Fluid volumes in the crust

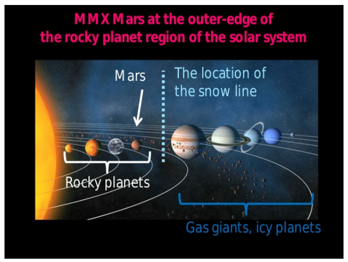
M.Geo.239
30 oct 2019
Elco Luijendijk
eluijen@gwdg.de

Today's menu

- Part 1: Water in the solar system and how our planet got its water
- Part 2: Porosity and volumes of water in the crust

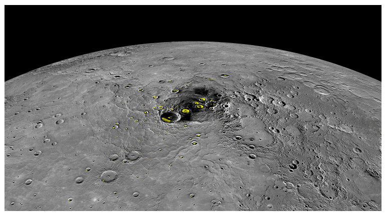
Water in the solar system

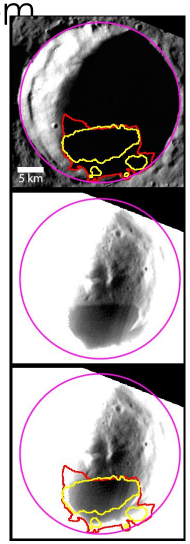
- Water is very abundant in the solar system
- Early history of water in solar system shaped by:
  - Temperatures that decreased with distance to the sun -> vapour in inner part of the solar system, liquid and ice in outer parts of solar system
  - Solar winds, which stripped interplanetary nebula (that contained abundant H and O) and atmospheres of vapour



Water in the solar system

- Recent discovery, still some water ice remaining on mercury, in spite of temperatures of ~400 ˚C
- Was found by NASA's Messenger mission, water ice was imaged in a crater along the pole

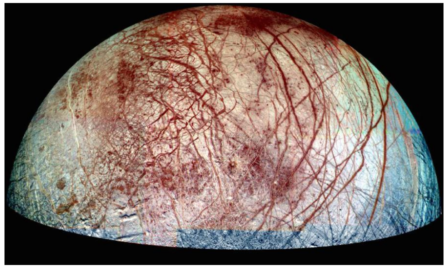


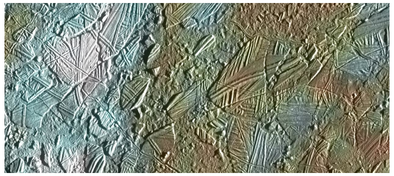


Source: NASA

Liquid water in the solar system

- Liquid water beneath fractured water-ice surface of Jupiter's moon Europa

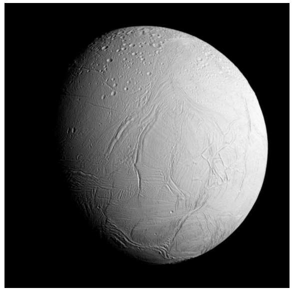


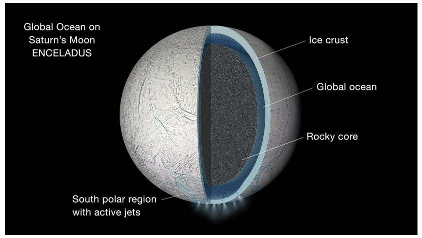


Source: Nasa/JPL

Liquid water in the solar system

- Recently discovered: liquid ocean beneath surface of Saturn's moon Enceladus
- Wobble in rotation axis can only be explained by 10-30 km thick ocean beneath ice surface

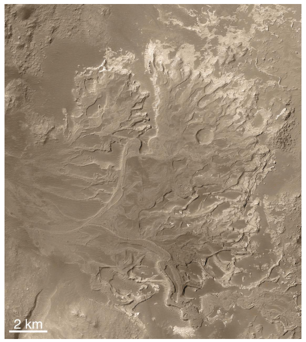




Source: Nasa/JPL

Liquid water on Mars?

