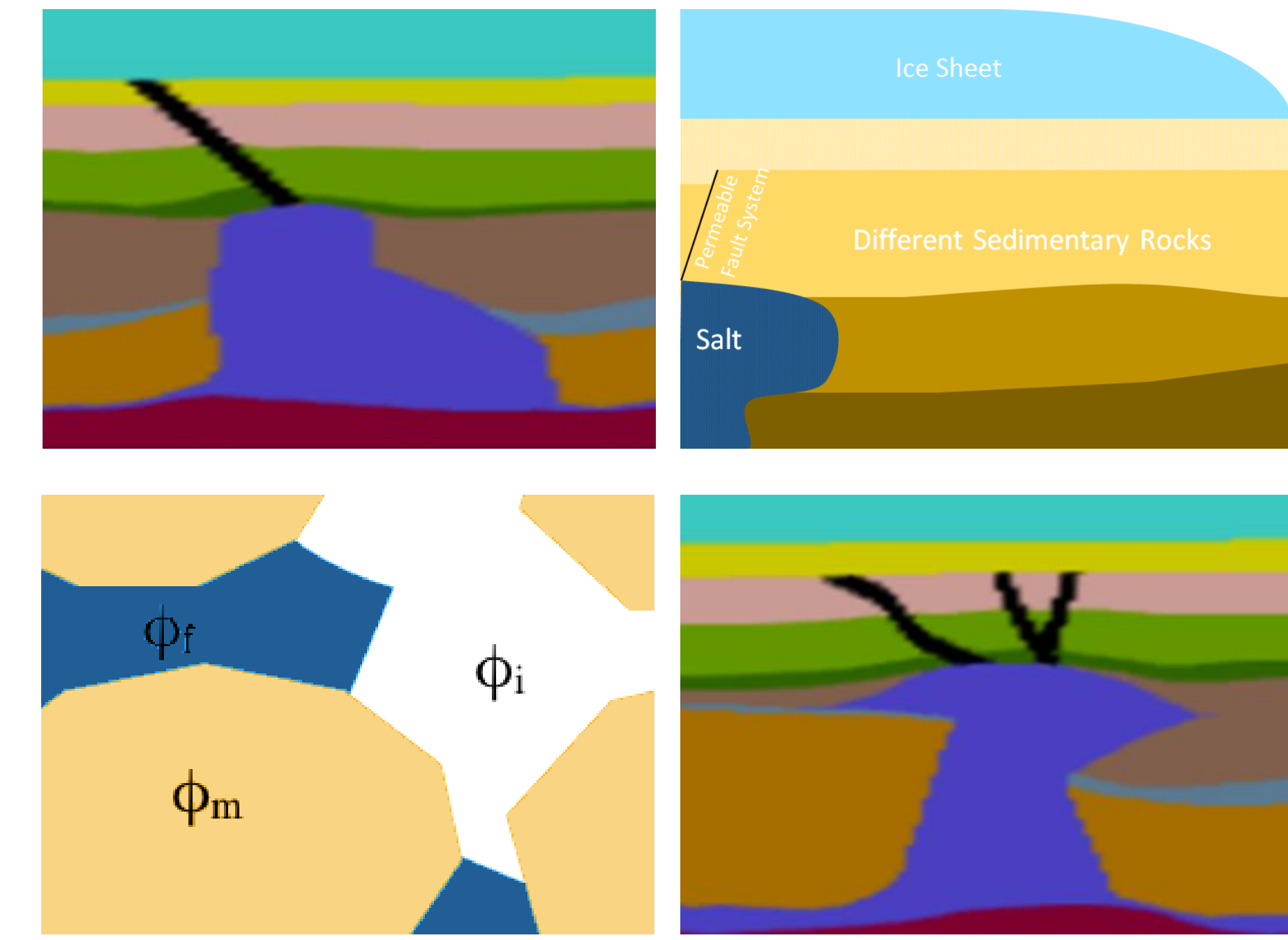
