Fluid Flow in Evolving Sedimentary Deposits

Matthew A. Wolinsky

DOE CSGF Conference, June 21, 2005

Overpressure and Fluid Flow…

- Are caused by rapid sedimentation
- Strongly affect slope stability:
  - tsunamis, gravity flows, exploration
- Strongly affect consolidation:
  - subsidence, morphodynamics
- Transport (advect) heat and solutes:
  - diagenesis, hydrate stability, maturation

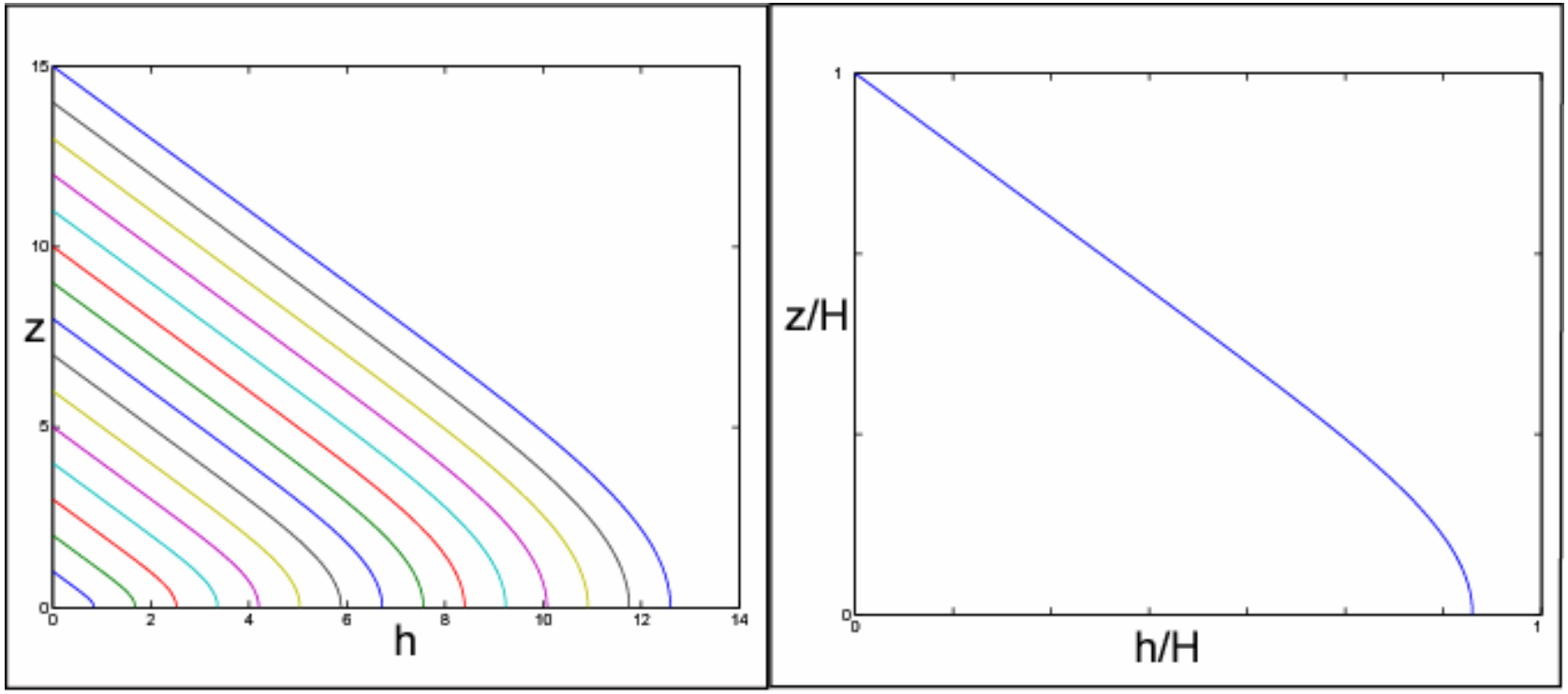
Coupled Modeling of Strata Formation and Overpressure: Why?

- Explore sedimentation driven overpressure generation, and feedbacks to stratigraphic evolution
- Impossible to study experimentally (scaling issues)
- Natural systems evolve too slowly to observe

Overpressure in 1D

- 1D coupling well understood

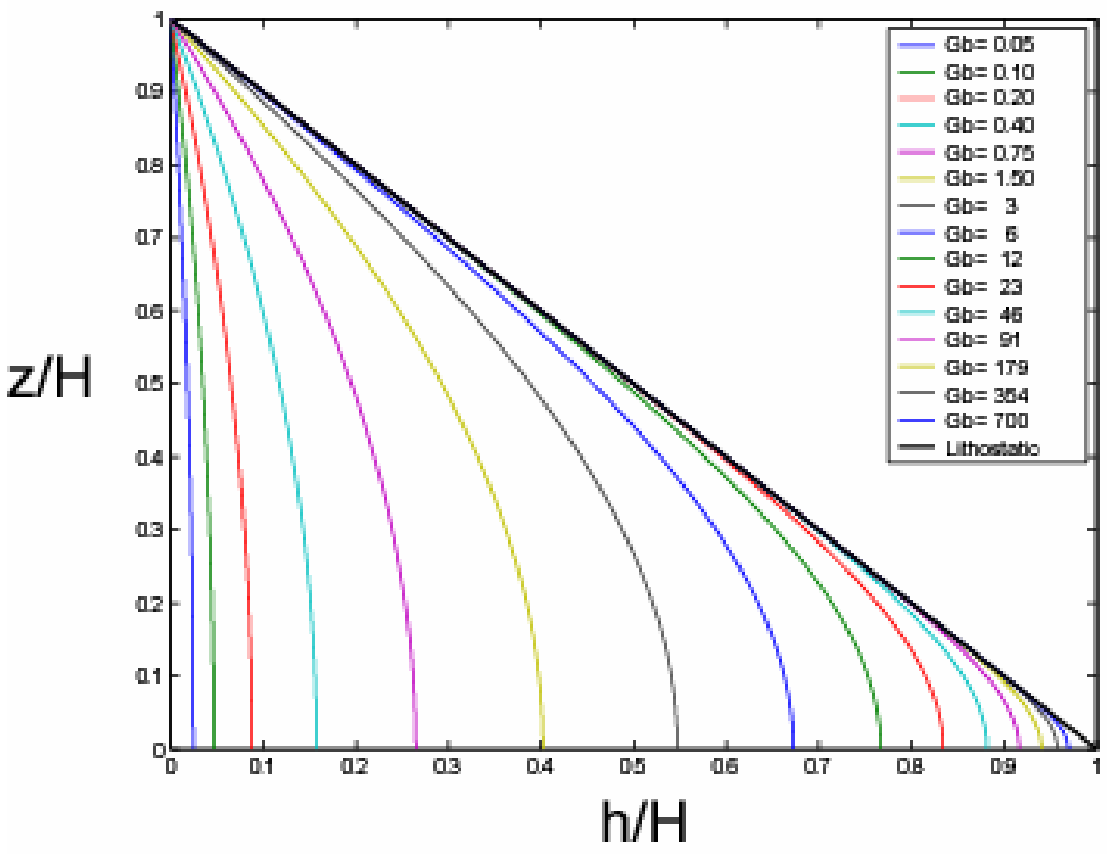
- Diffusion Equation with Moving Boundary → Similarity Solutions



