Reduction of scenario uncertainties through climate models (REDUKLIM)

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URS final cluster Meeting – Potsdam

Marc Johnen, Philipp Horenburg, Judith Flügge, Jens Wolf

Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH

Christine Kaufhold, Andrey Ganopolski

Potsdam Institut für Klimafolgenforschung (PIK)

Klaus Fischer-Appelt, Frank Charlier

Lehrstuhl für Endlagersicherheit (ELS)

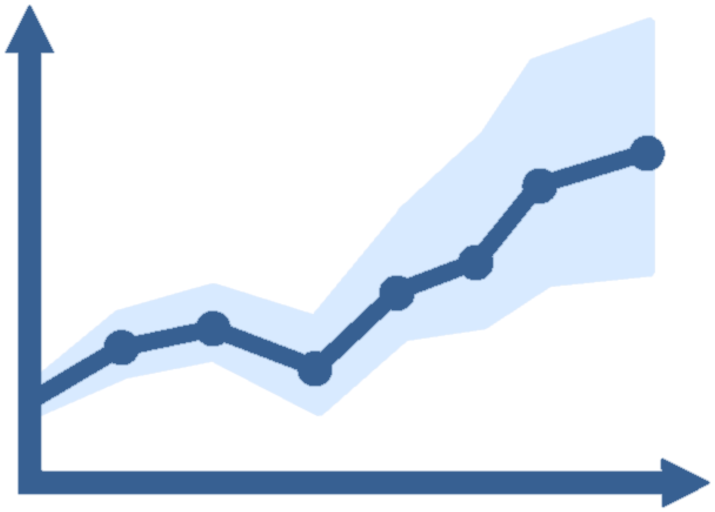
Introduction and overview

- Project background:
  - Assumptions regarding the suitability as a location with the best possible safety according to site selection act (StandAG) are necessary.
  - Assumptions are based on geological and geophysical results and model calculations based on them.
  - Each of these components is fraught with uncertainties.
- Goals of the project:
  - Reduction of complexity, e. g. by
    - Assigning uncertainties to categories
    - Developing recommendations for dealing with and characterizing uncertainties
    - Quantifying uncertainties
  - Improvement of the robustness of the repository system and thus of the safety

Introduction and overview

How can **future climate developments** be taken into account in the context of **long-term safety** and which **uncertainties** do these developments have?

- Assessment period of one million years (EndSiAnfV § 3)
- Consideration of the geological and climatic situation
  - Developing a better understanding of potential future climate developments
  - Linking of climate modelling to groundwater processes for the safety assessments
- Consideration of uncertainties in the context of the site selection



Outline

- WP1: Climate modelling (Kaufhold/PIK)
- WP3: Consequences and sensitivity: Groundwater modelling (Johnen/GRS)
- WP2: Impact of climate models on biosphere dose estimations (Horenburg/GRS)

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WP1: Climate modelling

Christine Kaufhold, Andrey Ganopolski

Potsdam Institut für Klimafolgenforschung (PIK)

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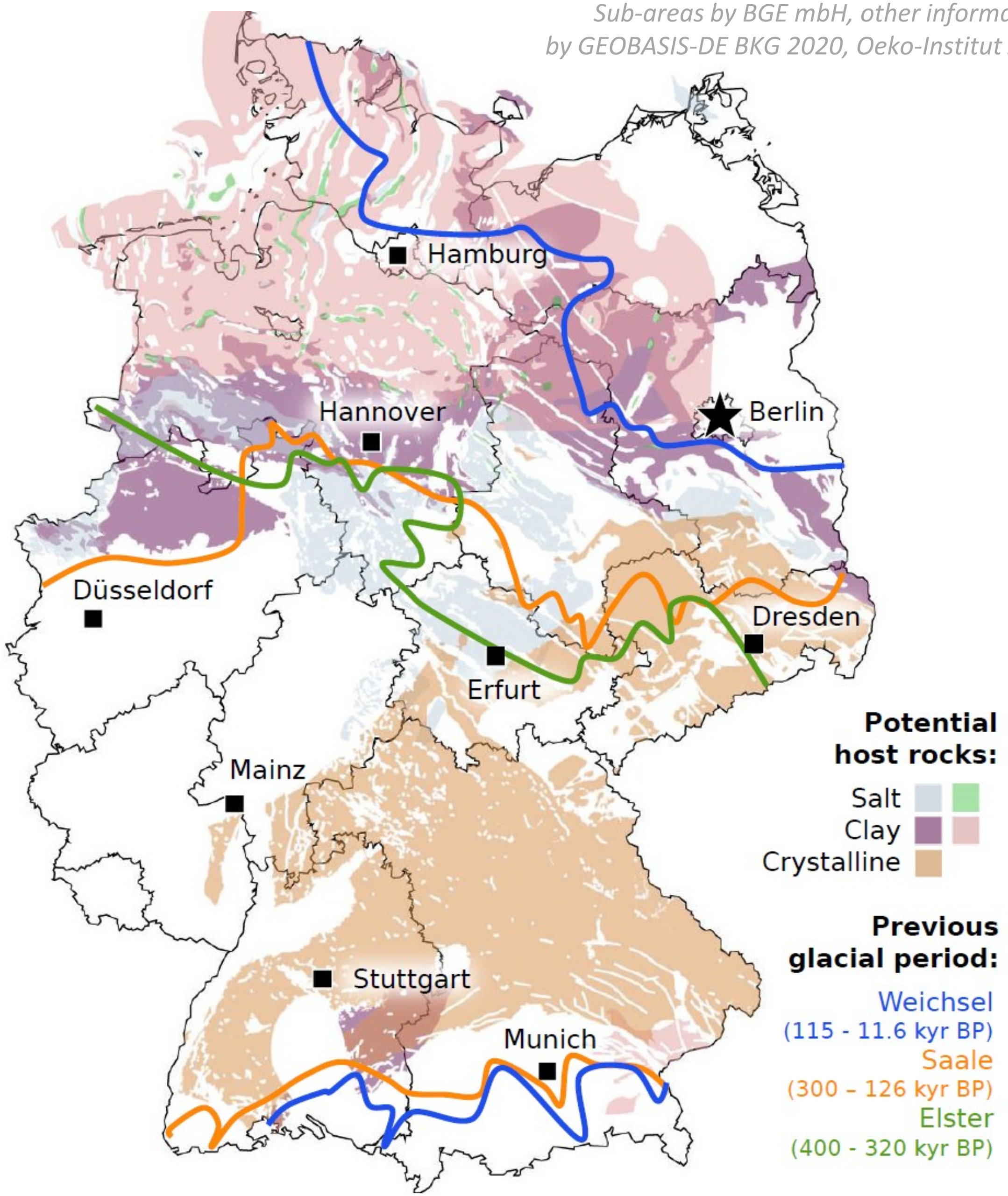
Why does this matter? Working outline

- Waste in Germany must be secure for a period of 1 million years (EndSiAnfV § 3)
- Portion of considered areas have been covered by ice sheets in the past; future glacial periods could potentially compromise long-term safety

The goals of PIK for REDUKLIM:

1) Climate model validation against paleodata
2) Assess uncertainties related to model parameters and poor constraints
3) Develop climate scenarios for next 100,000 years (more detailed) and 1 million years (less detailed)

Sub-areas by BGE mbH, other information by GEOBASIS-DE BKG 2020, Oeko-Institut 2023



* We will discuss these today

Progress and project output

1) Climate model validation against paleodata:

- transient simulations of the last glacial inception (*Willeit et al. 2024*) and termination

2) Assess uncertainties related to model parameters and poor constraints:

- examined how lifetime of anthropogenic CO_2 and removal timescales is affected by climate sensitivity, interactive methane, spatially explicit weathering, land carbon processes, emissions pathway, and strength of the weathering feedback (*Kaufhold et al. 2024, BG, in review*)
- examined the effect of our equilibrium condition for long-term simulations (*Kaufhold et al. 2025, in prep*)*

3) Develop climate scenarios for next 100,000 years (more detailed) and 1 million years (less detailed):

- detailed transient simulations of the next 1 kyr compliant with different policy-based scenarios and current climate modelling protocols (*Kaufhold et al. 2024, ERL, in review*)
- idealized transient simulations of the next 100-200 kyr, both coupled climate–carbon cycle (*Kaufhold et al. 2024, BG, in review*) and, climate–carbon cycle–ice sheets (*Kaufhold et al. 2025, in prep*)*
- integrated experimental data and paleo-knowledge to develop plausible future scenarios for the next 1 million years*

Can we predict when inception will occur?

- Climate has been changing for last millions of years via Milankovitch cycles; solar insolation known for the next ~50 Myr

