# Application of Monte-Carlo-Based Sensitivity Analysis to Long-Term Performance Assessment Models for Final Repositories

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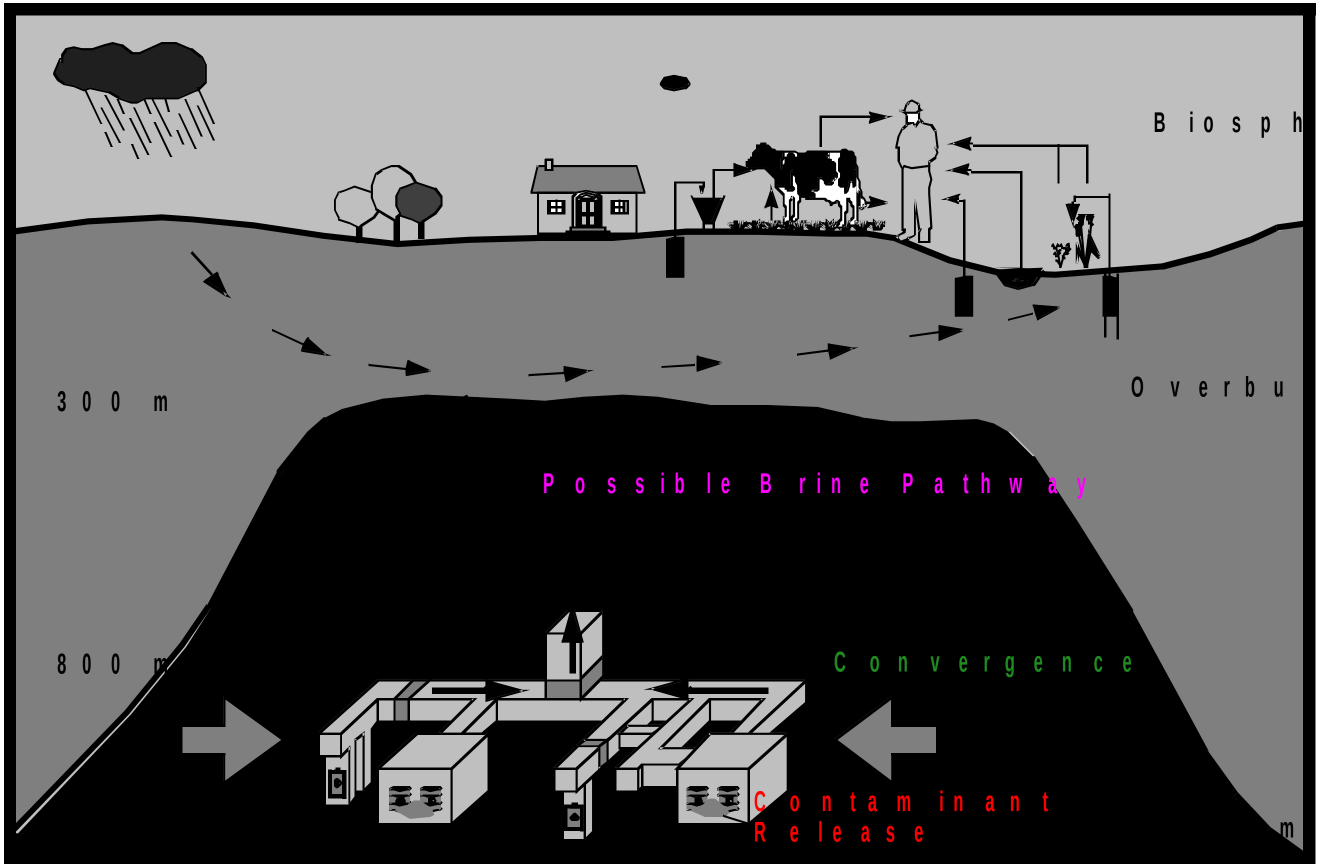
# GRS – Gesellschaft fuer Anlagen- und Reaktorsicherheit

- Technical Expert Organisation
- Financed by the German government
- Expertise and Research for
  - Reactor safety
  - Environmental safety
  - Repository safety

**Repository Safety Division (Braunschweig)**

- Identification of
  - Relevant effects
  - scenarios
- Modeling of
  - Physical effects
  - Radionuclide mobilisation and transport
  - Geochemical effects
  - Radioactive decay
- Integrated long-term modeling
- Analysis and interpretation of results
- Feedback to repository planning

# Final Disposal of Radioactive Waste in Deep Underground




- Brine intrusion cannot be excluded
- Canister corrosion and contaminant mobilisation
- Convergence of voids
- Fluid flow inside the near field
- Radionuclide transport
- Contamination of groundwater
- Chemical effects
- Radioactive decay
- Biosphere pathways
- Radioactive exposure of man
- Coupled system with complex behaviour!

# Sensitivity Analysis

- **Uncertainties**
  - Model and scenario uncertainties
    - Future development
  - Parameter uncertainties
    - Physical parameters
    - Technical parameters
    - Geological parameters
- **Why do we perform SA?**
  - Identification of research needs
  - Identification of technical needs
- **Deterministic SA**
  - Specific parameter variations
- **„Classical“ SA**
  - Rank transformation (highly non-linear systems)
  - Calculation of SPEA, SRRC, PRCC
  - Smirnov test
  - Application to
    - different points in time
    - maximum of each run
- **What do we learn?**
  - Qualitative parameter ranking
- **Open questions**
  - How reliable are the rankings?
  - Which parameters are really important?
  - Which parameters do not play a role?

