GEO4-1410, Deformation Mechanisms and Transport in Rocks.

Tentamen: *Transport and Effects of Fluids*

Docent: Dr. C.J. Peach
Datum: 06-03-2015, 13:30-16:30, Educatorium-Megaron

Instructions:

- Read all questions through, thoroughly, before answering.
- Answer question **1** plus any **3** from the remaining questions, (*i.e.* answer a total of **4** questions, including question **1**).
- Clearly label your answers with the question number.
- Use S.I. units, unless stated otherwise.
- Show any calculation steps clearly and use annotated diagrams where appropriate.
- Write your name clearly on each separate answer sheet.
- Duration of examination: 3 hours

Questions:

1.

a) Give three different physical/chemical processes involving fluids which directly affect rock deformation.

b) Give three examples of transport processes relevant to fluid/rock interaction. Show their mathematical similarity in form regarding flux *versus* driving force and describe geological scenarios where these transport processes may become coupled.

c) What is meant by the term representative elementary volume (REV), in descriptions of transport properties used for thermo-hydro-mechanical-chemical modelling? What is the consequence of choosing a too small value for a REV? Give an indication of the magnitude of the REV for fluid flow in the following cases: *i*) an isotropic permeable sandstone gas reservoir rock with grain-size ≤ 0.5mm, *ii*) a regular joint system of 50cm spacing in a massive limestone, *iii*) a fault system like the San Andreas in California. How would you expect these values be modified for modelling thermal conductivity?

d) Give 2 examples of fluid sources and 2 examples of fluid sinks, in geological formations. What is the significance of a zero value for divergence of the fluid velocity field in mathematical models of fluid flow in such formations?

e) Write Darcy's law in terms of hydraulic head, hydraulic conductivity and specific discharge (Darcy velocity) and state the units of each parameter?

f) Give the relation between hydraulic conductivity and permeability.

g) List the requirements for Darcy's law to be a valid description of fluid-flow in porous media? Give examples, together with an explanation, of geological settings and fluid/rock properties where problems of validity are likely to be encountered?

h) What relation is often used to link local microscopic (pore scale) flows to macroscopic measurable bulk flows described by Darcy's law? What factor links these two quantities in the relation?

i) Why is permeability to fluid not always a direct function of porosity?

j) Show the general structure of the permeability tensor for both isotropic and anisotropic porous media, giving geological examples of each type of medium.

k) Define tortuosity. What role does tortuosity play in the formulation of Darcy's law from simple equivalent channel models of connected microscopic flow elements (capillaries, *etc.*)?

l) By definition, the permeability of a rock is independent of the fluid flowing in the pores. Why then is the permeability of the same rock different when both oil and water are present in the rock together?

2.

a) Show how pore fluid pressure affects shear failure of porous rocks by change of effective stress. Use Mohr diagrams to illustrate this.

b) What are "lamba" values in descriptions of pore fluid pressure? What are the immediate likely consequences of fluid-filled rocks attaining lambda values greater than 1?

c) How can strength profiles for the lithosphere be affected by fluid pressure lambda values?

d) Why do thrust faults generally occur deeper in major fault systems than normal faults?

e) Given that salt rocks are mechanically weak and highly impermeable, why is there a future potential danger of brine release from abandoned and shut-in, brine-filled, solution-mined caverns in rocksalt?

f) How can gravity-driven sliding of regional scale rock units (nappes) occur on nearly horizontal, low angle slopes of less than 5°, when the angle of friction for most dry crustal materials is greater than 30°? Which scientists solved this problem in the 1950's and what concept did they introduce to allow its solution?

