Long-term Thermal Behaviour of Permafrost – Modelling the Effects of Tailings and Climate Change in Northern Canada

Grant Su
Canadian Nuclear Safety Commission

Ahmad Booshehrian and **Richard Wan**
University of Calgary

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- Canada's nuclear regulator: Canadian Nuclear Safety Commission
- Overview of the proposed Kiggavik Project
- Selection of climate change scenarios for modelling
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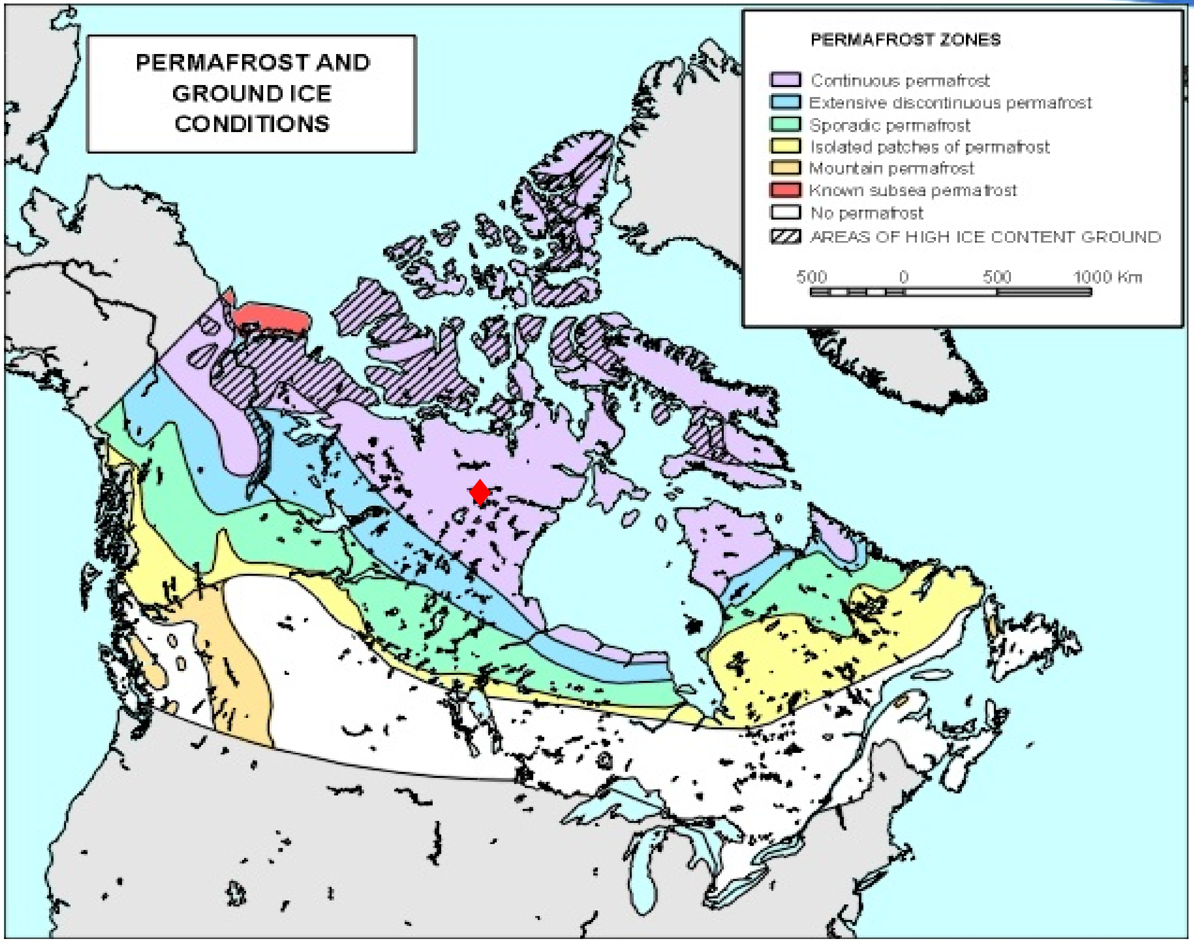
Canadian Nuclear Safety Commission

- Regulates the use of nuclear energy and materials to:
  - protect the health, safety and security of Canadians and the environment
  - implement Canada's international commitments on the peaceful use of nuclear energy
- Disseminates objective scientific, technical and regulatory information to the public

Overview of the Proposed Kiggavik Project



Location of the Kiggavik Project:

- Kivalliq region, 80 km west of Baker Lake, Nunavut
- Include Kiggavik, Sissons, Baker lake sites

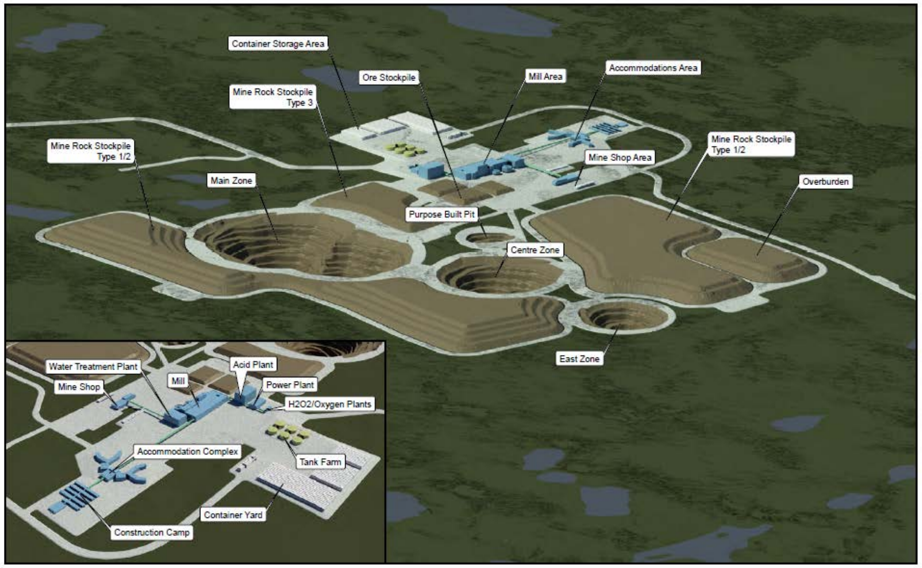
Permafrost depth:

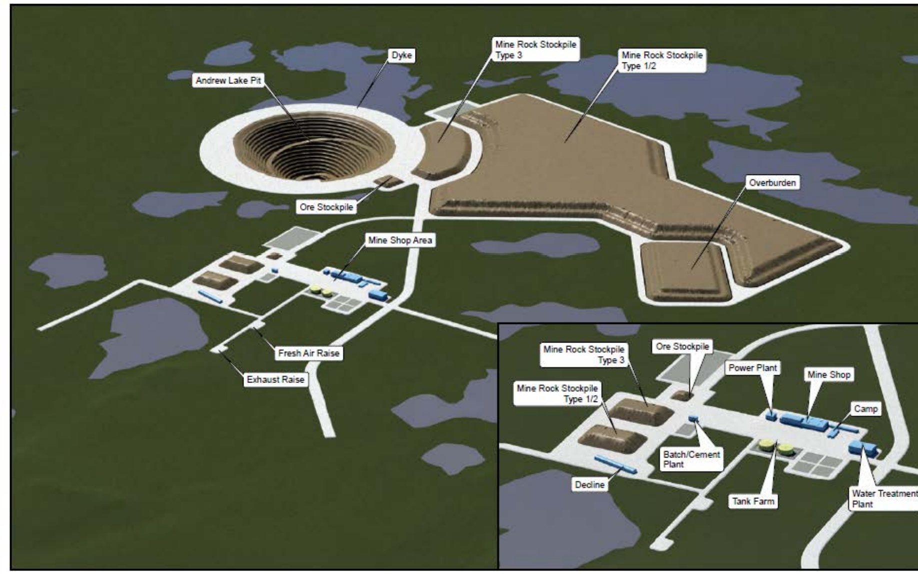
- 220~240 m, Kiggavik
- 260~280 m, Sissons

Mean annual air temperature: -12°C

Mean annual ground surface temperature: -6~7°C

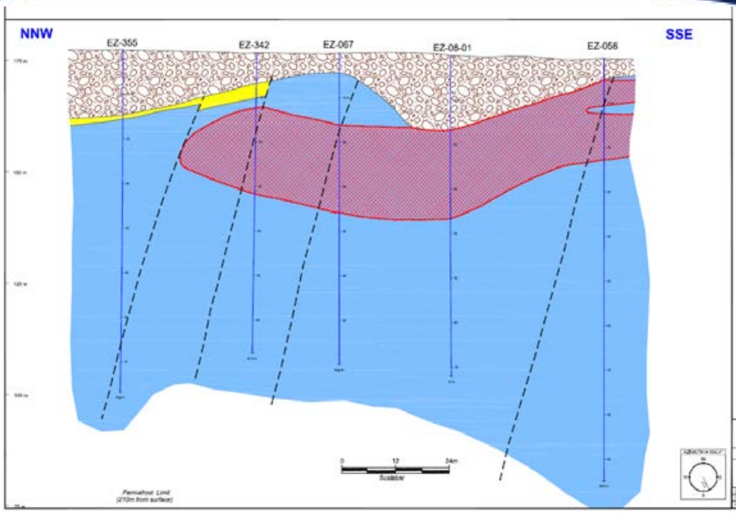
Kiggavik and Sissons Sites



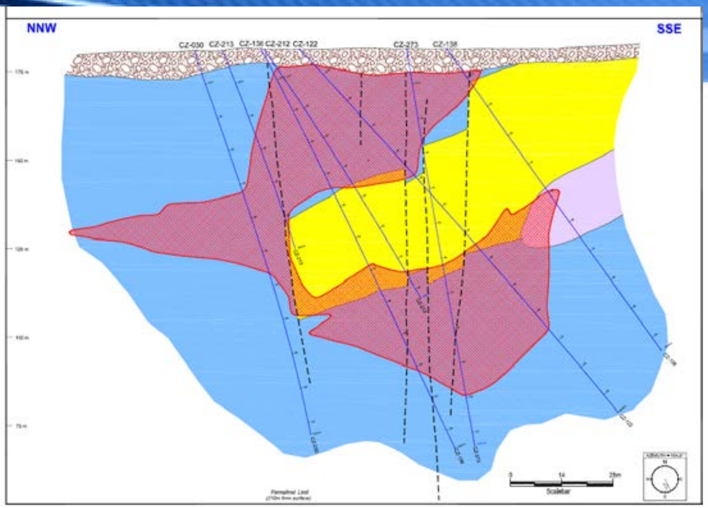


Pit	Footprint (ha)	Depth (m)	Dimension across the mine rim		Overall final pit slope (deg.)	Available pit volume for tailings (mm³)
			N to S (m)	E to W (m)		
East Zone	8.0	100	308	326	42	1.96
Centre Zone	15.0	110	425	445	49.5	5.4
Main Zone	39.2	235	600	840	51	30.0
Andrew Lake	44.0	275	790	715	45	38.4