# Variance-based Sensitivity Analysis: Fourier Amplitude Sensitivity Test (FAST)

- Systematic scan of parameter space using periodic functions
- Interference-free frequencies for different parameters
- Random element by introducing random phase shifts
- Fourier Analysis of model output yields parameter influence
- Calculation of first-order sensitivity indices
  - isolated influences of individual parameters
- Calculation of total-order sensitivity indices (E-FAST)
  - influences of parameters in interaction with all others
- Quantitative sensitivity measures
- Applicable to non-linear and non-monotonic systems
- High number of model runs necessary

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$$\frac{\mathrm{Var}_{X_j}[E(Y)|X_j)]}{\mathrm{Var}(Y)}$$

# The ERAM LLW / ILW Repository

- Old salt/potash production mine in eastern Germany
- Used as a repository from 1971 to 1998
- Disposal of low-level waste (LLW) and intermediate-level waste (ILW)
- Total inventory $4 \cdot 10^{14}$ Bq or ~3 MSv
- Currently in the procedure of licensing for closure
- Comprehensive performance assessment (PA) studies available
- Very complex mine structure
- Extensive simplification for modelling
- Annual radiation exposure calculated for different variants/scenarios

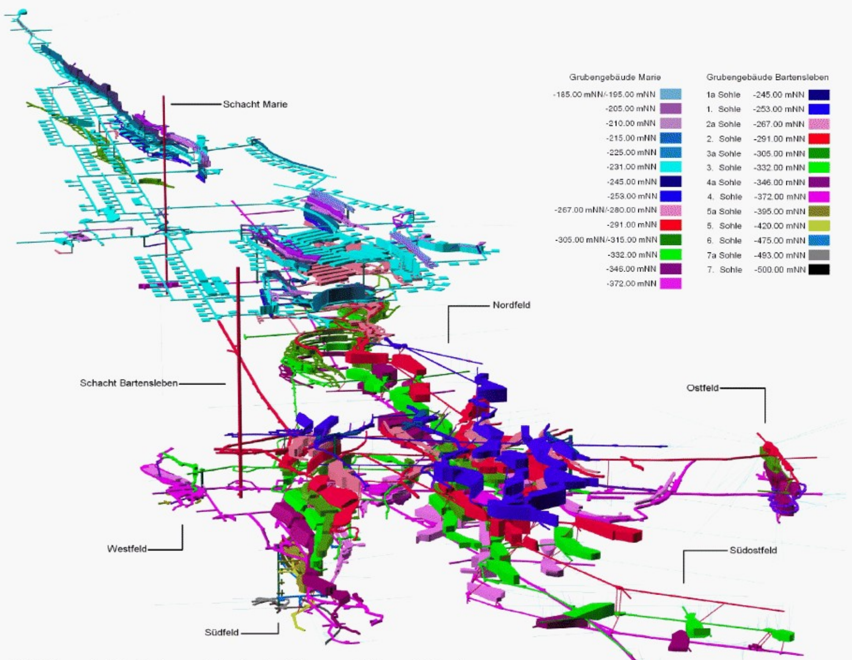


Abbildung 2.1-3: Grubengebäude, Ansicht von Süd nach Nord

# FAST Analysis of the ERAM Model

- 43 parameters
- Two sets of model evaluations:
  - 10019 runs each
  - Different random seeds
- FAST evaluation for many points in time
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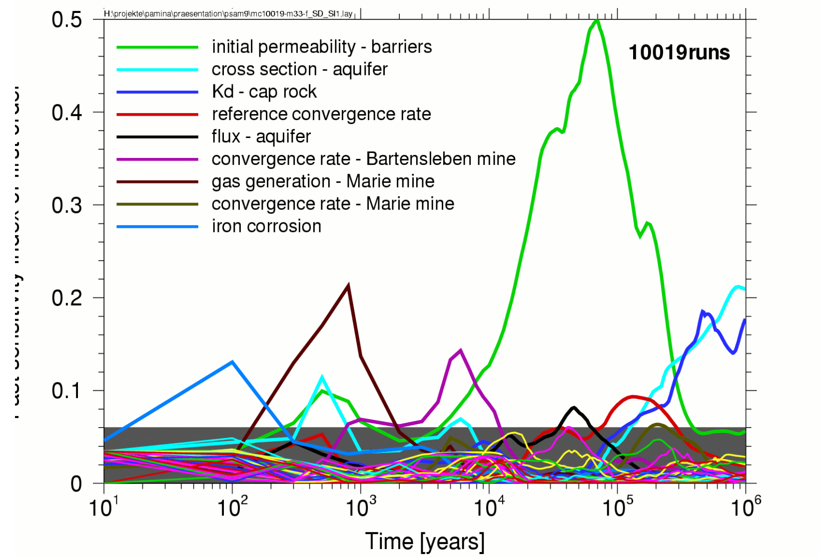
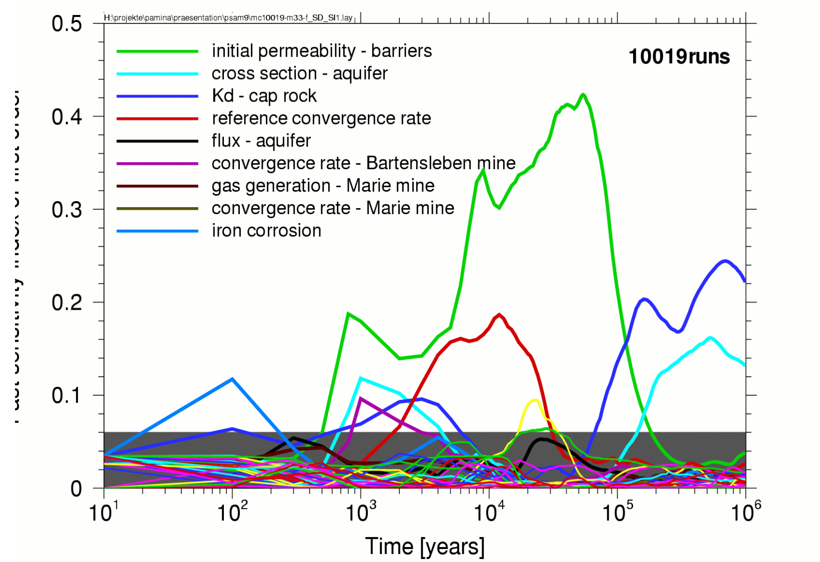
  - Initial permeability dominates clearly over long time period
  - Importance of far field parameters increases at late times
  - Many parameters are of nearly no importance at any time