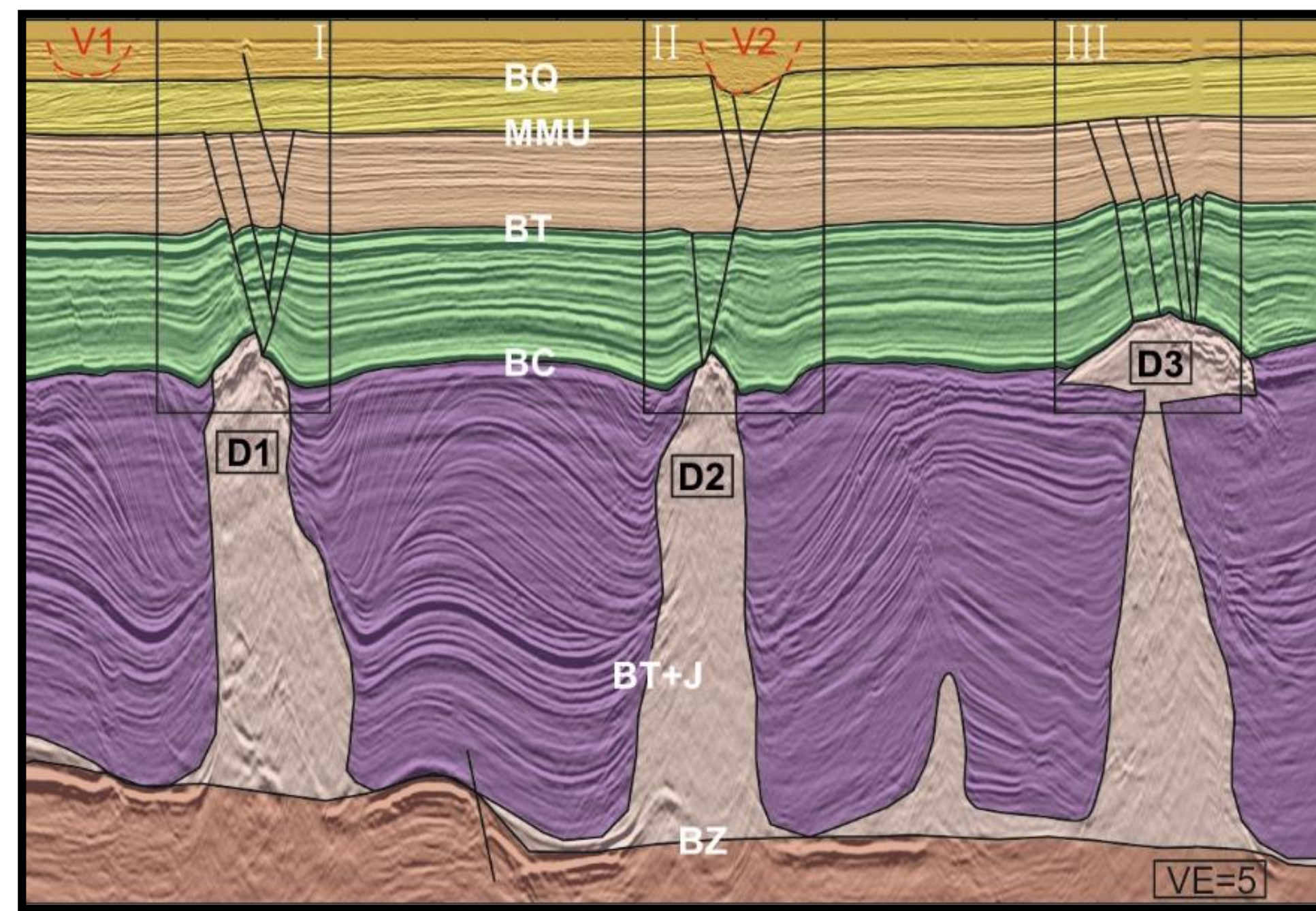