3.

a) What is percolation theory and how may it be applied to poorly connected systems to provide estimates of permeability?

b) What tests can be applied to systems of poorly connected elements or possible transport paths to estimate their degree of connectivity?

c) What is a fractal object and where do percolation systems behave as fractals?

d) The percolation probability P (probability that a bond or site belongs to the percolating cluster), and rate of growth of through-connection for site or bond clusters in percolation, by random addition of sites or bonds at occupation-probability p, is given by critical-growth power laws such as $P = (p - p_c)^{\beta}$, just above the percolation limit p_c. For "2D" percolation systems, near p_c, the growth is very rapid with $\beta = 5/36$. Why does transport (*e.g.* conductivity, σ), on such percolating networks, grow much more gently as $\sigma = (p - p_c)^{\mu}$, with an exponent $\mu = 1.3$?

e) The sizes of percolation clusters S_{∞}, near the percolation threshold, grow as $S_{\infty} \propto L^{D}$. Where $D = 91/48$ for "2D" percolation systems and L is the length scale of interest. What are the important properties of percolating systems near the percolation limit which could explain why maps of fracture systems in some hydrothermal fields often exhibit fractal geometry with fractal dimensions in the range 1.8-1.9? Why should the spatial geometry of intersecting hydro-fractures share the same fractal geometry with percolation systems at the point of through-connection?

f) Explain, by listing the steps and links in the process chain, how the dehydration rate of certain rocks, that undergo prograde thermal metamorphism, may be used to estimate the time to failure by hydro-fracture and thus to formation of mineral veins.

4.

a) Explain why the bulk physical properties of fluids may not be applicable to thin films and narrow pores in meta-sedimentary rocks. How may we verify this experimentally?
b) Why do the grain boundaries in quartzites often meet at triple junctions and what can the interfacial angles tell us?
c) What can equilibrium pore geometry and fluid/rock dihedral angle studies tell us about permeable connectivity in deep crustal rocks?
d) To what degree, can laboratory measurements of permeability on such texturally equilibrated rocks provide us with values of permeability associated with deformation and metamorphism?
e) What methods of permeability measurement allow investigation of low permeability materials and explain their advantages over the methods pioneered by Darcy himself? What extra rock property information is required to apply such methods?
f) What other methods can be used to determine the fluid transport properties of porous rocks besides direct permeability measurement?

None

5.

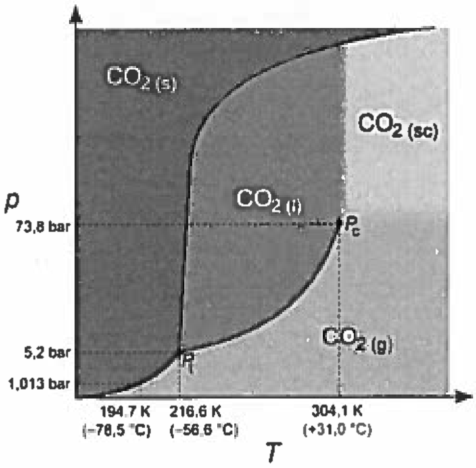
a) What are seismic pumping and fault valve behaviour?
b) Describe the geometry of extensional veins that are associated with thrust faulting. At what stage in a seismic faulting cycle are extensional veins likely to form and in what direction do these open?
c) In what geological environment is fault valve behaviour expected to occur and how may we recognize its former action in ancient slate rock terranes?
d) What processes give rise to crack-seal veins?
e) How can fluids be transported in lower-crustal and mantle rocks when the conduits for flow have a natural tendency to close by creep?
f) What factors affect the morphological development of, and the faulting styles within, accretionary wedges? Why are low-angle thrust faults unfrequent in shallow, permeable, rock formations?

6.

a) What are the stages of progressive surface hydration after fracture of a quartz crystal in a humid environment? Illustrate your answer with a diagram of surface energy versus hydration.
b) Why should the ionic concentration and pH of a hydrous solution affect the ease of crack formation in stressed rock samples submerged in the solution?
c) Describe three limitations to sub-critical crack propagation that relate to the fluid transport properties of the host material and properties of the crack-filling fluid.
d) Explain how the anisotropic properties, of fluid filled fractures associated with earthquake faults, could be utilized as an earthquake prediction tool using long term seismic monitoring of shear waves from surrounding sources?
e) Why is the tensile strength of deep and wet crustal rocks assumed to be negligible over geological time periods?
f) What controls the dry sliding frictional strength of fault gouge consisting of platy minerals? How does water affect the frictional strength of these materials and in what materials is its effect maximised?

