Driving forces part 3: Porosity and flow driven by compaction

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15 jan 2020
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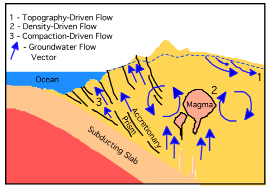
This week: more on the driving forces of fluid flow

- Driving forces, why do crustal fluids flow?
  - Recharge-driven flow
  - Buoyancy, density-driven flow, free convection
  - **Flow driven by compaction, sedimentary or tectonic loading**
  - Fluid production or consumption by chemical reactions



Today's lecture

- Part 1: Porosity, compaction and effective stress
- Part 2: Measuring porosity
- Part 3: Compaction driven flow

Porosity-depth curves

- Porosity-depth / effective stress for different sediments
- Sand: 40% at surface, relatively low compressibility
- Clay: high porosity at surface, ~60%, high compressibility, most porosity loss within ~ 1000 m of burial
- Carbonates: very high porosity at surface for most marine carbonates (up to 70%), high compressibility. chemical processes (dissolution/precipitation) often dominate over mechanical compaction

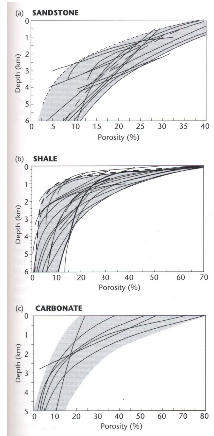
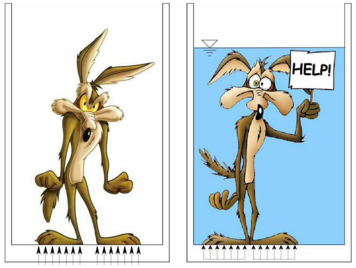


Fig. 9.3 Compilation of porosity–depth curves for sandstones (a), shales (b), and carbonates (c). Sources of datasets in Giles (1997). Note that shales compact early compared to sandstones. The porosity–depth relation for carbonates varies according to grain types and amount of cementation. Reproduced courtesy of Springer.

Compilation fo porosity-depth curves, Giles (1997)

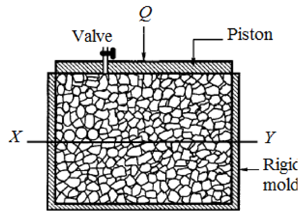
Porosity as a function of effective stress

- Porosity is a function of effective stress that a rock experiences
- The effective stress is not just a function of the weight of the overburden, but also of the fluid pressure

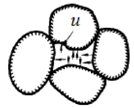


Porosity as a function of effective stress

- Porosity is a function of effective stress
$$\sigma_e = \sigma - \alpha p$$
- Effective stress: difference between total stress σ and porewater pressure (p). in most cases α = 1
- Total stress: In most cases that we'll discuss here total stress is the stress by the overburden, ie the overlying rock including the pore fluids
- Note that loading (vertical) or tectonic compression (horizontal) have the same effect on porosity



Soil under load in a rigid container



Pore water pressure

Porosity as a function of effective stress

- Effective stress theory developed by Austrian Scientist Karl von Terzaghi in 1923
$$\sigma_e = \sigma - \alpha p$$
- Experiments showed that α=1
- However, why α=1 was not fully explained until 1971 by Nur and Byerlee
- Correct version of equation: $$\sigma_e = \sigma_t - \left(1 - \frac{\beta_s}{\beta_b}\right) P$$
- βs, βb=compressibility of solid grains, bulk rock
- In most cases bulk sediment much more compressible than the solid grains themselves -> therefore in most cases α≅1

Karl Terzaghi: Founder of Modern Geotechnology. Photo courtesy of The MIT Museum

Porosity is a function of effective stress

- Consequence: Compaction is not only caused by external loading (sedimentation, burial), but can also be caused by a decrease in pore pressure

$$\sigma_e = \sigma - \alpha p$$

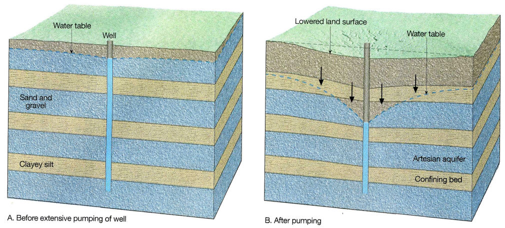


FIGURE 12.8 Before **(A)** and after **(B)** extensive pumping of a well. Note in **B** the lowering of the water-pressure surface, compaction of confining beds between the aquifers, and resulting subsidence of land surface. Arrows indicate the direction of compaction caused by the downward force of gravity, after the opposing water pressure was reduced by excessive withdrawal (discharge) of groundwater from the well.