# Feedback Mechanisms between Heterogeneous Geothermal Heat Fluxes and the Dynamic Ice Sheet Reinforce the Formation of Tunnel Valleys

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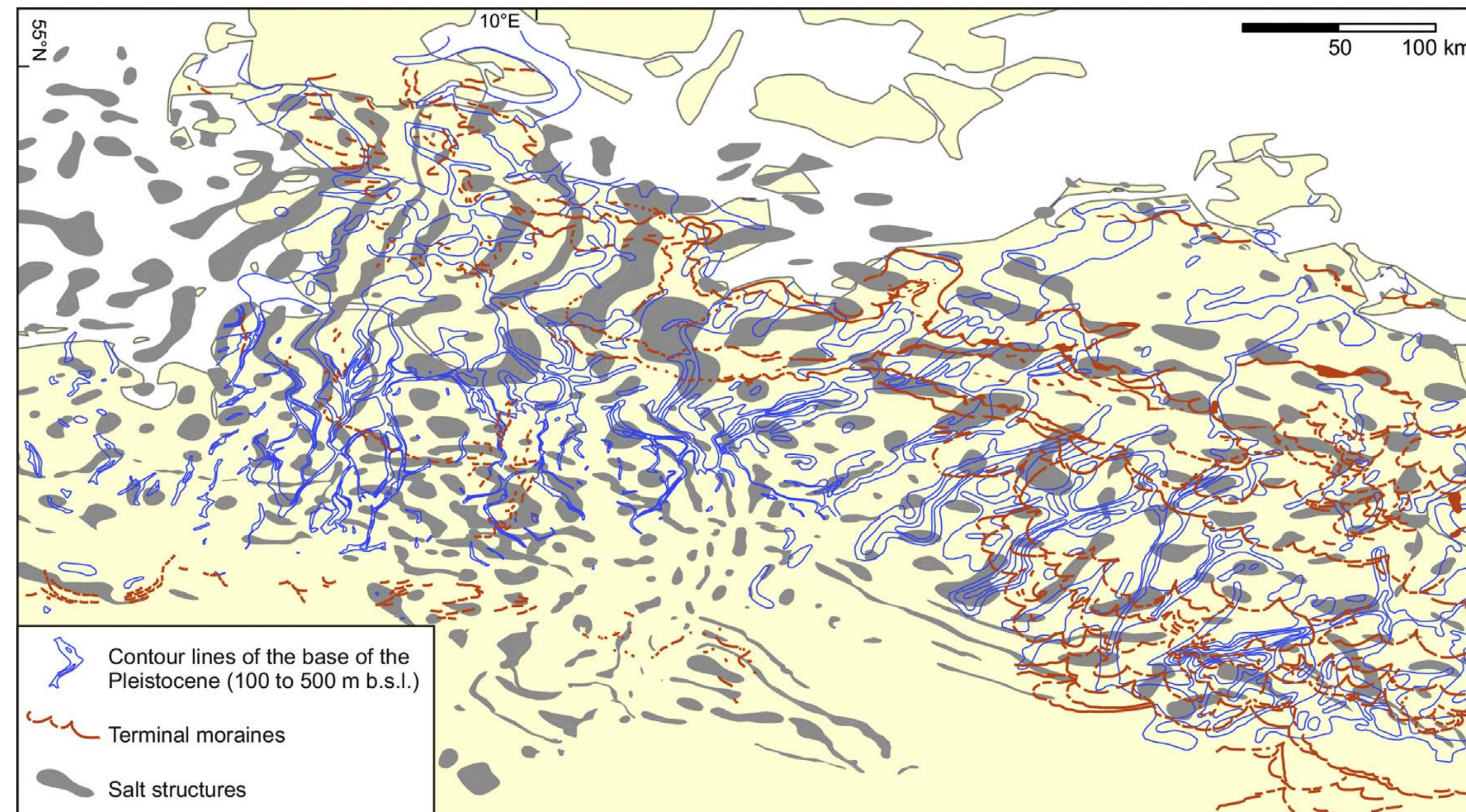
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# Research Motivation and General Idea