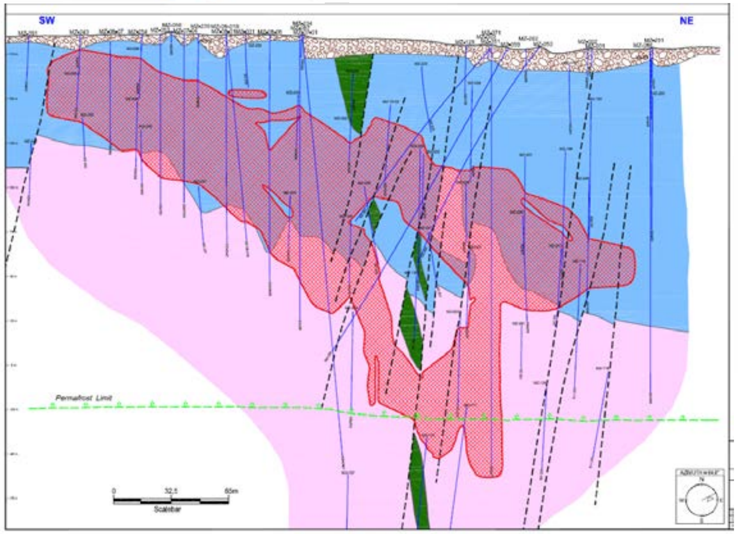
Geology and Ore Deposits at Kiggavik



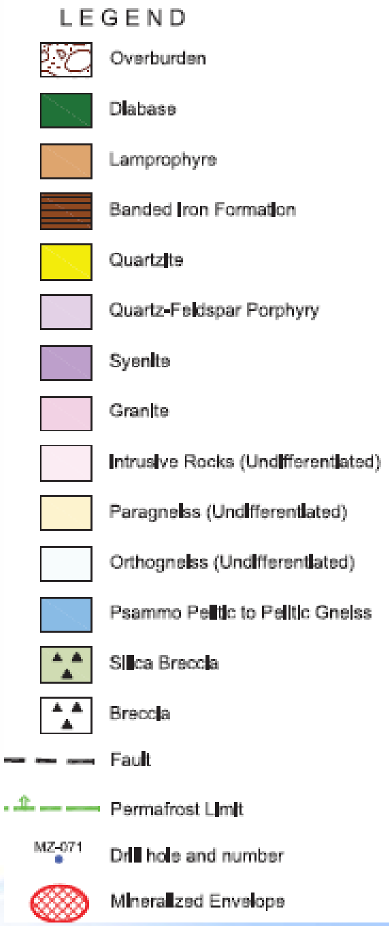
East Zone



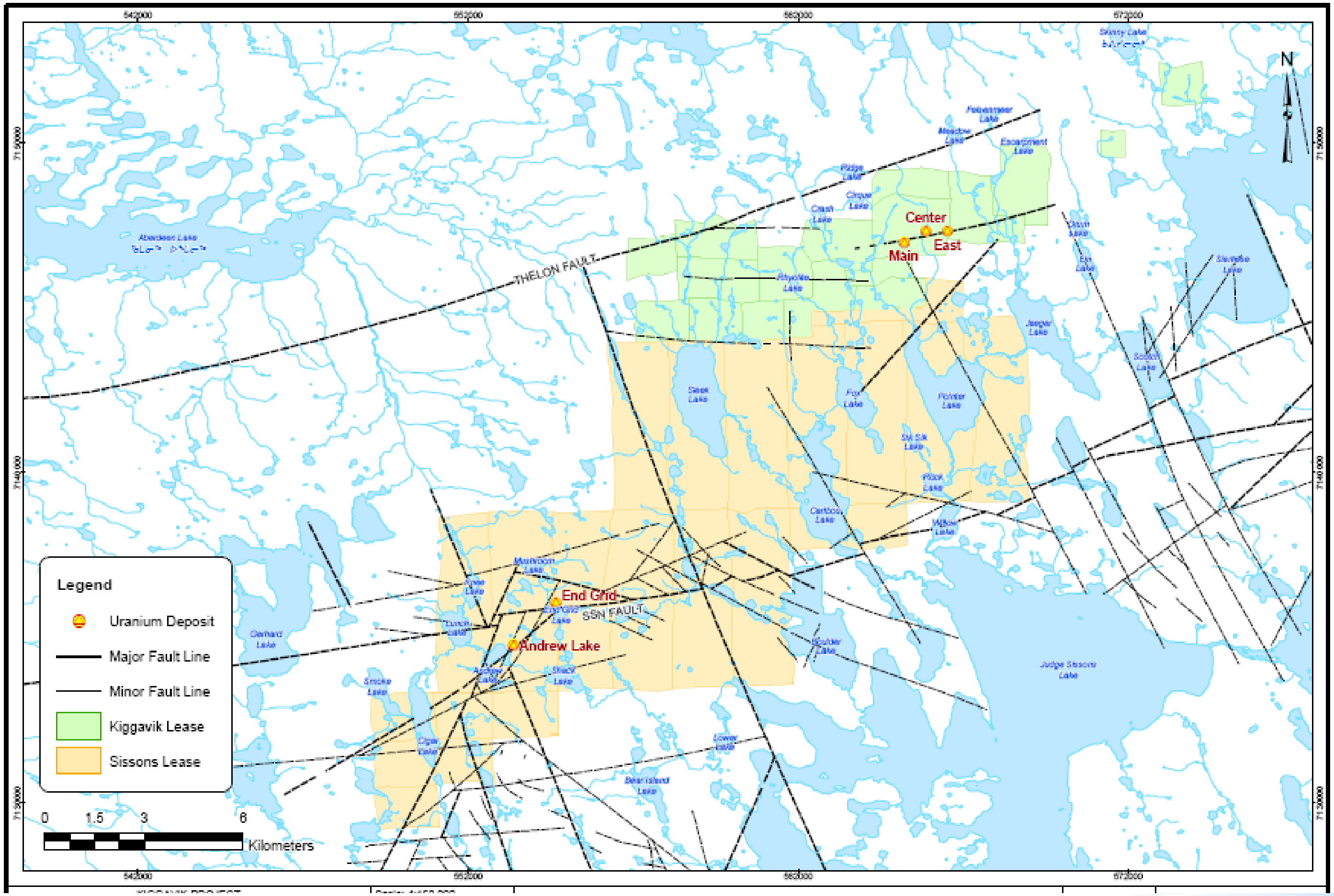
Centre Zone



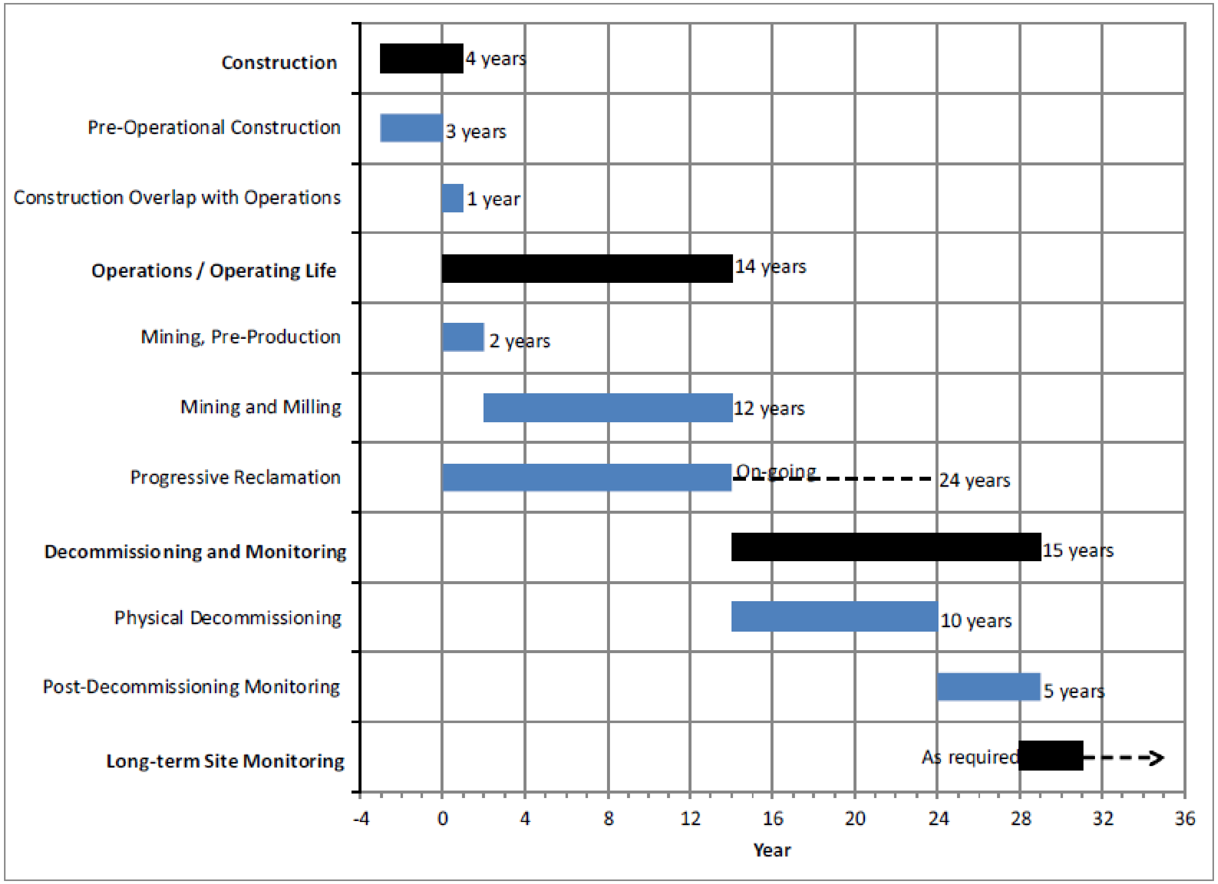
Main Zone



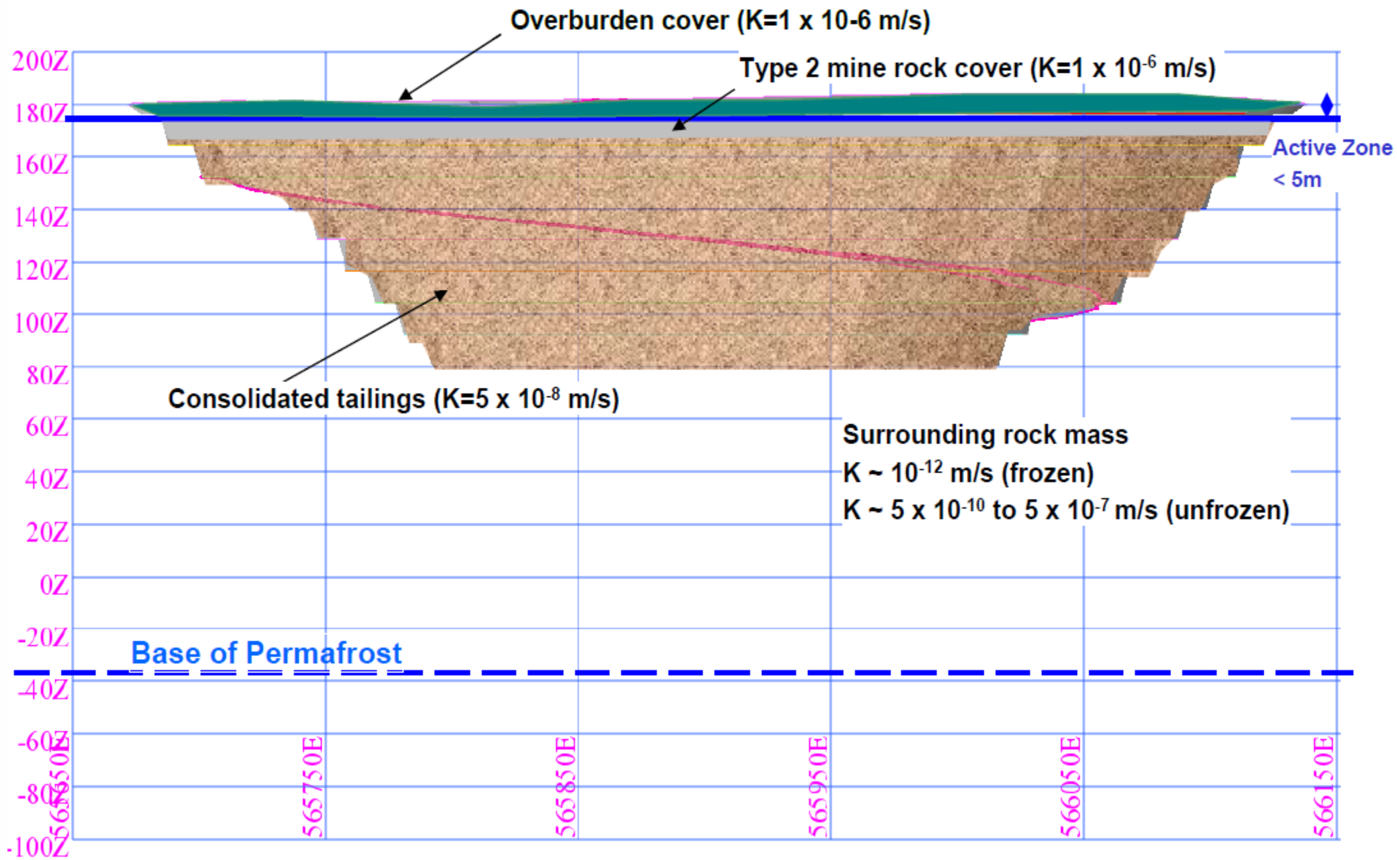
Geological Structure