Porosity is a function of effective stress

- Compaction can be caused by a decrease in pore pressure

$$\sigma_e = \sigma - \alpha p$$

Porosity

- Why does porosity change as a function of effective stress?
- Elastic change: relatively small
- Inelastic change in porosity
  - Mechanical compaction, dominant up to a depth of 2-3 km
  - Pressure solution
  - Diagenesis: clay mineral transformation, silica mineralization, ect…. dominant at depths > 2-3 km and T > ~80 ˚C

Elastic vs inelastic change in porosity:

- Elastic change during unloading relatively small compared to overall change
- Porosity decrease is largely irreversible

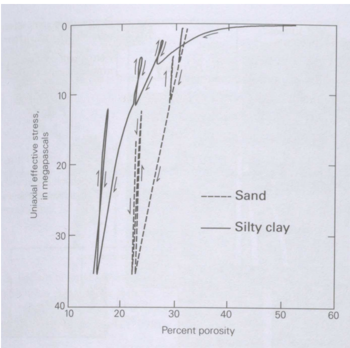
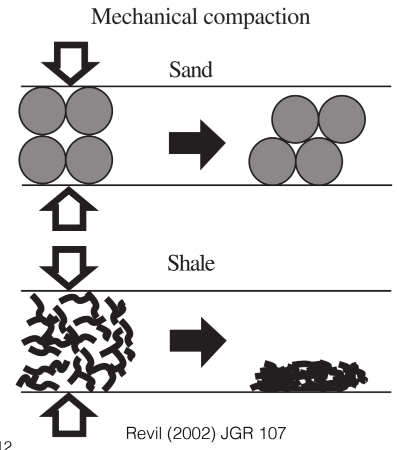


Figure 11.1. Plot of uniaxial effective stress versus porosity for sand and silty clay undergoing laterally confined (no lateral strain) compaction and decompaction under laboratory conditions. Downward arrows indicate loading phases and upward arrows indicate unloading phases. These particular laboratory data are notable for the high stresses attained; the maximum effective stress of 35 MPa corresponds (under hydrostatic fluid pressures) to a depth of about 2.7 km. After Karig and Hou (1992).

Mechanical compaction

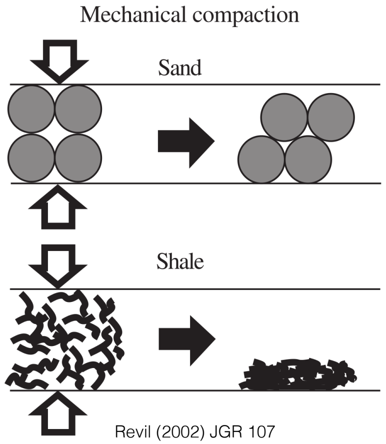
- Mechanical compaction processes, in order of importance:
  - Grain reorganisation
  - Ductile deformation of grains (clays, micas)
  - Grain crushing



Revil (2002) JGR 107

Mechanical compaction

- Grain reorganisation -> probably most important cause for compaction
- Slippage -> existing contacts fail due to overburden stress. Move to new closer packing until friction between grain contacts balances compressive stress



Revil (2002) JGR 107

Mechanical compaction

- Grain crushing
- Occurs at high effective stress, >~50 MPa, >~3500 m depth
- Predominantly in very coarse sands with high initial porosity

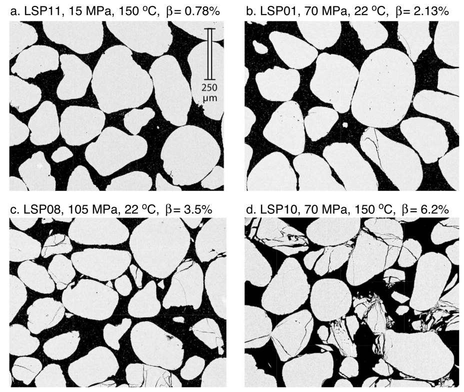
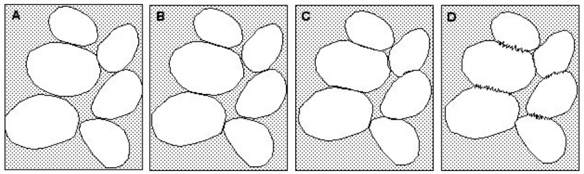


Fig. 6. BE images of sand showing increase in fracture intensity and development of complex systems as function of increase in volume strain. (a) LSP11, 0.8% strain. (b) LSP01, 2.1% strain. (c) LSP08, 3.5% strain. (d) LSP10, 6.2% strain.