Overpressure in 1D

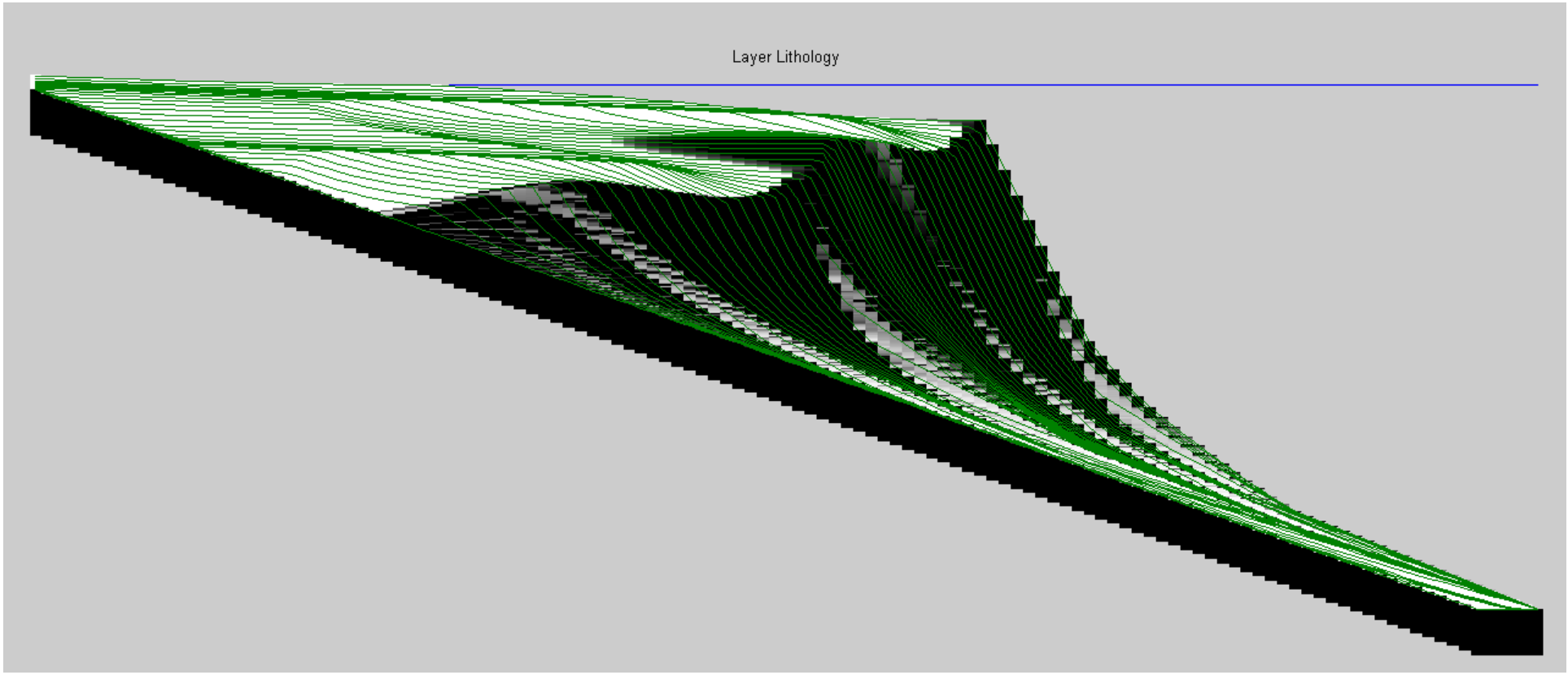
- Solution depends on dimensionless 'Gibson' number

  (analogous to Reynolds number)

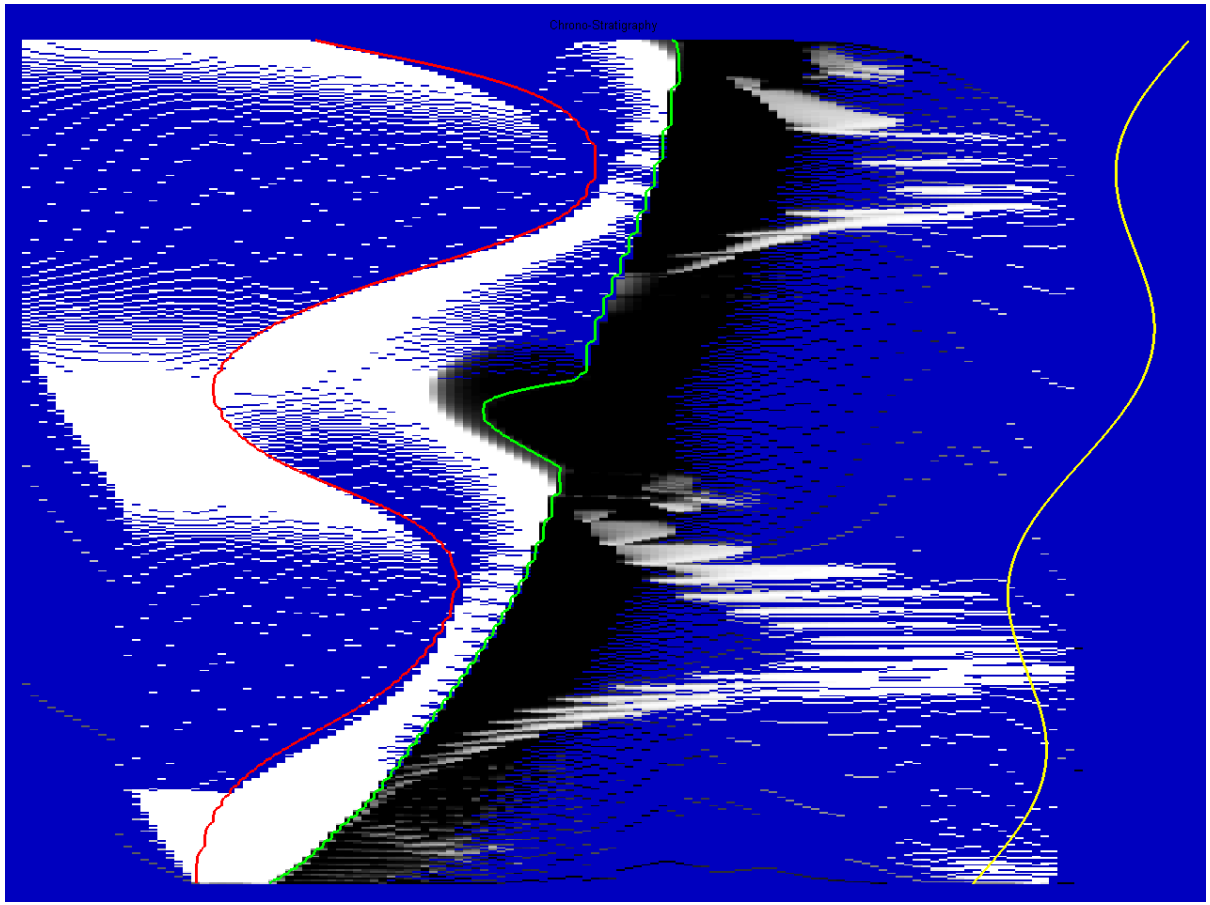


Need for 2D Models

- Stratigraphic evolution typically driven by migrating depocenters → inherently 2D



Need for 2D Models



- Many challenges have prevented effective modeling of fully 2D problems...