Anticipated Project Schedule

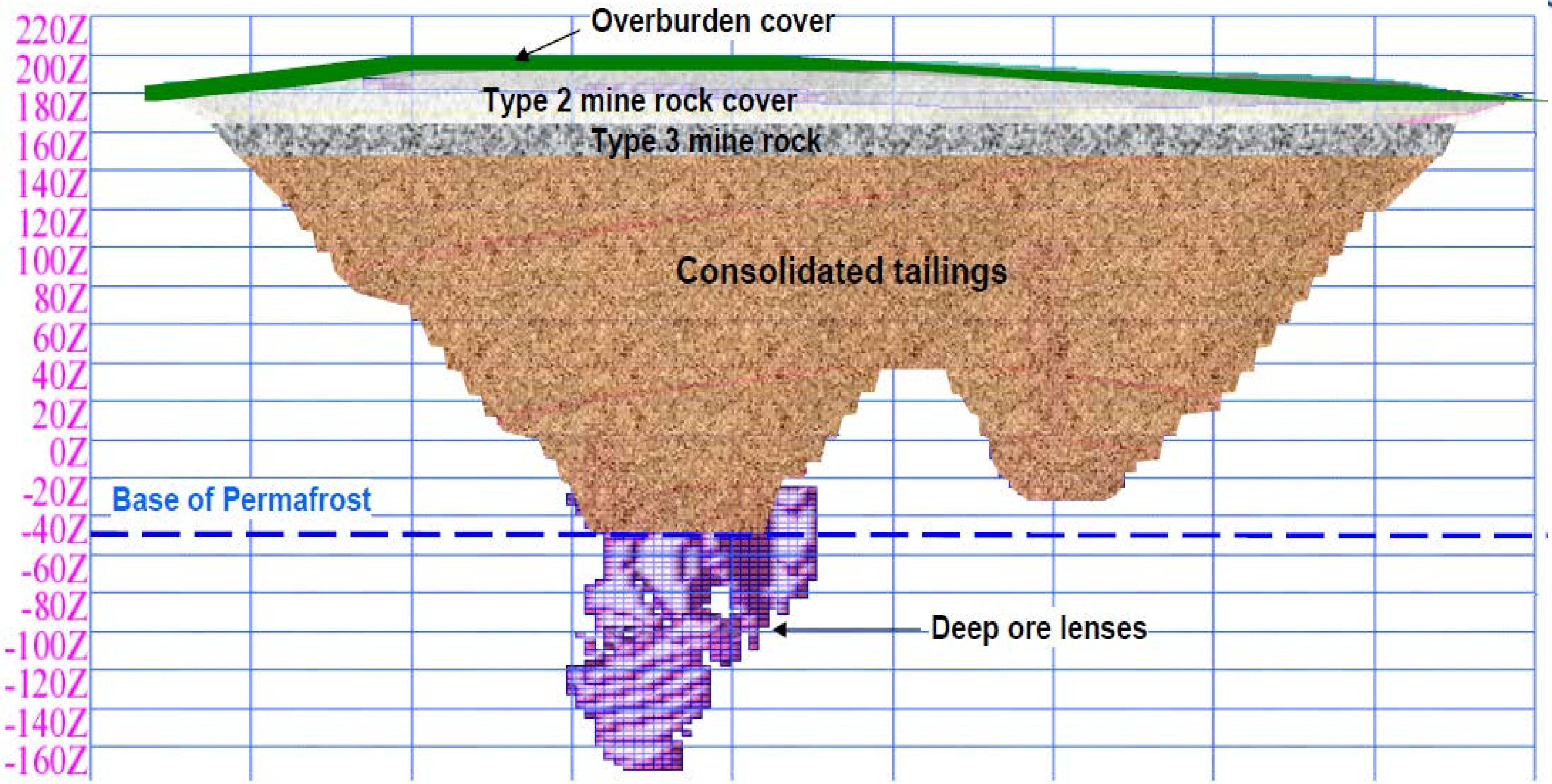


Proposed Decommissioning Plan for Tailings Management Facilities (1)



East Zone and Centre Zone tailings management facilities (TMFs)

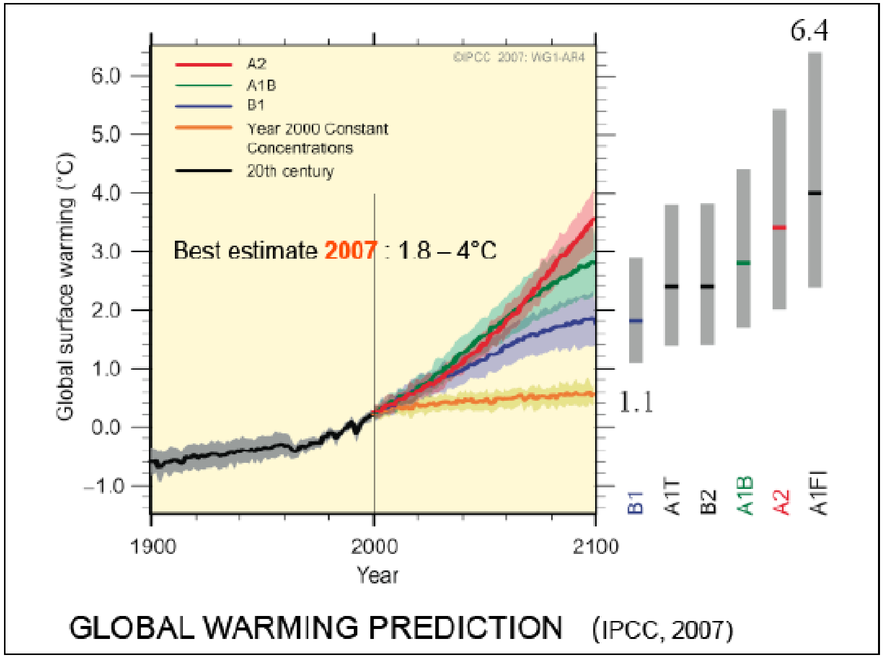
Proposed Decommissioning Plan for Tailings Management Facilities (2)