- Mars used to have a lot of water, abundant evidence for the flow of liquid water on the surface
- However Mars' atmosphere has largely disappeared, its magnetic field was probably too weak. So no more water vapor & liquid water on the surface



Eberswalde delta, source: ESA

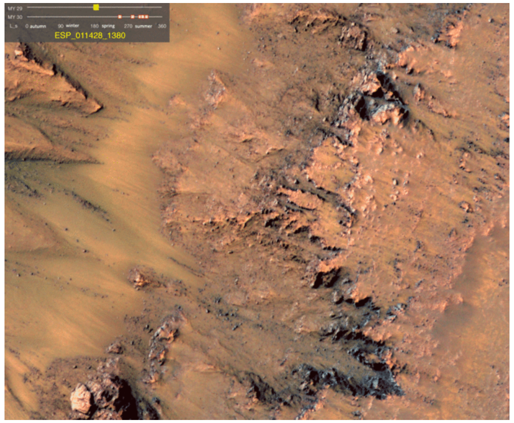
Liquid water on Mars?

- At present the only water at the surface is in the form of ice in craters:

Source: ESA

Liquid water on Mars?

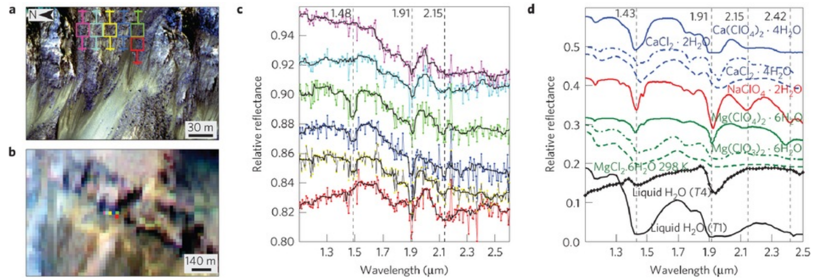
- Seasonally changing linear features on crater slopes:



Source: NASA/JPL

Liquid water on Mars?

- Observed spectra of slope lines indicates they are formed by hydrated salts
- Compare observed slope spectra on Mars (c) and lab measured spectra on earth (d)
- Results have been contested, there may be issues with the spectral analysis. However other explanations arguing for a sedimentary orogin are also problematic

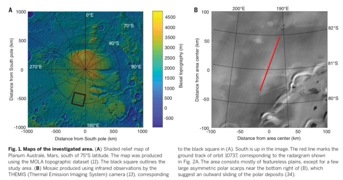


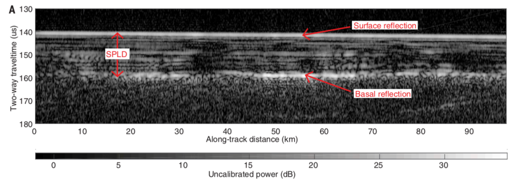
Ohja et al. (2015) Nature Geoscience 8

Groundwater on Mars?

- Radar images below an ice deposit show high reflections that may indicate the presence of liquid water:

Orosei et al. (2018) Science 361





Earth

- Earth is unique: stable reservoirs of liquid water, all three phases of water present
- Without water: no plate tectonics (probably) -> relatively boring earth science
- Water affects the strength and viscosity of the mantle, mantle convection, subduction and volcanism
- a planet with no water would probably mean a planet with no plate tectonics and a 'stagnant lid' / stable crust/lithosphere, possibly like Venus

Mars, Earth and Venus. Source: ESA

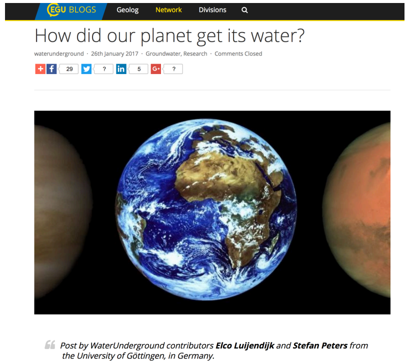
Where did earth's water come from?