Chester et al. (2004) EPSL 220

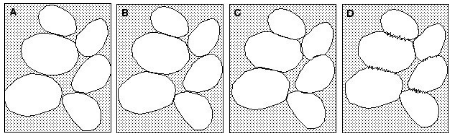
Pressure solution

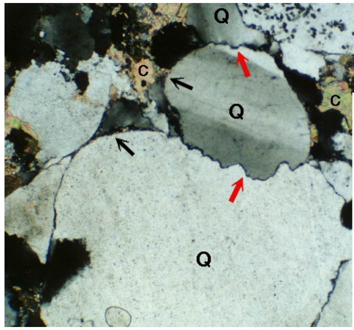
- Pressure increases solubility of quartz
- Initial small contact are between grains -> very high local pressure -> Dissolution of silica
- Lower pressure away from grain contact -> precipitation of silica
- Net result: -> broader grain contact, reduction in porosity
- Important for porosity reduction in 'clean' sandstones and carbonates. Sandstones: operates at high eff. stress/depth (>~2.5 km) and at low rates compared to mechanical compaction



Pressure solution

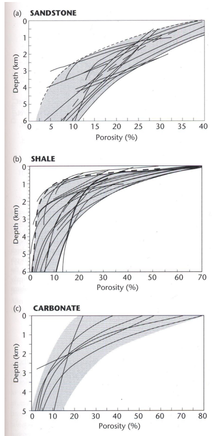
- Visible in grain contacts in thin sections:





Porosity vs effective stress

- Predicting porosity as a function of depth or overburden stress
- Empirical: Athy's law (1930) observed an exponential porosity decrease with depth and effective stress in Paleozoic shales
- Exponential porosity-depth/eff. stress function widely used ever since, but no theoretical basis until much later



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Porosity vs effective stress: Athy's equation

Athy's equation:

$$\phi = \phi_0 e^{-cz} \tag{1}$$

ϕ = porosity, ϕ_0 = porosity at surface, c is compressibility m^{-1} and z is depth (m).

$$\phi = \phi_0 e^{-\beta\sigma_{eff}} \tag{2}$$

ϕ = porosity, ϕ_0 = porosity at surface, β is compressibility Pa^{-1} and σ_{eff} is effective stress (Pa).

Porosity vs effective stress: Athy's equation

- Full mathematical solution by Fowler and Yang (2008), based on fluid and force balance

$$\text{(42)} \qquad \frac{\partial \phi}{\partial t} = \frac{\lambda}{1-a}\frac{\partial}{\partial z}\left\{\tilde{k}(1-\phi)\left[-\tilde{p}'(\phi)\frac{\partial \phi}{\partial z} - (1+ar-\phi)\right]\right\} - \dot{b}\frac{\partial \phi}{\partial z}.$$

- For slow compaction (ie. geological timescales) equation reduces to much simpler Athy's equation:
- (Note that z and h(0) are normalised, thats why the exponent looks different still, see paper for more info)

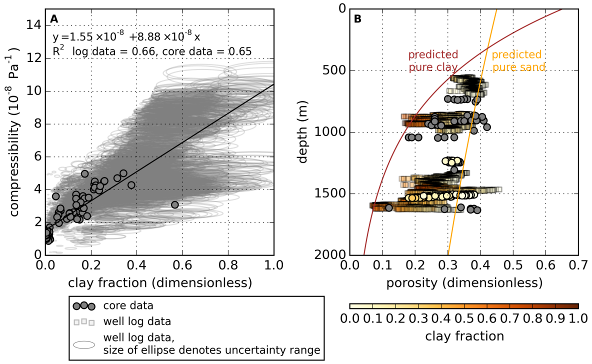
Its solution is

$$\text{(67)} \qquad \phi^{(0)} = \phi_0 e^{-(h^{(0)}-z)}.$$

Fowler & Yang (2008) SIAM Journal on Applied Mathematics

Porosity-depth curves

- Compressibility siliciclastic sediments scales approximately linearly with clay content:



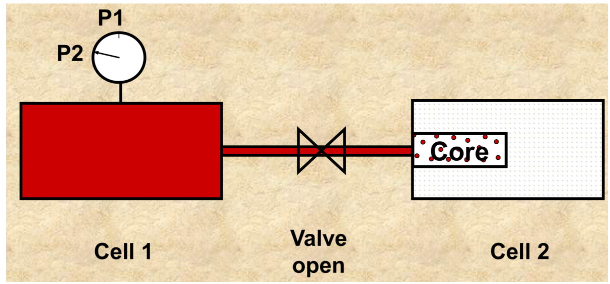
Porosity data from non-cemented siliclastic sediments in a sedimentary basin in the Southern Netherlands