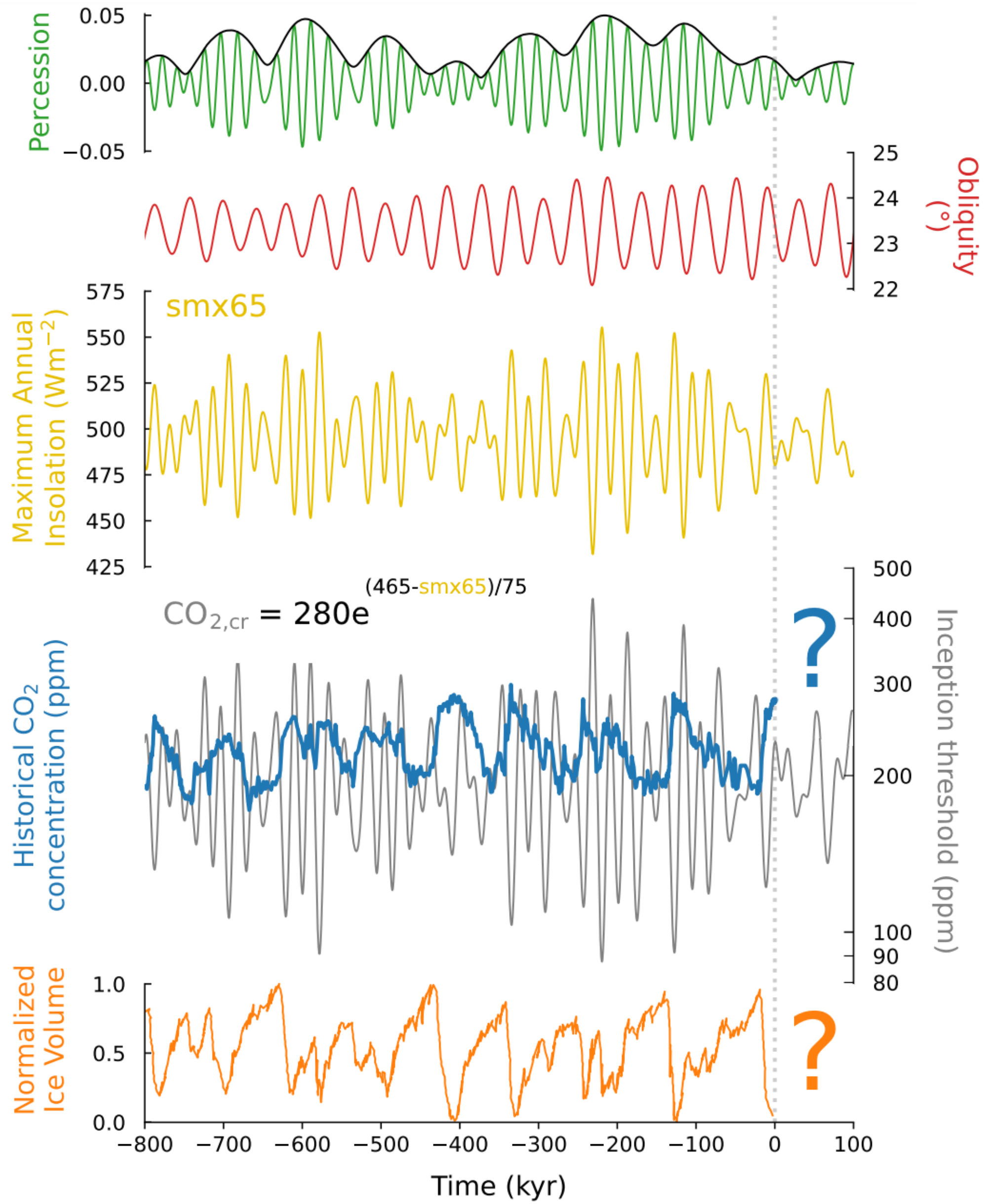
- Fundamental relationship exists between maximum summer insolation at 65°N $smx65$ and atmospheric CO_2 concentration

- Relationship can be used to predict the timing of the next glaciation

- If simulated atmospheric CO_2 falls below the critical CO_2 ‘inception’ threshold $CO_{2,cr}$, conditions are favourable for inception to occur

$$CO_{2,cr} = 280e^{(465-smx65)/75}$$

Eq. 1 – Ganopolski et al. 2016; Talento et al. 2024



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Experimental set-up

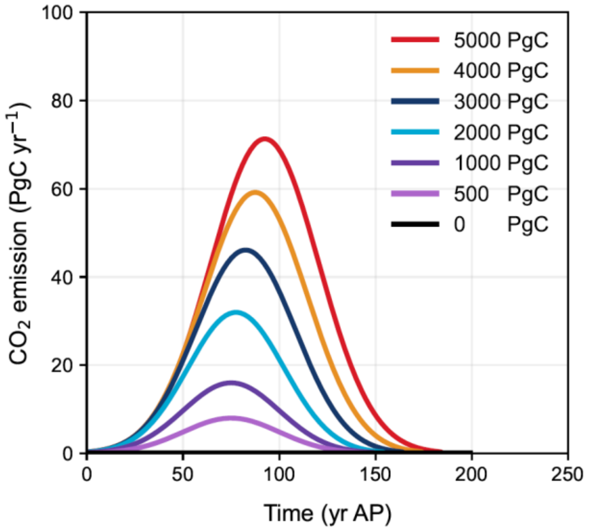
- Generate an ensemble of long-term future climate change scenarios
- All experiments:
  - forced by idealized CO_2 emission scenarios of 0 PgC to 5000 PgC
  - start from a pre-industrial equilibrium climate state
  - run with changing orbital parameters

In a first step…

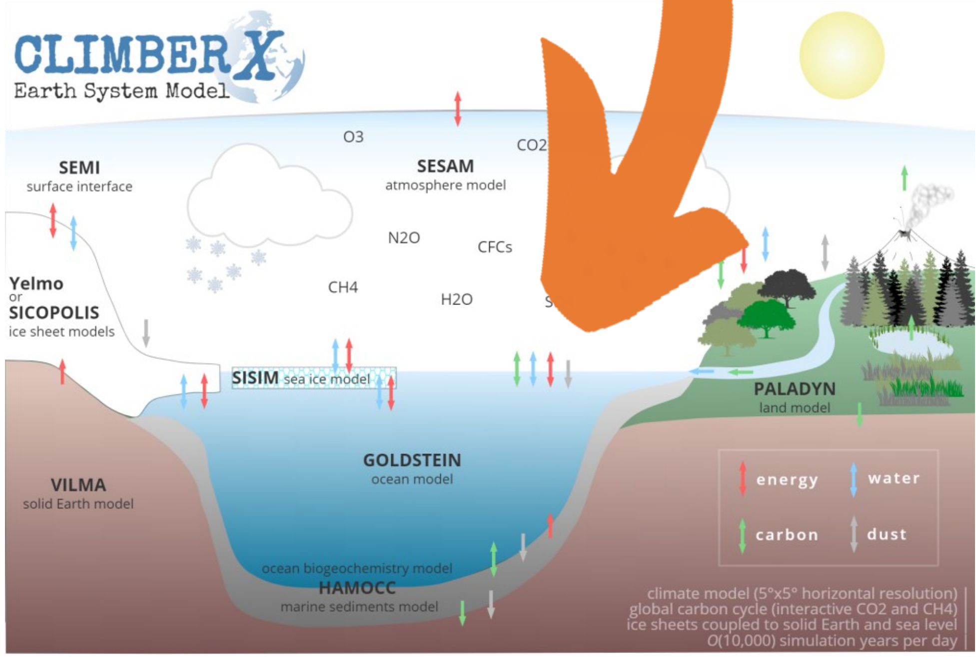
- Transient coupled climate—carbon cycle experiments to (1) project long-term future CO_2 concentrations and (2) predict when glacial inception will occur based on *Eq. 1*

In a second step…

- Transient coupled climate—carbon cycle—ice sheet experiments to evaluate our predictions



5000 PgC ≈ all fossil fuels
500 PgC ≈ currently emitted
0 PgC ≈ natural evolution



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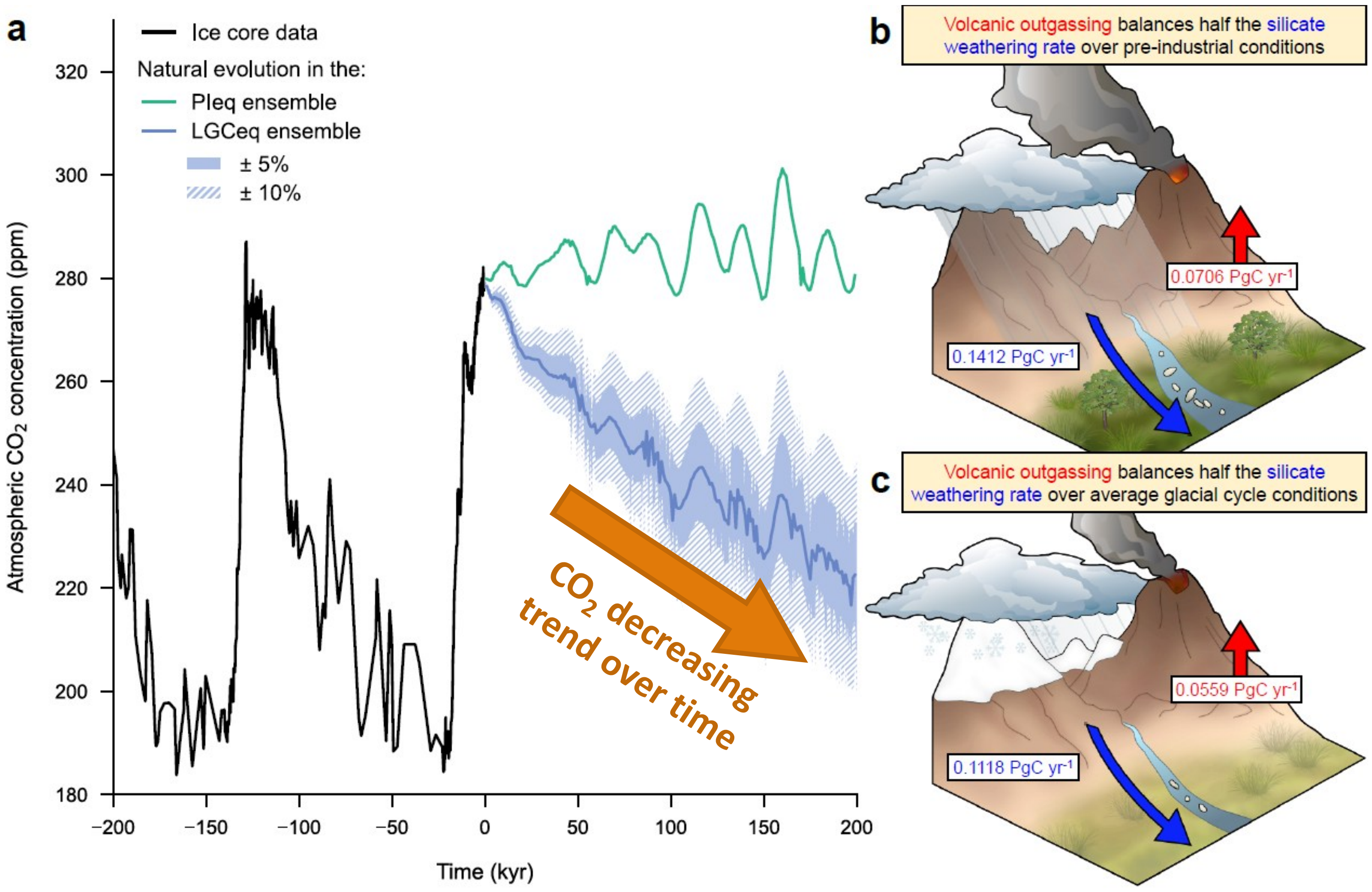
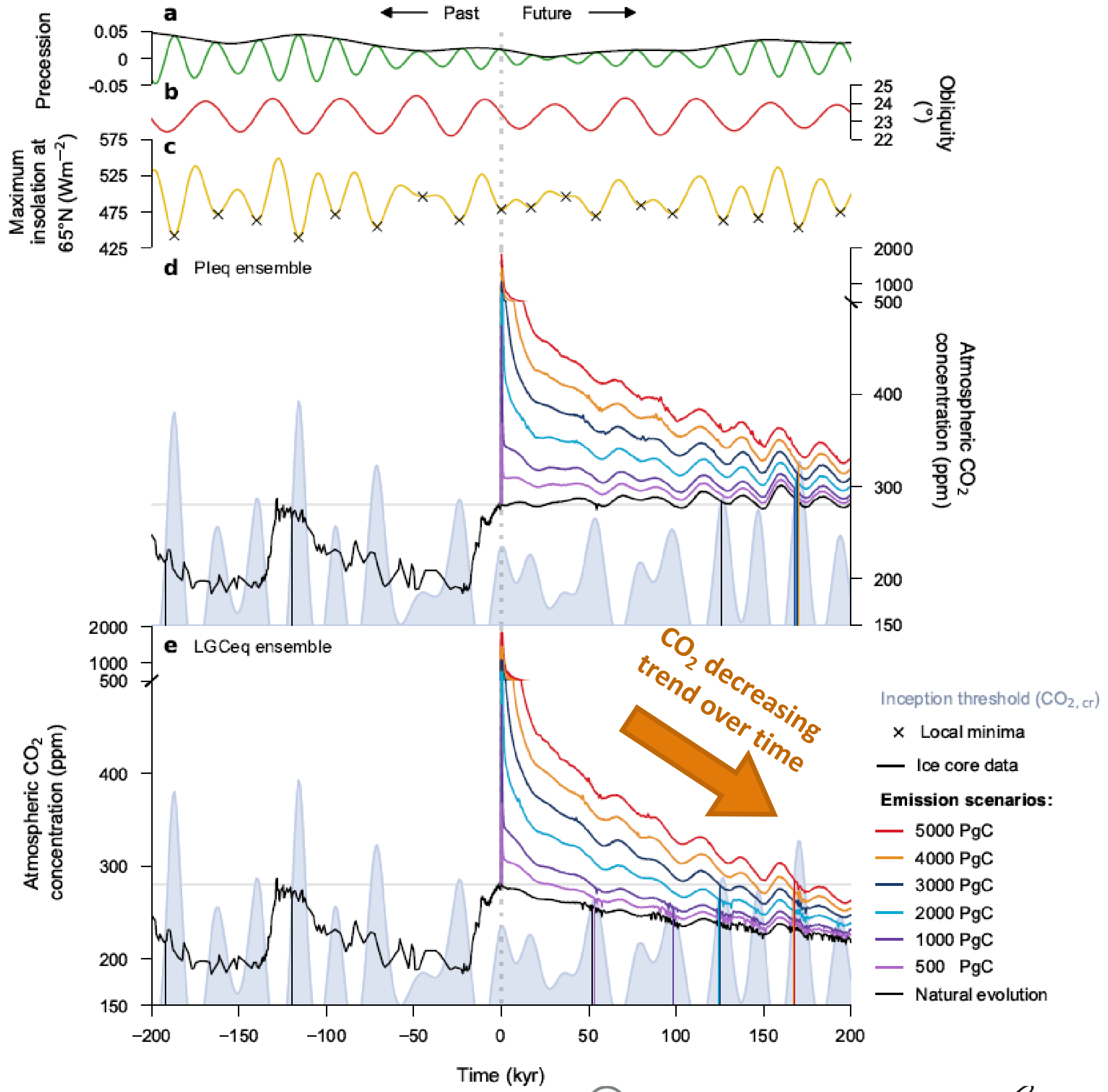
Effect of the equilibrium condition in CLIMBER-X