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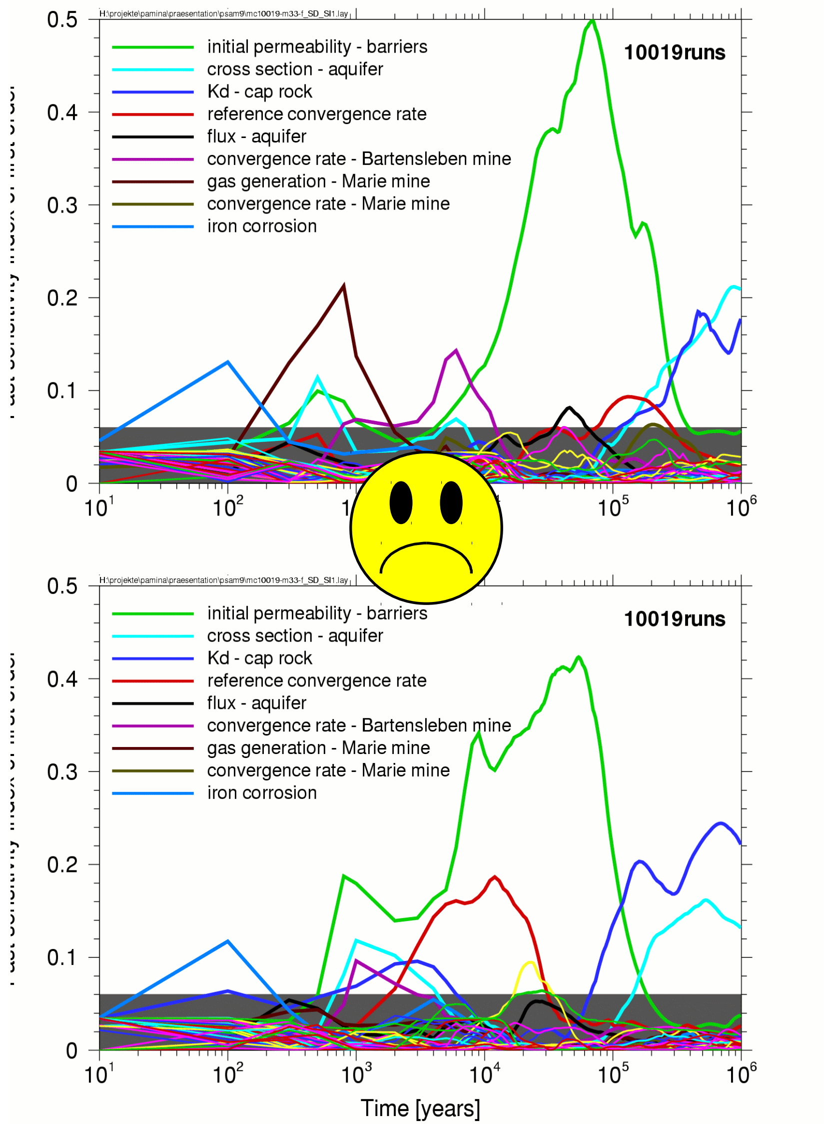

# FAST Analysis of the ERAM Model

- Unsatisfying results
  - Essential discrepancies
  - No unique assessment of parameter importance possible

***Why?***

- FAST doesn’t perform well with discrete parameters
- Several switch-like parameters of minor importance
  - Omitting them does not help
- “Close-to-discrete” behaviour of initial permeability at each point in time
  - Nearly sudden failure of seal in each run at a characteristic time, dependent on initial permeability
  - Model output highly depends on whether or not seal has failed

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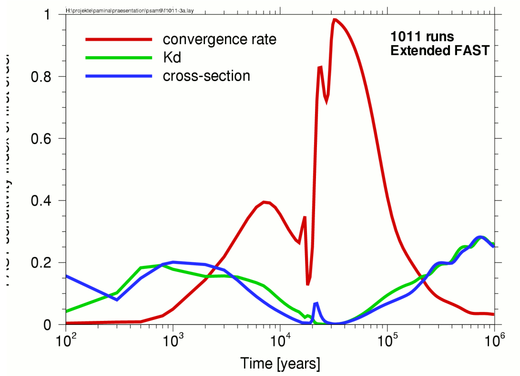


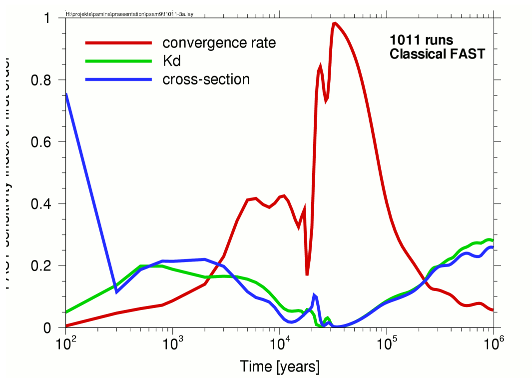


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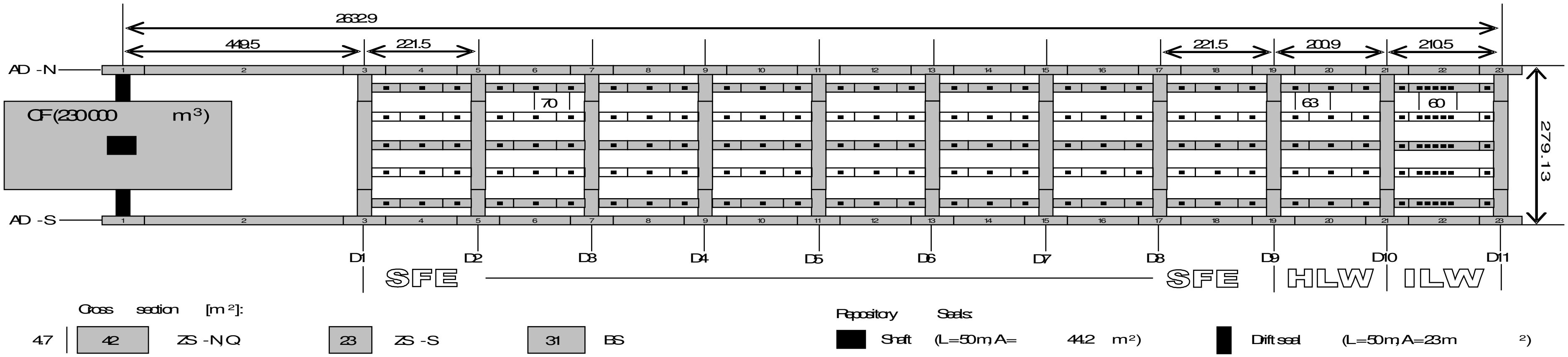
  - Nearly sudden failure of seal in each run at a characteristic time, dependent on initial permeability
  - Model output highly depends on whether or not seal has failed
  - Omitting the most important parameter essentially improves consistency!
  - Parameter seems to disturb the FAST evaluation!

