GEO4-1410, Deformation Mechanisms and Transport in Rocks.

Tentamen: *Transport and Effects of Fluids*

Docent: Dr. C.J. Peach
Datum: 04-03-2016, 09:00-12:00, Educatorium-Alfa

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 the mechanical strength of rock in geological environments.

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 hydrological fluid flow in the following cases: *i*) an isotropic permeable sandstone gas reservoir rock with grain-size ≤ 0.5mm, *ii*) a regular, open but narrow (< 1 mm wide) joint system of 50cm spacing in a massive fine grained limestone, *iii*) a regional 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 systems that host fluid flow.

e) What is the significance of a zero value in divergence of the fluid velocity field, other than the absence of sources or sinks of the fluid that relates to a particular physical fluid property and requirement of Darcy's law?

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

g) Give the relation between hydraulic conductivity and permeability.

h) Are hydraulic "heads" a measure of fluid potential per unit mass or weight?

i) 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?

j) Name the relation 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?

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

(continued)

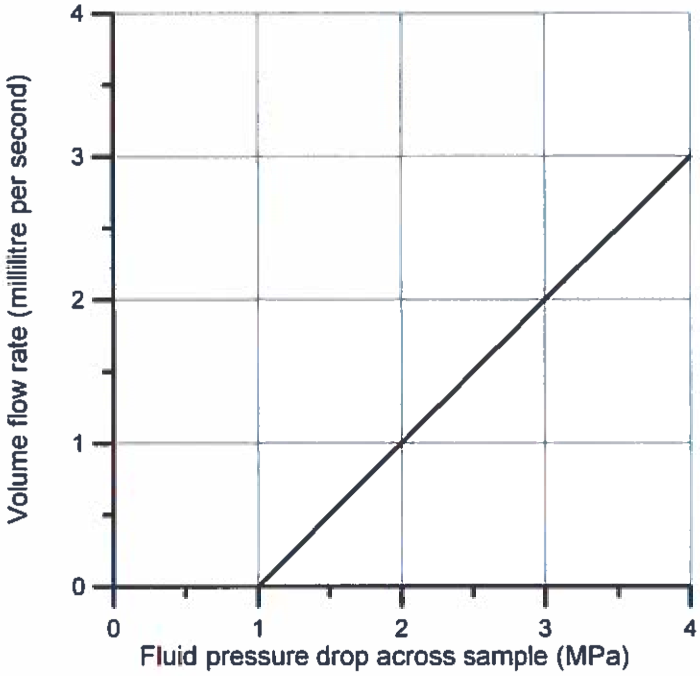
l) Show the general structure of the permeability tensor for both isotropic and anisotropic porous media, giving geological examples of each type of medium.

m) 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.*)?

n) 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?

o) Archie's law for the effective electrical conductivity of hydrous fluid filled porous rocks relates conductivity (or resistivity) to porosity. What are the basic assumptions in this relation and when might these not be applicable in real geological systems?

2. An experiment to investigate the permeability of micro-fractured oil shale under elevated temperature conditions, necessary to encourage *in situ* petroleum decomposition ("cracking") and enhance hydrocarbon recovery, was carried out in a special heated pressure vessel using molten tin as a pore fluid. The temperature of the experiment was 400°C and under these conditions the molten tin had a dynamic viscosity of 2×10^{-3} Pa s. The sample was a $10\times10\times10$ cm cube and flow was measured normal to and through two opposite faces, over their complete areas. A non-reactive metal jacket sealed the other 4 sides, parallel to the applied fluid pressure gradient. The molten tin was injected into the gas filled oil shale, and the volume of tin flowing out of the specimen was measured as a function of fluid pressure drop across the specimen. The graph of volume flow rate (ml/s) versus fluid pressure difference (MPa) across the sample during steady state flow was:



After the experiment and cooling to room conditions, the tin solidified in the sample and defined the porosity. The average pore radius was measured as 1.0×10^{-6} m, and statistically the pore sizes had a very narrow frequency distribution. The tin formed droplets on free surfaces within dead-end pores and the contact angle was measured to be 155°. Assuming the shape of the droplets had not changed on cooling and solidification, then the tin was inferred to be a non-wetting fluid during the flow-through experiment.

Given, $$\frac{Q}{A}=\frac{\kappa}{\eta}\frac{\Delta P}{L}, \quad \text{(I)} \qquad \Delta P_c=\frac{2\gamma_{LV}\cos\theta}{r}, \quad \text{(II)}$$

a) What is Equation (I) and describe its terms?

b) What is Equation (II) and describe its terms?

c) Explain why the graph of volume flow rate *versus* pressure drop does not pass through zero on both axes? (continued)

d) Using the graph, calculate the permeability of the micro-fractured oil shale, in the measured flow direction?

e) If the petroleum gas, associated with the chemically "cracked" oil shale, which under test conditions has a dynamic viscosity of 1.0×10^{-6} Pa s, had been used as the pore fluid instead of tin, then what would the permeability be?

f) Assume the geometry of the sample and fluid did not change on cooling, then calculate the surface tension of the molten tin?

3.

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 rock-salt?

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?

4.

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.

5.

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 thermally equilibrated, monomineralic, metamorphic rocks 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?

6.

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 infrequent in shallow, permeable, rock formations?

7.

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 maximized?

Good Luck!