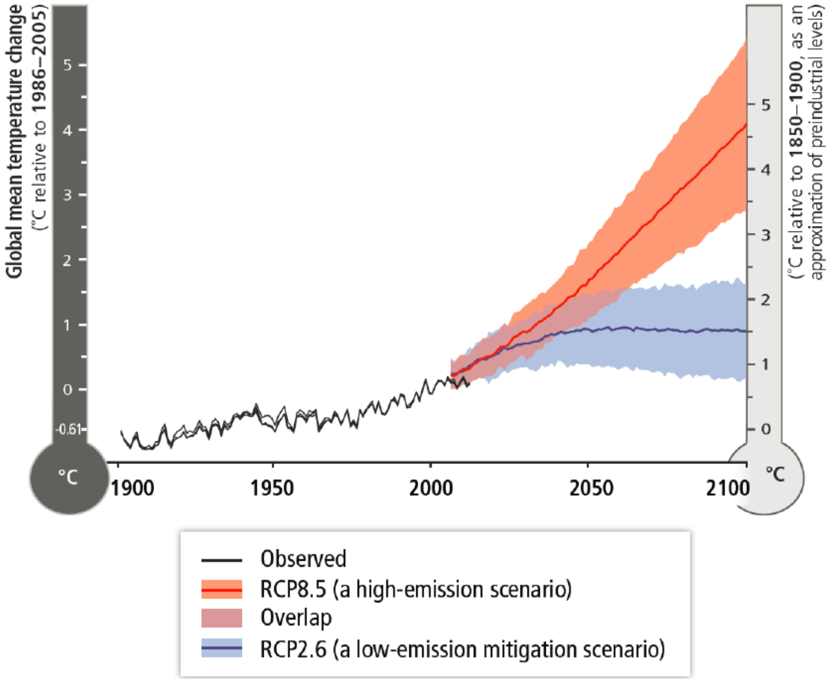
Main Zone TMF

Possible Climate Change Scenarios

Possible global climate change based on various greenhouse gas emissions

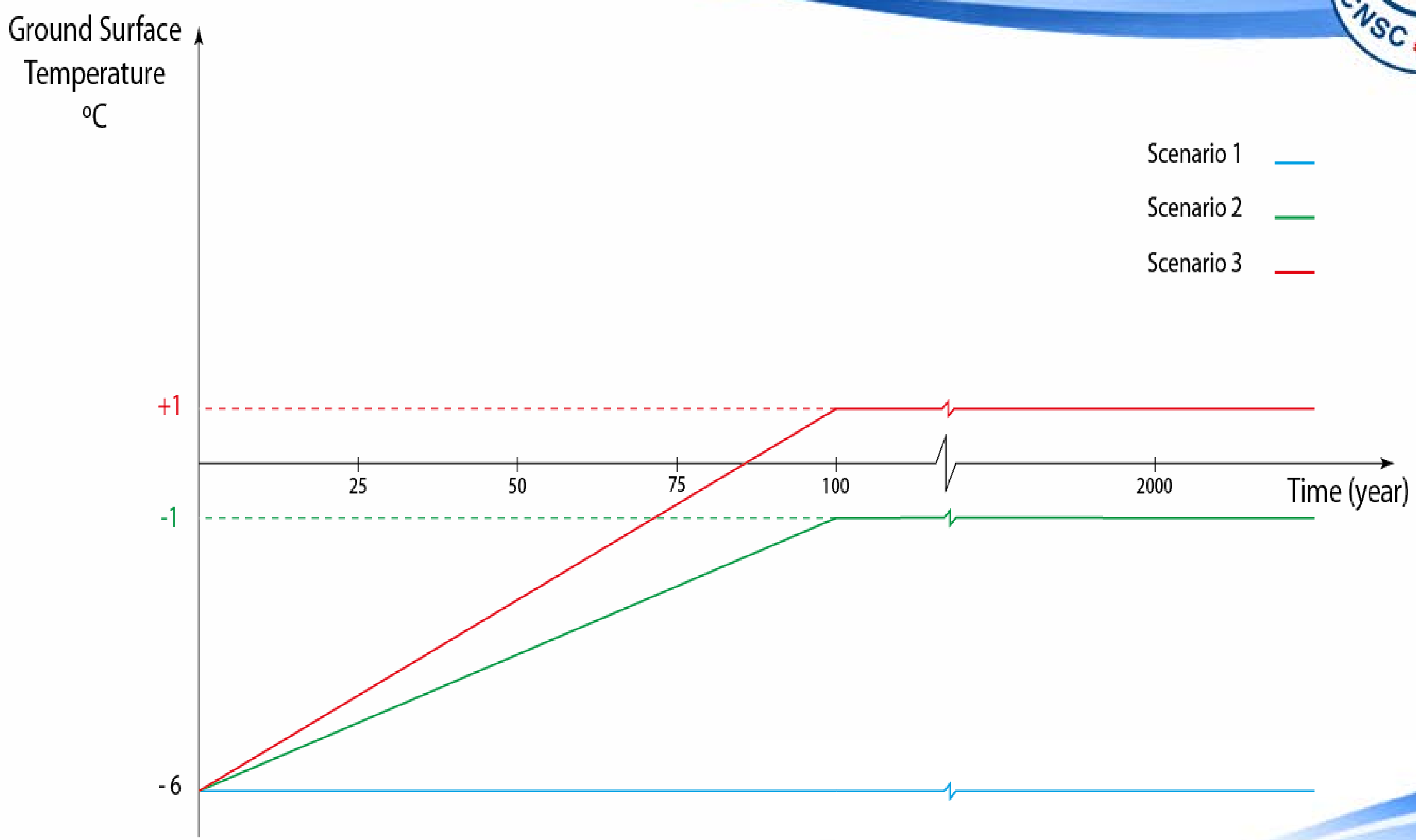


IPCC 2007

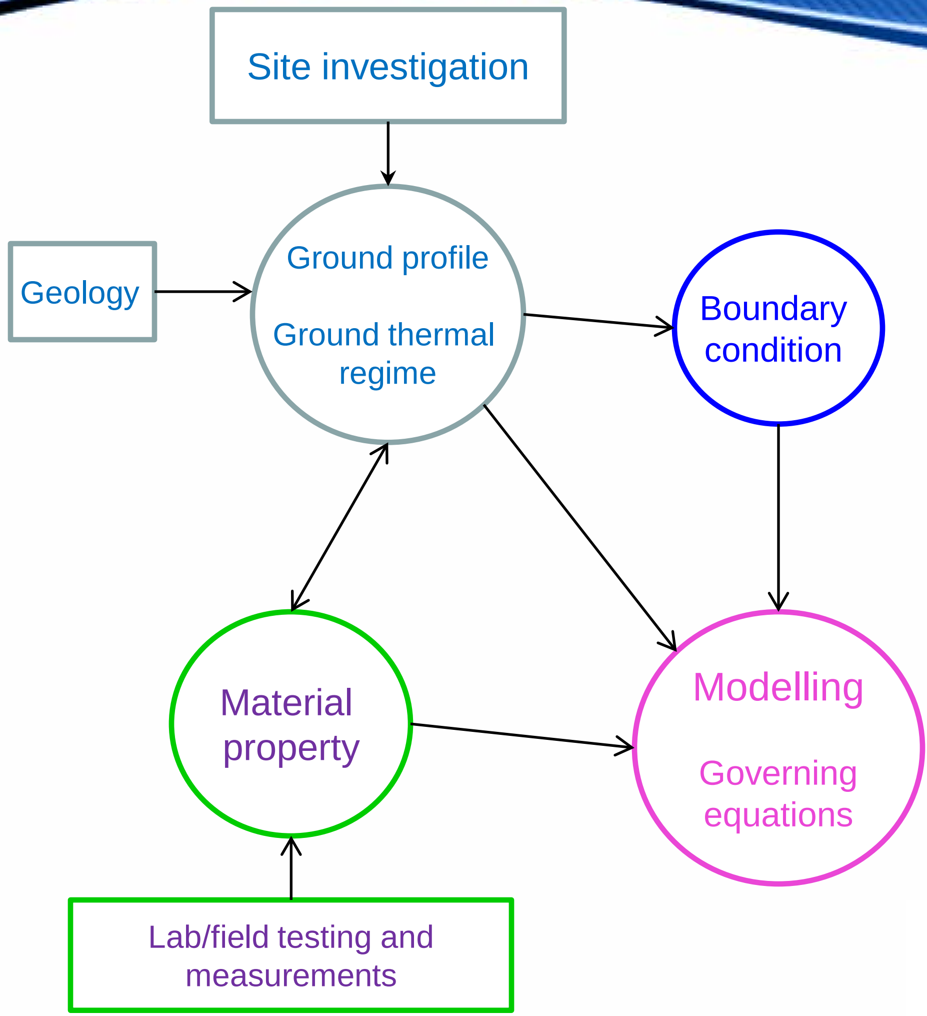


IPCC 2014

Climate Change Scenarios for Modelling



Numerical Modelling of Long-Term Permafrost Evolution



Time-dependent thermal analysis:

- Ground profile
- Material properties
- Boundary conditions
- Material phase change modelling

Governing equation:

$$(\rho C)_{eq}\frac{\partial T}{\partial t}+\nabla\cdot\left(-K_{eq}\nabla T\right)-Q=0$$

$$(\rho C)_{eq}=\theta_m\rho_m C_m+\theta_w\rho_w\left(C_w+\frac{\partial\Theta}{\partial T}L\right)+\theta_i\rho_i\left(C_i+\frac{\partial\Theta}{\partial T}L\right)$$

$$K_{eq}=\theta_m K_m+\theta_w K_w+\theta_i K_i$$

Material Properties (1)

Thermal properties of waste rock and bedrock materials

Material	Thermal conductivity $\frac{W}{m \cdot K}$		Volumetric heat capacity $\frac{kJ}{m^3 \cdot K}$		Porosity	Volumetric water content
	Unfrozen	Frozen	Unfrozen	Frozen		
Waste rock traffic	1.56	1.86	2099	1722	0.30	0.18
Waste rock	0.82	0.86	1597	1471	0.30	0.06
Bedrock	3.15	3.19	2314	2293	0.01	0.01

Material Properties (2)

Calibrated material thermal properties

Material	Thermal conductivity W/m·K	Heat capacity J/kg·K	Volumetric ice/water Content %
Overburden	2.8	700	5
Metasediment	3.0	670	3
Granite	3.0	670	1
Tailings	2.5	680	70

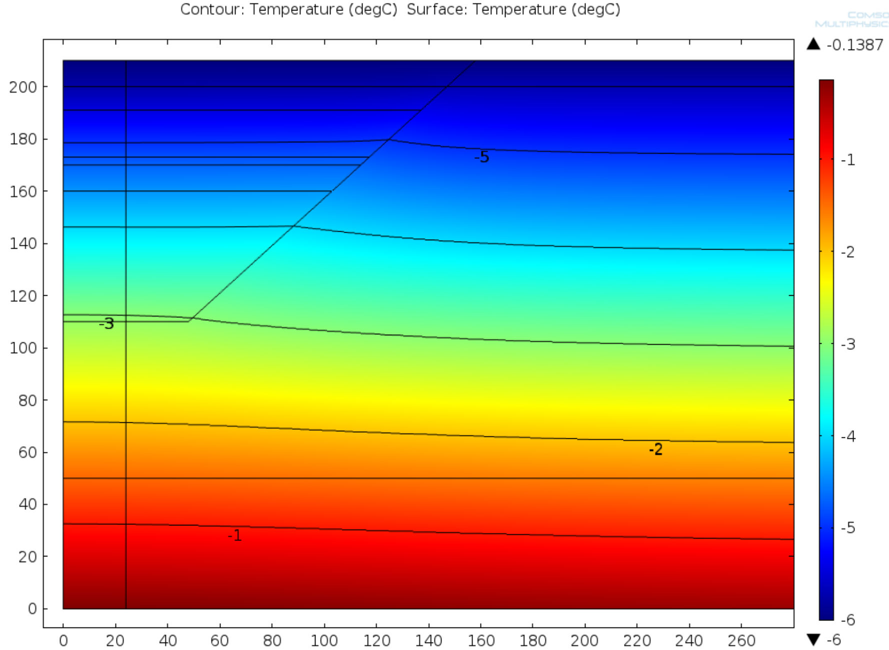
Material Properties (3)