Part 2: Measuring porosity

- Core plug samples: helium porosity
- well logs:
  - sonic logs
  - neutron logs
  - density logs

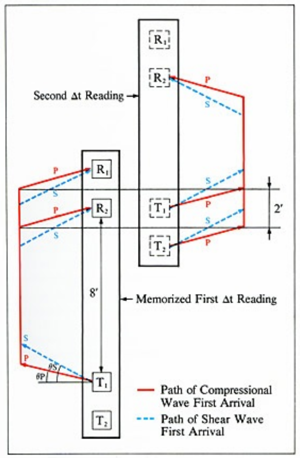
Measuring porosity

- Helium porosity: Measure porosity by gas displacement in vacuum core sample
- Normal size of samples = 2.5 cm diameter x 10 cm long



Measuring porosity

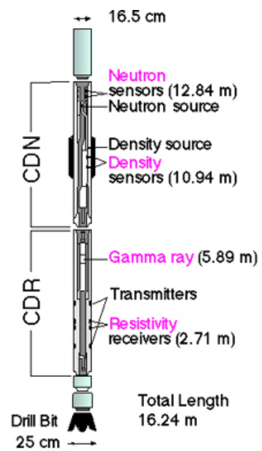
- Sonic velocity log: Records travel time of sound waves
- Travel time function of properties of matrix, pore fluid and porosity
- Difficult to get good estimate of porosity
- However, often only source of data, especially in older boreholes (pre 1980s)



IODP, http://iodp.ldeo.columbia.edu

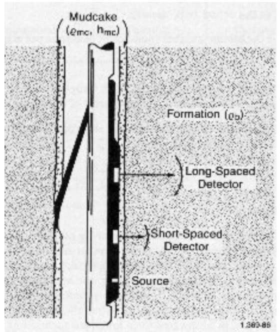
Measuring porosity

- Neutron logs:
  - emitted neutrons slowed down by collision, mostly with hydrogen atoms
  - Neutron log tool measures hydrogen in surrounding formation
  - Hydrogen found in clay minerals as $Al(OH)_6^{-3}$
  - And as water bound to mineral surface
  - Neutron log = clay content + porosity



Measuring porosity

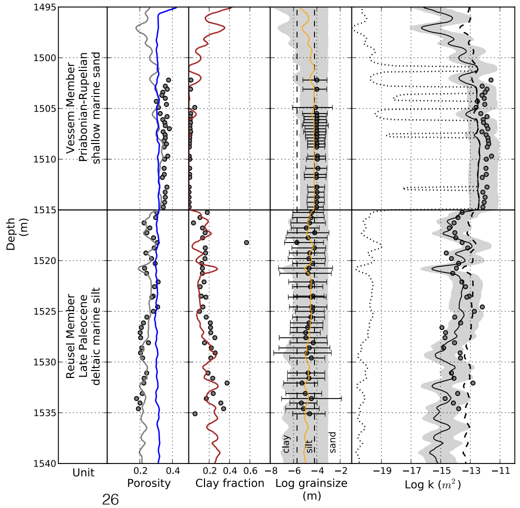
- Density logs: Gamma-gamma ray tool
- Source and recorder of gamma rays
- Scatter of gamma rays=function of electron density



$$\phi = \frac{\rho_m - \rho_b}{\rho_m - \rho_f}$$

Measuring porosity

- Example of porosity estimates using density log data:



Compaction driven flow

- Porosity changes very important for permeability, see lecture on porosity-permeability relations
- Porosity changes also drive fluid flow directly: adding/removing water from a volume in the subsurface due to a change in porosity can be described as an additional source term (Q_c)
- Increase in water volume must be balanced by 1) an increase in porewater pressure/hydraulic head, or 2) an increase in fluid flow (or both)

$$S\frac{\partial h}{\partial t} = \nabla K \nabla h + Q_c$$

$$Qc = \frac{\partial \phi}{\partial t}$$

Overpressure

- In low permeability environments and high subsidence rates: flow cannot balance additional water -> fluid pressure increases above hydrostatic levels
- p > hydrostatic is termed overpressure

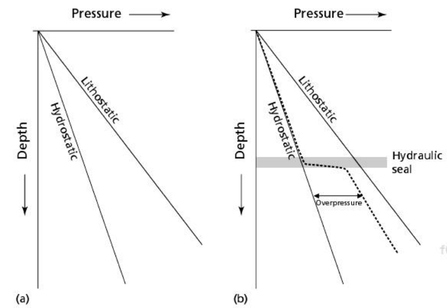
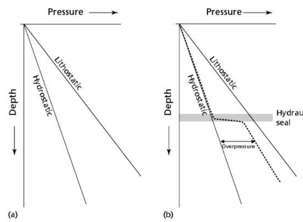