Challenges

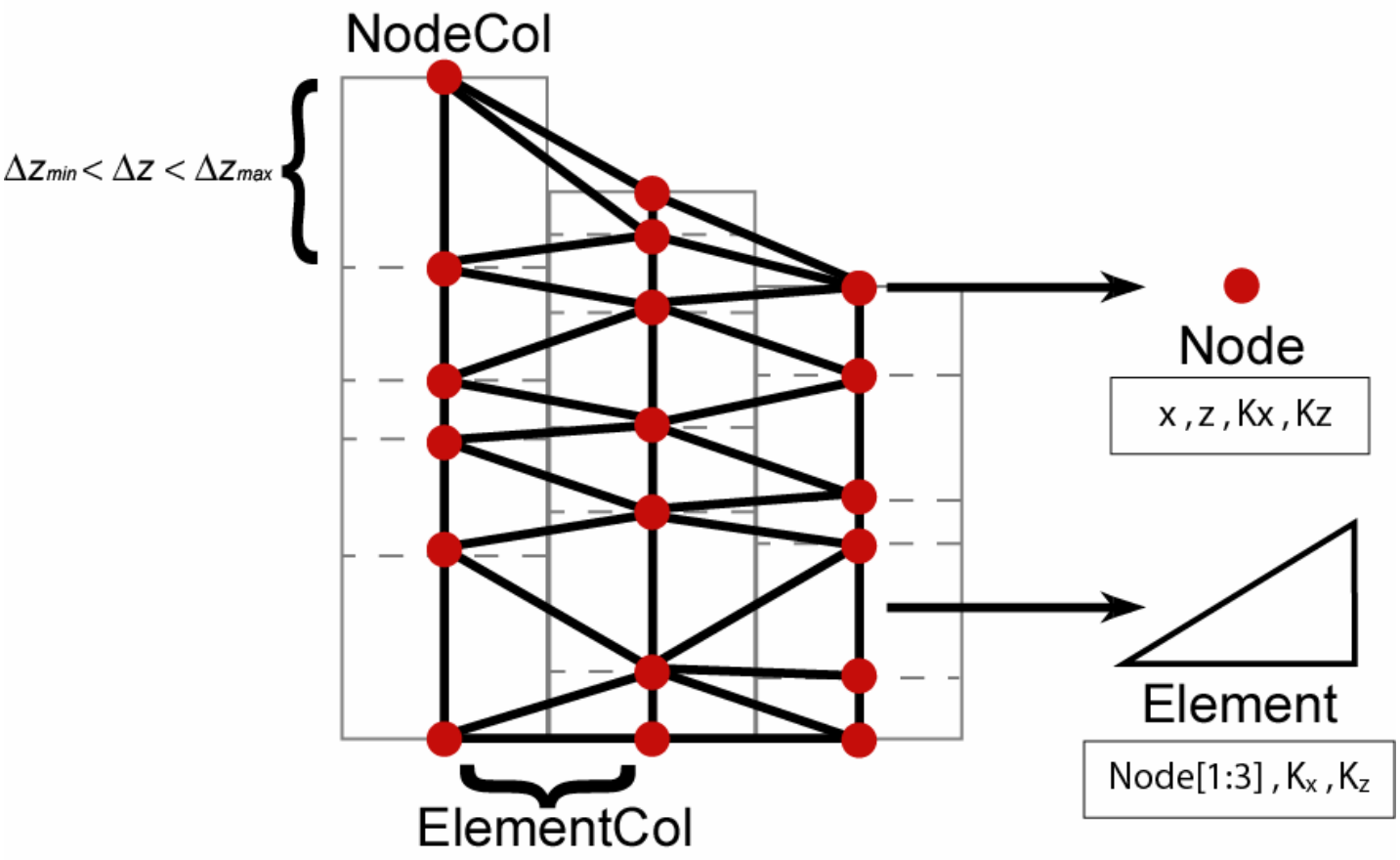
- Dynamic evolving domain…
  - requires frequent remeshing
- Localized deposition…
  - structured meshes inappropriate
- Large domain aspect ratio…
  - narrow elements inaccurate
- Large contrast in horizontal and vertical stratigraphic variation…
  - stratigraphic resolution vs FEM accuracy

Challenges

How to overcome challenges?

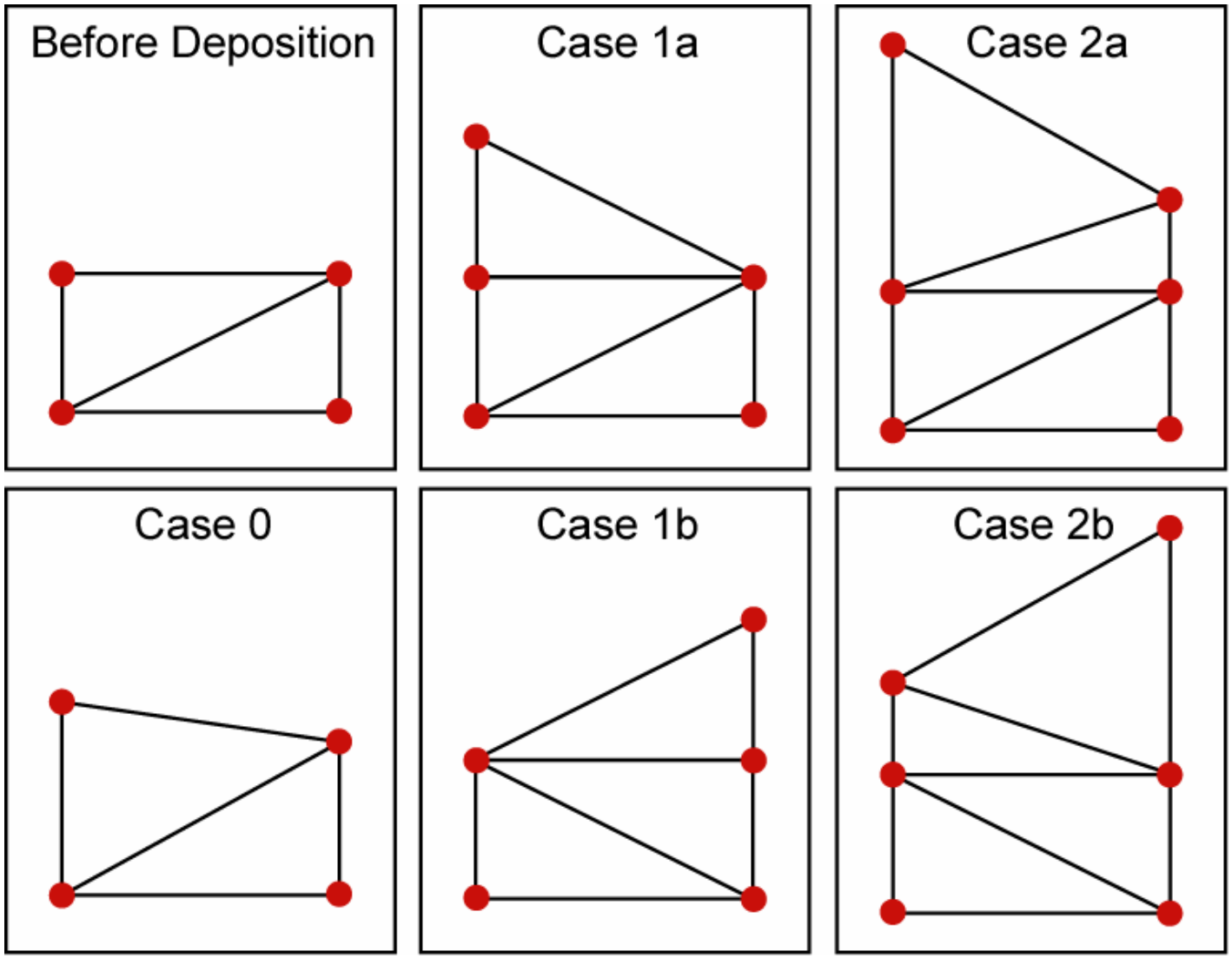
- Dynamic meshing…
  - must be simple, robust, efficient
- Sub-grid model…
  - over long timescales, sub-grid slaved to larger scale feedback → quasi-static