Hydraulic properties of in-situ rock and backfill materials

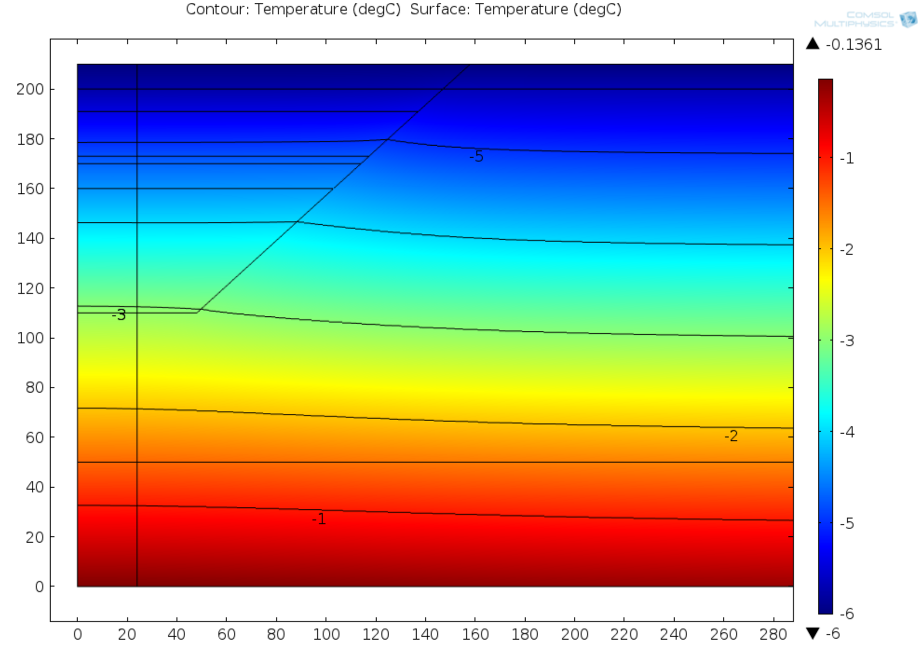
Material	Hydraulic conductivity (m/s)		
Permafrost	$1x10^{-12}$		
Meta-sediment	Depth	0~5 m	$5x10^{-5}$
		5~100 m	$5x10^{-8}$
Granite	Depth	100~215 m	$5x10^{-8}$
		215~450 m	$1x10^{-8}$
		>450 m	$1x10^{-9}$
Overburden cover	$1x10^{-6}$		
Mine waste rock (Type 2 / Type 3)	$1x10^{-6}$		
Tailings	$5x10^{-8}$		

Results of Numerical Modelling (1)

Effect of initial tailings temperature on the long-term thermal regime



Tailings initial temperature +5C

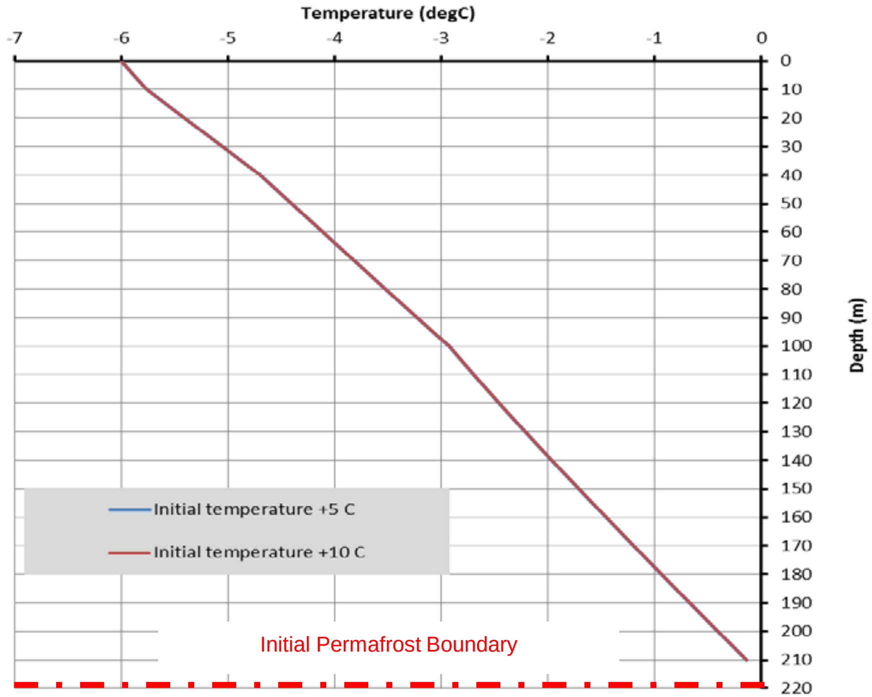


Tailings initial temperature +10C

Thermal regime of the East Zone TMF 2000 years after decommissioning

Results of Numerical Modelling (2)

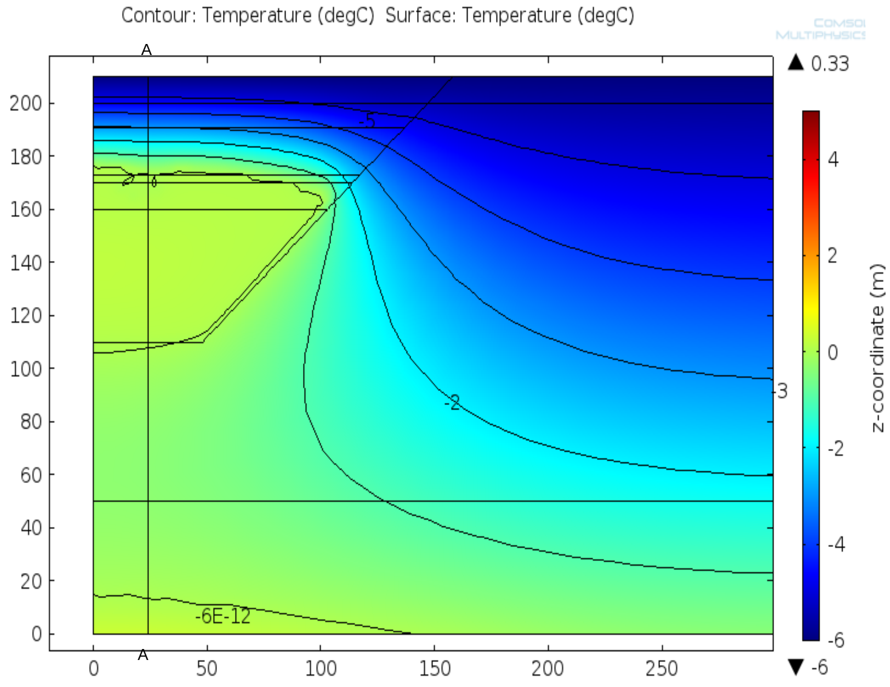
Effect of initial tailings temperature on the long-term thermal regime



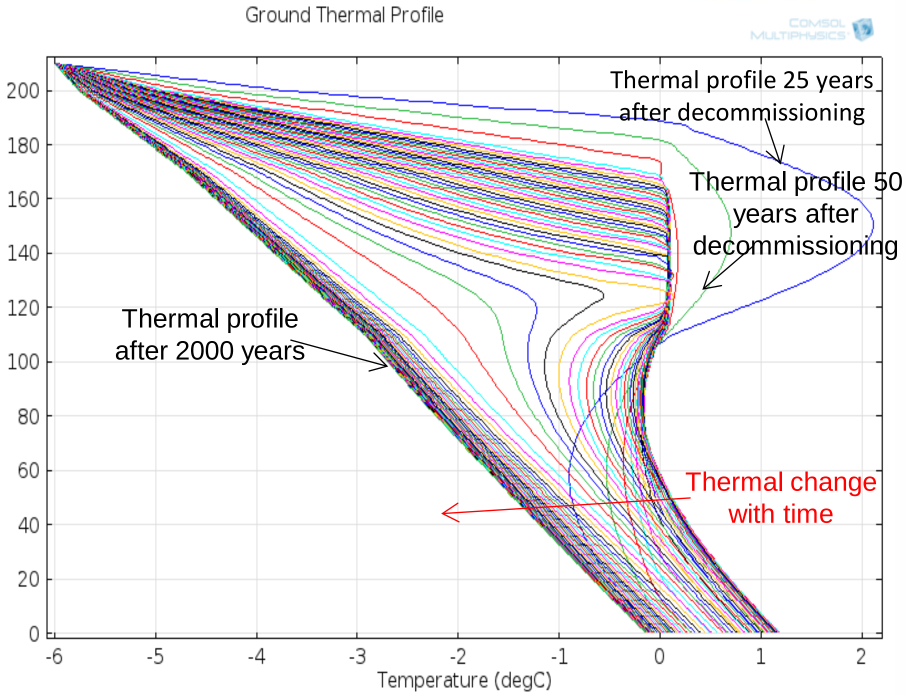
Thermal profile of the East Zone TMF 2000 years after decommissioning

Results of Numerical Modelling – No Climate Change (1)

East Zone TMF



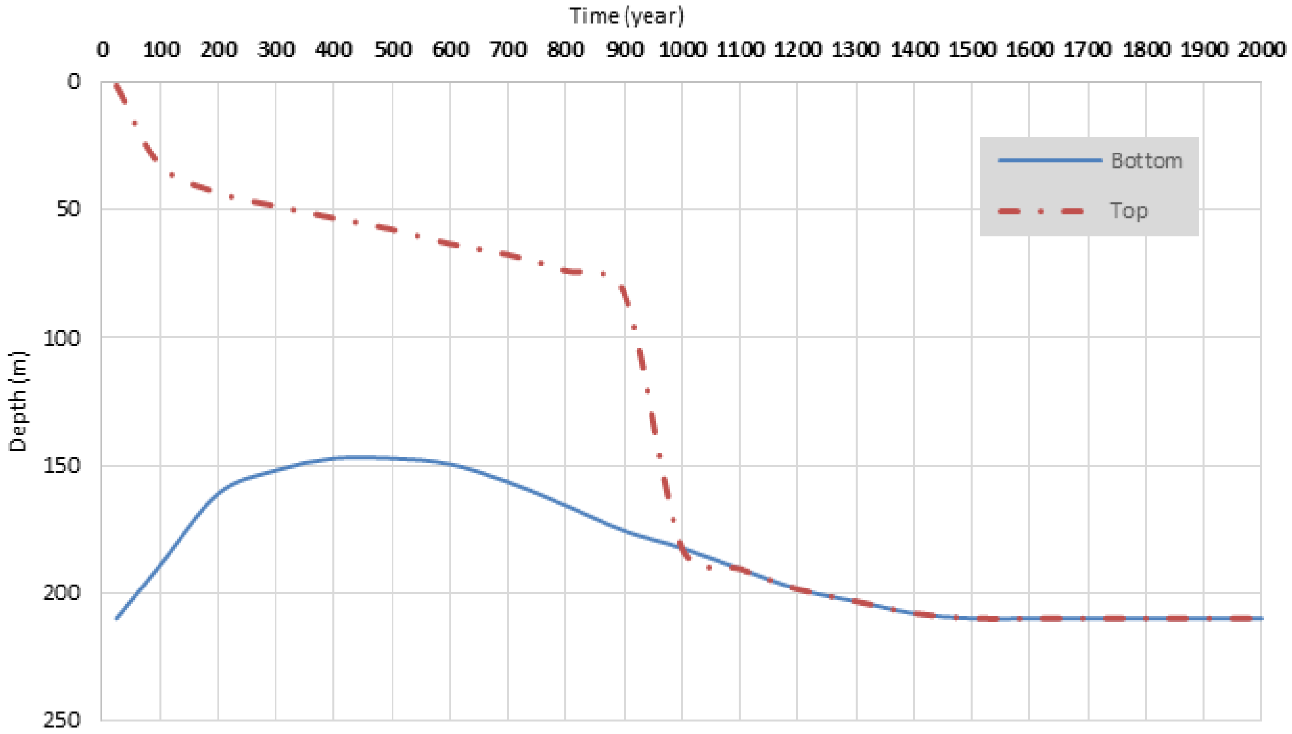
Thermal regime: 100 years after decommissioning



