CREEP FLOW SYSTEMS IN THE EARTH CRUST:

A COMPLEMENT TO GROUNDWATER FLOW SYSTEMS

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OUTLINE

- GLOBAL CLIMATE CHANGE
- MODEL-BASED ANALYSIS
- CRUST'S CREEP HEAD SYSTEMS
- CRUST'S CREEP FLOW SYSTEMS
- ORDERS OF MAGNITUDE
- SUMMARY AND CONCLUSIONS

GLOBAL CLIMATE CHANGE

- Earth's Average Global Temperature (AGT) rises at rate 1.5—1.8 °C / century
- Limiting global warming ➔ Carbon Capture, Utilization and Storage (CCUS)
- Storage in aquifers, depleted gas fields, …
- Learning from Gravitational Groundwater Flow Systems Analysis for storage of nuclear waste (Tóth)

MODEL-BASED ANALYSIS

- Observations + Forecast model + (Kalman) Filter ➔ weighted average of Observations + Forecast
  with Uncertainty

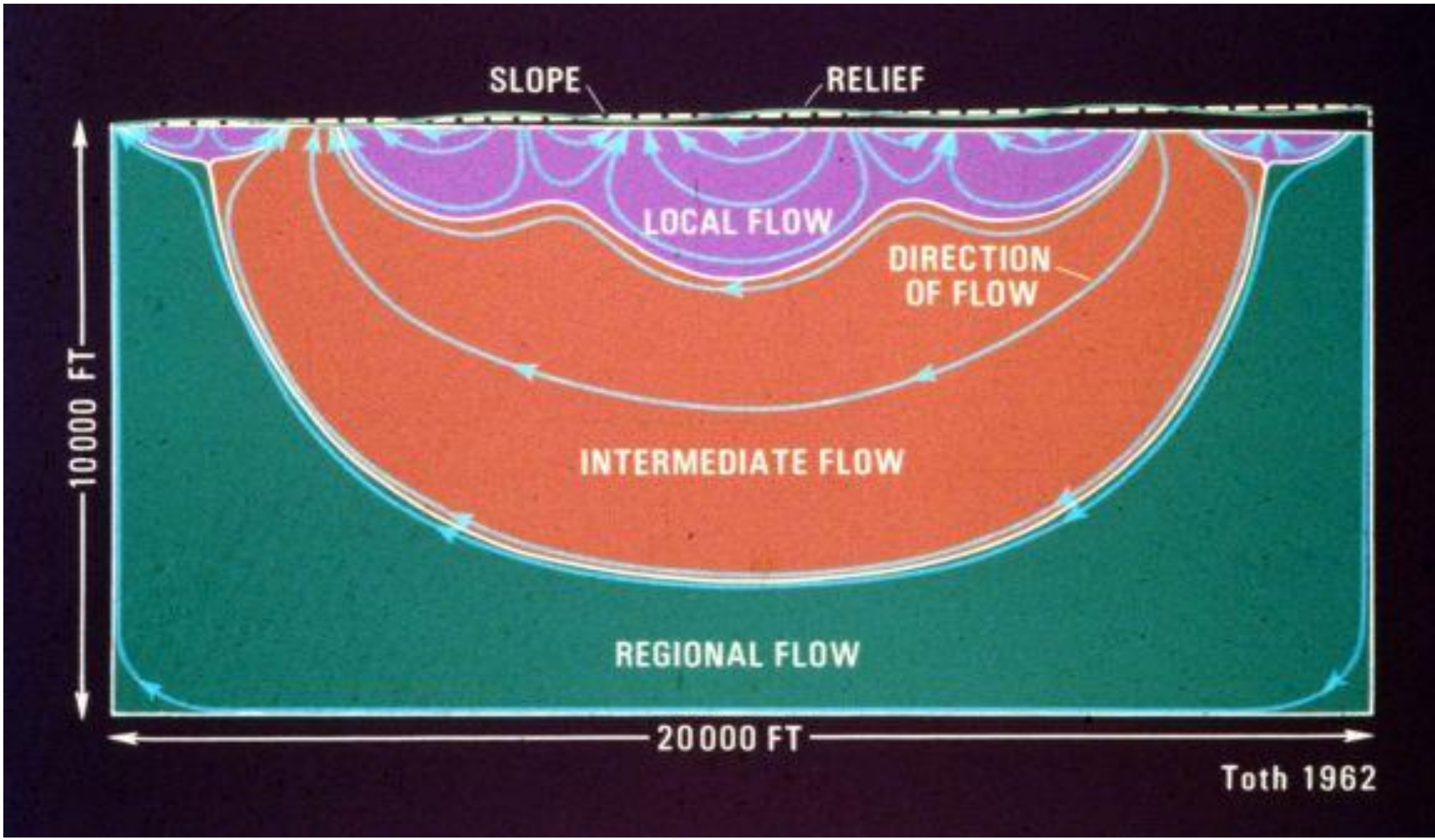
- Comprehensive models (many grid blocks)
- Simple models (analytical)
- Indices (like AGT, BMI, GDP)

- Groundwater flow indices:
  Penetration depth, Decay time
- Similar indices for Earth Crust's creep flow