- Volcanic outgassing is a tunable parameter that must be chosen in our model
- Equilibrium condition requires volcanic outgassing to be ½ global CO_2 consumption by silicate weathering
- Many long-term future climate simulations assume that the pre-industrial state was in equilibrium (**PIeq**)
- Instead reasonable to assume that volcanic outgassing should balance the average silicate weathering rate over the last glacial cycle (**LGCeq**)



Length of the current interglacial

- The timing of the next glacial cycle under natural conditions could shift from ~125 kyr AP to ~50 kyr AP, depending on carbon cycle equilibration assumptions
- The ~50 kyr AP estimate aligns better with previous projections, confirming LGCeq may be more realistic
- In LGCeq, glacial inception would occur around 50 kyr AP under present-day anthropogenic emissions
- Inception occurs before 200 kyr in nearly all scenarios, regardless of volcanic outgassing
- This is due to the strong silicate weathering feedback, which significantly reduces the atmospheric lifetime of CO_2 emissions



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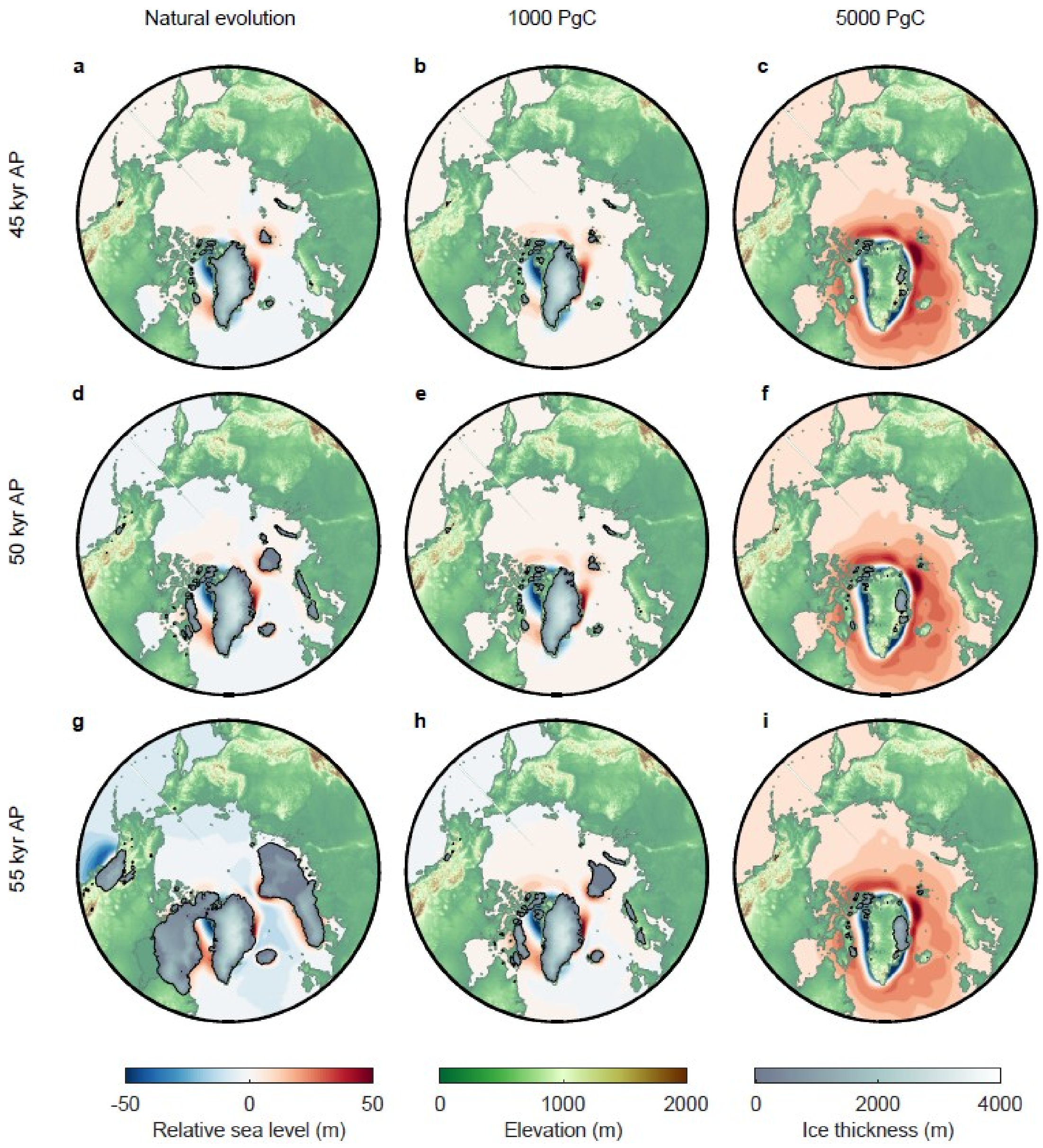
What will future ice sheets look like?

- Re-run same experiments with interactive ice sheets to determine if our predictions hold
- Glacial inception marked by rapid ice sheet expansion over the Canadian and Scandinavian Arctic
- Inception begins with ice nucleation in high-altitude areas (Svalbard, Scandinavian Mountains, Novaya Zemlya) before coalescing
- Glacial inception simulated under the natural evolution around 50 kyr as predicted
- Emissions >1000 PgC (where inception was not predicted to occur at 50 kyr) does not undergo a rapid NH ice expansion