Mesh Data Structure

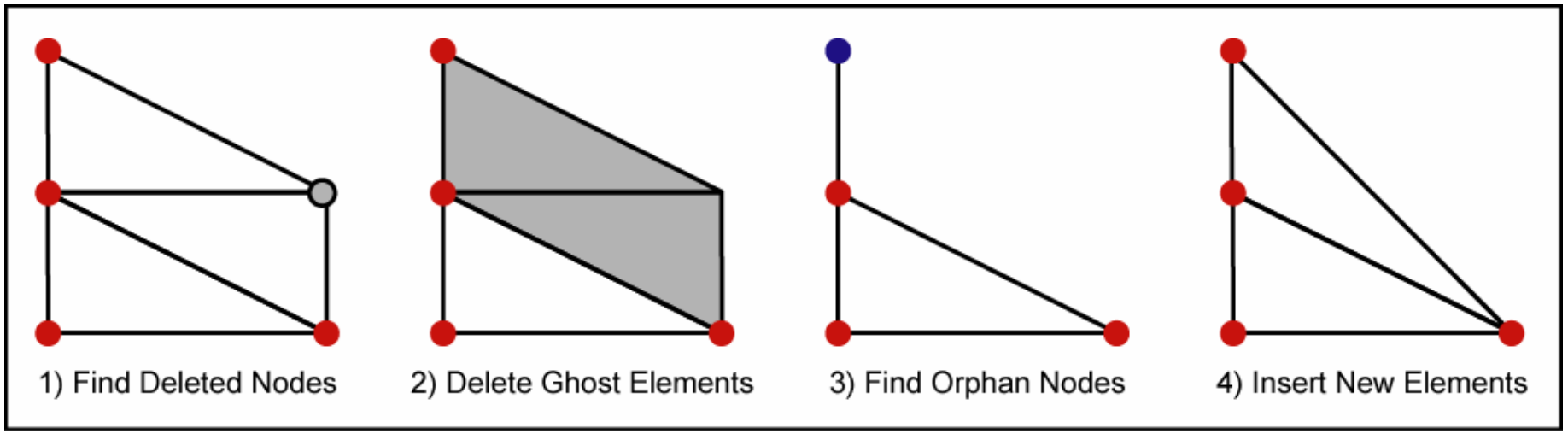


- Cell size constraints automatically bound FEM error and conditioning

Robust Dynamic Meshing: Deposition



Robust Dynamic Meshing: Erosion



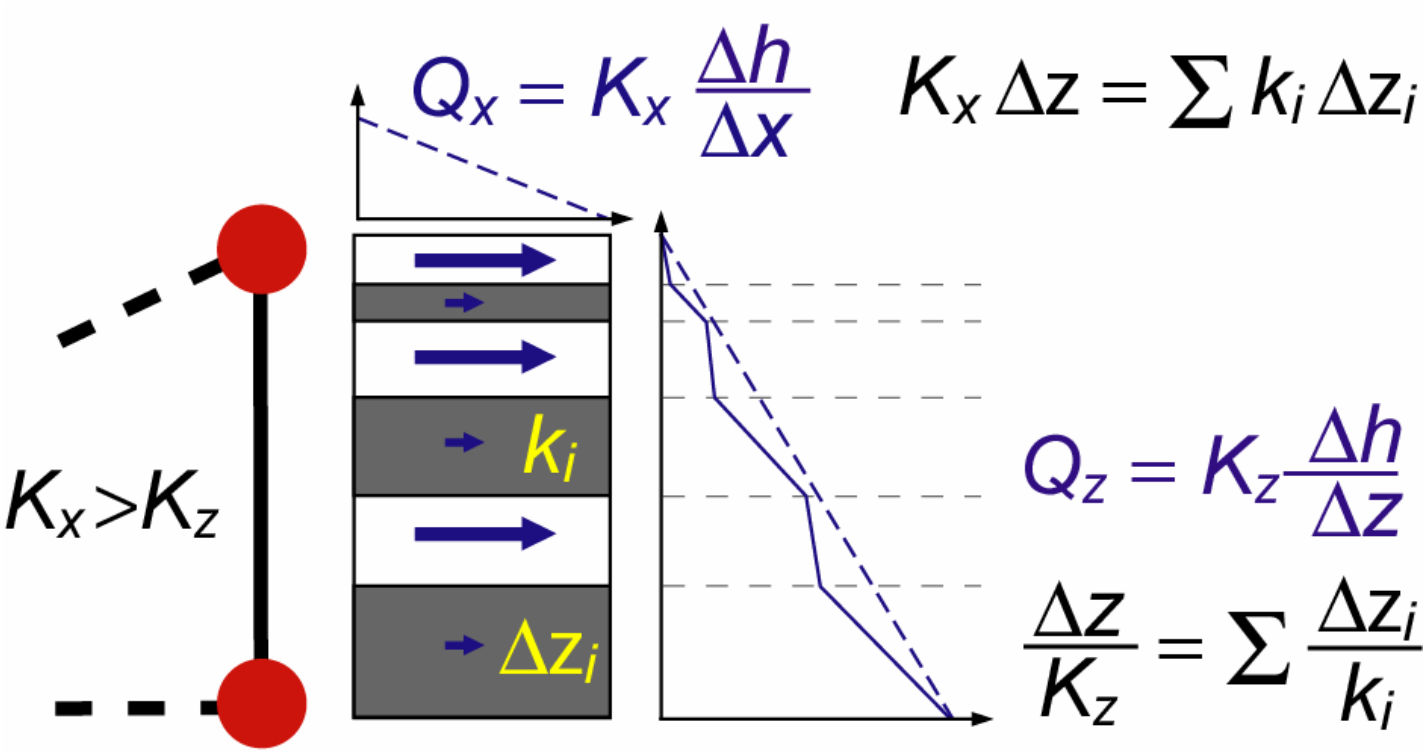
- Allows rapid meshing of arbitrary deposits while maintaining FEM error bounds