Thermal profile up to 2000 years after decommissioning at 25-year intervals

Results of Numerical Modelling – No Climate Change (2)

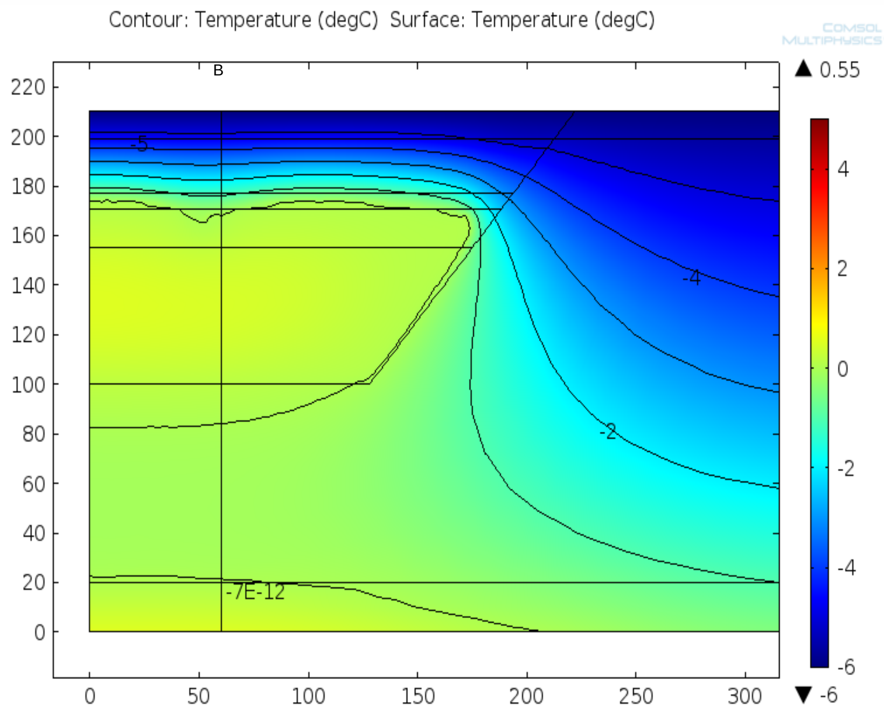
East Zone TMF



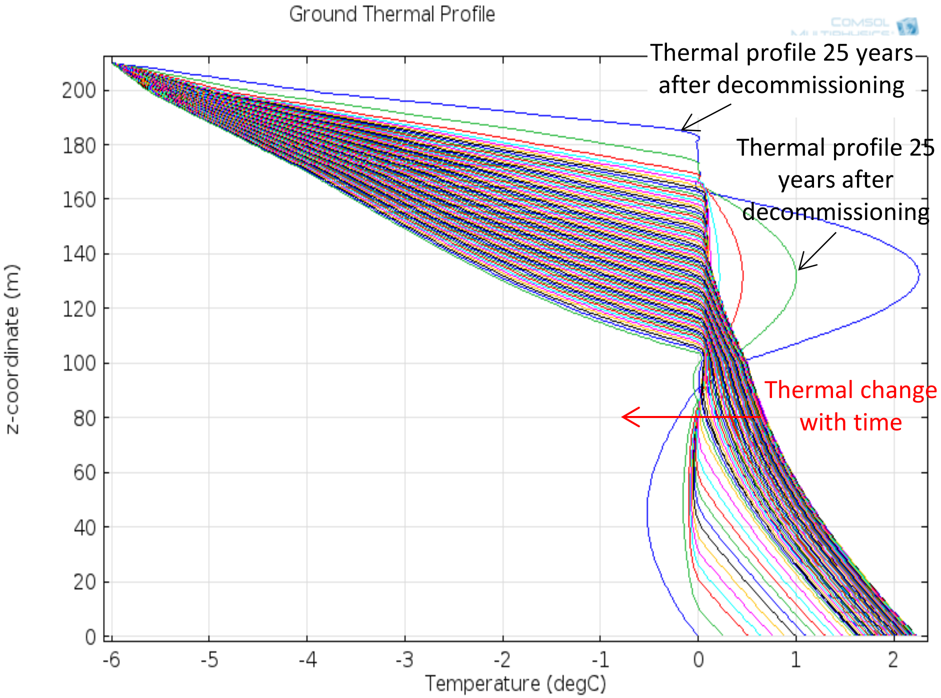
Permafrost evolution within the East Zone TMF
up to 2000 years after decommissioning

Results of Numerical Modelling – No Climate Change (3)

Centre Zone TMF



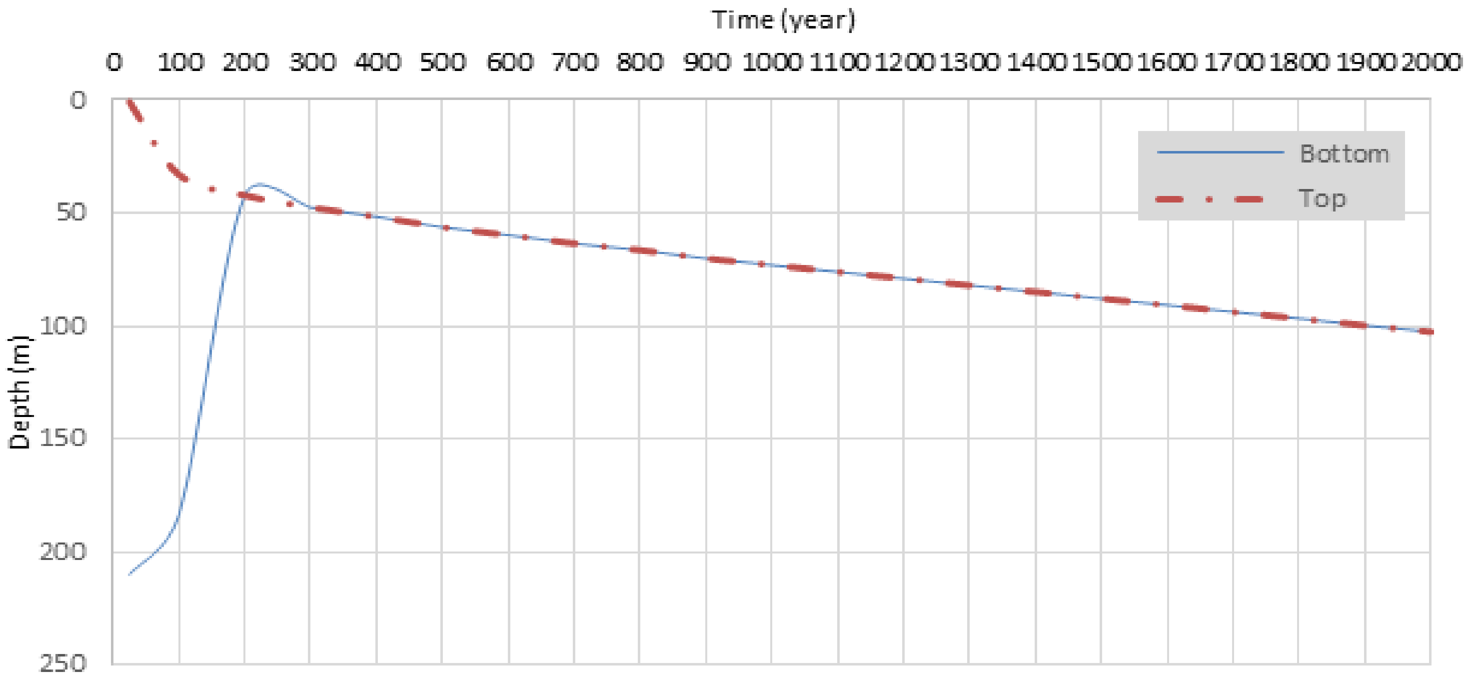
Thermal regime: 100 years after decommissioning



Thermal profile up to 2000 years after decommissioning at 25-year intervals

Results of Numerical Modelling – No Climate Change (4)

