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

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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)

**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

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

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

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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: \((\rho c)_a = \phi_m \rho_m c_m + \phi_f \rho_f c_f + \phi_i \rho_i c_i - \rho_i L d \phi_i \frac{dT}{dt}\)

Boundary Conditions and Time Dependency:
- Surface temperature: \(T_{\text{surface}} = \text{const.}\)
- 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

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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 $T_{\text{Surface}}$ 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°C
- Surface air temperature (summer): -10 – -2°C

Vertical Ice Motion:
- Mean annual accumulation at surface: 300 – 800 mm/a (Colleoni et al., 2009)
- Meltwater to erode tunnel valleys: $\sim$10¹⁸ m³ 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: \( Q \) = \( q_z L \rho_f F \)

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

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

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

Boundary Conditions:
- Surface temperature of -20°C
- Geothermal heat flux of 50 mW/m²
- No heat flux to the sides
- No water flow through any boundary

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References


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