# Generic SF/HLW Repository in Salt

- Recent generic concept for salt host rock
- Disposal of heat-generating waste
- Spent Fuel elements (SF)
- vitrified high-level waste (HLW)
- intermediate-level waste (ILW)
- Disposal of all waste accumulating in Germany until 2080

- To be set up in homogeneous salt
- Simple repository structure
- Model close to real structure
- Model yields “zero-output” for most scenarios and parameter combinations (no brine intrusion)
- Radionuclide release for specific disturbed-evolution scenarios



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  - Two sets of model evaluations
  - 3030 and 6054 runs, respectively
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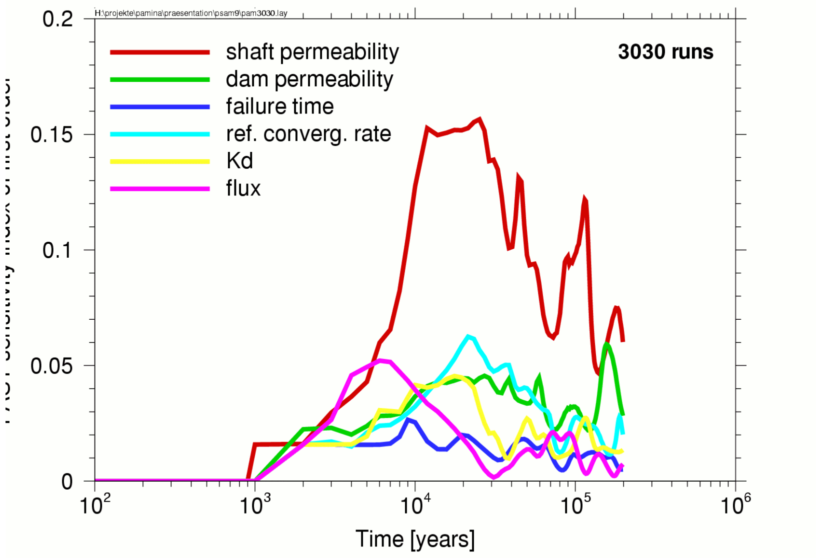


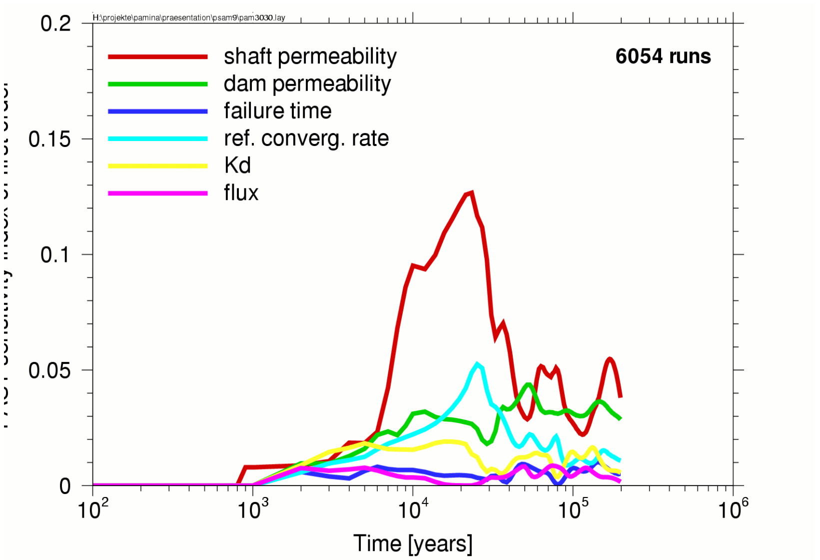

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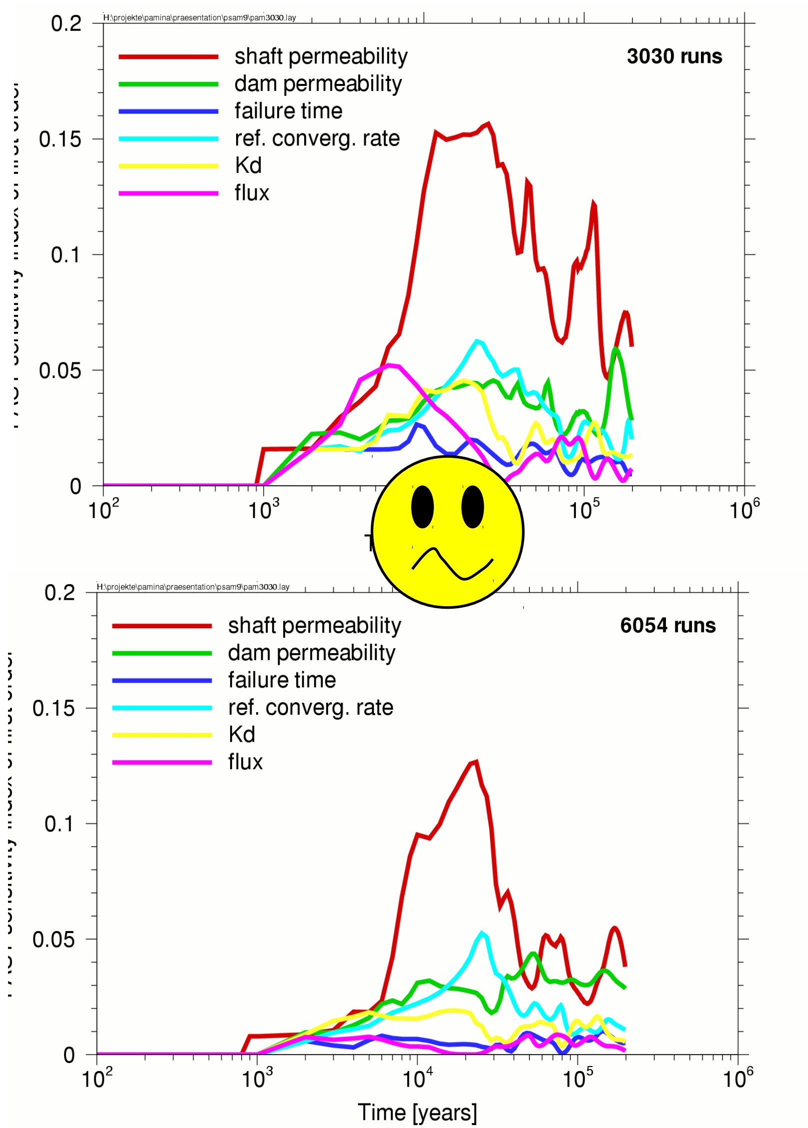