Fig. 3.3 Fluid pressure in a pore network will follow a hydrostatic trend when the vertical connectivity of the pore network is efficient. In (a) lithostatic pressures reflect the pressure exerted by the rock matrix. In (b) when the vertical equilibration of fluid pressures is hampered during basin subsidence, for example by the presence of a hydraulic seal such as a low-permeability shale, so called 'overpressures' can develop at depth. A field example of pressure-depth profiles showing overpressure can be found in Box 3.2. (Adapted from Domenico and Schwartz 1998. Reproduced with permission from John Wiley & Sons.)

Source: Hiscock and Bense

Over and underpressures

- Over and underpressures: fluid pressures that are significantly higher than the normal hydrostatic pressure
- Normal pressure = hydrostatic pressure = pressure of the overlying water column
- Stress = pressure. Units = force per m^2 = N/m^2 = Pa



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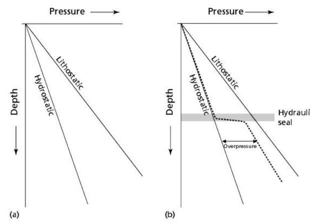
Source: Hiscock and Bense (2014)

Over and underpressures

- Hydrostatic fluid pressure = pressure of the overlying water column
- Hydrostatic fluid pressure: $P = \rho_{fluid}\ g\ d$
- Properties of fluids: stresses / pressure are transmitted equally in all directions



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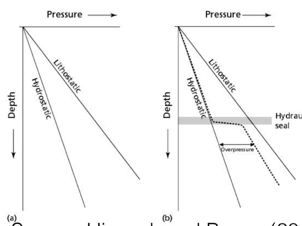
Source: Hiscock and Bense (2014)

Over and underpressures

- Lithostatic fluid pressure: fluid pressure is equal to the pressure of the overlying rock column
- lithostatic pressure -> fluid pressure (p) equals the total stress (σ): effective stress = σ - p = 0
- $P = \rho_{total}\ g\ d = (1 - \Phi)\ \rho_{rock}\ g\ d + \Phi\ \rho_{fluid}\ g\ d$
- Lithostatic fluid pressure: fluid pressure is sufficient to lift the overlying rock mass -> formation of new fractures or reactivation of existing fractures



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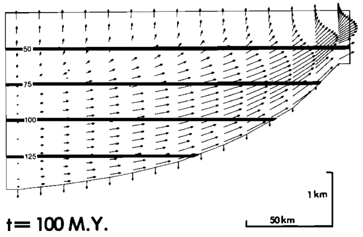
Source: Hiscock and Bense (2014)

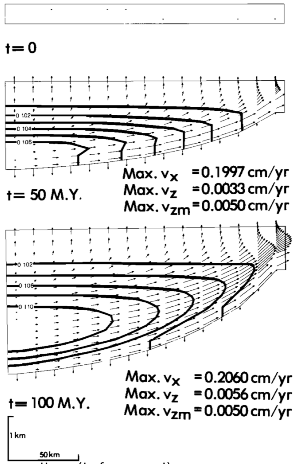
Compaction-driven flow

- Flow due to external loading can be caused by:
  - Deposition of sediments and resulting compaction
- Question: what additional processes can cause compaction-driven flow?
  - Emplacement of ice sheets
  - Emplacement of thrust sheets
  - Tectonic compression
  - Loading by groundwater recharge, atmospheric pressure changes, earth tides

Compaction-driven flow

- Example from a slowly subsiding intercontinental basin (such as the Illinois, Williston basins in north America):

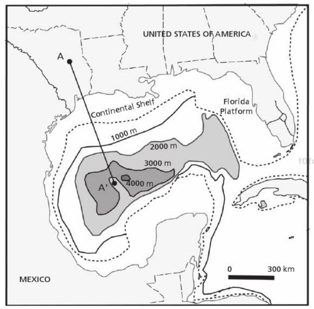


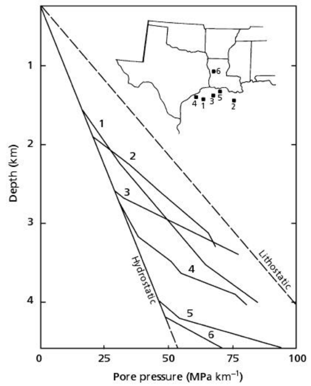


Compaction-driven flow does not generate any thermal anomalies (left panel)
Bethke (1985) Jrnl of Geophys. Res.