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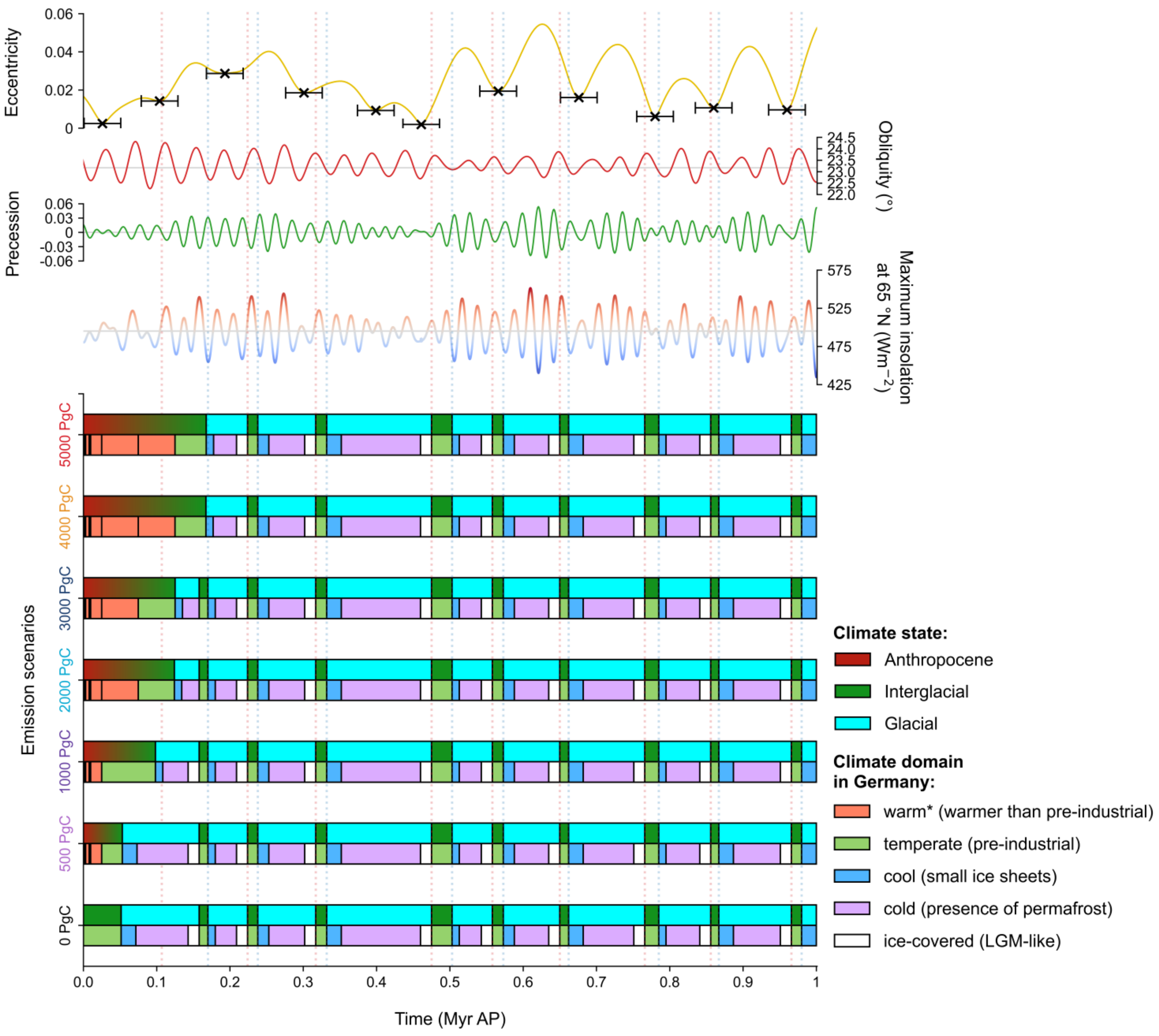
Climate domains for Germany

- Timeline of future scenarios based on these experiments and past glacial cycles
- First glacial inception and length of warm climate domain taken from LGCeq (*Kaufhold et al. 2025, in prep*)
- Glacial terminations follow GMT (*Ganopolski 2024*): occur during rising boreal summer insolation if the previous precession maximum was at low eccentricity and anti-phase with obliquity
- Subsequent inceptions align with the next significant insolation minima



Summary

- Deep-future simulations face many uncertainties, but these can be explored
- CLIMBER-X, an intermediate-complexity model, enables studies beyond GCMs while offering higher complexity than similar models
- We reviewed past progress: model validation, constraints on the atmospheric lifetime of anthropogenic CO_2, and transient simulations of the next 1 kyr compliant with different policy-based scenarios
- Results on the next glacial inception will be in Kaufhold et al. 2025 (in prep)

Key takeaways:

- Present-day emissions are unlikely to delay the glacial inception that would naturally occur at 50 kyr AP
- Glacial inception will likely occur before 200 kyr under all emission scenarios and configurations
- Ice sheets will remain small for the next 150 kyr due to weak insolation minima; unlikely to reach Germany before then
- Ongoing work on a conceptual model to assess if future cycles can change in frequency based on the CO_2 decreasing trend since the beginning of the Pliocene

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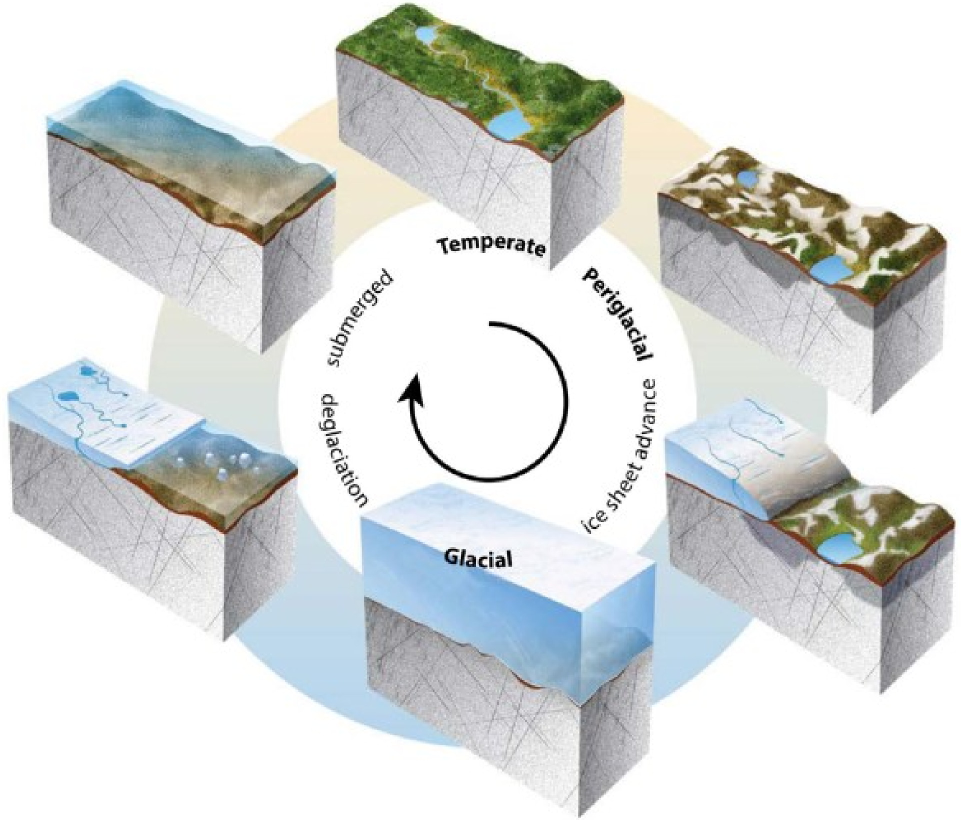
WP3: Consequences and sensitivity: Groundwater modelling

Groundwater models – methods and aims

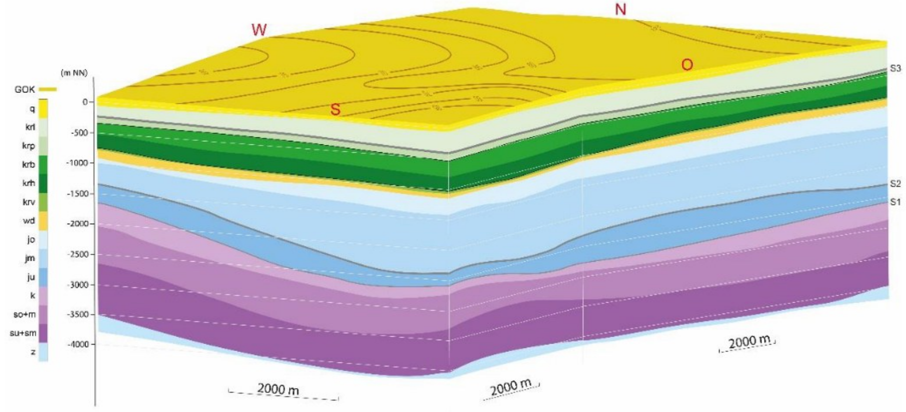
- Climate developments are stylized and transferred to groundwater models with different climate states
- Flow- and Transport simulations to show the potential changes in mass distribution in geosphere
- Estimate transport paths and lengths over the assessment period of 1 million years
- Consideration of uncertainties in the context of the site selection and long-term safety analysis
- GRS groundwater flow and transport code d^3f++ for complex numerical simulations



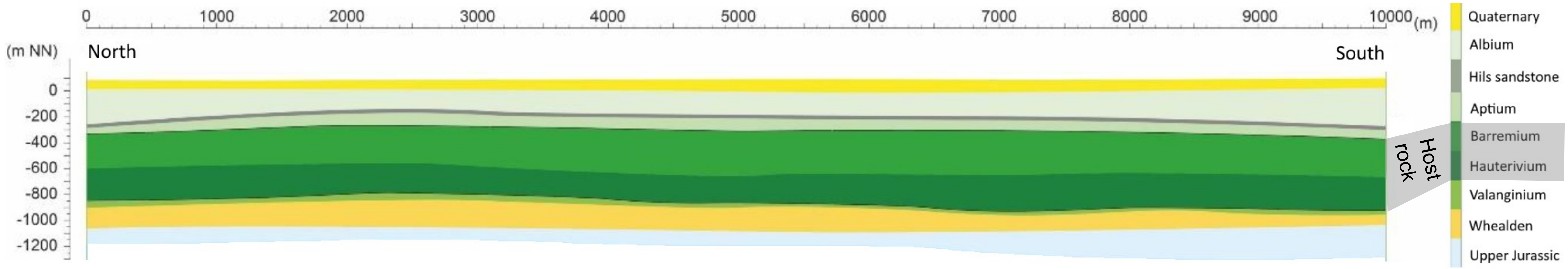
Brandefelt et al. 2019 /SKB TR-19-04

Model region – “Ansicht Nord”

- Generic site for claystone as host rock for a final repository
- 2D cut out model area with 9 lithostratigraphic units with different characteristics
  - Quaternary to Jurassic with Lower Cretaceous as host rock
  - Around 300 m covering host rock above the repository
- The dimensions of the model area are approximately 10 km in width by up to 1.400 m in height.