## Observations:

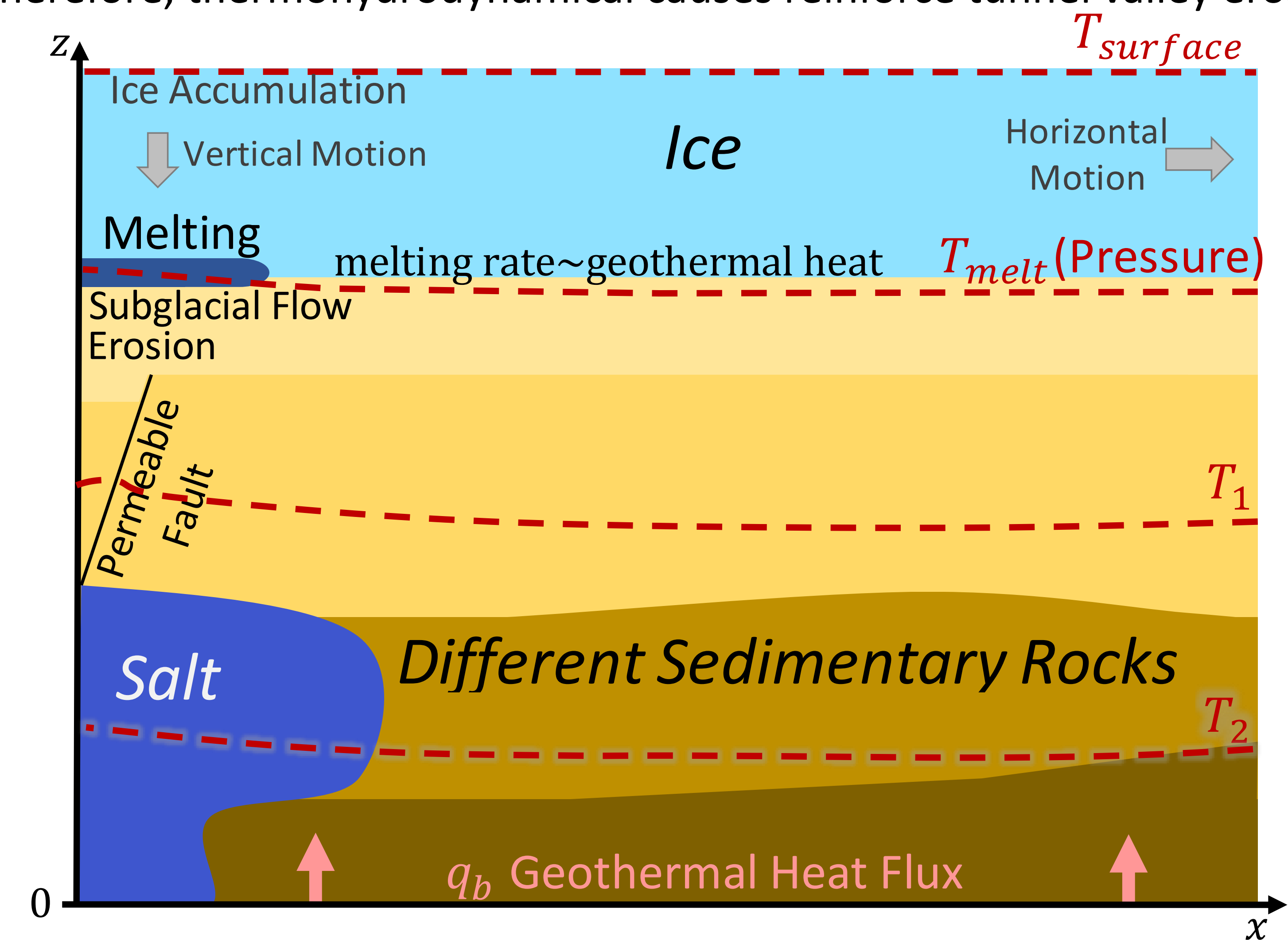
- Tunnel valleys can be more than 400 m deep, 4 km wide and 100 km long (Ó Cofaigh, 1996)
- Tunnel valleys often occur above salt structures (Lang et al., 2014 or Wenau and Alves, 2020)
- Salt has a higher thermal conductivity than sedimentary rocks
- Faults have higher permeabilities enhancing groundwater flow
- Crestal faults above structures facilitate erosion and therefore tunnel valley formation (Wenau and Alves, 2020)



Map of the North German Basin including tunnel valleys in blue and salt structures in grey (Lang et al., 2014)

## Hypothesis:

- The higher thermal conductivity of salt structures lead to an augmented geothermal heat flux above salt structures.
- Crestal faults above salt structures enhance hydrothermal flow of warm and possibly saline groundwater
- These processes lead to an augmented geothermal heat flux through the subsurface-ice interface
- This augments the subglacial melting rate above salt structures
- Therefore, thermohydrodynamical causes reinforce tunnel valley erosion



**Aim:** Investigate to which extent this thermohydrodynamical process has the potential to reinforce tunnel valley formation

