Errata 2011-10

SKB TR-10-49

Climate and climate-related issues for the safety assessment SR-Site

In the earlier distributed report, there are errors that have now been corrected. The corrected pages 198, 199 and 208 are enclosed. The changed text is marked with a vertical line in the page margin. An updated pdf version of the report, dated 2011-10, can be found at www.skb.se/publications.

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4.5.3 Permafrost evolution

The permafrost modelling is described in Section 3.4.4. The input data of geological, hydrogeological, geothermal, geochemical and geomechanical properties are based on site-specific descriptions and are summarised in /SKB 2006a/ and /Hartikainen et al. 2010/. In the reconstruction of last glacial cycle conditions, permafrost develops during the progressively colder phases of the glacial cycle. When the ice sheet subsequently comes to cover an area of permafrost, the permafrost typically stops developing and starts to slowly diminish. When the ground is re-exposed to a cold climate permafrost starts to grow again.

In the SR-Site *reference glacial cycle*, the development of permafrost at Forsmark starts about 7 kyrs after present (Figure 4-27 and 4-28). The 1D modelling approach used for the results in Figure 4-27 could, in certain situations, result in somewhat higher temperatures than would be calculated using a multi-dimensional model. However, a comparison between the 1D modelling results /SKB 2006a/ and the results from the 2D model /Hartikainen et al. 2010/, using the same air temperature curve as input, shows that the results for this site and settings are in line with each other (Figure 4-28). Since lateral groundwater flow only has a minor role in permafrost development compared to heat conduction, e.g. /Hartikainen 2010/, it is likely that modelling including a 3D groundwater flow (instead of the used 2D groundwater flow, and the 1D approach without groundwater flow) would only contribute with minor changes of the permafrost and perennially frozen depths.

When permafrost starts to grow over the site, it starts as sporadic permafrost (i.e. with a spatial coverage less than 50%). As climate gets colder, discontinuous permafrost (with a spatial coverage between 50 and 90%) and continuous permafrost (more than 90% spatial coverage) form over the site (Figure 4-29). Examples of permafrost development along the investigated profile (for profile location, see Figure 3-58) for the dry climate variant of the *reference glacial cycle* are seen in Figure 4-30. The upper panel in Figure 4-30 shows the situation at 8.5 kyrs after present when a Subarctic climate prevails at the site. The profile is partially submerged by the Baltic and sporadic permafrost has started to grow at the site (too shallow to be seen in the figure). At this time the temperature is at its maximum within the repository, which has a large influence on the temperature of surrounding bedrock. Figure 4-30 middle panel shows the situation at 25 kyrs after present in the *reference glacial cycle*, with discontinuous permafrost coverage over the site. In Figure 4-30 lower panel, the situation 50 kyrs after present is shown. At this time an Arctic climate prevails at the site which has resulted in a continuous permafrost cover. At this time the permafrost reaches its maximum depth in the *reference glacial cycle*. As seen from the temperature contours, the heat from the repository has decreased considerably at this time.

During periods of permafrost an unfrozen active layer develops above the permafrost during summer conditions. The thickness of the active layer could typically be c. 40–70 cm deep, depending on the vegetation and soil. For a bare surface the active layer thickness is greater, up to ~1 m.

During the permafrost development prior to the first ice sheet advance, unfrozen taliks are formed under the two future lakes that are located along the profile (Figure 3-58).This is exemplified by the dry climate variant of the *reference glacial cycle* (Figure 4-31). The upper panel shows the situation at 25 kyrs after present when the taliks have formed 9 and 15 km from the south-western starting point of the profile. Groundwater recharge and/or discharge is likely to occur in such taliks. The lower panel of Figure 4-31 shows the situation at 46 kyrs after present. At this time permafrost growth has developed further and none of the taliks reach through the permafrost anymore. In this situation groundwater flow is heavily reduced or stopped.

The permafrost and frozen ground depth reach a maximum prior to the first major glacial advance, at about 50 kyrs after present. At this time the maximum modelled permafrost depth reaches ~260 m at Forsmark (Figure 4-27 and 4-28). The perennially frozen depth is, at the same time, a few tens of metres shallower. When the ice sheet advances over the site, the permafrost stops developing and instead starts to diminish, for example around 60 kyrs after present. Subsequently, permafrost develops again at the site during the ice-free interglacial period between the two major ice advances, but at this time to a somewhat shallower depth, about 180 m (Figure 4-27). During the major phase of ice coverage, including the ice sheet maximum at more than 100 kyrs after present, the maximum permafrost depth (defined by the 0°C isotherm) is around 100 m at Forsmark. Note that, at this time, the permafrost consists only of a completely unfrozen cryopeg due to the insulation effect of the ice sheet and due to the high pressure induced by ice load. Hence all bedrock is at this time at the pressure melting point temperature (Figure 4-27).