Compaction-driven flow

- Example from a rapidly subsiding sedimentary basin, the Gulf of Mexico

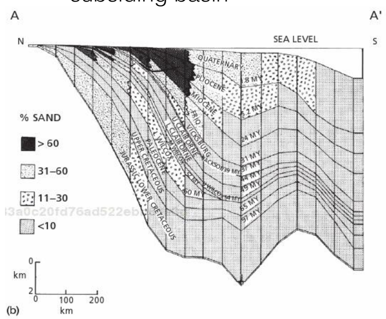


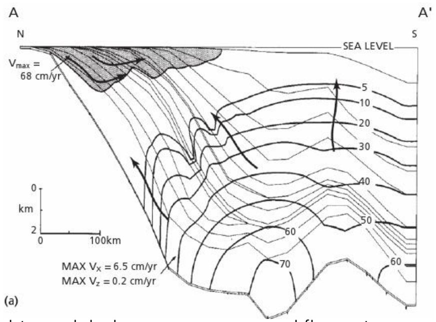


Source: Harisson and Summa (1991) Am. Jrnl of Science

Compaction-driven flow

- Overpressure at shallower levels in basin center -> rapid subsidence and more clay-rich (low k) sediments
- Flow rates still relatively low, cm/yr even in an exceptionally rapidly subsiding basin



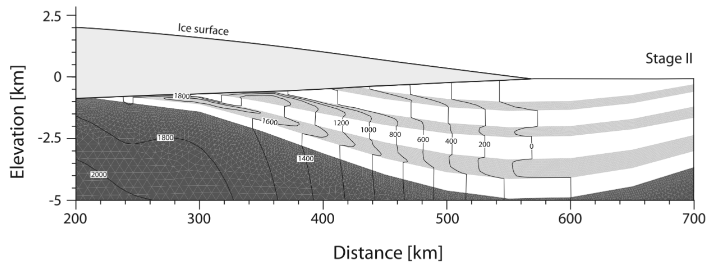


Left: distribution of clay-rich sediments, right: modeled over pressures and flow rates
Source: Harisson and Summa (1991)

Compaction due to loading by ice sheets:

- Advance of ice-sheet: increase of hydraulic head/pressures, most pronounced in shale layers where fluid flux cannot compensate for decrease in pore space

b.



Modeled hydraulic head response to loading by an ice sheet.
Dark layers are low permeable shales, contour lines show hydraulic head (m)
Bense and Person (2008) JGR

Compaction due to loading by ice sheets:

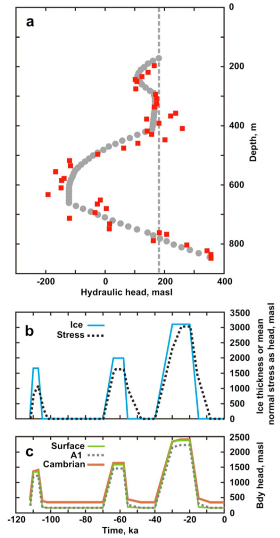
- Unloading: effective stress decreases, rock matrix expands, porosity increases
- Response: lower fluid pressure
- Unloading: time since unloading (interglacial) much shorter than loading time (glacial)
- For low-permeability units: no time yet for the pore pressure to return to hydrostatic -> the pore fluid is underpressured (lower than hydrostatic pressure)

$$S\frac{\partial h}{\partial t} = \nabla K \nabla h + Q_c$$

change in hydraulic head = fluid flux balance + source term

Compaction due to loading by ice sheets:

- Underpressure in Michigan basin in shale unit
- (grey line = hydrostatic pressure = constant hydraulic head)



Modeled and observed hydraulic head (top) and ice sheet loading (bottom panels)
Neuzil & Provost (2014) JGR

Fluid expulsion by thrust sheet loading

- What volumes and rates of fluids can we expect from thrust belts into forelands as a result of thrust sheet loading?

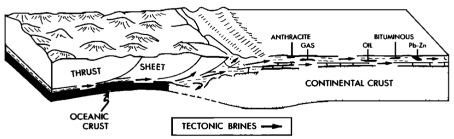
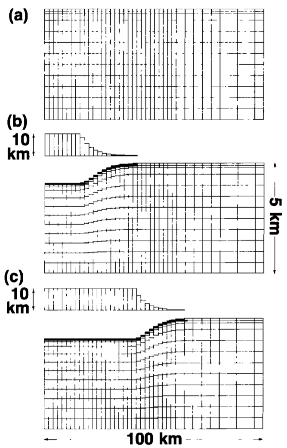


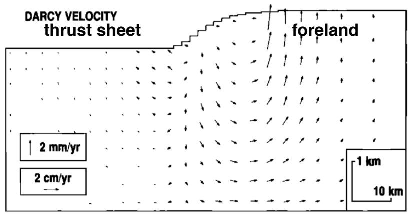
Fig. 1. Schematic illustration of "squeegee" hypothesis [after *Oliver*, 1986].