# Thermohydrodynamical Model for a Complex Subsurface Structure Including Phase-Change Processes

## Process model:

- Coupled model of the subsurface and the ice allowing for feedback mechanisms
- Include ice dynamics
- Include a heterogeneous subsurface including groundwater flow
- Include phase change processes at the subsurface-ice interface
- Evaluate the geothermal heat flux through the subsurface-ice interface
- Quantify the subglacial melting rate

## Physical Model:

- Heat equation:  $(\rho c)_a \partial_t T = \nabla \cdot (\lambda \nabla T - \rho c T v)$
- Apparent heat capacity:  $(\rho c)_a = \phi_m \rho_m c_m + \phi_f \rho_f c_f + \phi_i \rho_i c_i - \frac{\rho_i L d\phi_i}{dT}$

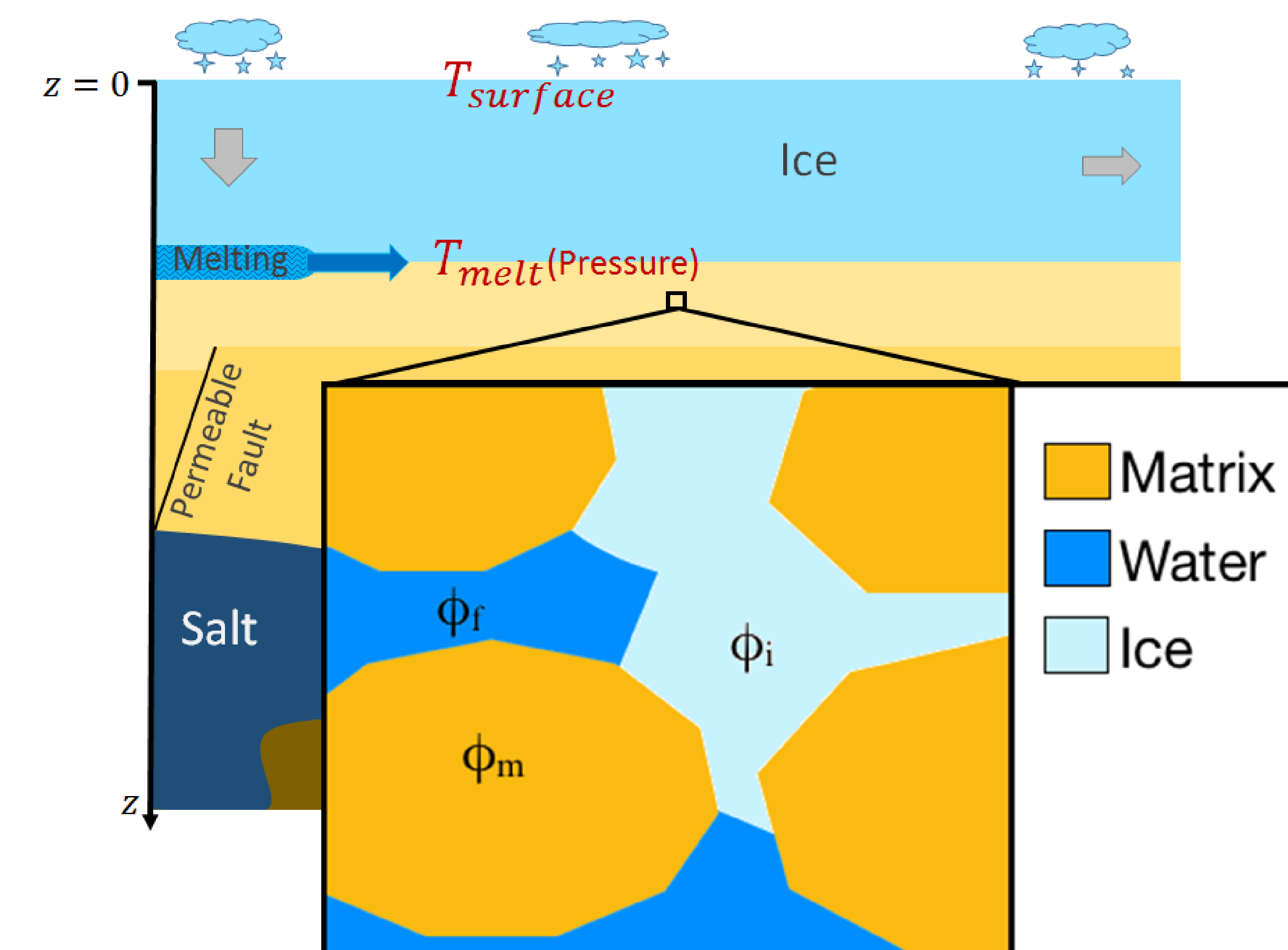
|              |                        |                           |        |                |          |
|--------------|------------------------|---------------------------|--------|----------------|----------|
| $(\rho c)_a$ | Apparent heat capacity | [J / (K m <sup>3</sup> )] | $\phi$ | Volume content | [-]      |
| $\rho$       | Density                | [kg / m <sup>3</sup> ]    | $L$    | Latent heat    | [J / kg] |
| $c$          | Heat capacity          | [J / (K kg)]              | $T$    | Temperature    | [K]      |
| $\lambda$    | Thermal conductivity   | [W / (m K)]               | $v$    | Velocity       | [m / s]  |
|              |                        |                           | $t$    | Time           | [s]      |