# FAST Analysis of the Generic SF / HLW Model

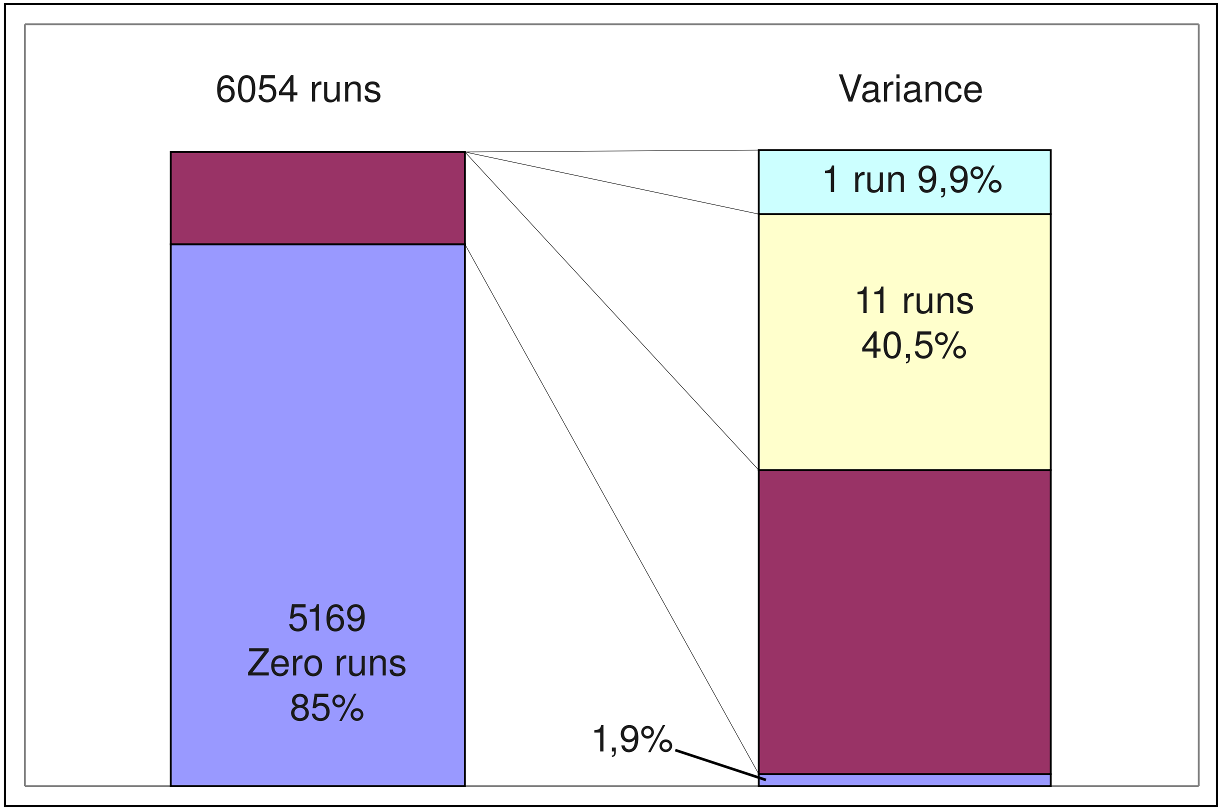
- Again: Unsatisfying results
  - Essential discrepancies
  - No unique assessment of parameter importance possible

***Why?***

- There are no discrete or switch-like parameters in this model!
- The zero-run “problem”:
  - About 85 % of all runs yield an exact zero output
  - Many of the other runs yield very low output
  - This is beneficial for safety, but bad for probabilistic SA!
  - Poor performance of FAST is plausible

# FAST Analysis of the Generic SF / HLW Model

- Variance is dominated by just a few runs
    - Low robustness of variance-based evaluation



# FAST Analysis of the Generic SF / HLW Model

***Improving Robustness by Transformation of Model Output***

- Perform transformation: $y^* = \log_2(\frac{y}{a} + 1)$
  - 0 ➔ 0
  - Near-zero ➔ near-zero
  - $a$ ➔ 1
  - High value ➔ log (high value)

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- *How to find a proper value for $a$ ?*
  - Parameter discriminates “low” values from “high” values
  - Could be fixed subjectively
  - <u>Here</u>: calculated such that
    $$E(y^*) = 1$$
    for each point in time