- Theory 1: Early accretion and subsequent outgassing of volatiles from the mantle, early in earth's history
  - However, inner part of early solar system may have been too warm for volatiles to condensate
- Theory 2: Late accretion by comets and/or asteroids
  - However, recent rosetta mission found very different D/H isotope ratios in water-ice of comet 67P/Churyumov-Gerasimenko than found on earth

Comet 67P/Churyumov-Gerasimenko losing water and other volatiles as it approaches the sun. Source: ESA

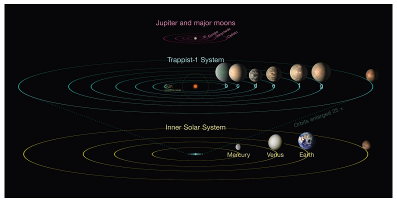
Where did earth's water come from?

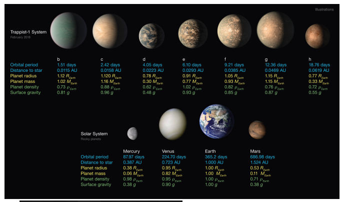
- More on this question in a blog item by Stefan Peters and me: http://blogs.egu.eu/network/water-underground/2017/01/26/how-did-our-planet-get-its-water/

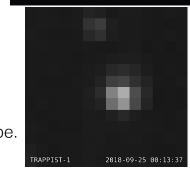


Water in exoplanets

- Planets in the recently discovered Trappist-1 system may host more water than earth, based on orbit & density estimates. Distance only 40 lightyears, so perhaps a beach holiday destination in the future…



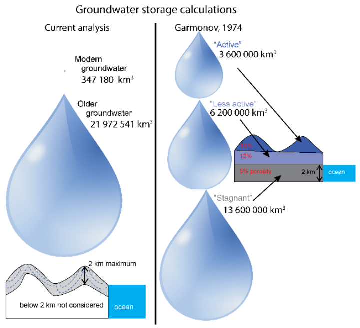




Trappist-1 as seen with the Kepler space telescope. Source: NASA, Ames Research Center

Part 2: Groundwater volumes in the crust

- Surprisingly no quantitative estimates exist of crustal groundwater volumes.
- Existing estimates date back to 1970s and are educated guesses



Right hand side: 1970s estimate

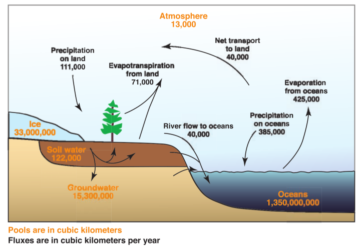
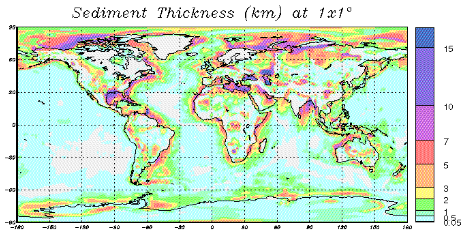


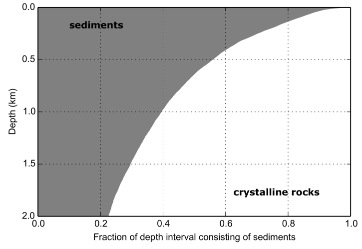
Fig. 1. Global pools and fluxes of water on Earth, showing the magnitude of groundwater storage relative to other major water storages and fluxes. [Reproduced from (*82*) with permission from the publisher, Elsevier Science (USA)]

Recent paper citing 1970s figures
Alley et al. (2002) Science 596

Groundwater volumes in the crust

- Most groundwater in upper crust resides in relatively porous sedimentary rocks
- Sedimentary rocks cover large part of the surface, but % sedimentary rocks rapidly decrease with depth, crystalline rocks are dominant overall in the crust
- global map of sediment thickness, based on compilation of seismic data:

