneath the margin of an advancing ice sheet but melts as it is overridden and effectively insulated by the overlying ice (Zhang et al., 1999). In addition, the presence of an overlying ice sheet can serve to increase the subglacial groundwater pressure by around two orders of magnitude, so that the freezing point can decrease to such a degree that the subglacial ground is kept unfrozen (Busby et al., 2016). At present, about 25% of the Earth's land area is underlain by permafrost (Anisimov et al., 1996).

At its most extreme, permafrost in northern Canada, reaches to depths of 500–700 m (Ruskeeniemi et al., 2004) while in northern Sweden, discontinuous permafrost, is reported to be 100–350 m thick at an altitude of 1500 m above sea level (Isaksen et al., 2001). Modelling of potential permafrost depths at Prudhoe Bay, Alaska, has shown that it could extend to 600 m deep within 50 ka at surface temperatures only slightly lower than today (Lunardini, 1995). In northern Europe modelling estimates of permafrost depths for proposed GDF sites range from 400 m at Forsmark in Sweden (SKB, 2014) to 215 m in northern Belgium (Govaerts et al., 2011). Recent modelling of permafrost thickness by Busby et al. (2015, 2016) across Great Britain range from 20 to 180 m for the average estimate climate and 180–305 m for the cold estimate climate (Table 2). The depth of permafrost is highly site specific and will be dependent on a number of factors including location, presence and thickness of ice/snow cover, groundwater chemistry, hydrogeology and geothermal gradient. The impact of permafrost in crystalline terrains, for example the safety assessment of the SR-Site in Sweden summarised in SKB (2014), has been studied in detail but this is not yet the case for the UK.

If permafrost were to extend to the depth of a GDF, it could reduce the performance of the engineered components (McEwen and de Marsily, 1991). However, Posiva (e.g. Schatz and Martikainen, 2010) and SKB (e.g. Birgersson and Karnland, 2015) have shown that clay based backfill/buffer regains its properties after thawing. Similarly, even at greater depths than permafrost penetration, there would be possible impact on the performance of the geological barrier of a GDF. These could be because of brine formation and migration, intrusion of freshwater from melting permafrost or gas hydrate formed beneath the permafrost layer (Rochelle and Long, 2009), and cryogenic-pore pressure changes associated with volume change during the water-ice phase transition.

At shallower depths, permafrost development could also directly affect the hydrogeological properties of rocks, often significantly affecting groundwater flow and recharge and discharge (see for example the SKB studies for Forsmark (SKB, 2014). Frozen ground will create barriers to groundwater flow, but once thawed permeability may be increased leading to temporary or permanent changes to groundwater flow paths. However, in glaciated regions near ice margins, hydrogeologically processes are more complex and transient than those beneath or further away from the ice margins (Scheidegger and Bense, 2014).

2.3.5. The impact of glacial erosion

Erosion and deposition by glaciers can have a dramatic effect on landscapes, with high rates of erosion reshaping upland areas, overdeepening and oversteepening pre-existing valleys and modifying pre-existing

Table 2

Maximum modelled depths of permafrost at the ten locations resulting from average (a minimum mean annual air temperatures −12 °C relative to present day) and cold (a minimum mean annual air temperatures of −18 °C relative to present day) estimate climates (Busby et al., 2015).

Location	Geology	Max depth of permafrost (m) (average)	Max depth of permafrost (m) (cold)
Dartmoor	Permian granite pluton	80	220
Weald	Mesozoic argillaceous, arenaceous and limestone rocks	65	245
East Anglia	Chalk and Mesozoic argillaceous rocks overlying Lower Palaeozoic basement	65	245
South Midlands	Argillaceous Jurassic and Triassic rocks overlying Lower Palaeozoic basement	30	180
Mid-Wales	Silurian mudstone, sandstone, siltstone and conglomerate	105	215
South Yorkshire	Carboniferous Coal Measures overlying Millstone Grit	90	180
Stainmore Trough	Carboniferous sedimentary rocks of mixed lithologies	20	205
Southern Uplands	Silurian greywacke	150	305
Midland Valley	Carboniferous Coal Measures and Clackmannan Group limestone, sandstone and mudstone	110	215
Northwest Highlands	Precambrian psammite	180	235

drainage patterns and depositing large quantities of sediment underneath glaciers and in large spreads beyond their limits (Boulton, 1982; Boulton, 1996). During periods of climate change, alterations in the landscape may be both fast and unpredictable, especially in the very active hydrological regime that occurs at the margin of a retreating ice sheet where complex sequences of river terraces may be formed.

The extent and depth of glacial erosion is dependent on the speed of flow and thickness of the ice, as well as the nature of its bed with enhanced rates of erosion occurring in areas of fast flowing ice, such as ice streams, which drain the more stable areas of the ice sheet. The areas where deep erosion occurs will be localised and dependent on where active ice streams, major glacial meltwater drainage routes and major fluvo-glacial outflow incisions occur. In, and adjacent to, upland areas these are likely to be mainly controlled by the location of existing valleys which will control where future glacial and fluvial erosion is likely to occur. The eventual depth that the valleys and channels attain will depend on factors such as ice thickness and sea level.