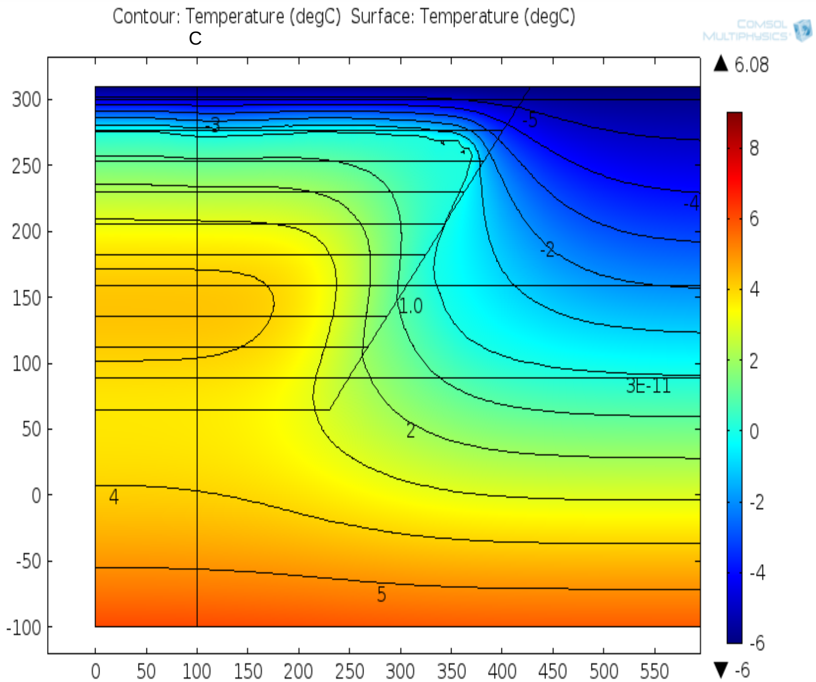
Centre Zone TMF



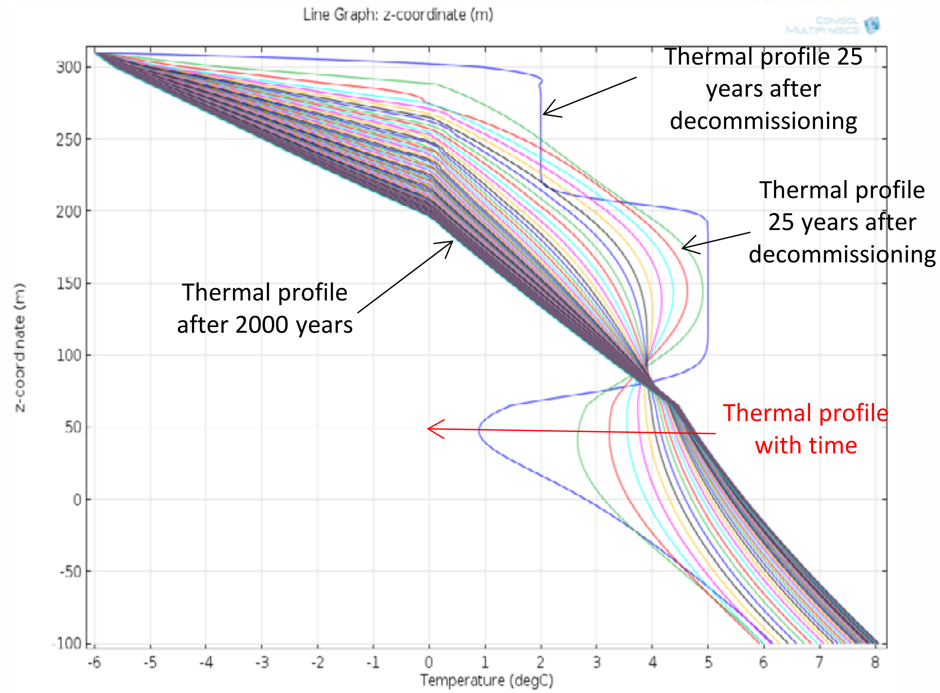
Permafrost evolution within the Centre Zone TMF up to 2000 years after decommissioning

Results of Numerical Modelling – No Climate Change (5)

Main Zone TMF



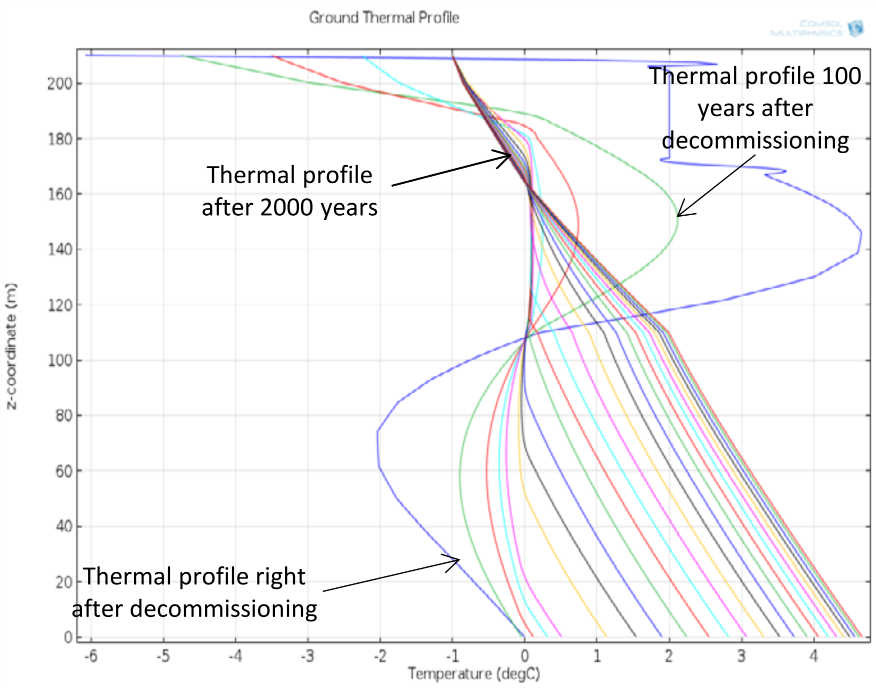
Thermal regime: 100 years after decommissioning



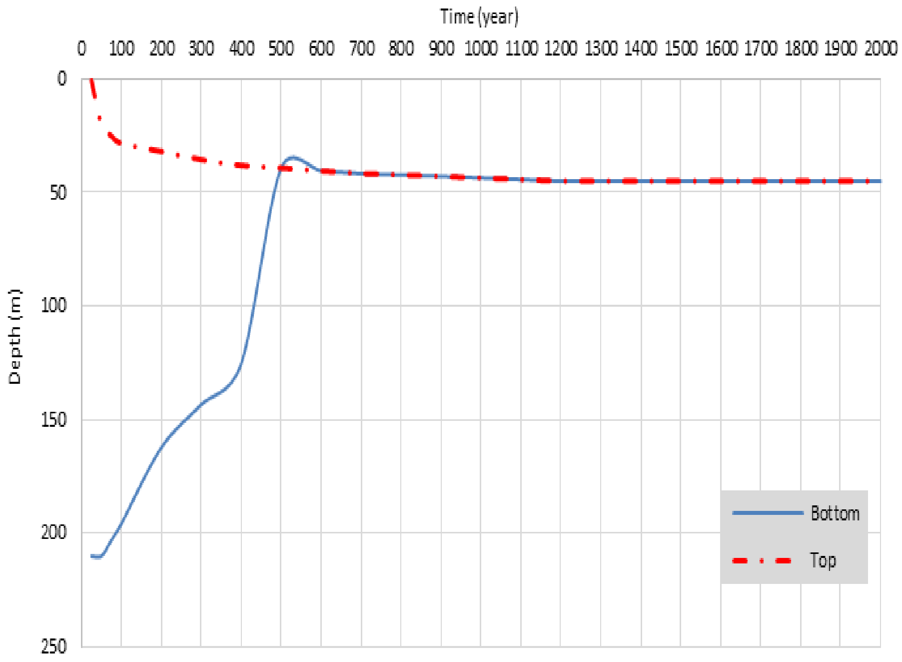
Thermal profile up to 2000 years after decommissioning at 25-year intervals

Results of Numerical Modelling – Climate Change Scenario 2 (1)

East Zone TMF



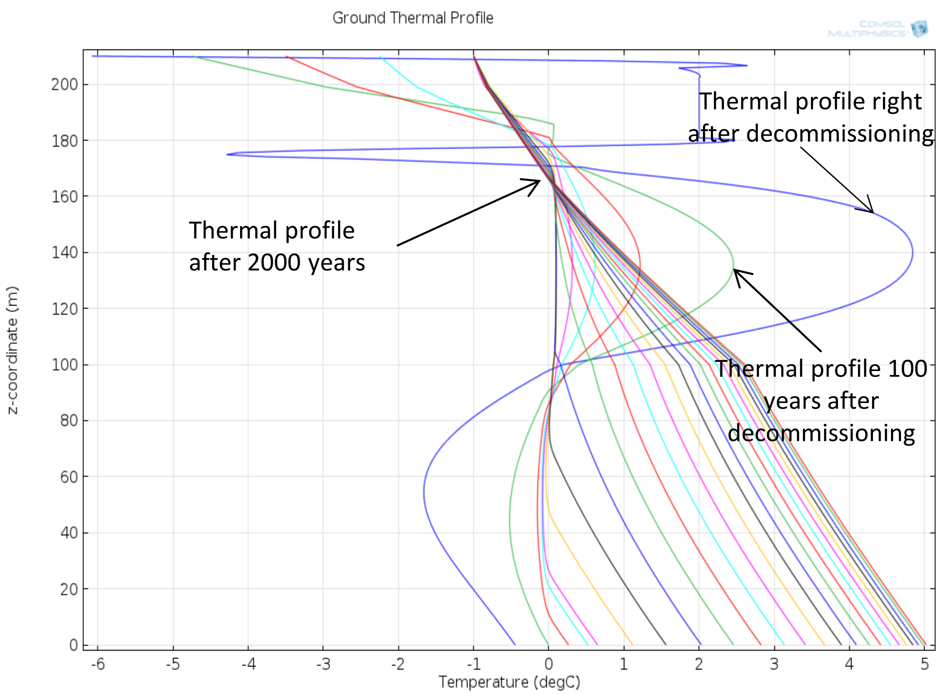
Thermal profile up to 2000 years after decommissioning at 100-year intervals



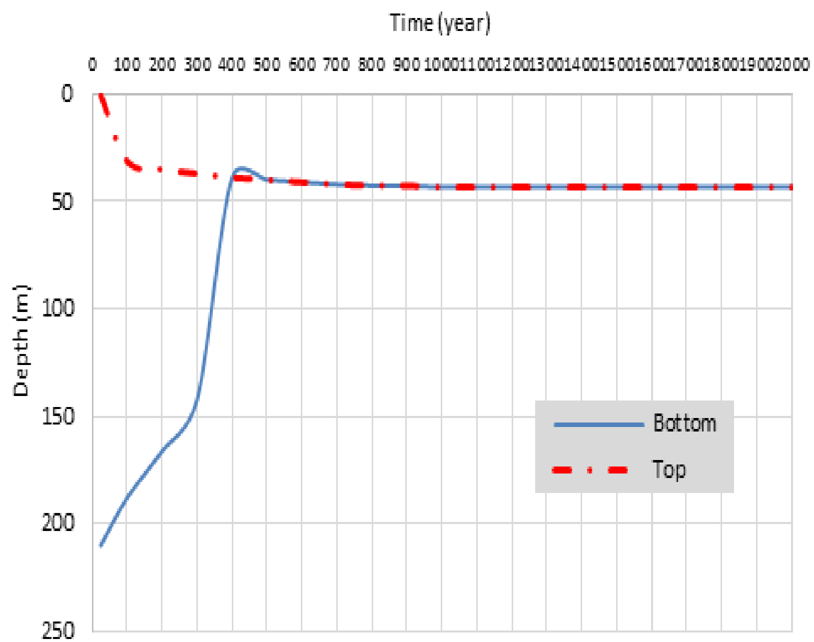
Permafrost evolution within the East Zone TMF up to 2000 years after decommissioning

Results of Numerical Modelling – Climate Change Scenario 2 (2)