7.

a) The phase diagram for carbon dioxide is given (on right). The critical point P_c is shown at 73.8 bar (7.38MPa) and 31°C. What is the expected phase for CO_2 when injected into water reservoirs at below 2000m depth? (Assume fluid pressure is hydrostatic and a normal continental geothermal gradient of 25°C per kilometre).



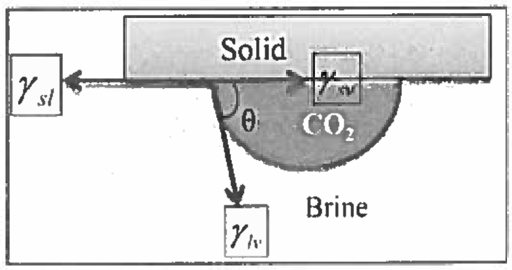
b) The solubility of ionic salts changes dramatically for water near its critical point (22MPa and 374°C), why do these changes occur and what property of water is responsible for the extreme solubility of sodium chloride salt in water at ambient conditions?

c) Capillary pressure provides useful pore blocking to trap fluids below cap-rocks in many reservoirs. Indeed without it, many of the North Sea oil and gas fields would not contain anything worth drilling for! The Washburn equation (right) used in mercury porosimetry gives the relation between injection pressure and pore-throat radius, r. How is mercury porosimetry carried out and what can it tell us about the pore structure of rocks?

$$\Delta P = \frac{2\gamma_{LV}\cos\theta}{r}$$

d) Experiments carried out by Farokhpoor *et al.*, 2013, using contact angle measurement of sessile CO_2 drops have determined the wetting characteristics of CO_2 versus water and NaCl-brines on quartz, under pressures and temperatures typical of hydrocarbon reservoirs.

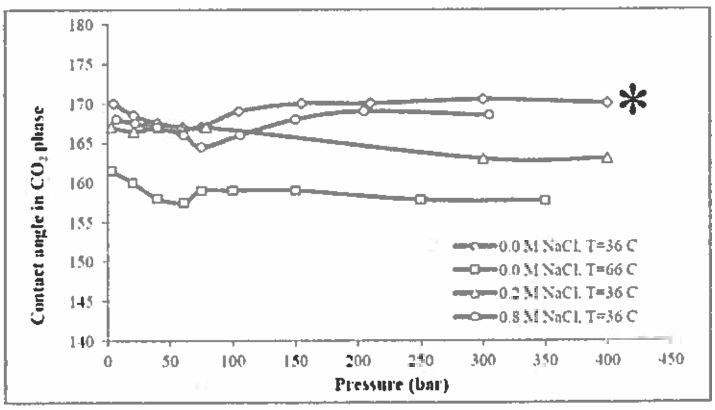
Schematic diagram of the experimental setup, showing the CO_2 drop and the relevant surface tensions that determine the contact angle θ. In practice the contact angle is >90° and CO_2 only partially wets the solid quartz.



Use the above diagram to derive the Young-Dupré equation relating interfacial tension to contact angle, on an undeformable solid substrate.

e) Given the following data from Farokhpoor *et al.* 2013, for CO_2 contact angles on quartz, estimate the height of a water column which may be supported by capillary pressure in a very fine quartz cap-rock with an average pore diameter of 100 nm at a depth of 2000m. Use the data for non-saline water at 36°C (data line marked with *). Use an interfacial tension between liquid water and CO_2 vapour of $32\times10^{-3}\,\mathrm{Nm^{-1}}$.

f) Why is the data less steady between 50-80bar (5-8MPa) at these temperatures?



Farokhpoor, R. *et al.*, 2013. CO_2 wettability behavior during CO_2 sequestration in saline aquifer – An Experimental study on minerals representing sandstone and carbonate. *Energy Procedia* **37**, pp5339-5351.

Good Luck!