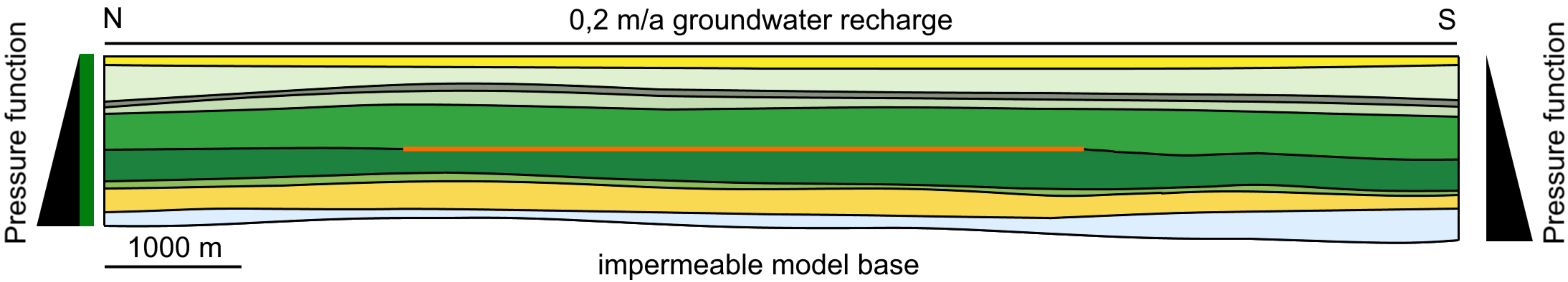


Jobmann et al. 2017/
Alfarra et al. 2020



Boundary conditions "temperate climate"

- Generic homogeneous layers
- No geometry changes during the simulation
- Mechanical and biological processes are not included in these simulations
- Parameterization partly after Alfarra et al. 2020
- Hydraulic gradient of 0.002 m/m added to the depth depended pressure function
- Instantaneous tracer release in repository as starting condition (orange line)



Stylized climate states

Permafrost

- Water in pore space is frozen → reduced permeability
- No groundwater recharge in permafrost areas

Glaciation

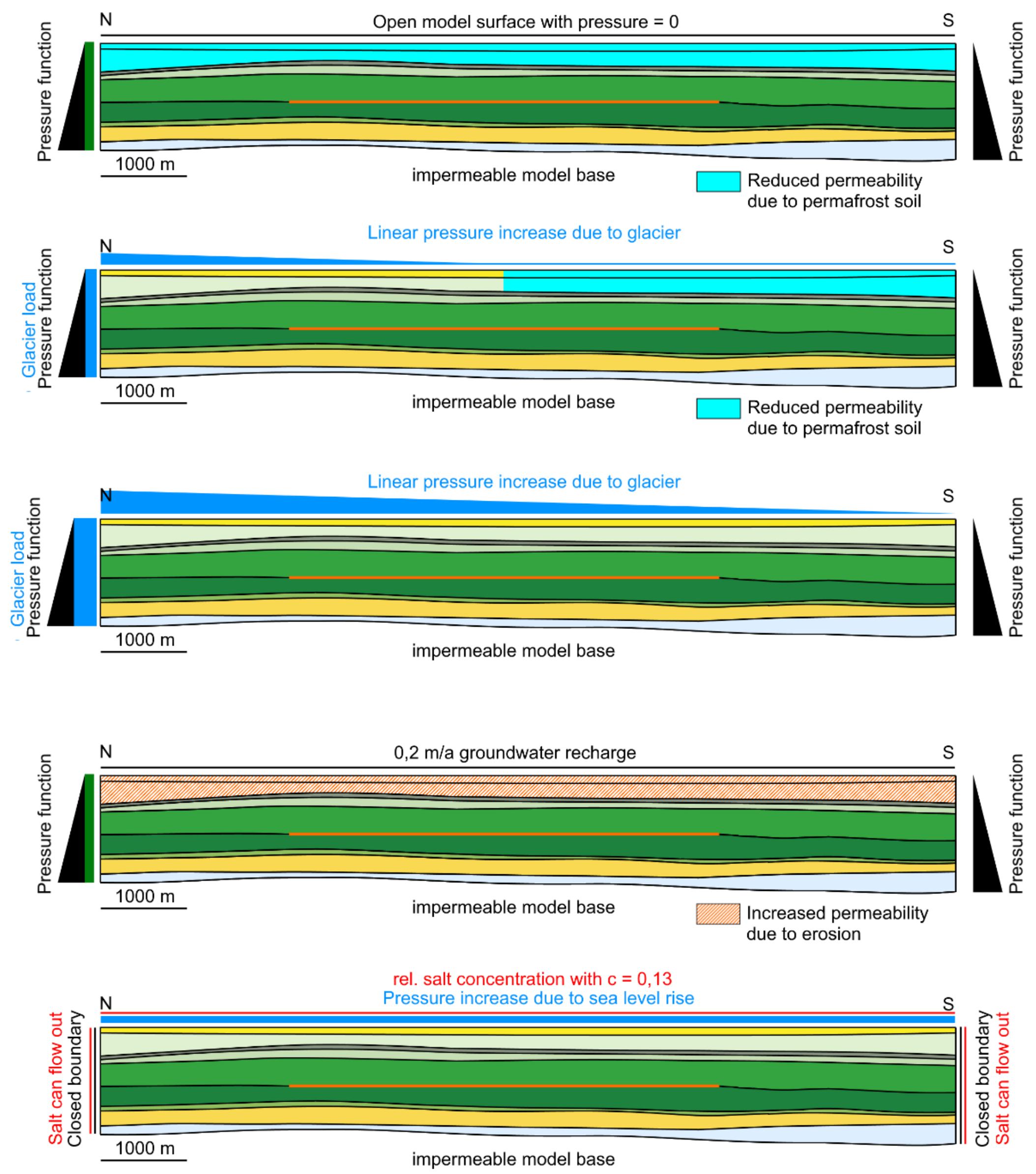
- Additional pressure at model surface and boundary
- Increased groundwater recharge rate in the model area

Erosion

- High pressure under glacier can cause glacial channels
- Filling of the glacial channels with sandy facies
- Increase in permeability and porosity values in channels

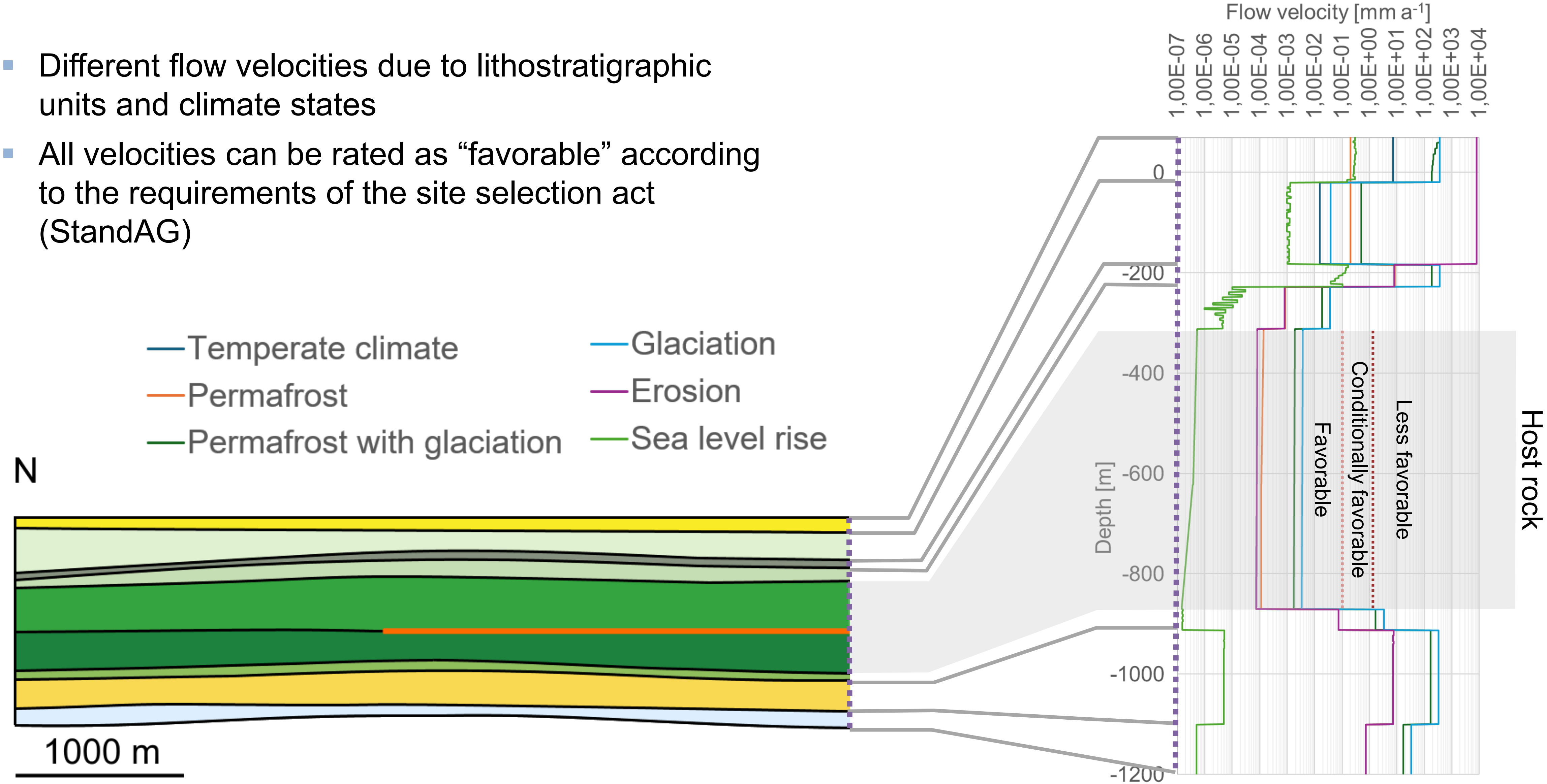
Sea level changes

- Saltwater intrusion
- Higher pressure at the surface with sea level rise
- Stagnating groundwater flow conditions



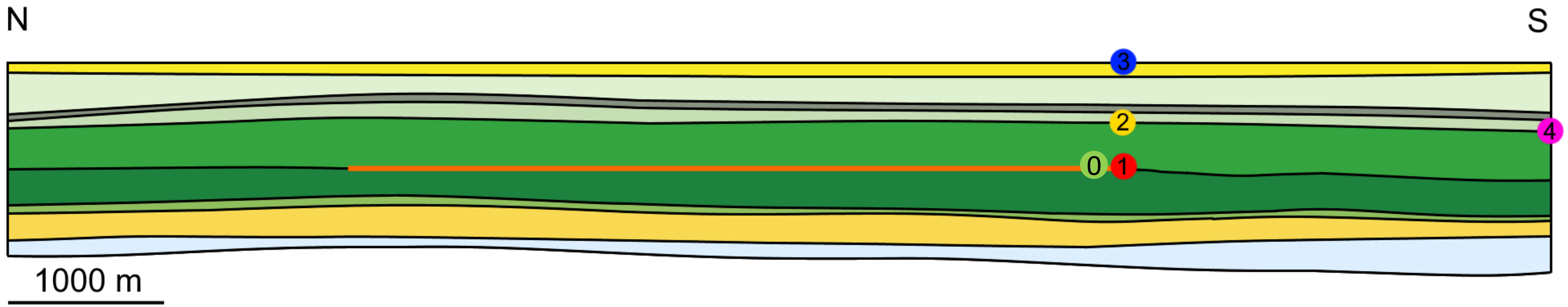
Results – flow velocities

- Different flow velocities due to lithostratigraphic units and climate states
- All velocities can be rated as “favorable” according to the requirements of the site selection act (StandAG)