## Boundary Conditions and Time Dependency:

- Surface temperature:  $T_{surface} = \text{const.}$
- Geothermal heat flux at the bottom:  $q_b = \text{const.}$
- Pseudo-time integration into a steady-state

## Geometry:

- Structural model of the subsurface interpreted from seismic data
- State prior to Quaternary tunnel valley erosion estimated by replacing the Quaternary strata by strata of the same physical properties of the Paleocene to Miocene strata
- Ice sheet assumed as geological layer with a porosity of 100 %, fully saturated with water or ice



# Characteristic Scales of the Coupled Process

## Temporal Scales:

- Cycle length of ice ages: 100 000 a (Bick, 2006)
- interglacials of 10 000 a (Bick, 2006)
- If the surface temperature  $T_{surface}$  is changed by 10°C for 10 000 a (see figure left), the half life time of the thermal adaption is  $\sim 12\,000$  a (in 1000 m depth)

## Spatial Scales:

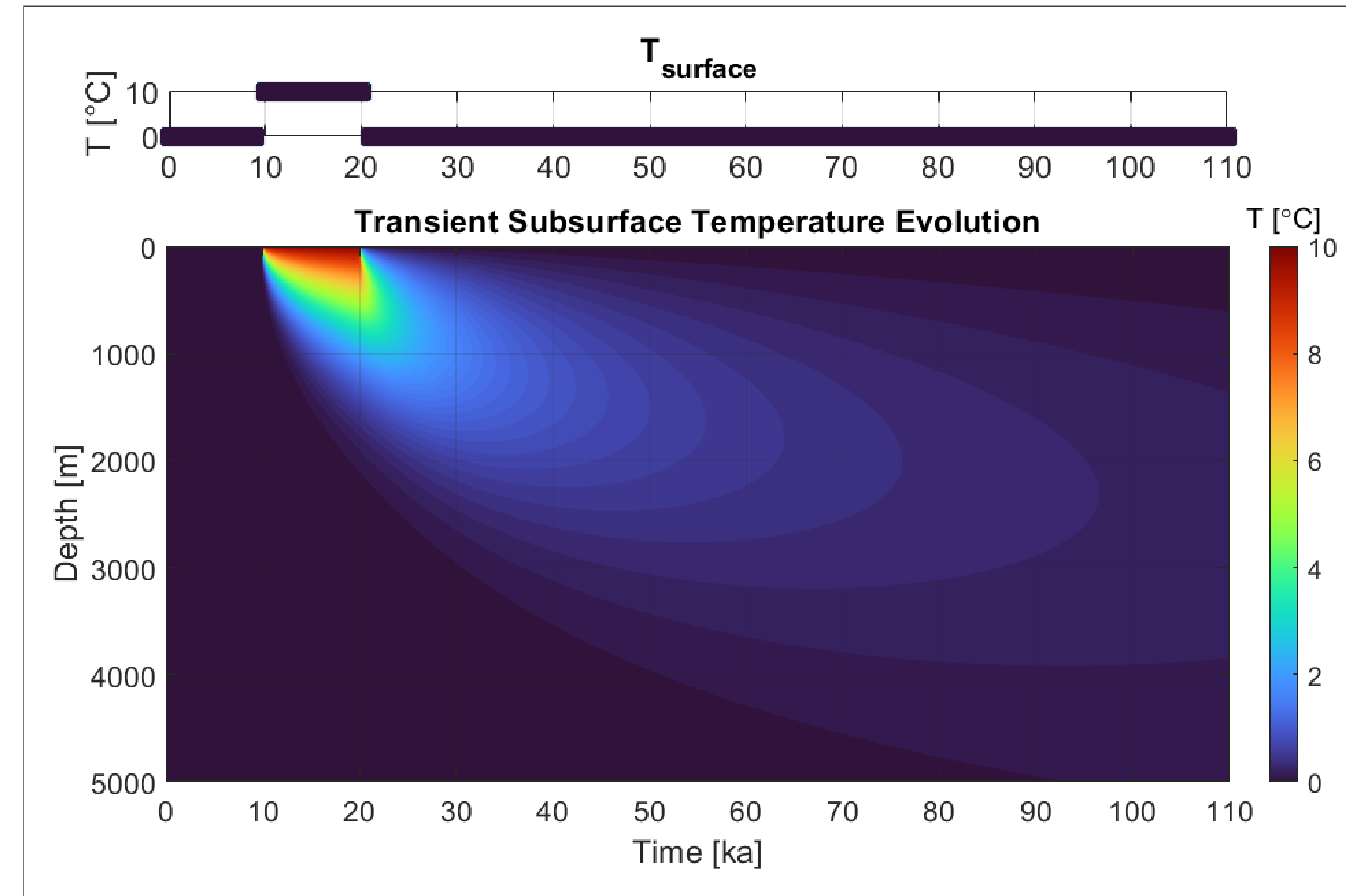
- Ice sheet thickness: 300 – 1700 m (Sachse and Littke, 2018)
- Tunnel valleys (Ó Cofaigh, 1996):
  - Depth: more than 400 m
  - Length: more than 100 km
  - Width: more than 4 km