Sub-Grid Model

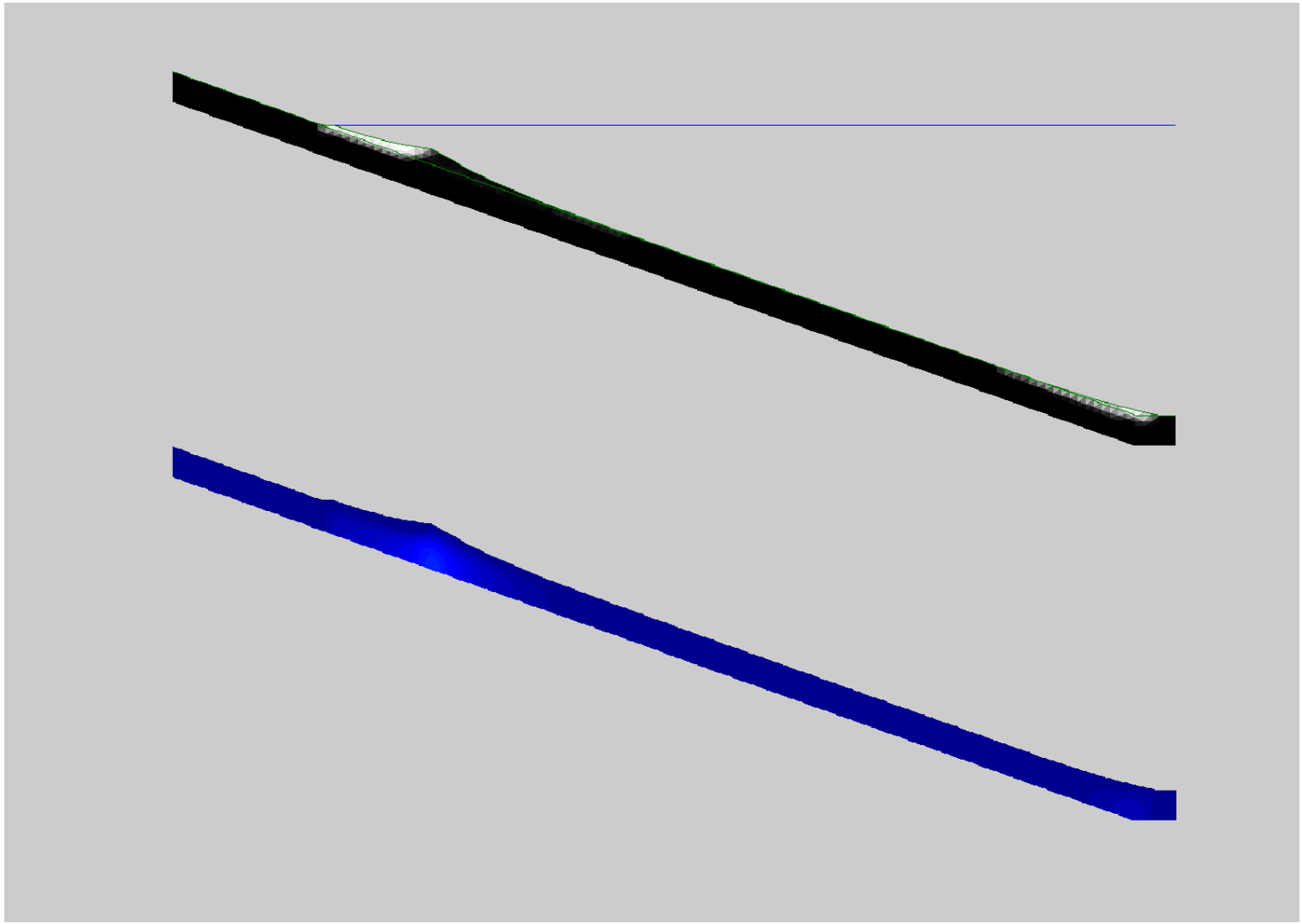
- Shape quality requires large elements → many sediment layers per grid cell
- large $\Delta t \rightarrow$ sub-grid steady state $\rightarrow$
  element effective conductivity
- embed stratigraphic boundaries without explicit mesh adaptation

Sub-Grid Model

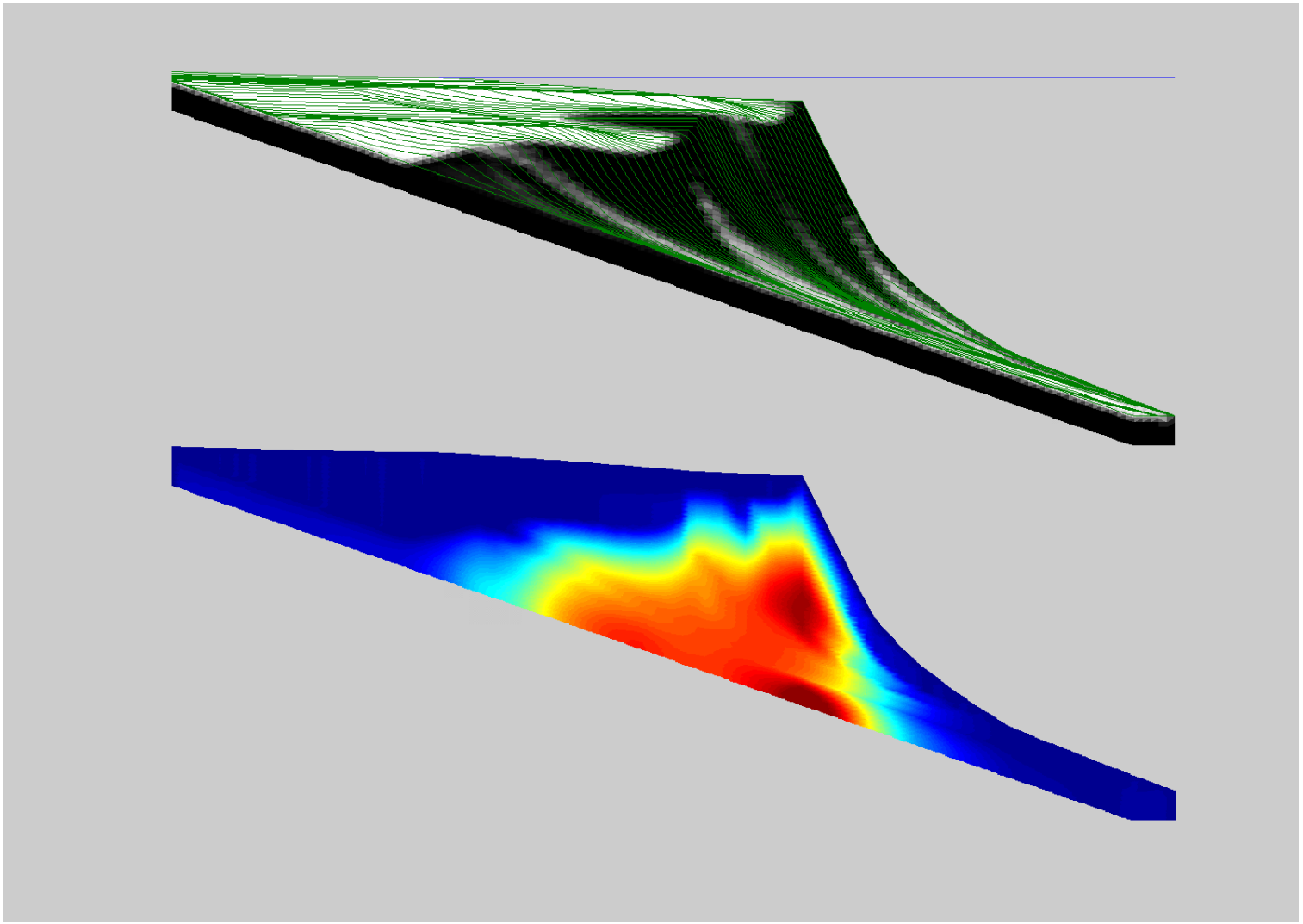
Large time steps → Sub-grid steady state → Anisotopic Effective Conductivity