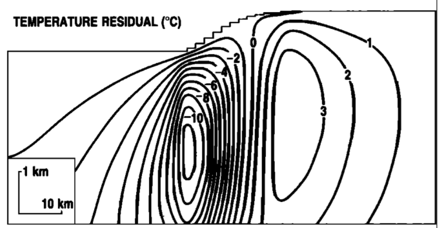


Model setup for simulation of thrust sheet loading
Deming et al. (1990) Jrnl of Geophys. Res.

Fluid expulsion by thrust sheet loading

- However, even with a 10 km thick thrust sheet, compaction-driven flow only reaches velocities up to 2 cm/yr
- Relatively minor thermal anomalies, up to 3 ˚C in foreland, cooling up to 10 ˚C below tip of thrust sheet





Modeled fluid fluxes (right) and thermal effect of fluid flow (right)
Deming et al. (1990)

Fluid flow and thrust sheet loading

- Loading by depositing sediments and emplacing thrust sheets: low velocities (up to cm/yr), minor thermal anomalies
- Exception: channeling fluids through permeable faults
- How about the effects of tectonic stress?

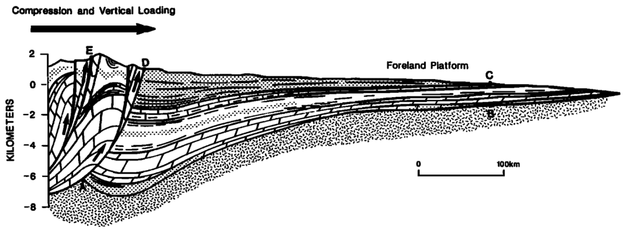
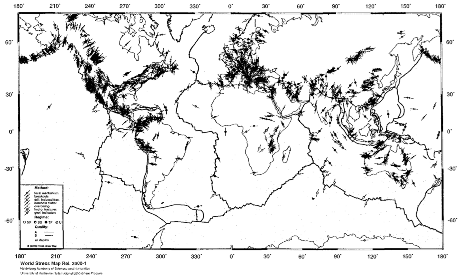


Fig. 4. The conceptual model of a generic foreland basin. The mathematical model is represented by the flow domain ABCD which is assumed to contain only indurated sedimentary strata [after *Ge and Garven*, 1989].

Ge and Garven (1992) Jrnl of Geophys. Res.

Tectonic stress

- Stress directions in the crust are fairly well known from borehole breakouts, earth-quake focal mechanisms, fault slip data
- However, stress magnitude is very poorly constrained….



World Stress map, Sperner et al. (2000) Geol. Soc. London. Spec. Publ.

Tectonic stress

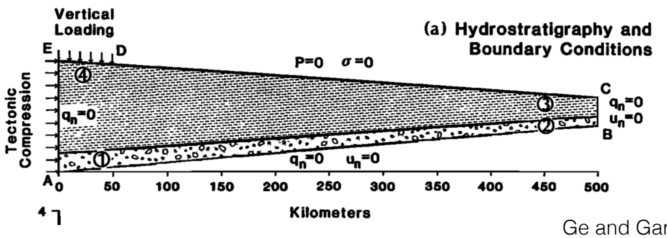
- Some constraints on differential stress in the subsurface:
  - Frictional heating required to generate pseudotachylite along fault planes -> approx. 250 MPa
  - Stress required to maintain topography ~100 MPa
  - Stress buildup between fault slip events: up to 50 MPa
  - There are probably a lot more estimates out there in the literature, all very uncertain

Tectonic stress

- Typical value of tectonic stress: 1×10^7 to 1×10^8 Pa
- How much is 1×10^7 Pa?
- density of column of rocks ~2000 kg/mr, gravity number = 9.81 m s^2
- 1×10^7 Pa = equal to load exerted by a 500 m thick column of rock
- 1×10^8 Pa = 5000 m thick column of rock

Modelling fluid expulsion

- Generic model of fluid expulsion due to tectonic stress and thrust sheet loading