## Temperature During the Saalian Glaciation (Colleoni et al., 2009):

- Surface air temperature (winter):  $-40 - -30\text{ }^{\circ}\text{C}$
- Surface air temperature (summer):  $-10 - -2\text{ }^{\circ}\text{C}$

## Vertical Ice Motion:

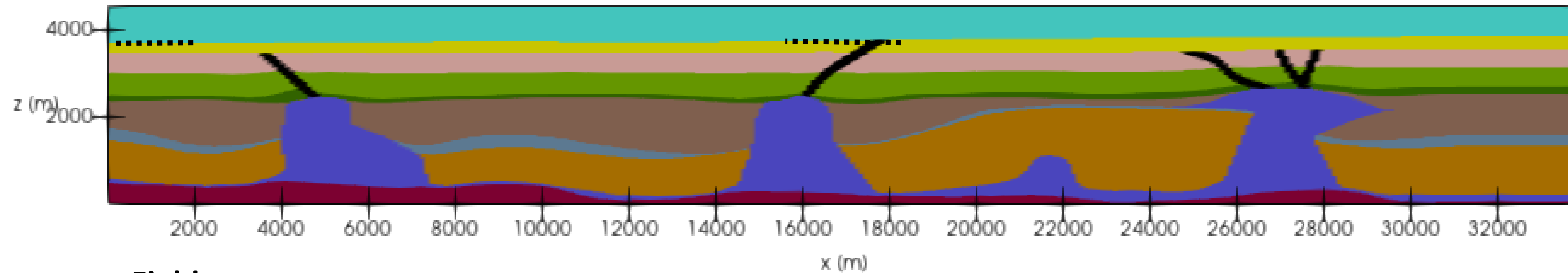
- Mean annual accumulation at surface: 300 – 800 mm/a (Colleoni et al., 2009)
- Meltwater to erode tunnel valleys:  $\sim 10^8\text{ m}^3$  per melt season (Beaud et al., 2018)