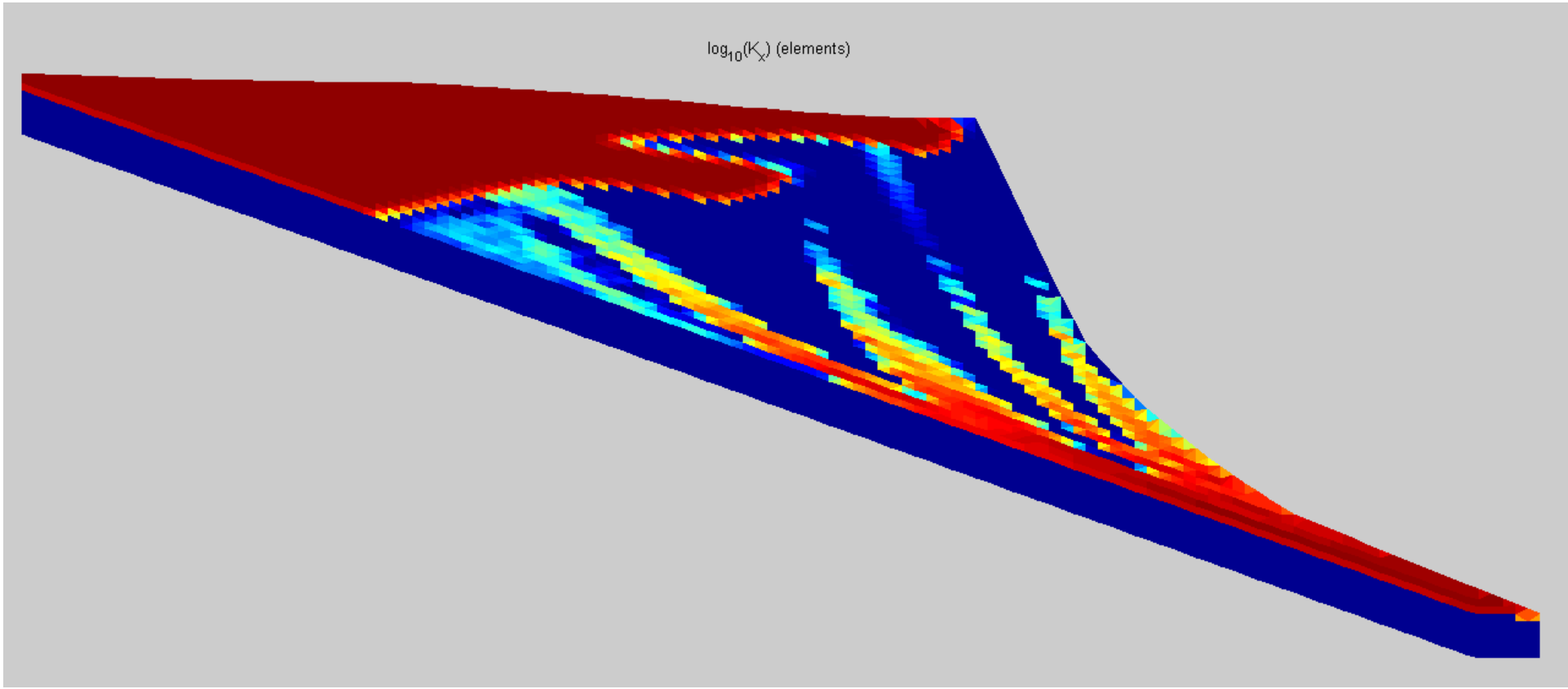
Example Simulation



Example Simulation

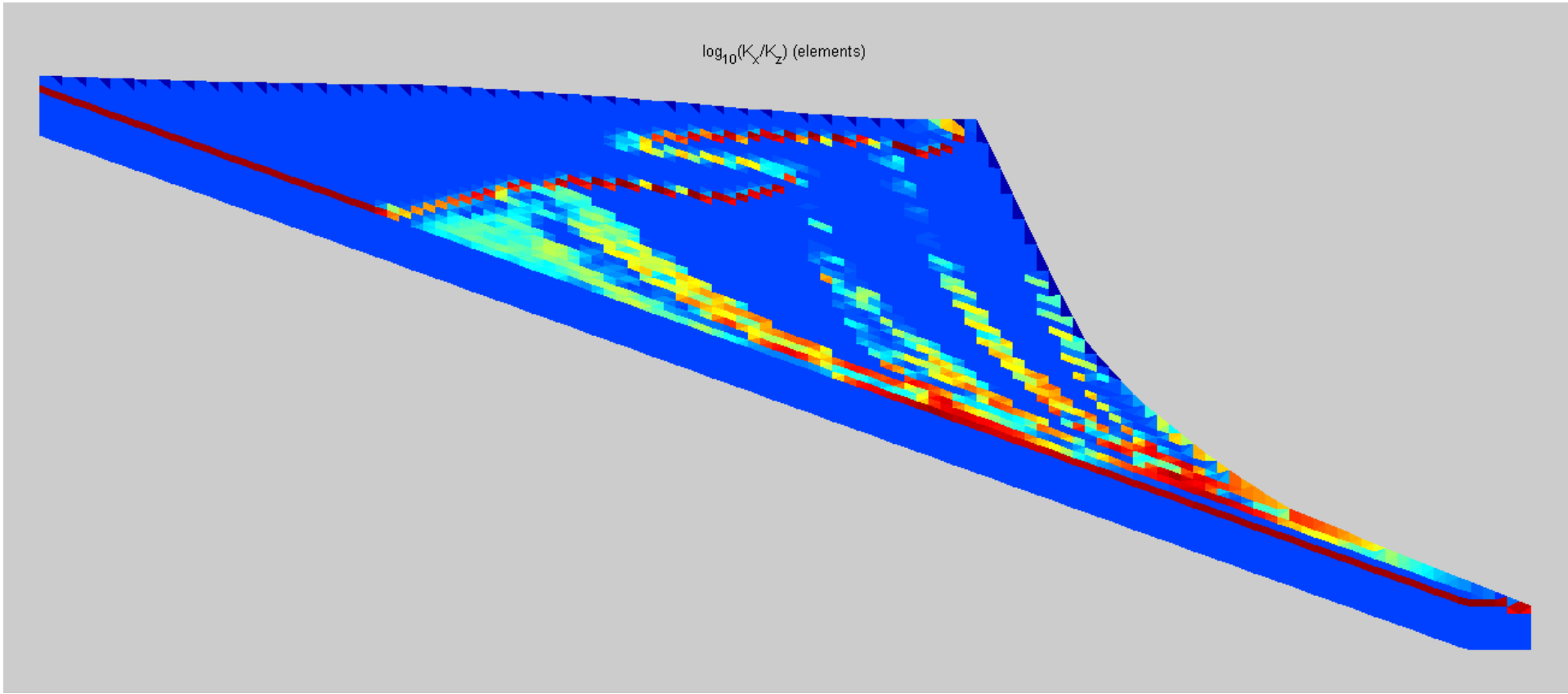


Hydrostratigraphy: Local Anisotropy , Confined Aquifers



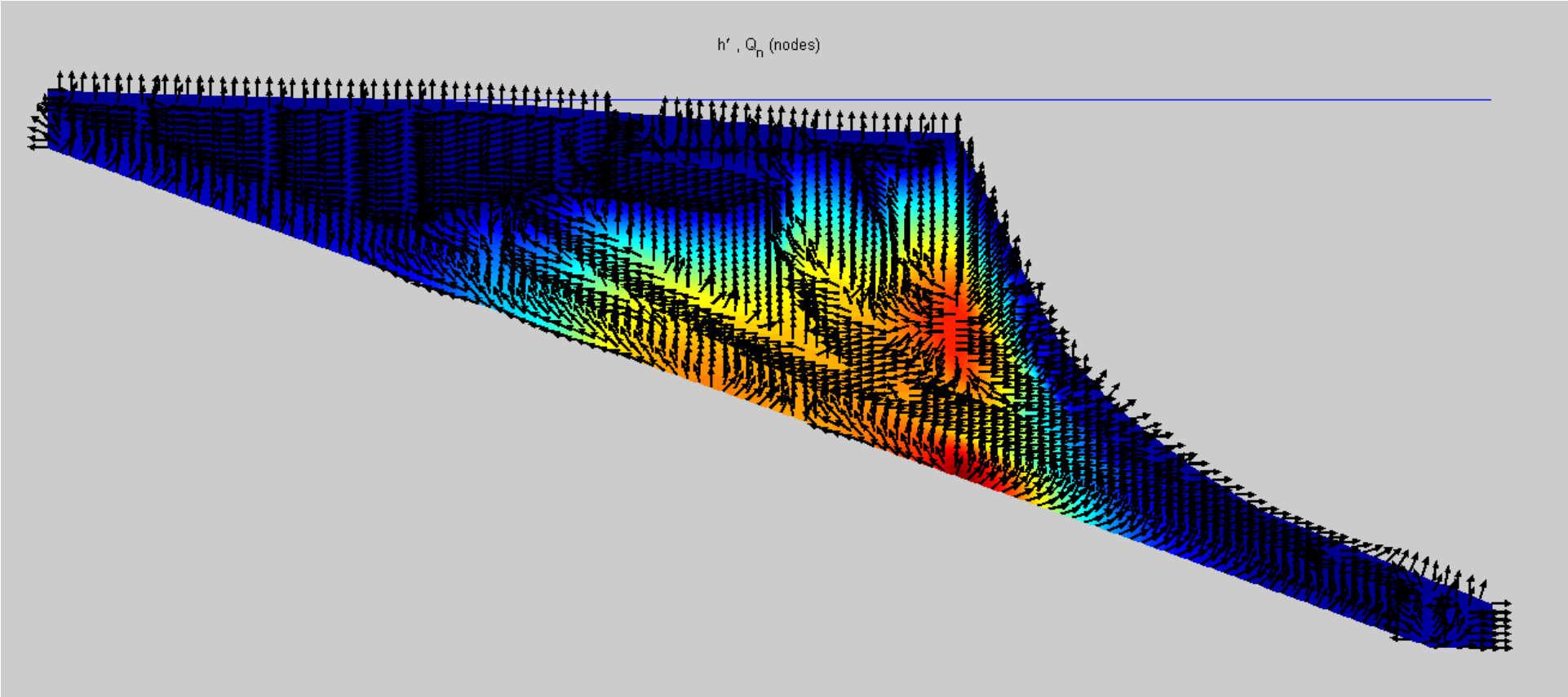