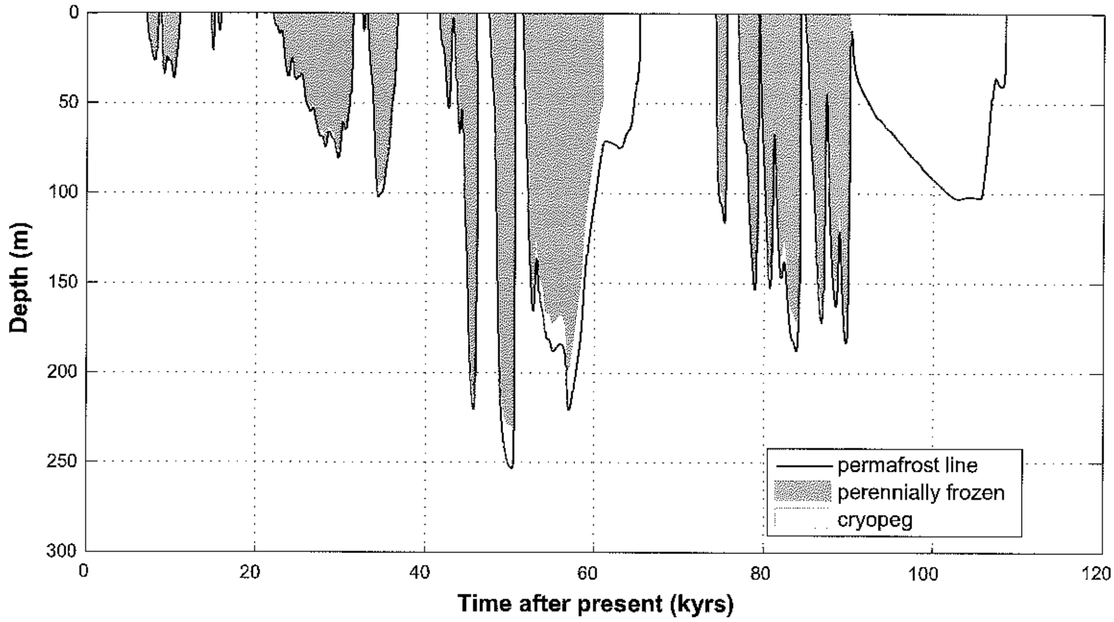

Figure 4-27. *Evolution of permafrost and perennially frozen ground depth for the reference glacial cycle for the repository location in Forsmark. The results were obtained using a 1D permafrost model (Section 3.4.4). Due to the high pressure, a thick unfrozen cryopeg exists within the permafrost (defined by the 0°C isotherm) after 60 kyrs and 90 kyrs after present.*