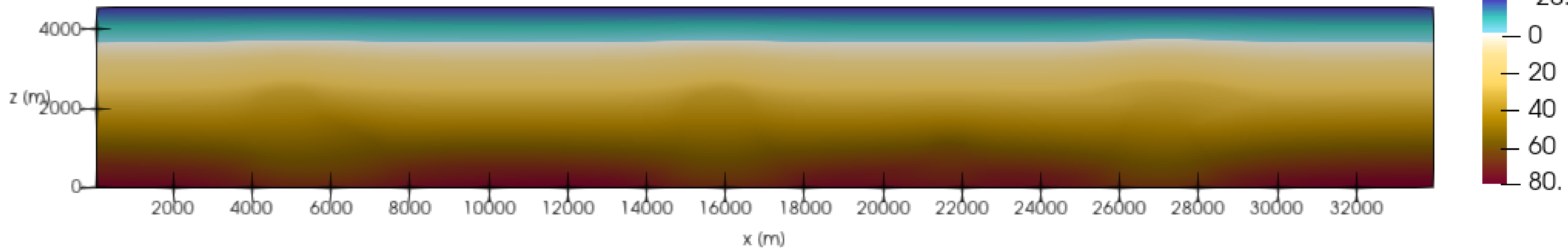
# Case Study with SHEMAT-Suite: Southern North Sea

## Geological Model:

State prior to Quaternary glaciations estimated, tunnel valley locations indicated by dotted lines

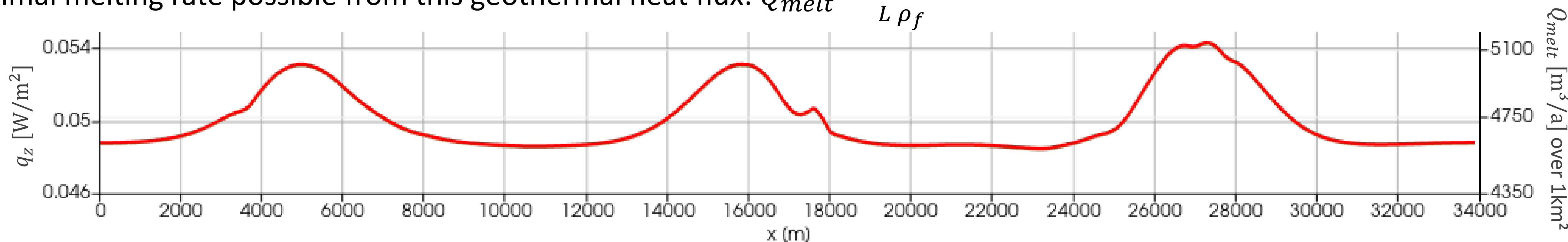


## Temperature Field:



## Vertical Heat Flux Through the Subsurface-Ice Interface:

Maximal melting rate possible from this geothermal heat flux:  $Q_{melt} = \frac{q_z F}{L \rho_f}$



## Conclusions:

- The geothermal distribution has a complementary effect to mechanical processes
- The role of hydrothermal flow processes will be quantified in the next step

## Volumetric water/ice content $\phi$ and thermal conductivity $\lambda$ of the different geological units

| Unit             | $\phi$      | $\lambda$ [W/(mK)] |
|------------------|-------------|--------------------|
| Ice Sheet        | 100 %       | 2.3                |
| Fault Zones      | 4 %         | 2.4                |
| Miocene          | 0.1 %       | 2.2                |
| Tertiary         | 0.1 %       | 2.9                |
| Upper Cretaceous | 6 %         | 2.1                |
| Lower Cretaceous | 6 %         | 2.1                |
| Keuper           | $10^{-7}$ % | 2.3                |
| Muschelkalk      | $10^{-7}$ % | 2.3                |
| Buntsandstein    | 4 %         | 2.4                |
| Zechstein Salt   | $10^{-7}$ % | 4.9                |
| Pre-Zechstein    | 3 %         | 3.3                |

Thermal Parameters adapted from Beha et al. (2008) and Evans (1977)

## Boundary Conditions:

- Surface temperature of  $-20^{\circ}\text{C}$
- Geothermal heat flux of  $50 \text{ mW/m}^2$
- No heat flux to the sides
- No water flow through any boundary

|            |                        |           |
|------------|------------------------|-----------|
| $Q_{melt}$ | Melting rate           | [m³ / s]  |
| $q_z$      | Vertical heat flux     | [W / m²]  |
| $F$        | Area                   | [m²]      |
| $L$        | Latent heat            | [J / kg]  |
| $\rho_f$   | Density of fluid water | [kg / m³] |

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