- Diffusivity high in sandy deposits, low in muddy deposits

Hydrostratigraphy: Local Anisotropy , Confined Aquifers



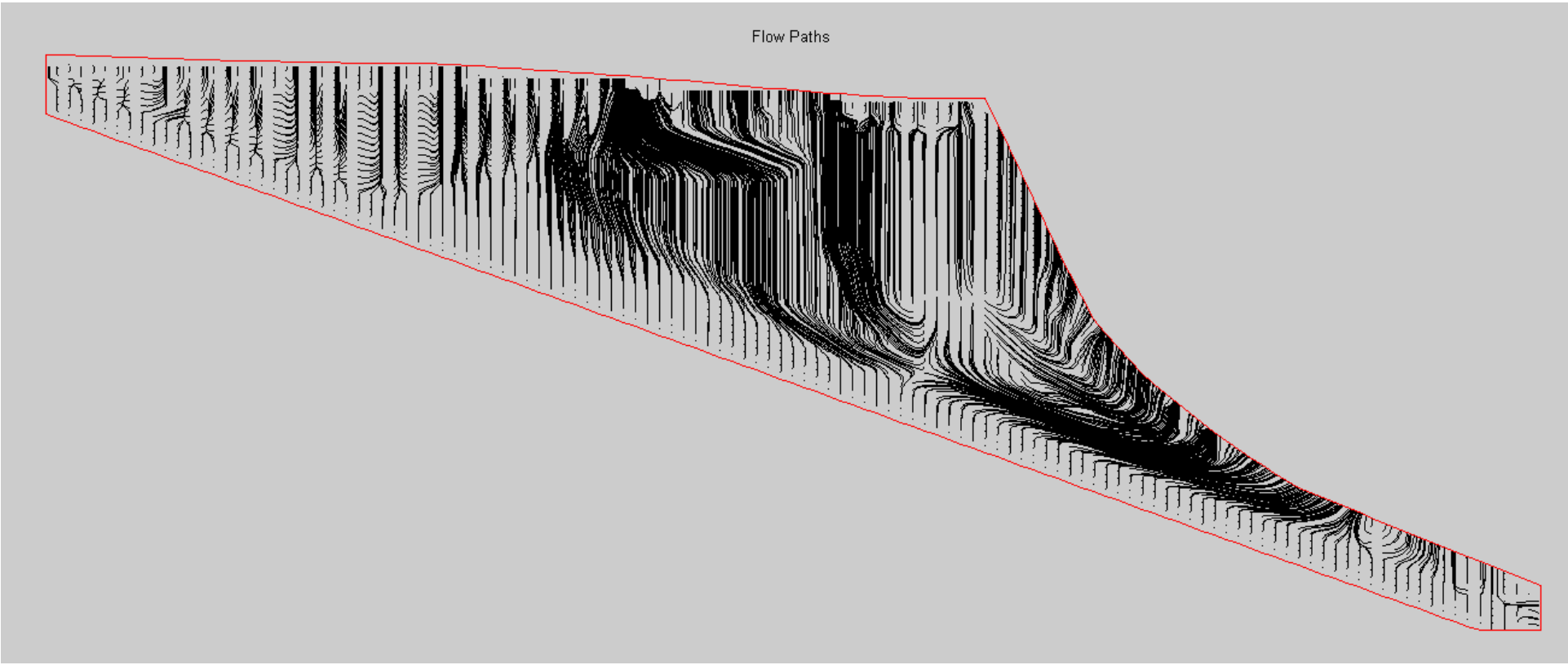
- Anisotropy high where sand and mud are interbedded