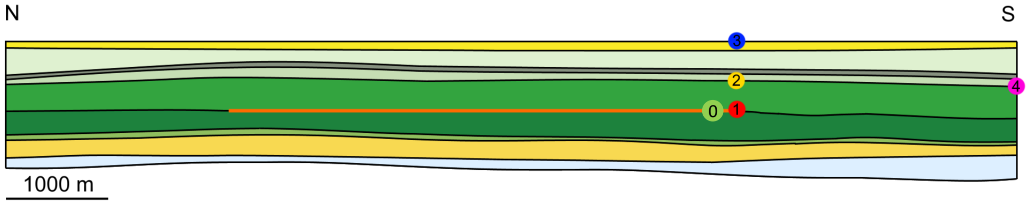
Results – transport

- Instantaneous release of mass into the model
- Repository is abstractly represented as a line (orange line)
- No decay is assumed in this simulations



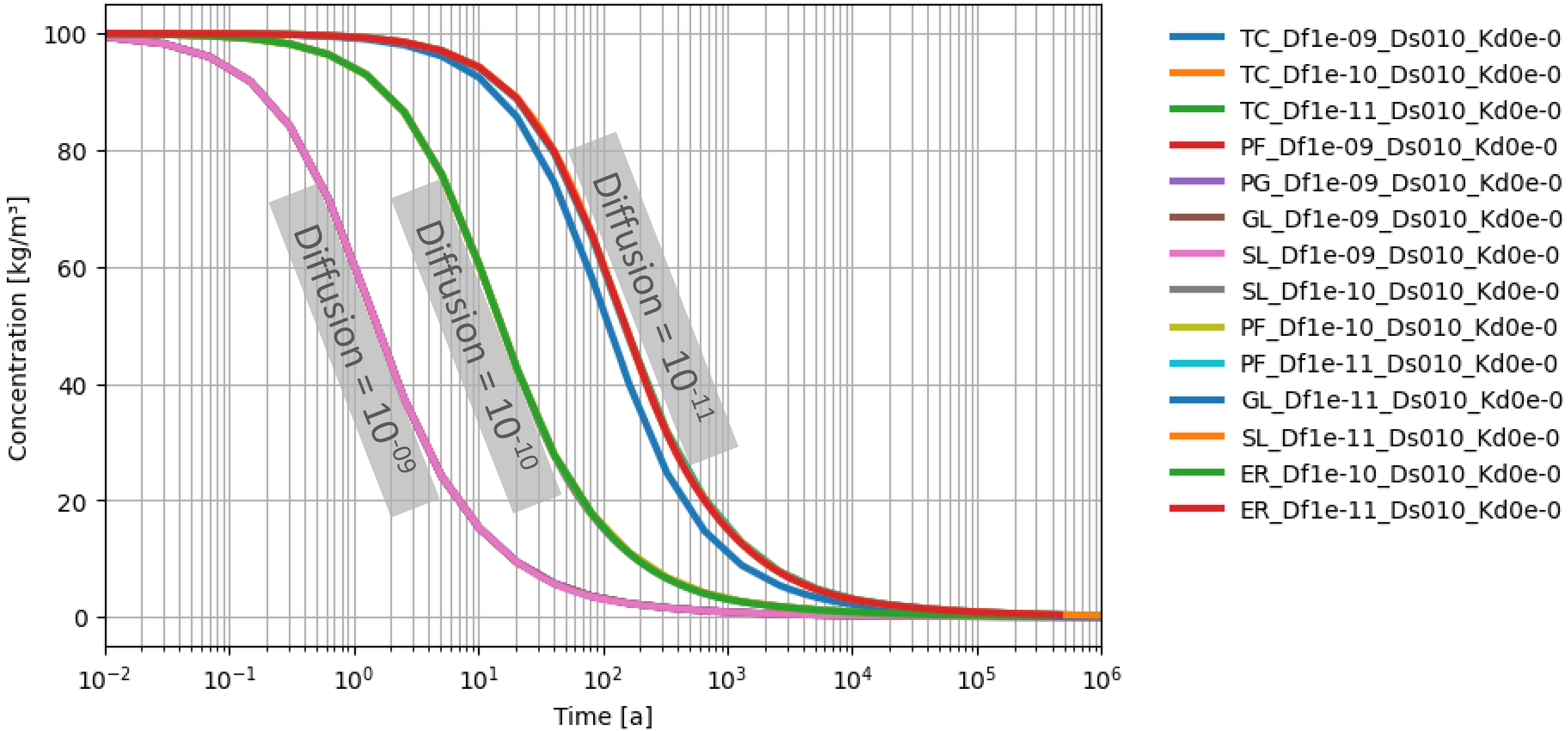
- Comparison between the climate states and parameter variations through breakthrough curves and mass evaluation in the lithostratigraphic units

Results – breakthrough curves (climate states)

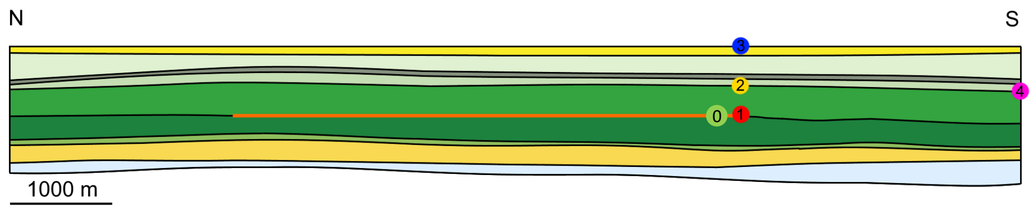


- Diffusion coefficient dominates transport velocities
- Climate states do not change the concentration trend

0

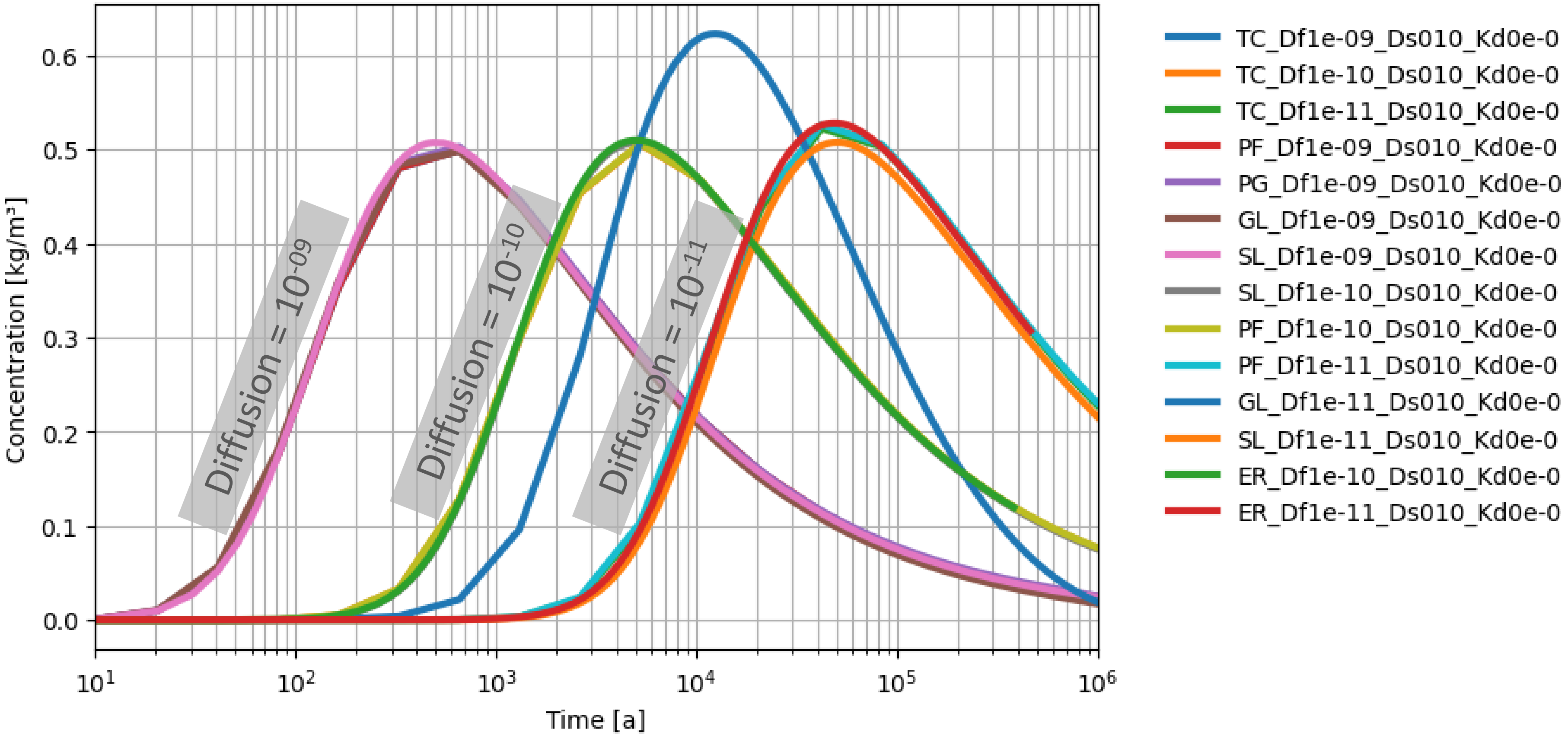


Results – breakthrough curves (climate states)

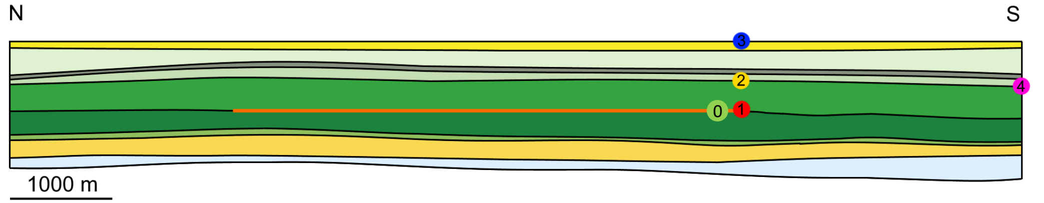


- Glaciation scenario with low diffusion coefficient shows influence of hydraulic gradient