## FAST Analysis of the Generic SF / HLW Model

### *Improving Robustness by Transformation of Model Output*

- Perform transformation: $y^* = \log_2(\frac{y}{a} + 1)$
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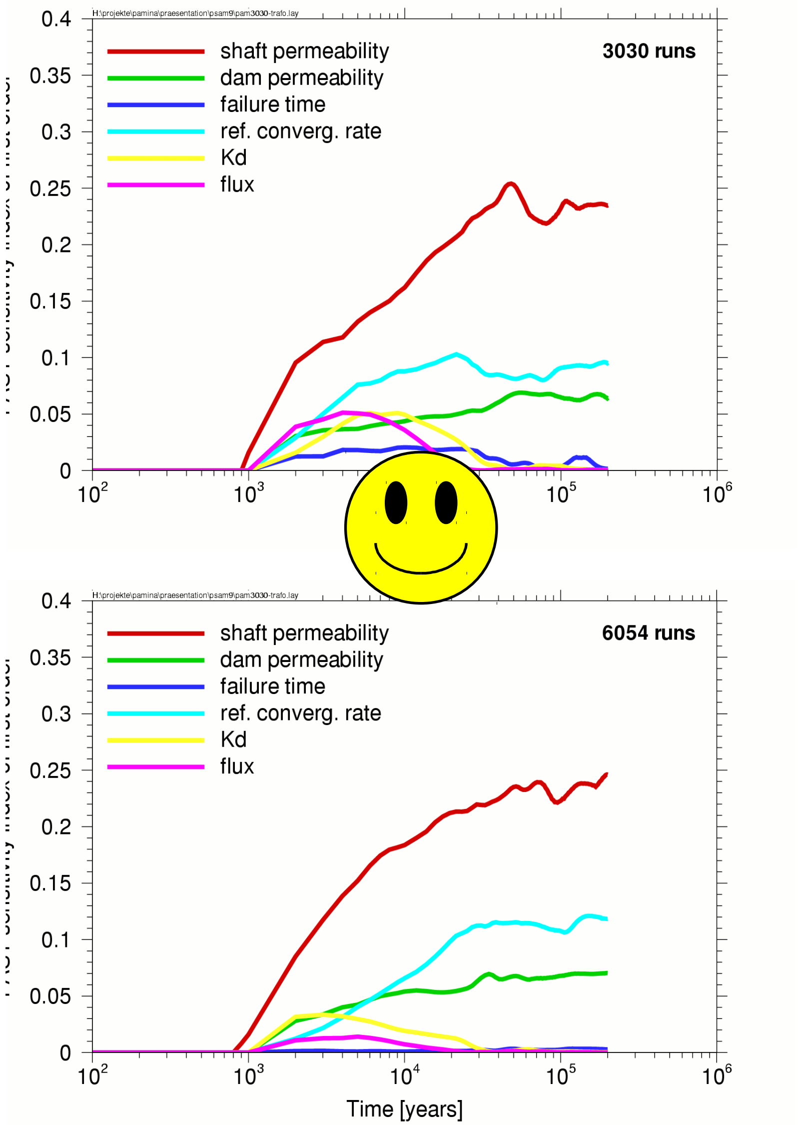
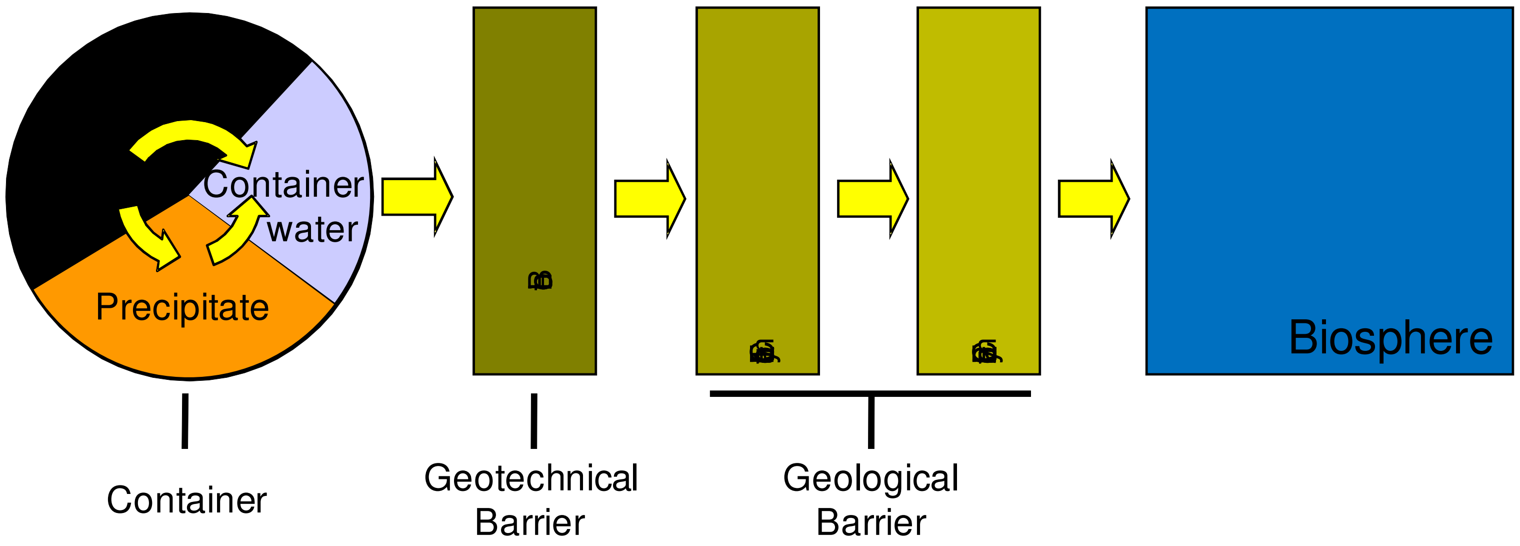
  - High value ➔ log (high value)

- Results become much more significant!
- Clear dominance of shaft permeability
- Essential contributions from dam permeability and convergence rate
- Low significance of failure time and Kd



# Generic SF/HLW Repository in Clay

- Generic repository for high level waste in a consolidated clay host rock formation
- Mobilisation of radionuclides
- Precipitation
- Transport of radionuclides by diffusion through
  - the technical barriers
  - the host rock
  - any overlying, low-permeable rock strata up to the water-bearing overburden
- Retention of radionuclides



