GEO4-1410, Deformation Mechanisms and Transport in Rocks.

Tentamen: *Transport and Effects of Fluids*

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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 negative value for divergence of the fluid velocity field in mathematical models of fluid flow in such formations?
e) Give three factors that control the hydraulic conductivity of a rock.
f) Write Darcy's law in terms of hydraulic head, hydraulic conductivity and specific discharge (Darcy velocity) and state the units of each parameter? Give the relation between hydraulic conductivity and permeability.
g) A reservoir rock has an intrinsic permeability of 3×10^{-15} m^2 to water with a dynamic viscosity of 1 mPa.s. What will the permeability of this rock be to oil with a higher viscosity of 10 mPa.s and lower density of 800 kg.m^{-3}?
h) 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?
i) 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?

j) Why is permeability to fluid not always a direct function of porosity?
k) Show the general structure of the permeability tensor for both isotropic and anisotropic porous media, giving geological examples of each type of medium.
l) Why do flows in porous media containing multiple immiscible fluid phases, exhibit hysteresis and even blockage under low fluid pressure gradients?
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) What properties of rock and fluid are required for transient permeametry? What are the advantages of such methods over steady-state Darcy flow-through methods?
o) What is Archie's law and how is it used?

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) What parameters control the surface slope angle of accretionary wedges at convergent plate margins and what are their individual effects?
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?

[Part 3.f) continued on next page]

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) What are seismic pumping and fault valve behaviour?
b) In what geological environment is fault valve behaviour expected to occur and how may we recognize its former action in ancient slate rock terranes?
c) 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?
d) Explain the significance of aqueous fluid phase properties for quartz transport and precipitation, near the critical point for water (22MPa, 375°C)? What electrical property is responsible for this and why does it affect solubility of ionic compounds?
e) Why do deep crustal rocks, in orogenic metamorphic belts, often show evidence for very high integrated fluid fluxes whilst their permeability is too low for pore-fluid circulation by convection, only allowing single-pass fluid expulsion? How can flow be maintained in fractures that have a natural tendency to close at deep crustal levels?
f) Why do such deep crustal-fluid systems apparently keep active for 100's of Ma?

5.

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) 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?.
e) 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?
f) Why is the tensile strength of wet deep crustal rocks assumed to be negligible over geological time periods?

per – flow – compression – delay time

6.

a) What is disjoining pressure and what rock materials are expected to show this? In rock deformation and fluid interaction what processes are likely to be affected?
b) In enhanced coal bed methane production (ECBM), carbon dioxide is used to displace adsorbed methane from unmineable coal seams. Why is injection of CO_2 often rapidly blocked by a reduction in formation permeability so inhibiting production of desorbed methane?

[Part 6.c) continued on next page]

vaccum H_2O vapor immersion adsorbed water electrolyte

c) Gas-shales are low-permeability, finely porous rocks that are rich in organic material. Methane (CH_4) is absorbed strongly to shale under the formation pressures expected at 3km depth and deeper, where gas could be extracted using current technologies. Such gas is known as "unconventional, tight or tough gas", reflecting the difficulty of production. How can adsorption be expected to affect the permeability to methane compared with much less adsorbing gases like argon (commonly used in laboratory measurement)? How would the choice of gas and test pressure affect laboratory determination of the permeability? What testing methods would be best to give relevant values for production modelling?

d) What can equilibrium pore geometry dihedral angle studies tell us about permeable connectivity in deep crustal rocks and to what degree can laboratory measurements of permeability, on such texturally equilibrated rocks, provide us with values of permeability associated with past deformation and metamorphism?

e) Explain why the bulk physical properties of fluids may not be applicable to thin films and narrow pores in deeper meta-sedimentary rocks. What are the consequences of these different fluid properties for deformation process models involving intergranular diffusional transport?

f) Why is infrared absorption used to characterize the properties of water in confined spaces and films?

Good Luck!