EARTH CRUST CREEP HEAD SYSTEMS

- Geological time scales: Earth crust flows as viscous fluid
- Crust viscosity: 10^{21}—10^{22} Pa·s
  (water viscosity: 10^{-3} Pa·s)
- Continuity eqn + Stokes eqn
- Driving force: gravity, undulating topography
- Creep head eqn: $\nabla^2\varphi = 0$
  like groundwater head eqn

Tóthian Creep Head-Gradient Systems: Lines denoted by 'direction of flow' show head gradient; NOT flow lines



Rock Upheaval: Blowout as Artesian Flowing Earth Crust Well

- Stationary point: point with zero head gradient
- Groundwater: stationary point = stagnation points
- Creep flow: stationary point ≠ stagnation point
- Water well in stationary zone ➔ artesian well
- Well drilled through earth crust into stationary zone with compacting groundwater may result in blowout

  April 20, 2010: Deepwater Horizon, drilling 5.6 km deep exploration well caused eruption of mud, methane gas, and water 73 m into the air.

EARTH CRUST CREEP FLOW SYSTEMS

- Fourier decomposition of ground level $h(\underline{x},\underline{y})$ into spatial waves with wavelength $2\pi L$
- Creep flow equations for Fourier System L in its own rotated vertical x-z cross section

  $\partial v_x/\partial x + \partial v_z/\partial z = 0$ (continuity eqn)

  $\omega \equiv \partial v_x/\partial z - \partial v_z/\partial x = 0$ (def of vorticity)

  $\rho\partial\omega/\partial t = \mu(\partial^2\omega/\partial x^2 + \partial^2\omega/\partial y^2)$ (Stokes eqn)

- Is $\omega = 0$ a good approximation ?

Boundary conditions

- **Approximations**

  Geometric linearization: top bc on $z = 0$

  Math linearization: neglect terms $O(\partial h/\partial x)$

- **Boundary conditions on $z = 0$**

  Rate of ground level rise equals vertical upward velocity: $\partial h/\partial t = -v_z$

  Viscous stress balances Earth's weight: $2\mu \partial v_z/\partial z = -\rho g h$

Evolution in time

- Initially, for $t < 0$, flat topography, no flow
- At $t = 0$, sudden change of topographic height (e.g. sudden retreat of land ice)
- For $t > 0$ flow until flat topography

$$h = h_0 \sin(x/L) \exp(-t/T)$$

$$v_x = v_{x0} \cos(x/L) \exp(-z/L_Z) \exp(-t/T)$$

$$v_z = v_{z0} \sin(x/L) \exp(-z/L_Z) \exp(-t/T)$$

Solution

- $T = 2\mu/\rho g L$ = relaxation time
- Define $T_D = \rho L^2/\mu$ = vorticity diffusion time
- Define inertia number $I = 2.598 \times (T_D /T)$

- $I > 1$ ➔ under-damped flow: oscillating waves with decreasing amplitude
- $I = 1$ ➔ critically-damped flow
- $I < 1$ ➔ over-damped flow:

  the smaller I, the slower the decay

Negligibly small vorticity

- $T_D / T << 0.385$ ➔ negligible vorticity,
  penetration depth = wavelength = $2\pi L$
- Vortex-free flow ➔ potential flow
- $v_x = -K\, \partial\varphi/\partial x$, $v_z = -K\, \partial\varphi/\partial z$ (Darcy-like eqn)
  $K = \rho g L^2/2\mu$ (Fourier mode-dependent ‘creep conductivity’)
- Shallow system ➔ hardly any creep flow
- Deep system ➔ appreciable creep flow

ORDERS OF MAGNITUDE

Specified Data

- Earth crust's density $\rho = 3000$ kg/m^3
- Earth crust's viscosity $\mu = 5 \times 10^{21}$ Pa·s
- Gravitational acceleration $g = 10$ m/s^2
- Consider Fourier Flow Systems

  $\pi L = 300$—3000 km = half wavelength

  average slope = 0.02%

  (Brussels—Paris ≈ 300 km

  Brussels—Tromsø ≈ 3000 km)

Calculated indices

- Penetration depths: 600—6000 km
- Relaxation times: 100 000—10 000 year
- Decay times: 600 000—60 000 year

  (relaxation: 0.37 × original value

  decay: 0.002 × original value)
- Creep *K*-values: 1—100 m/year
- Creep velocities: 0.5—50 mm/year

Creep flow vs. Groundwater flow

- Reservoir rock (limestone, dolomite) at 3 km depth

  Permeability: 0.01 millidarcy

  Porosity: $n = 0.1$
- Groundwater: $K = 3$ mm/year

  Darcy velocity: $q = 1.5$ mm/year

  Transport velocity: $v = q/n = 15$ mm/year
- Crust's creep velocity: 0.5—50 mm/year

CREEP FLOW COMPLEMENTS GROUNDWATER FLOW

SUMMARY AND CONCLUSIONS

- Av Global Temp rise 1.5-1.8 °C/century
- Carbon Capture, Utilization and Storage
  in aquifers, depleted gas fields, etc.
- Modeling: Simple Indices
- Long-term behavior: Earth crust's creep flow
- Gravity-driven nested creep flow systems
- Penetration depth, decay time
- Darcy-like creep flow equation with Fourier mode-dependent 'creep conductivity' (*K*-value)
- Creep flow complements groundwater flow