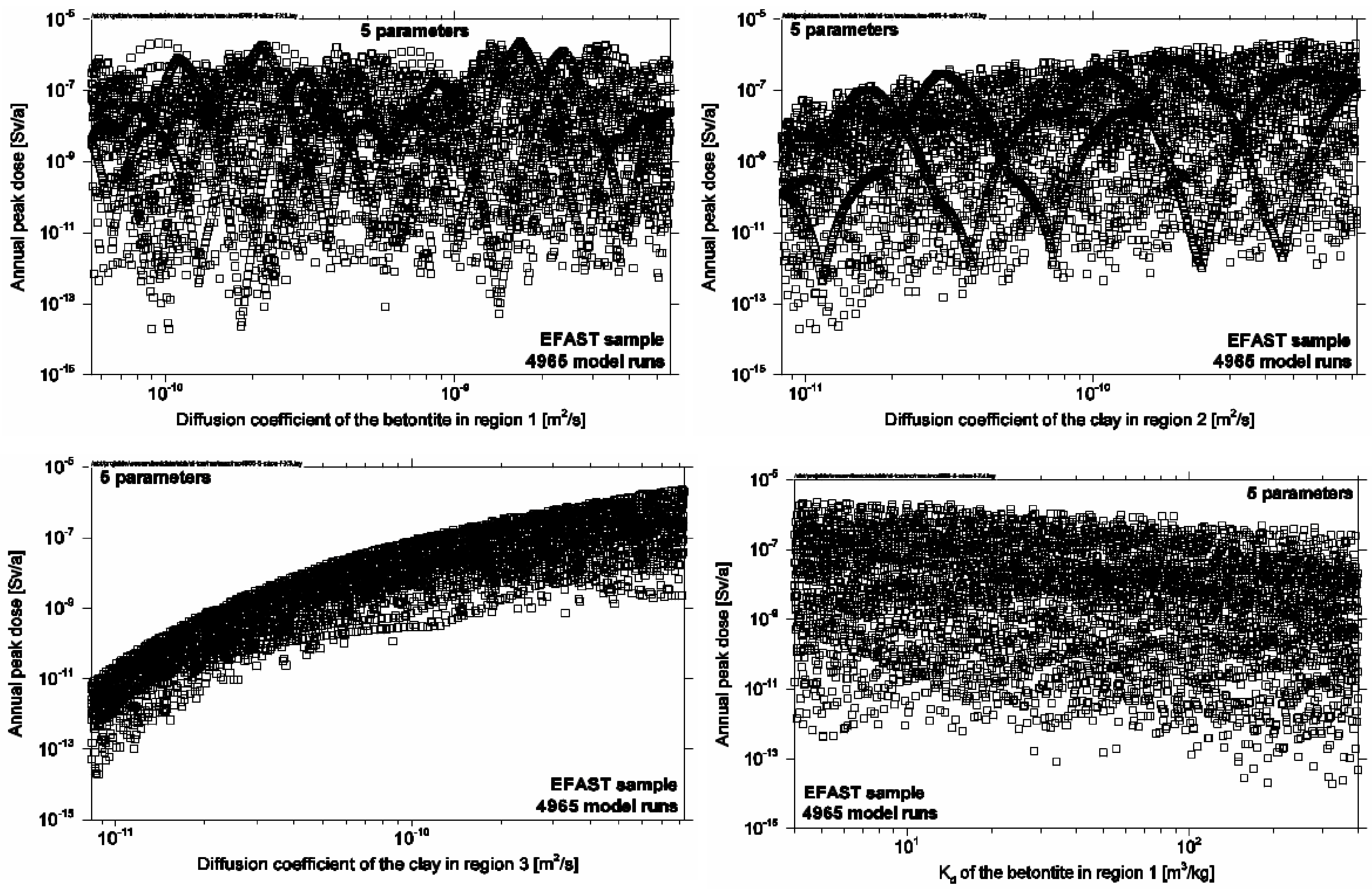
# Sensitivity Analysis of the Clay System

- Original model with 13 parameters
- Reduced model with 5 parameters
- Graphical analysis
  - scatterplots
  - CSM plots
- FAST analysis
  - Classical FAST
  - EFAST

**10 EFAST samples**

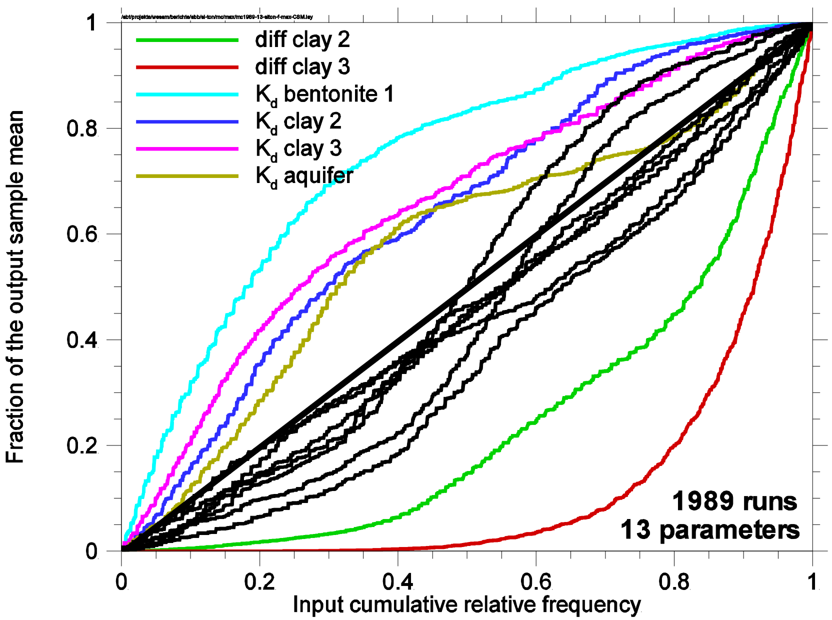
- 2 samples with 13 parameters
  - 1989
  - 3965
- 8 samples with 5 parameters
  - 765
  - 1525
  - 2485
  - 4965
  - 9965
  - 9965s (different seed)
  - 19965
  - 19995s (different seed)

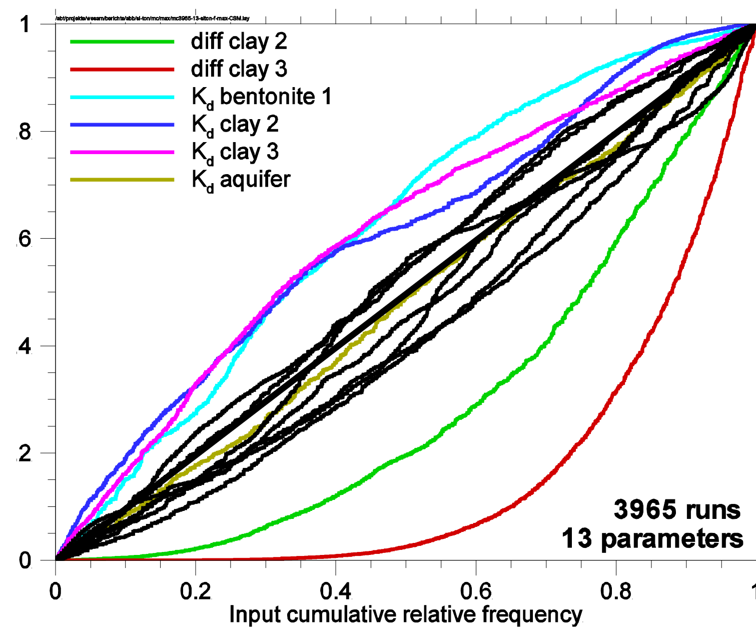
# Sensitivity Analysis of the Clay System