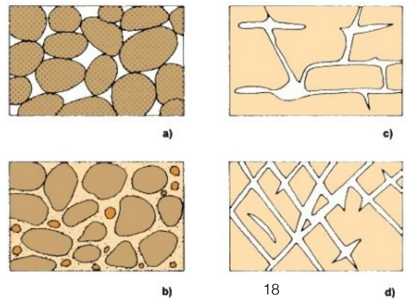




Crust1.0, Laske et al., http://igppweb.ucsd.edu/~gabi/rem.html

Porosity

- Types of porosity:
  - Primary or matrix porosity
  - Secondary porosity: dissolution features or fractures



Meinzer (1923)

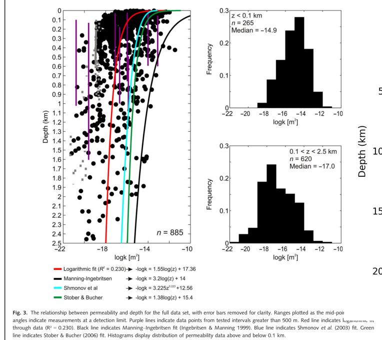
How do we know anything about porosity?

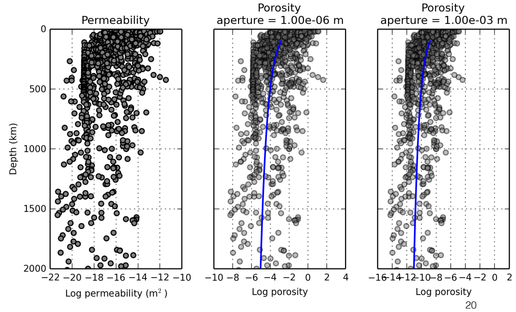
Different methods available to measure porosity in the subsurface:

- Core plug samples: helium porosity
- Well logs:
  - Sonic logs: Records travel time of sound waves
  - Neutron logs: Neutron emission & receiver, slowed down by hydrogen
  - Density logs: Source and receiver of gamma rays, scattering is a function of electron density and ~bulk density
- More on this later in lecture series (lecture 9, compaction)

Groundwater stored in crystalline rocks

- Groundwater in crystalline crust: predominantly located in fractures
- Lack of porosity data, alternative: porosity calculated from compilation of permeability data crystalline rocks using the cubic law of fracture permeability (more on fracture permeability later in lecture on permeability in week 4)
- Very low overall porosity (<0.1%) in crystalline rocks. Note that fluid fluxes in fractured crystalline rocks can still be high due to efficient transport in fractures





Ranjram et al. (2015) Geofluids

Groundwater stored in sedimentary rocks

- Ideal porosity-depth / effective stress curves 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

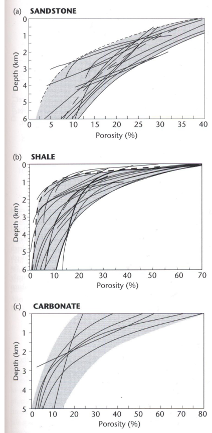


Fig. 9.3 Compilation of porosity–depth curves for sandstones (a), shales (b), and carbonates (c). Sources of datasets in Giles (1997). Note that shales compact early compared to sandstones. The porosity–depth relation for carbonates varies according to grain types and amount of cementation. Reproduced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

Compilation fo porosity-depth curves, Giles (1997)

Why does porosity change with depth?