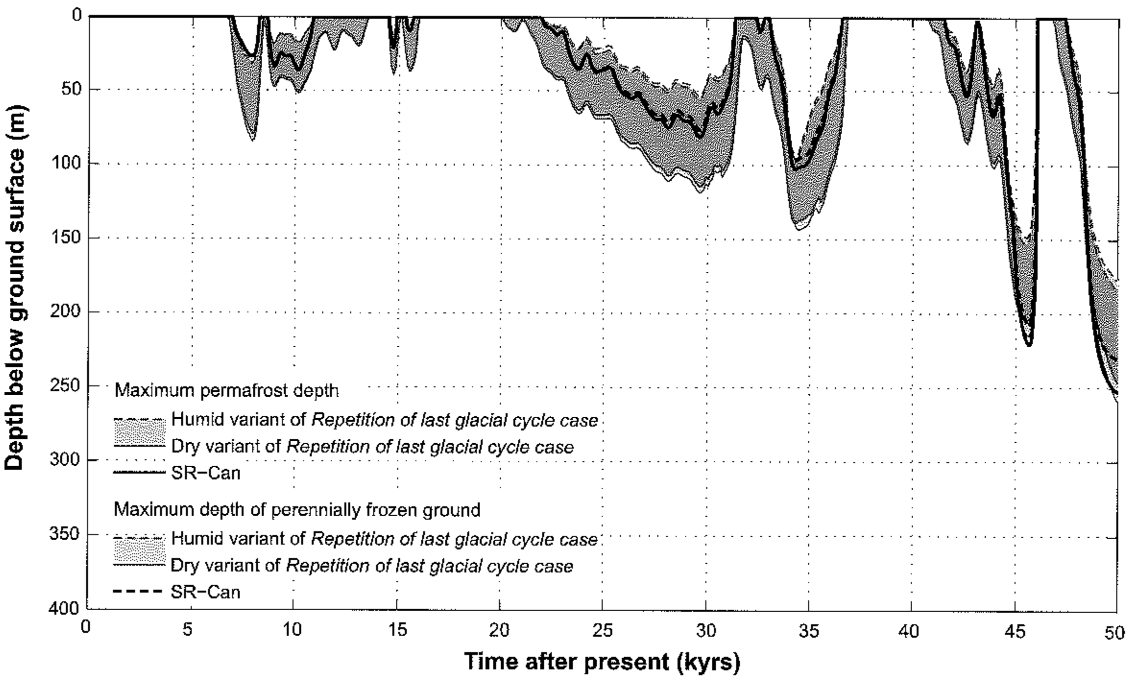

Figure 4-28. *Evolution of permafrost and perennially frozen ground depth at the repository location for the first 50 kyrs of the reference glacial cycle as simulated by the 2D and 1D permafrost models (Section 3.4.4). The shaded area in blue and red represents the range obtained from the 2D modelling when considering one wet and one humid climate variant. Further uncertainties in the permafrost modelling are discussed in Section 3.4.4. Both model simulations show that permafrost starts to grow around 7 kyrs after present and that the maximum permafrost depth is ~250 m around 50 kyrs after present.*

The uncertainties in the *actual* length of the present and future interglacial periods are naturally very large. Given these uncertainties, it is again emphasized that the evolution of climate domains as described in the *reference glacial cycle* (Figures 4-33, 4-34, 4-35), and corresponding base case of the SR-Site main scenario (Figure 1-3), is not an *expected* future climate evolution. It is one relevant example of an evolution covering the climate-related conditions that can be met in a 100 kyr time perspective. Other possibilities for the length of the present interglacial period are handled in the additional climate cases, including the *global warming case* and *extended global warming case* (Chapter 5).

The sequence of main climate-related events for the *reference glacial cycle*, including times of transitions between events and corresponding climate domains, is summarized in Table 4-5.

For the set up of the groundwater modelling, a simplified climate development for the reference glacial cycle has been produced (Figure 4-36, Table 4-6). In the simplified reference glacial cycle, climate periods of short duration have been removed and longer periods are used to describe the general climate development in Figure 4-33 and 4-34. In the simplified reference glacial cycle, the total duration of each climate domain is however the same as in the detailed reference glacial cycle presented in Table 4-4.

Table 4-5. Sequence of climate-related events for the reference glacial cycle, including the full Holocene. The same sequence of events is seen in Figure 4-33 and 4-34.

Event	Time for transition between events	Climate domain
Deglaciation/ Start Holocene interglacial (locally defined as time of deglaciation of Forsmark)	10,800 before present (BP) (8800 BC)	–
Holocene interglacial	–	Temperate climate domain (incl. submerged conditions)
Present	0 BP	
End of Holocene interglacial (locally defined as first occurrence of permafrost in reference glacial cycle)	7000 after present (AP) (9000 AD)	–
Periglacial and temperate conditions (progressively longer periods of permafrost conditions)	–	Periglacial- and temperate climate domains (progressively shorter phases of temperate climate conditions)
End of periglacial and temperate conditions. Start of glacial conditions	57,600 AP (59,600 AD)	–
First phase with glacial conditions	–	Glacial climate domain
Deglaciation at site. Start interstadial conditions	66,200 AP (68,200 AD)	–
Interstadial conditions	–	Mainly periglacial climate domain (incl. submerged conditions and short temperate periods)
End of interstadial conditions. Start of glacial conditions	90,800 AP (92,800 AD)	–
Second and main phase with glacial conditions	–	Glacial climate domain
Deglaciation/start of interglacial (locally defined as time of deglaciation of Forsmark)	109,500 AP (111,500 AD)	–