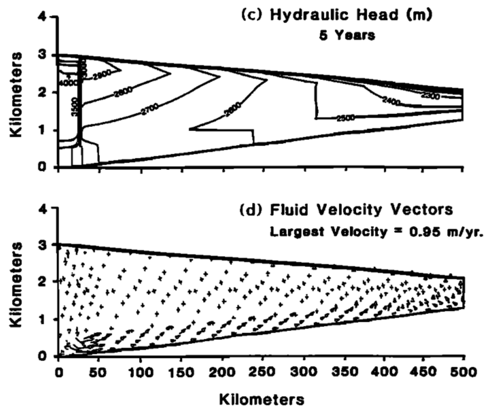


Ge and Garven (1992)

$$\nabla \cdot (\mathbf{K} \cdot \nabla h) + \alpha \frac{\partial \sigma_t}{\partial t} = S_s \frac{\partial h}{\partial t}$$

Modelling fluid expulsion

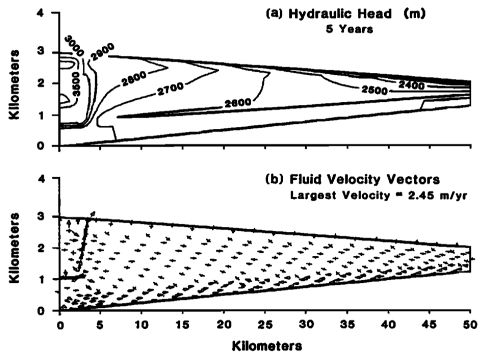
- Combined effects of thrust sheet loading and tectonic stress
- Strong increase in hydraulic heads/pressures
- Flow velocities still relatively slow, velocities up to ~1 m/yr
- = approximate threshold for a very minor thermal effect
- but sufficient for solute transport



Ge and Garven (1992)

Modelling fluid expulsion

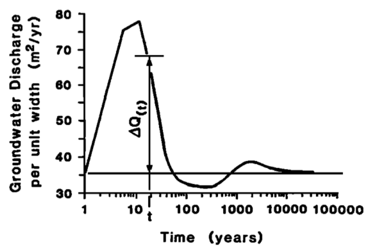
- Stronger effects for focused flow through a permeable fault



Ge and Garven (1992)

Modelling fluid expulsion

- Fluid expulsion relatively short-lived (< 100 yrs), fluid fluxes relatively low (<1 m/yr)
- Reason: The compressibility of water is very low, so a high volume of overpressured pore water will only generate a small flux (ie volume change) when the pressure is released



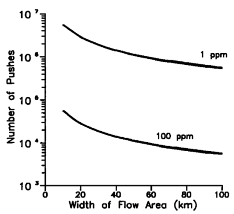
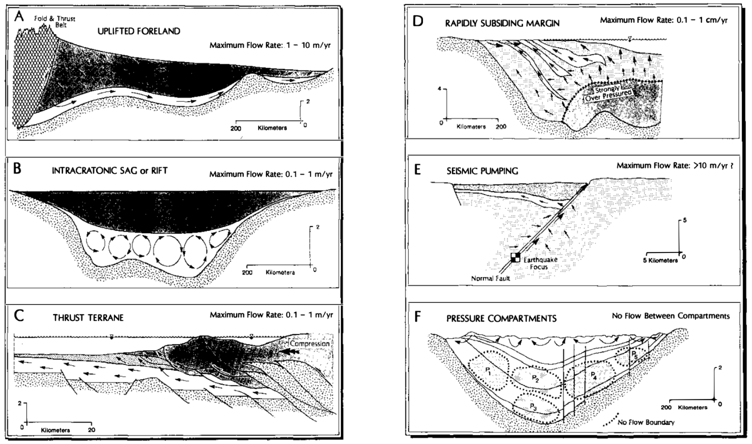


Fig. 23. Relationship between flow area, metal concentration in basinal brine, and number of tectonic pulses or thrust events needed to account for the amount of metal in Southeast Missouri District.

Ge and Garven (1992)

Comparison of flow rates different flow mechanisms



Garven (1995)

Summary

- Processes for porosity loss in rocks -> mechanical compaction (grain reorganisation, grain crushing), pressure solution
- Porosity change is a function of effective stress, which is a function of tectonic or sedimentary loading
- Porosity-effective stress follows Athy's law: porosity = exponential function of effective stress
- Change in porosity due to change in effective stress. Decrease in porosity -> expulsion of water -> increase in pressure, increase in flux or both
- Compaction either by sediment burial, loading by glaciers, or thrust sheets can drive flow at basin-scale. However only at relatively low flow rates, probably too low for any thermal effects
- However, in low-permeable formations overpressures may be maintained over geological timescales. Current fluid pressures still affected by tectonic or glacial history
- Direct effects of tectonic stress can generate very short lived events with moderate velocities