- Why does porosity change as a function of depth and 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, etc…. 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
- This means that porosity decrease is largely irreversible

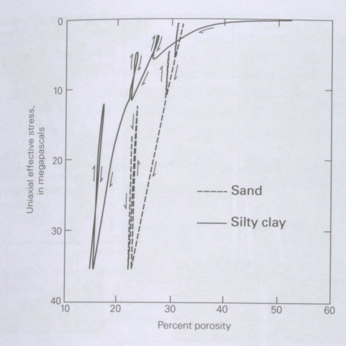
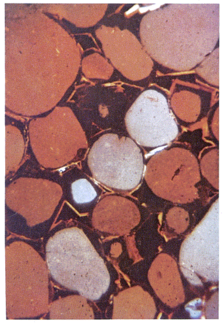


Figure 11.1. Plot of uniaxial effective stress versus porosity for sand and silty clay undergoing laterally confined (no lateral strain) compaction and decompaction under laboratory conditions. Downward arrows indicate loading phases and upward arrows indicate unloading phases. These particular laboratory 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

- Example of a non-compacted and compacted sediment
- More on porosity, compaction and the expulsion of fluids later in this lecture series….

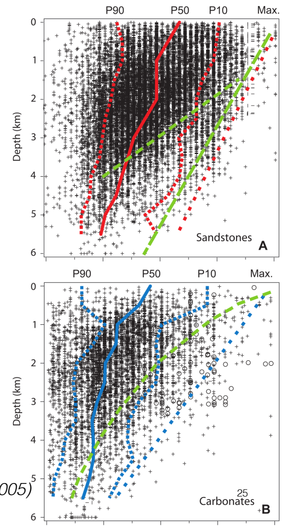


Grains shortly after deposition

Grains after compaction and cementation

Groundwater stored in sedimentary rocks

- Ideal porosity depth-curves are only part of the story. Sedimentary rocks do not follow these curves with depth, due to uplift and diagenesis
- First order estimates of groundwater volume in the crust from large porosity-depth compilations sedimentary rocks
- Porosity data from 40,000 hydrocarbon reservoirs
- Potentially biased towards permeable formations, but only available global dataset as of yet

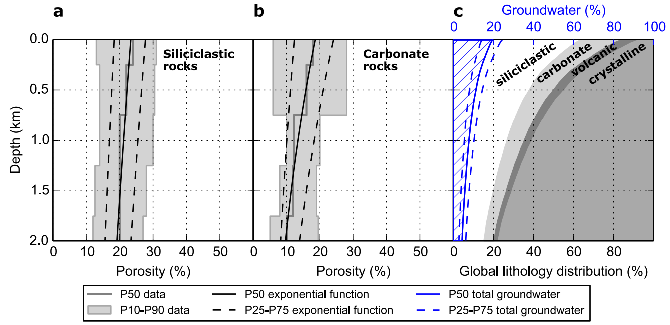


Ehrenberg & Nadeau (2005) AAPG Bulletin 89

25

Groundwater volume in the upper crust

- Combining porosity-depth compilations, with estimates sediment thickness ->
  - First order estimate of volume of water in the upper 2 km of the crust = 23 million km^3
  - = ~1.5% of the total ocean volume = equal to antarctic ice sheet volume
  - = layer of 180 m of water over continental surface



26

Gleeson et al., Nature Geosc. (2016)

Groundwater in the active hydrological cycle

- What is the importance of groundwater in the active hydrological cycle?
- Important for water supply, water quality, weathering, global geochemical cycles

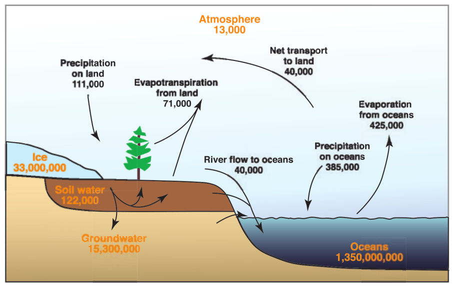


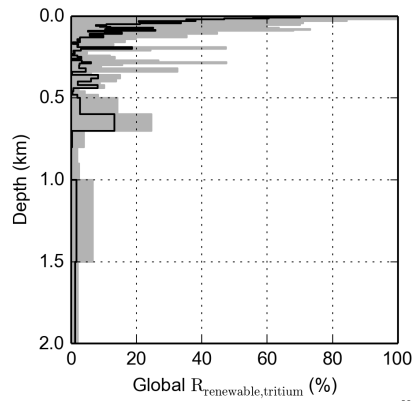
Fig. 1. Global pools and fluxes of water on Earth, showing the magnitude of groundwater storage relative to other major water storages and fluxes. [Reproduced from (82) with permission from the publisher, Elsevier Science (USA)]