1

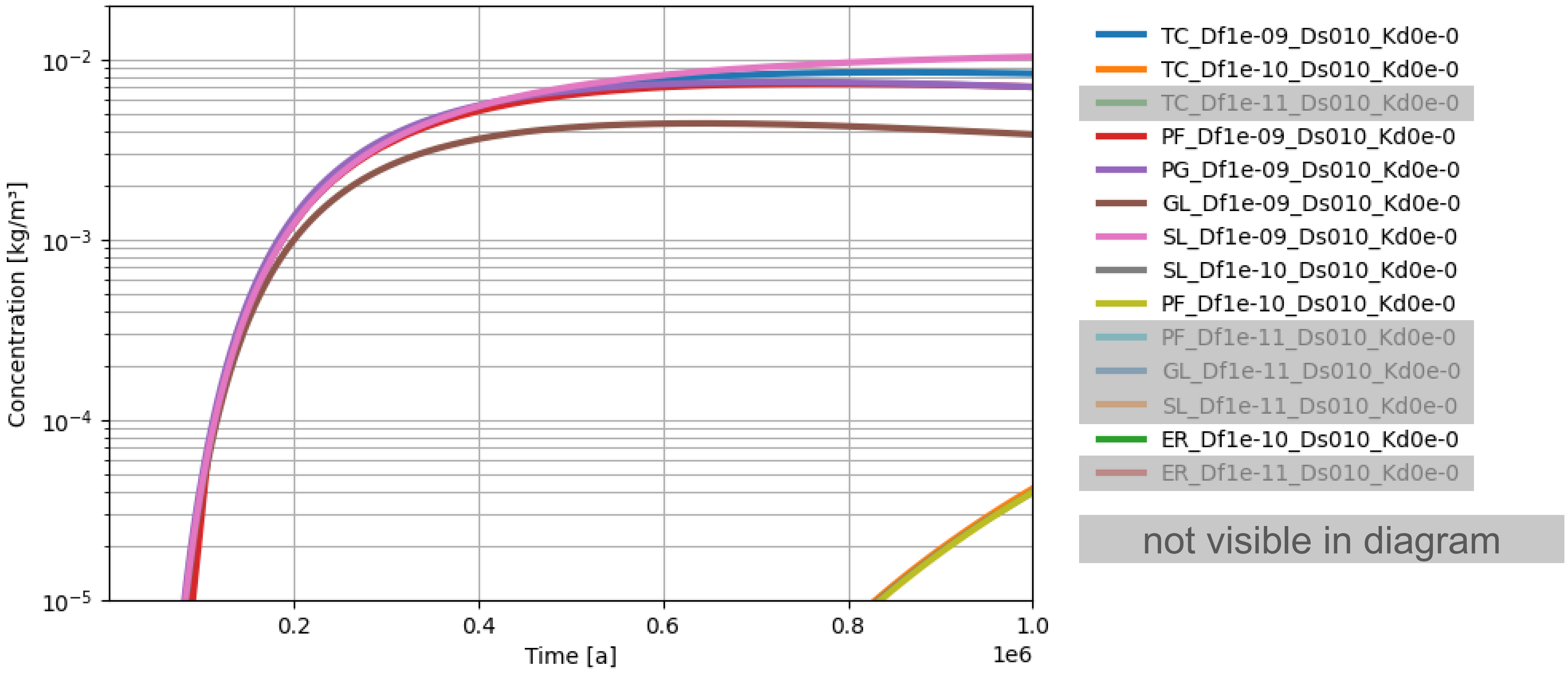


Results – breakthrough curves (climate states)



- Concentrations slightly differs for climate states at the surface of the host rock

2



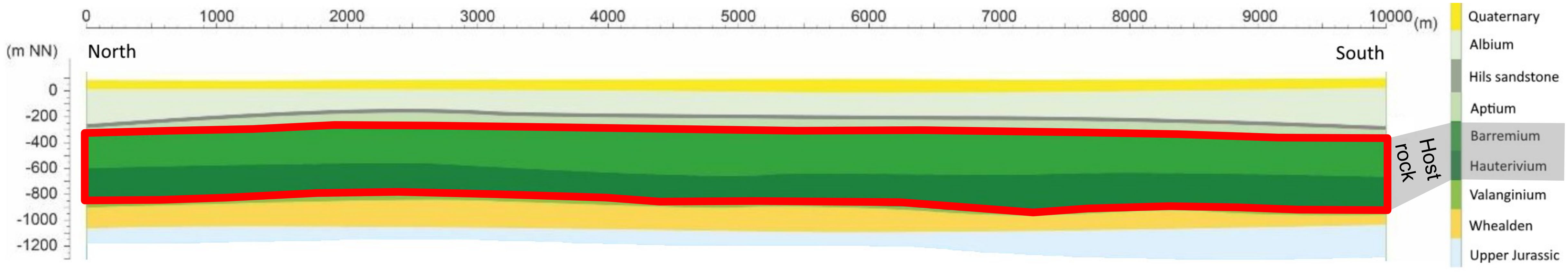
Mass evaluation

- Requirement for the long-term safety according to the EndlSiAnfV:
  - §4 Safe enclosure of radioactive waste: (5) *"For the expected developments, it shall be examined and demonstrated that during the assessment period*

    1. a maximum total proportion of 10^{-4} and

    2. annually at most a proportion of 10^{-9}

    [...] is discharged from the area of the essential barriers.“

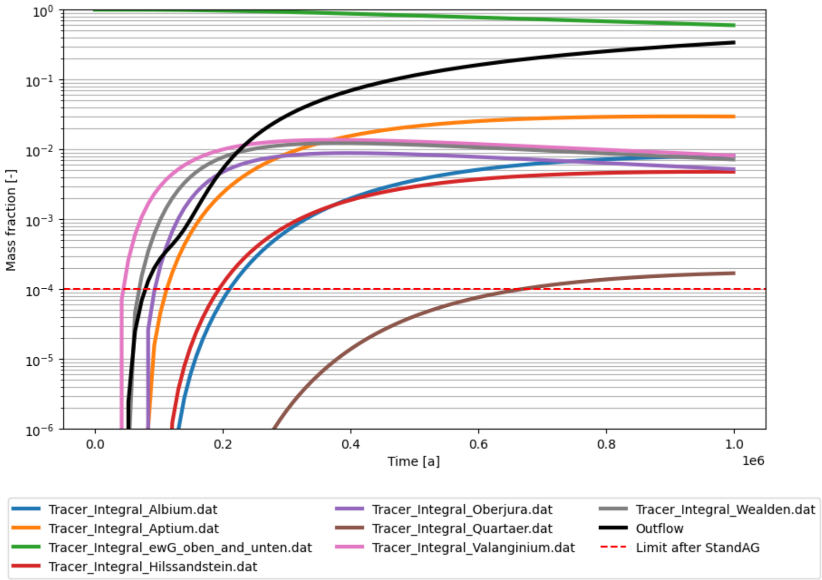


Results – mass integrals (diffusion)

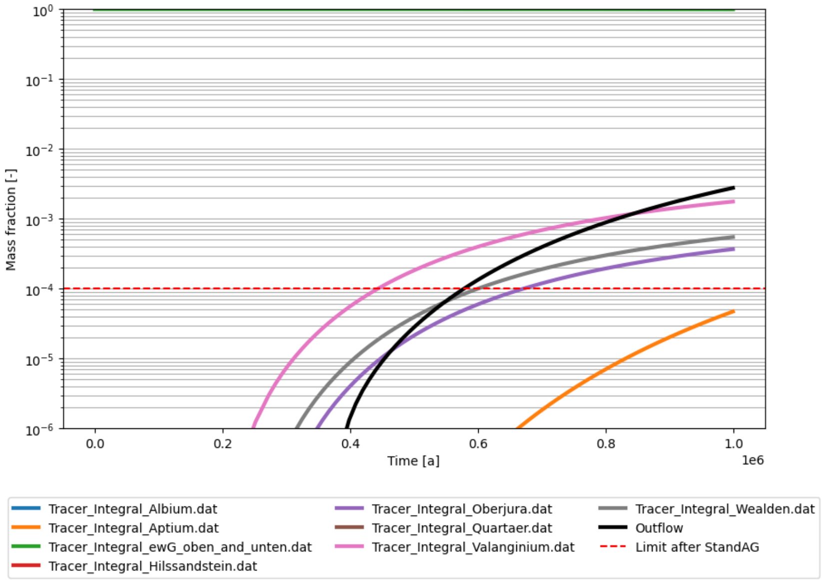
- Different mass distribution due to different diffusion coefficients in simulation cases
- Fast transport of mass out of the host rock with high diffusion coefficient
- Slower transport out of the host rock, still exceed the limit after StandAG with diffusion coefficient 10^{-10} m^2 s^{-1}
- No visible transport of mass out of the host rock with diffusion coefficient 10^{-11} m^2 s^{-1}