Centre Zone TMF



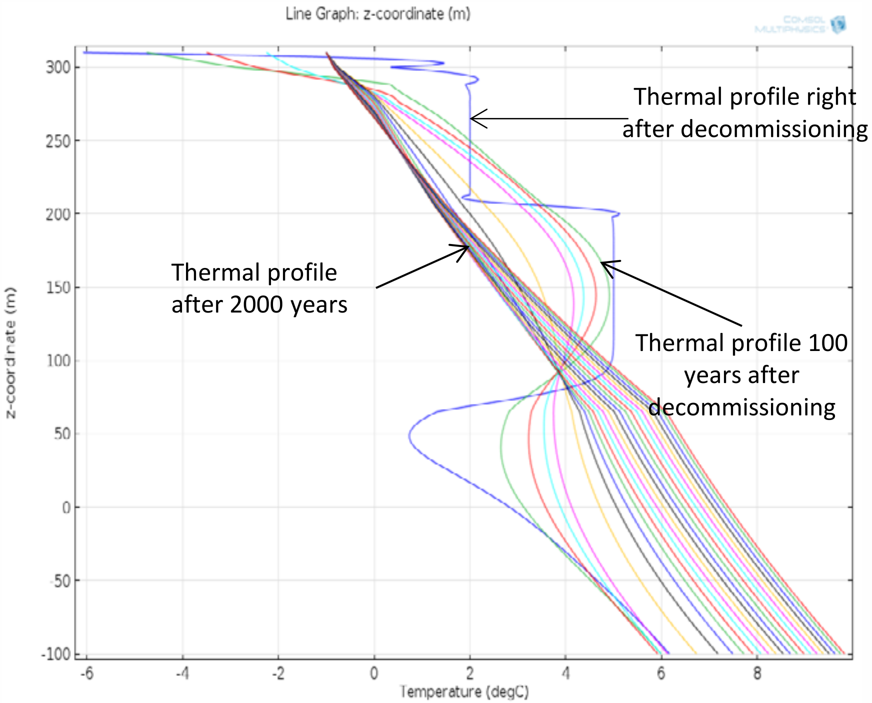
Thermal profile up to 2000 years after decommissioning at 100-year intervals

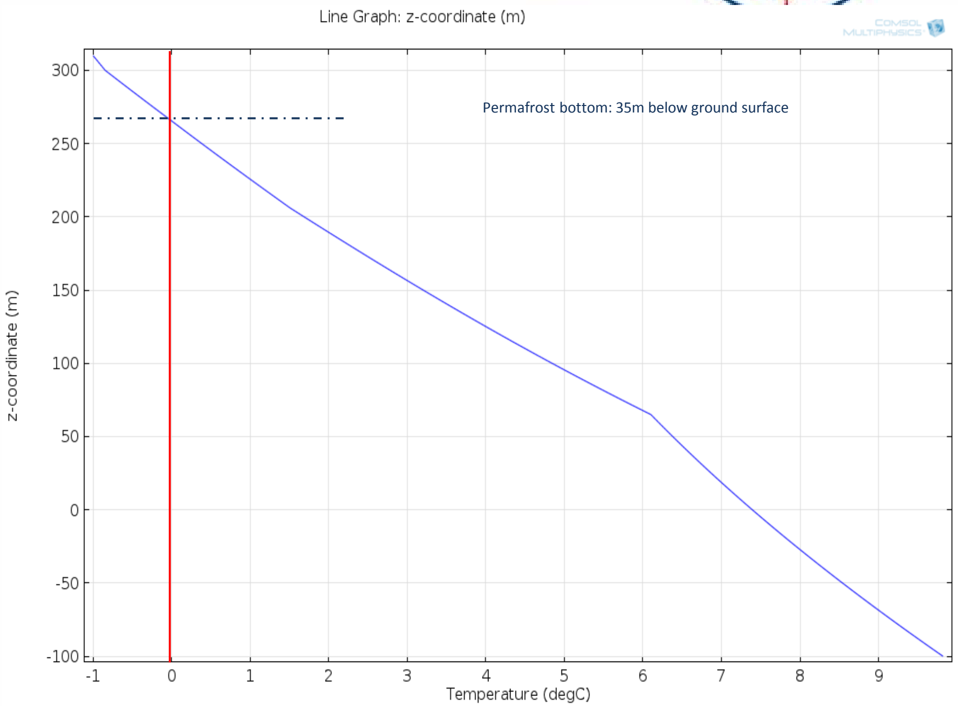


Permafrost evolution within the Centre Zone TMF up to 2000 years after decommissioning

Results of Numerical Modelling – Climate Change Scenario 2 (3)

Main Zone TMF



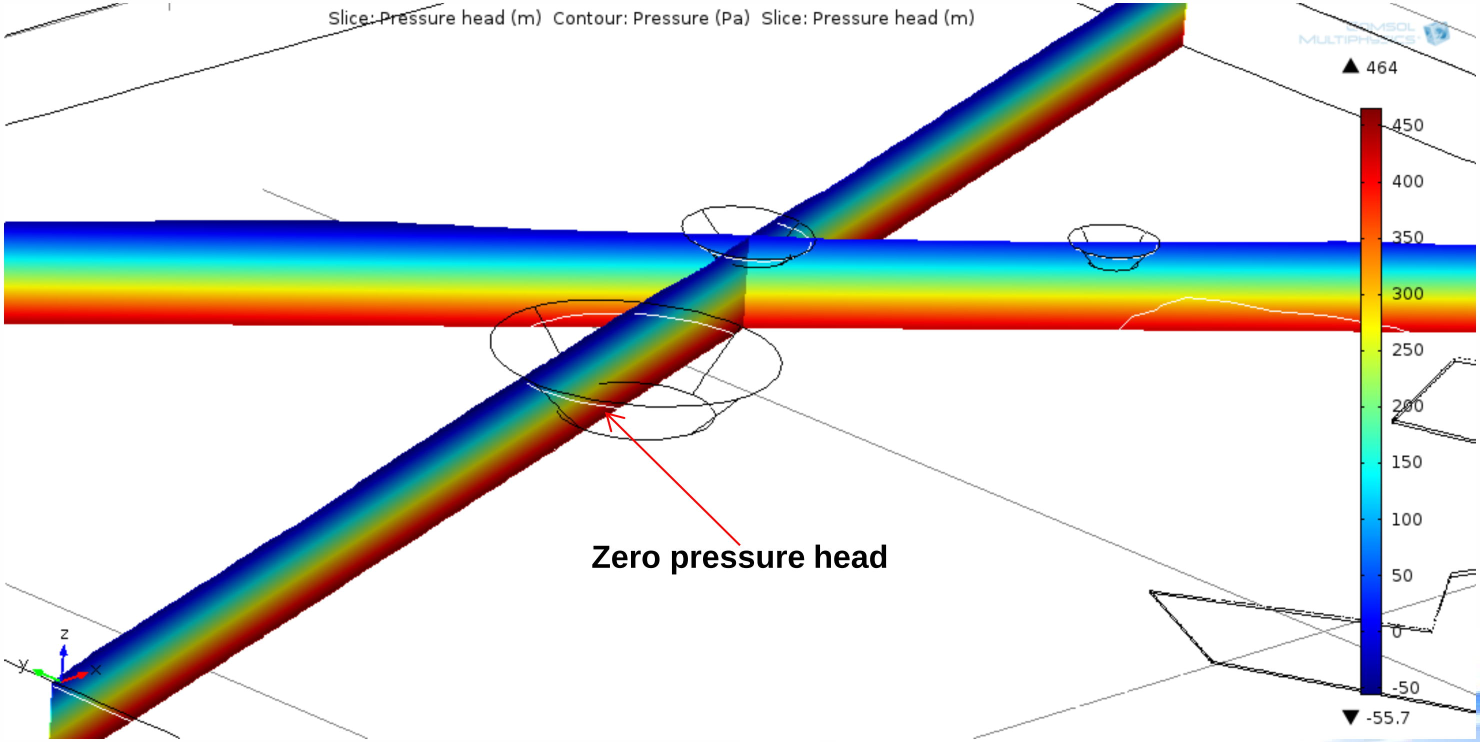


Thermal profile up to 2000 years after decommissioning at 100-year intervals

Thermal profile at the end of 2000 years after decommissioning

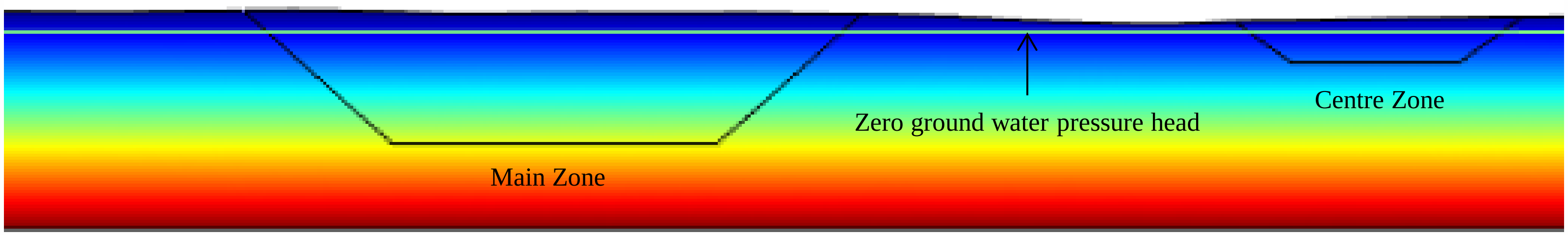
Results of Numerical Modelling – Climate Change Scenario 3 (1)

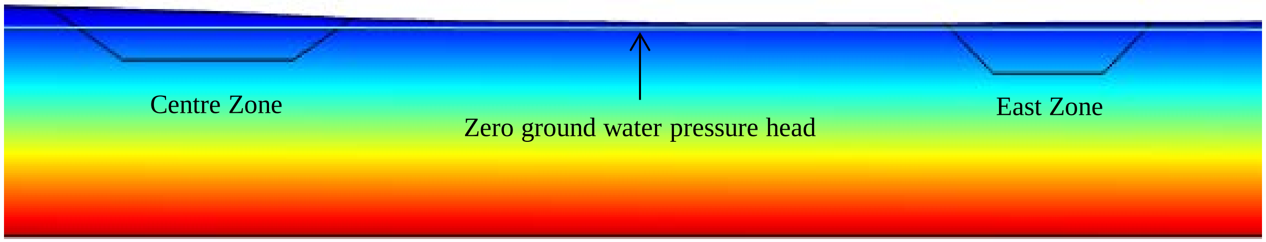
3D pressure head distribution in the Main Zone, Centre Zone and East Zone TMFs



Results of Numerical Modelling – Climate Change Scenario 3 (2)

Ground water pressure head distribution at 2D cut plane through the Main Zone, Centre Zone, and East Zone TMFs





Summary and Conclusions (1)

- If no climate change is assumed, the permafrost at the East Zone TMF could be recovered to its original thickness of around 220 m in 2000 years, while the permafrost at both the Main Zone and Centre Zone TMFs could only freeze back to about 120 m at the end of 2000 years after decommissioning

- If the mean annual ground surface temperature increases 5°C in 100 years, a 35-m thick permafrost layer would be maintained or produced on top of the TMFs in the long term

Summary and Conclusions (2)

- If the mean annual ground surface temperature increases 7°C in 100 years, all of the permafrost would disappear in about 600 years. However, the ground water level would remain at about 30 m below the ground surface at the area of the Kiggavik TMFs
- Deposition of the tailings into the converted TMFs would not likely cause any significant adverse impacts to the surface environment immediately surrounding the decommissioned TMFs with an appropriate TMF design and decommissioning plan

Questions?

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