27

Alley et al. (2002) Science 596

Groundwater in the active hydrological cycle

- Percentage of actively renewed groundwater over a timeframe of 50 years decreases strongly with depth
- Source: global compilation of groundwater tritium (3H) data
- Tritium spike in atmosphere and rainfall due to above ground nuclear tests in 1950's,
- gradual nuclear decay after test-ban treaty 1963, half life=12.3 yrs
- Largest groundwater tracer experiment ever

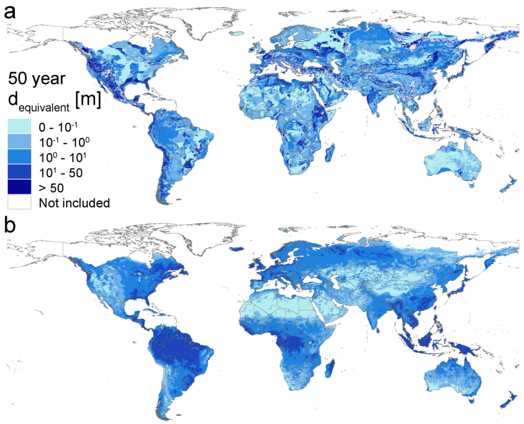


28

Gleeson et al. (2016) Nature Geosc.

Groundwater in the active hydrological cycle

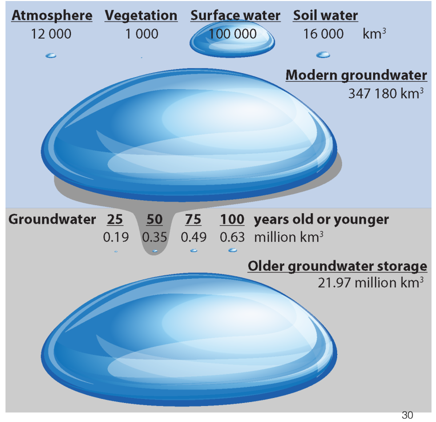
- Model study of active groundwater flux shows similar trends with depth as tritium data compilation
- Spatial distribution shows strong relation between active groundwater volume and climate/recharge



Modeled depth of <50 years old groundwater
Gleeson et al. (2016), Nature Geosc.

Groundwater in the active hydrological cycle

- Groundwater in the upper crust is the largest volume of the active hydrological cycle (over a timescale of 50 yrs)
- However, volume <50 yrs old groundwater small (~1.5 %) compared with total groundwater volume in upper crust
- Equal to thickness of 3.0 m when spread over land surface



Gleeson et al. (2016), Nature Geosc.

Summary

- Water in solar system: Liquid water present on many planets in the outer part of the solar system (earth and beyond), such as on Enceladus, Europa, Mars
- Earth: the only planet with stable reservoirs of water in all 3 phases.
- Source of water still unresolved, early accretion or late 'veneer' by meteors or comets
- Crustal groundwater predominantly found in sedimentary rocks, total volume in upper part of crust ~1.5% of the global ocean volume
- Groundwater = largest volume of water in active hydrological cycle
- Significant volume of water may reside in earth's mantle = up to 1 ocean volume

Next week

- Introduction to diffusion and the transport of fluids, heat and solutes in the subsurface
- Reading material:
  - Sections 1.1 and 1.3 of Ingebritsen et al. "Groundwater in Geologic Processes"
  - -> scanned pdf's available on google drive, will send link

Groundwater in the news

- Dont forget to look for groundwater news!