Overpressure and Fluid Flow



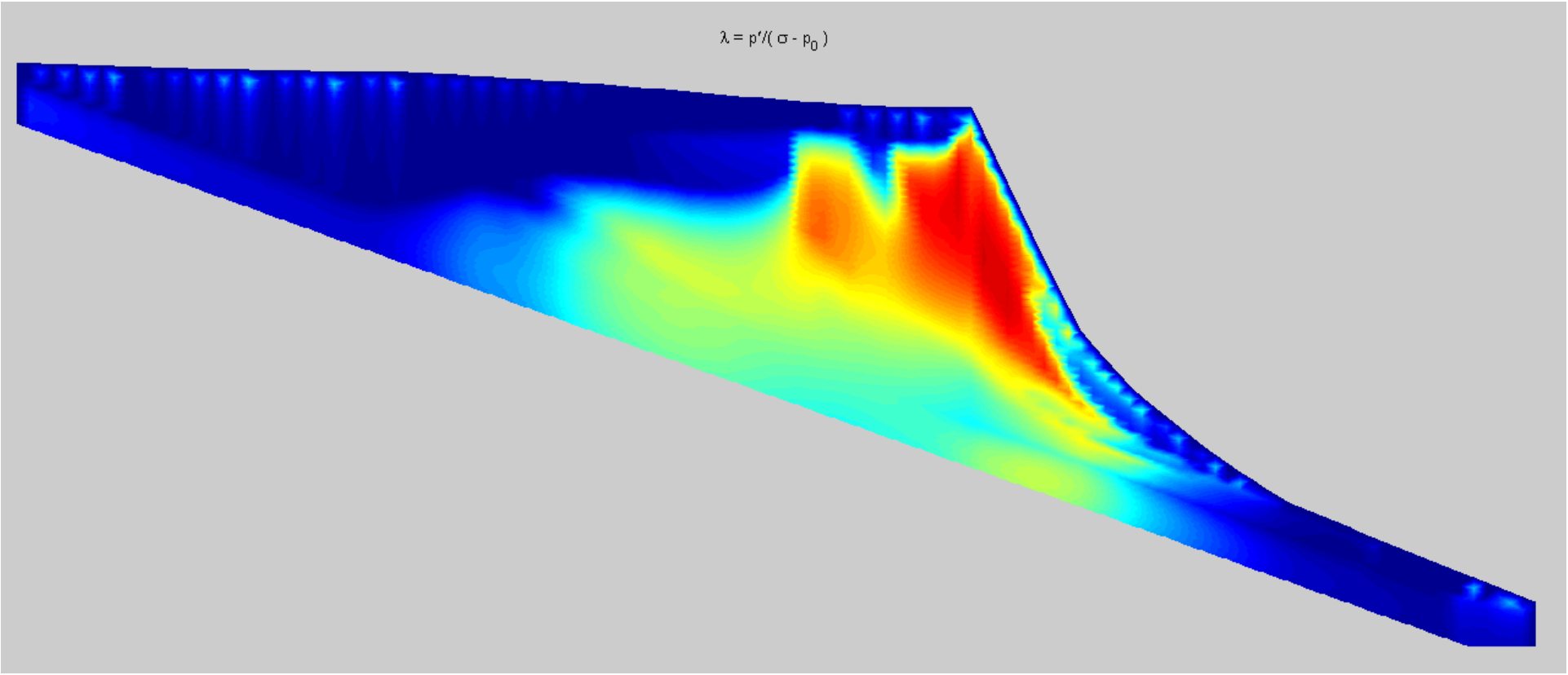
- Overpressure centered around shelf break depocenter, which forms flow divide

Overpressure and Fluid Flow



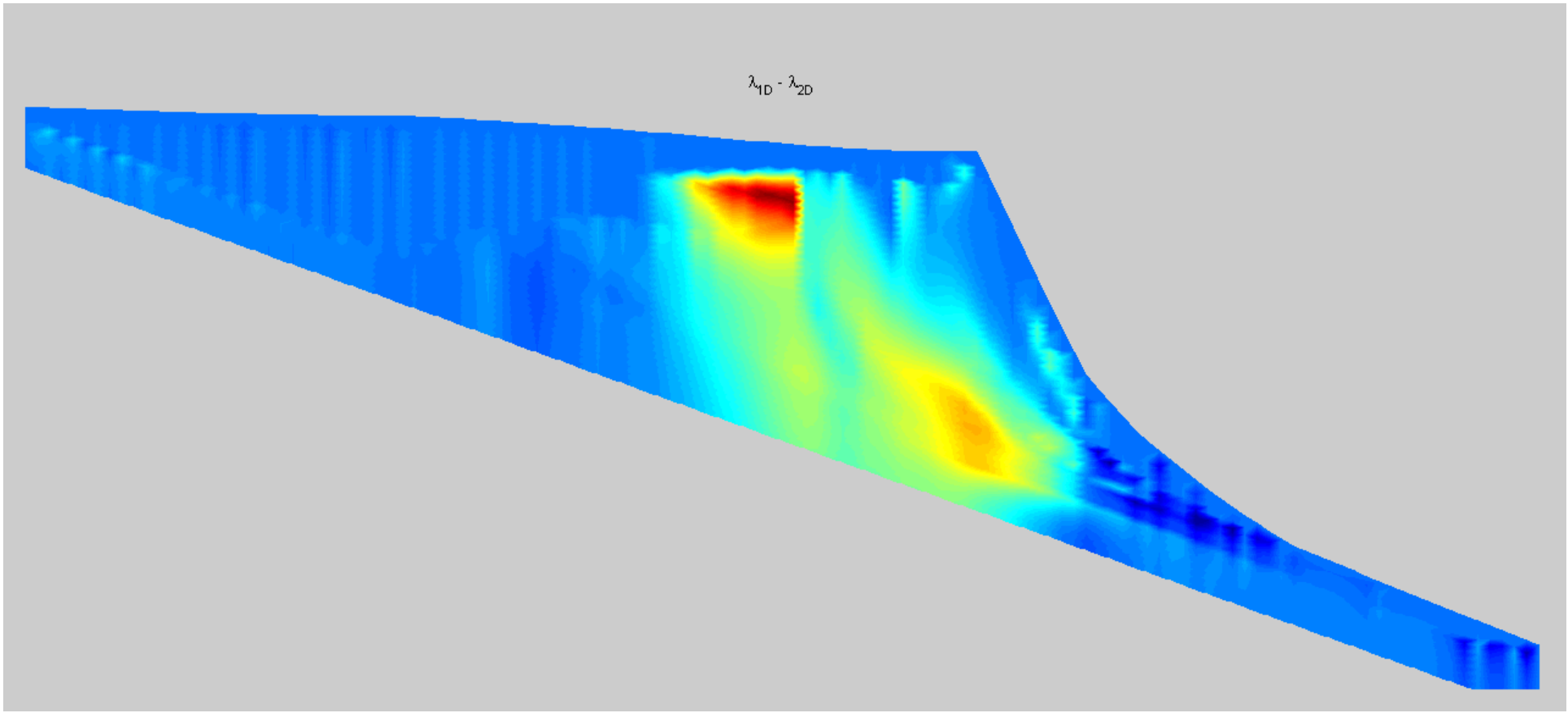
- Confined sands form lateral fluid conduits
- Many flowpaths significantly horizontal

Effective Stress and Stability



- Max overpressure near basement
- Max *relative* overpressure higher up on slope → far from conduits (vents)

Quasi-1D vs Fully 2D



- Quasi-1D overpredicts instability near flow conduits → conduits vent overpressure

Conclusions

Heterogeneous lithology induces flow anisotropy on bed and margin scales:

- interbedded sand/mud → *local* anisotropy

- laterally extensive confined sands → *regional* anisotropy

Conclusions

- Confined sandy aquifers form conduits that vent overpressure → particularly slope base turbidite fans

- Max overpressure near basement, but max instability (*relative* overpressure) higher up, away from vents → upper slope most susceptible to failure

Conclusions

- Quasi-1D consolidation cannot capture inherently 2D patterns of overpressure and fluid flow in passive margin systems

- 2D coupled models are needed … and can be efficiently implemented

Acknowledgements