# Sensitivity Analysis of the Clay System

## Analysis of the maximum dose rate – **CSM plots**

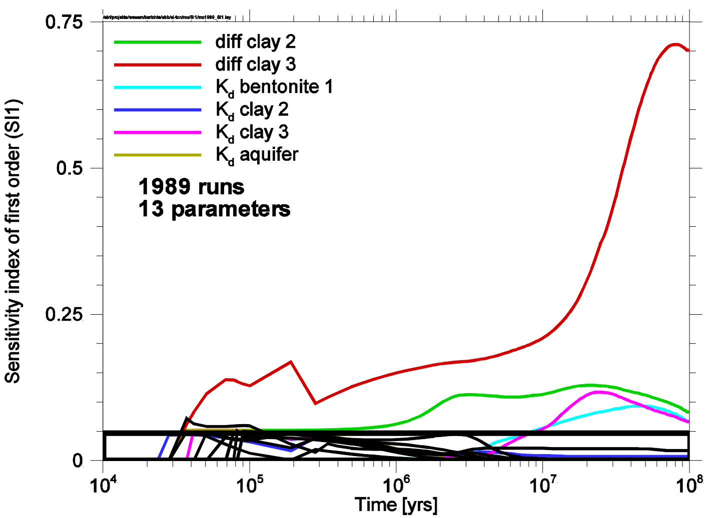


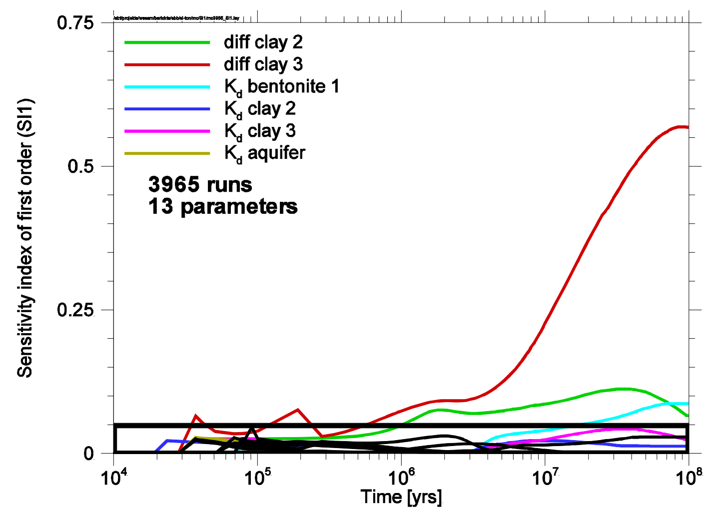




- CSM plots of the two samples with 13 parameters
- 153 and 305 runs per parameter
- Qualitative agreement

# Sensitivity Analysis of the Clay System

**EFAST Analysis:** SI1 sensitivity indices

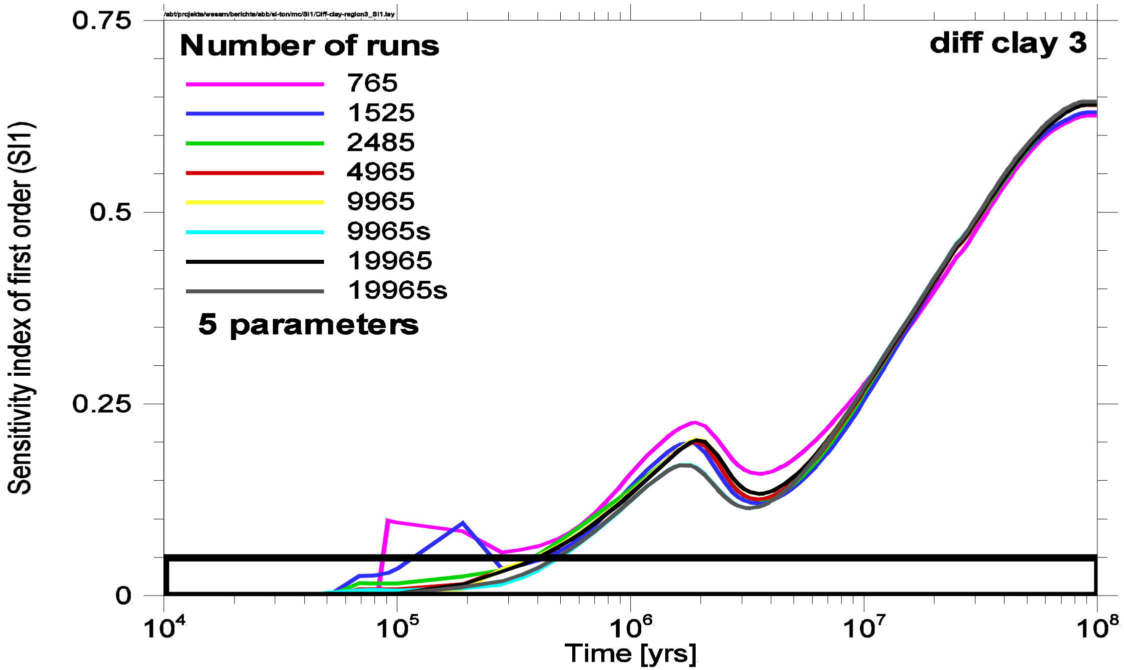



- SI1 plots of the two samples with 13 parameters
- 153 and 305 runs per parameter
- Qualitative agreement

# Sensitivity Analysis of the Clay System

- **EFAST analysis:** SI1 index




- Fair agreement for higher sample sizes
- > 305 runs per parameter recommended

## Conclusions

- Repository models typically produce a skewed and heavily tailed output distribution
- FAST does not always perform well with complex repository models
- Discrete or switch-like parameters can disturb FAST evaluation
- High zero-run probability impairs robustness of variance-based methods
- A suitable output transformation can mitigate this problem
- Generally, variance-based methods seem promising if applied carefully
- A sufficiently high sample size is requested for FAST, even for less problematic repository models

Thank you for your attention!