In upland areas, ice streams can erode channels with parabolic cross sections (troughs and fjords) up to depths of 2 km (Talbot, 1999). Within most of the UK landmass few incisions exceed 200 m in depth after multiple past glaciations. For example, whereas denudation rates of most hard rock types under non-orogenic conditions are likely to be well below 50 m ma^{-1} (Table 1) and river incision resulting from the isostatic change in the UK after glacial re-adjustment, has been found to reach around 160 m in the Thames river system over the duration of the Quaternary (Bridgland, 2000; Bridgland, 2010; Bridgland and Westaway, 2007) whereas over-deepening of glacial troughs may extend to around 200 m (for example, Glen Avon, Hall and Glasser, 2003). In low land areas, such as Norfolk, buried valleys are known to have reached a depth of 100 m, and it has been suggested that they were formed by sub-glacial streams incising into the chalk (Woodland, 1970), demonstrating the depths to which glacial meltwater erosion can occur.

The greatest eroding forces are those connected with the presence of ice sheets and glaciers. Infrastructure associated with a GDF in the near surface environment, such as backfilled access shafts and drifts, could therefore be affected by erosion processes. Although a GDF itself would not be impacted by this degree of erosion (because of its depth), incision or other erosional process occurring directly above a GDF will result in the thickness of cover rock being reduced. Erosion rates, therefore, need to be considered as part of a GDF siting process, where a conservative approach to siting could be to avoid existing valleys and glacial troughs that are likely to be re-occupied during future glacial advances.

2.4. Summary

Understanding and predicting the long-term changes in the natural environment significantly contributes to the evidence underpinning the safety case of deep geological disposal facility. The purpose of this contribution has been to illustrate the challenge of assessing the impact of long-term changes, in particular those mediated by plate tectonics and climate variation, on developing such a safety case. The main thesis is that, in contrast with tectonically active or recently deglaciated regions of the Northern Hemisphere, such as Finland and Sweden, where similar projects are at an advanced stage, the lower latitude, geologically variable but stable intraplate locations such as the UK pose a different challenge.

In the more dynamic tectonically active or recently deglaciated areas, much of the hazard and risk assessment can made against observation of process and more deterministic means. However, in stable intraplate settings, this is necessarily based on modelling and probabilistic assessments. Absence of active process, and consequently a lack of contemporary observational information, is compounded by the nature of natural processes that have complex patterns of interaction at all scales.

We have illustrated the nature of natural processes and their potential impact for a GDF in the UK. As the UK is located on the current passive Atlantic margin, active plate margin tectonic processes, such as fault rupture and volcanism, are assumed to have little impact during the next 1 ma as they are dependent on major changes in Atlantic plate configuration for which there are no detailed forward estimates. Similarly, overall changes in the stress tensor and a potential increase in seismicity are controlled by the same far field processes, although, in common with many safety-critical civil engineering projects, probabilistic assessment of seismic hazard, based on the distribution and magnitude of events in the earthquake record, is typically undertaken. Allied to these processes, uplift/subsidence and erosion/burial are ever present processes that are accelerated during times of active tectonism and certain climatic conditions. In the UK, the observed pattern of uplift and subsidence is largely attributed to glacio-eustacy, although some researchers argue that North Sea lithospheric stretching and a north Atlantic thermal anomaly are contributing factors.

Understanding the impact of climate change in the longer-term is predicated on models which simplify the main components of the climate system, known future variation in orbital parameters and for a range of anthropogenic CO_2 contributions, whose uncertainty is large on these timescales (Fischer et al., 2014). Any future assessment of climate impact on a GDF in the UK must therefore take account of a range of possible future climate scenarios to account for this uncertainty (Näslund et al., 2013). This is pertinent for the UK, whose mid-latitude position has proven particularly sensitive to such global-scale climatic changes with marked variations in prevailing climate over comparatively short periods of geological time (tens of thousands of years; e.g. Candy et al., 2011; Rose, 2009) as a result of its position relative to southward moving cold polar air masses (Polar Front), and low latitude warm ocean currents (North Atlantic Current).

Longer-term models typically predict a return to glacial conditions between around 90 ka AP and 170 ka AP, however levels of atmospheric CO_2 and the impact of the resulting global warming may result in the next cold phase not occurring or being much less intense. For those areas in the north of the UK that are likely to become ice covered, the degree of glacial erosion is a clear consideration, while further south in the UK, as well as in areas subsequently overridden by ice, the depth of penetration of permafrost and its impact on engineered components of the GDF becomes a consideration. Estimates of future permafrost penetration between about 215 and 320 m deep for northern Europe therefore become important consideration in GDF design. The impact of changing patterns of seismicity associated with syn- to post- and peri-glacial isostatic movements are also significant and it is not unreasonable that higher magnitude earthquakes than observed to date in the UK may also occur around ice margins around the time of glacial loading and unloading.

In the UK, national-scale assessments are being used to inform and guide the site selection process for underground geological disposal of radioactive waste. As the site selection process moves forward and sites are identified for detailed study, site specific studies will need to be undertaken because much of the understanding future natural change required for the safety case of the site is site specific. These will take account of the geological characteristics of the host rock and surrounding formations, and how they are likely to respond to the aforementioned natural changes and indeed how they might have been affected by such processes in the past. This information will be used to build an integrated understanding of the evolution of the subsurface environment of an area, in particular during the last tens of thousands to a few million years. The level of information and associated understanding of the evolution of an area will determine the confidence that can be applied to these uniquely long-term predictions and associated risks.

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