Diffusion coefficient

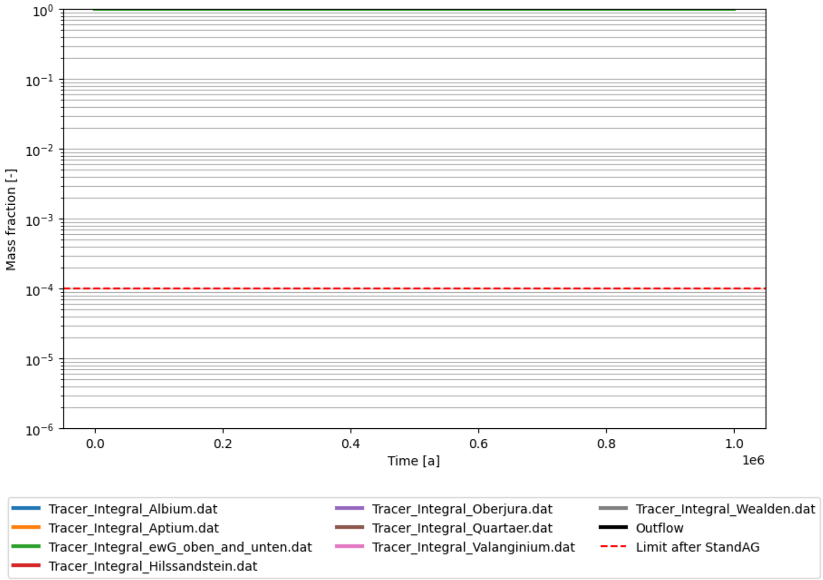
10^{-9} m^2 s^{-1}



10^{-10} m^2 s^{-1}



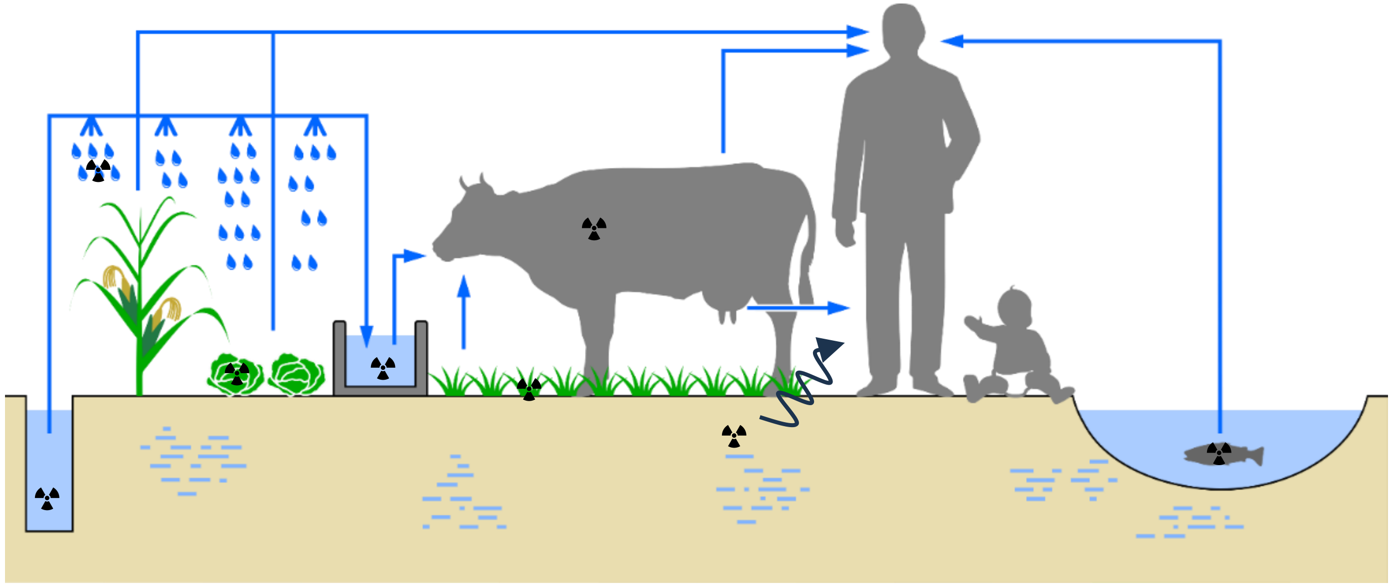
10^{-11} m^2 s^{-1}

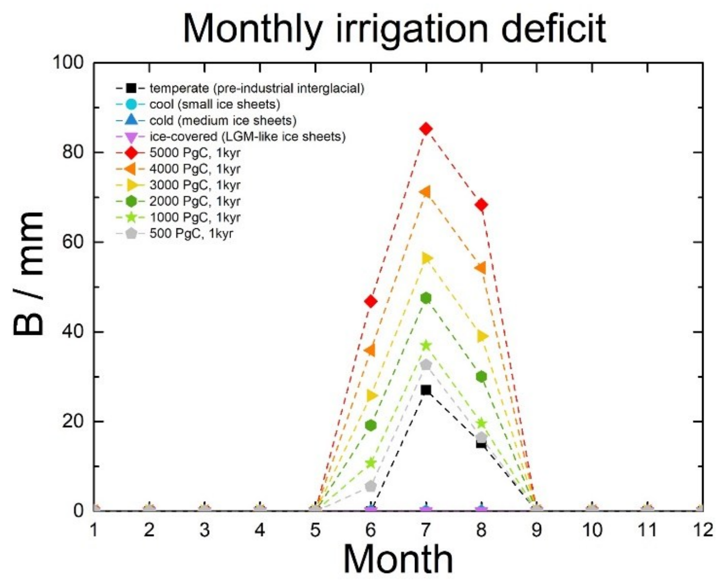


Summary

- Groundwater models contribute to a better understanding of groundwater processes and climate states
- Climate states influence flow velocities and concentration distribution, usually only to a small extent
- Parameter variations change the concentration distribution, sometimes significantly
- The choice of parameters or differences in rock properties can have a greater influence on the model results than different climatic states or conditions
  - Reduction of uncertainties regarding the consideration of climate states, climate developments and the sensitivity of parameters to the mass transport
    - ➢ Sufficient exploration and selection of parameters for the assessment is important when selecting a repository site

Impact of climate models on biosphere dose estimations



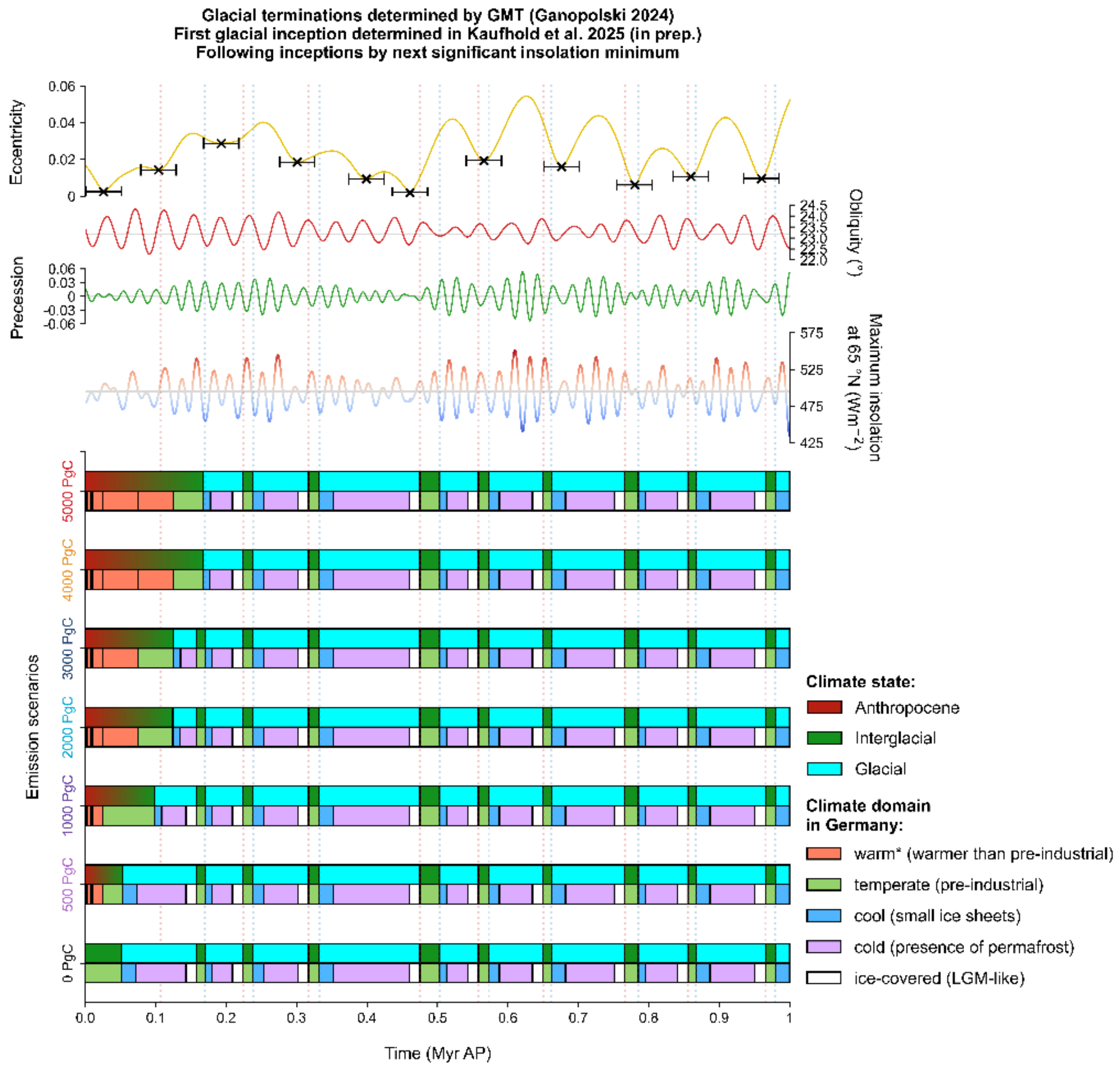


- Dose calculation required by EndlSiAnfV § 7
- Contamination pathways defined by BASE (2022)
- Irrigation deficit governed by climatic conditions
- Agricultural irrigation (groundwater) crucial pathway of radionuclides into biosphere
- Activity concentration in food and environmental media affect radiation dose
- Analysis of impact on dose estimation for modeled climate states

→ **Poster session: Impact of climate models on biosphere dose estimations (Horenburg et al.)**

Added value to the site selection process

- Determination of climatic developments for site selection
- Estimation of climate development impacts on the transport behavior
- Reduction of uncertainties regarding the consideration of climate states/climate developments
- Basis for required dose estimation scenarios (BASE 2022)
- Supports selection process for exploration objectives and methods
- Sets focus on climate states requiring particular consideration regarding the dose estimation in the biosphere



Identified uncertainties

Parameter uncertainties

- Generic RESUS/ANSICHT model assumptions but with partial wide bandwidths
- Diffusion and sorption coefficient, hydraulic gradient are generic but play important role for transport

Model uncertainties

- Abs. and rel. numerical error
- Grid refinement vs. simulation time and accuracy
- No near field repository structures
- No temperature modelling
- Homogenic geological units
- Complexity of processes on smaller scale

Scenario uncertainties

- Broad range of anthropogenic emission-scenarios possible
- Missing process understanding (e. g. volcanic outgassing)
- Poor constraints (e. g. climate sensitivity)
- Resolution in space and time for specific areas are complex

Conclusions

- Present-day emissions are unlikely to delay the glacial inception that would naturally occur at 50 kyr AP
- Glacial inception will likely occur before 200 kyr under all emission scenarios and configurations
- Ice sheets will remain small for the next 150 kyr due to weak insolation minima; unlikely to reach Germany before then
- Range of possible future climate states defined

- Impacts of future climate developments on long-term safety in case of hydraulic conditions are small
- Influence of parameter uncertainties investigated
- Deeper understanding of integral model behavior

- Climatic conditions affect irrigation demands in the biosphere and therefore the estimated radiation dose
- Expected anthropogenic effects on estimated dose proportional to total carbon emission

Acknowledgements

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Thank you for your attention!

Further information on the research project and the participating institutions can be found at https://urs.ifgt.tu-freiberg.de/en/home

Literature

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