Tentamen: GEO3-1304, Structure and Properties of Earth Materials

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Datum: (10-11-03 for AW3-3104) now for homework and discussion in final practical.
Naturally, we suggest you try all the questions!

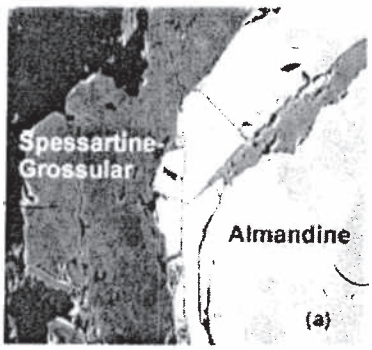
Instructions:
Read all questions through, thoroughly, before answering.
Answer **8** from the **10** questions and clearly label your answers with the question number.
Use S.I. units, unless stated otherwise.
Show any calculation steps clearly and use annotated diagrams where appropriate.
Write your name clearly on each separate answer sheet.
Duration of examination: 3 hours (14:00hr t/m 17:00hr)

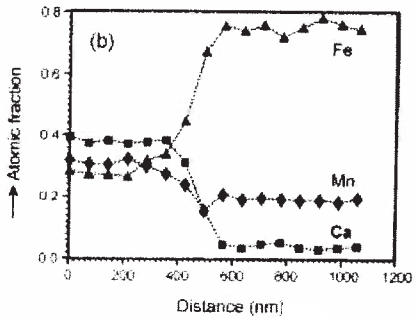
Use the following where needed:
Charge on electron, $e = 1.60219 \times 10^{-19}$ C, Rest mass of electron, $m_e = 9.10956 \times 10^{-31}$ kg
Avogadro's Constant, $N_A = 6.022 \times 10^{23}$ mol $^{-1}$, 1 electron volt (eV) = 1.602×10^{-19} J
Planck's constant, $h = 6.626 \times 10^{-34}$ J s, Universal Gas Constant, $R = 8.314$ J mol $^{-1}$ K $^{-1}$,
Boltzmann's constant, $k = 1.381 \times 10^{-23}$ J K $^{-1}$
$\log_a x = \log_b x / \log_b a$, Volume of sphere = $(4/3)\pi r^3$

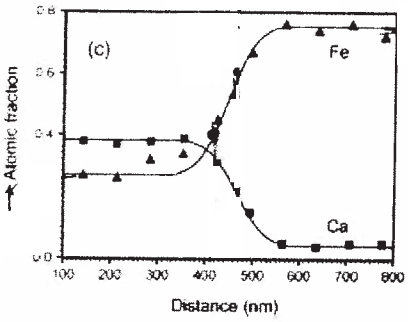
Questions:

1. Describe the two most important transformations that change the mineralogy of the Earth's mantle with depth. Illustrate your answer with (phase) diagrams as necessary.

2. (a) The following photograph and diffusion profiles come from the work of Ganguly *et al.*, (1996).







A natural diffusion couple has been produced by an overgrowth of a Spessartine-Grossular garnet upon a core of Almandine garnet (see Figure-a). The overgrowth was formed during a contact metamorphic event and has been subjected to a later, high temperature, prolonged metamorphism to produce a diffusion of Fe, Mn, and Ca between the overgrowth and core (see Figure-b). The Spessartine-Grossular overgrowth contains more calcium than the Almandine core, and the core contains more Fe. Using the smoothed diffusion profiles of Figure-c, and given the diffusion coefficient of Fe

at the conditions of metamorphism (biotite grade ~350°C) was ~7.5 $\times 10^{-32}$ $m^2 s^{-1}$, then calculate your best estimate for the duration of the metamorphic event.

(b) Why is this duration likely to be a rough estimate?

Hints:
Use the profile for Fe. Take the inflexion point at 460nm to represent the original interface and the concentration (atomic fraction) at 410nm to be 0.4. The extremes of concentration far away from the interface are 0.76 and 0.28.
For this solution, we may assume that we are dealing with a semi-infinite diffusion couple, so that the initial concentrations are preserved at sufficiently large distances from the interface, which is located at $x = 0$. Indeed, the distance over which the diffusion profiles may be measured is very small (just a few hundred nanometer (nm=10^{-9}m) compared with the crystal dimensions. So small, that an Analytical Transmission Electron Microscope had to be used rather than the coarser electron microprobe analyzer. The solution of the diffusion equation for these boundary conditions and concentration of species C_i, is (from Crank, 1983):

$$C_{i(t,x)} = C_{i(\min)} + \frac{C_{i(\max)} - C_{i(\min)}}{2}\left[\operatorname{erfc}\frac{x}{\sqrt{4D_i t}}\right]$$

don't have to remember

The error function erf(η) and its compliment erfc(η) = 1 - erf(η) are tabulated on the right:

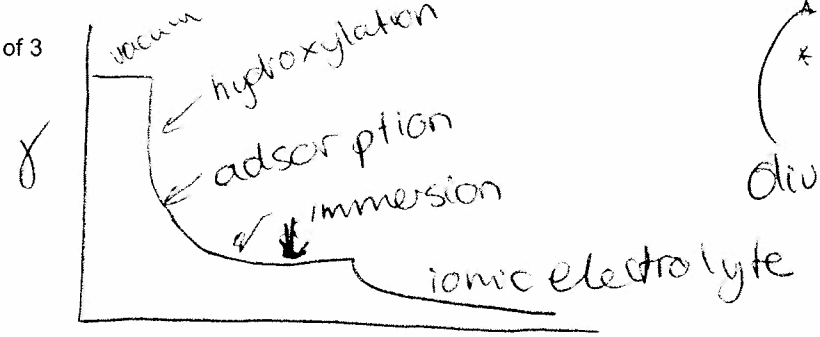
η	erf η	erfc η
0	0	1.0
0.02	0.022565	0.977435
0.04	0.045111	0.954889
0.06	0.067622	0.932378
0.08	0.090078	0.909922
0.10	0.112463	0.887537
0.15	0.167996	0.832004
0.20	0.222703	0.777297
0.25	0.276326	0.723674
0.30	0.328627	0.671373
0.35	0.379382	0.620618
0.40	0.428392	0.571608
0.45	0.475482	0.524518
0.50	0.520500	0.479500
0.55	0.563323	0.436677
0.60	0.603856	0.396144
0.65	0.642029	0.357971
0.70	0.677801	0.322199
0.75	0.711156	0.288844
0.80	0.742101	0.257899
0.85	0.770668	0.229332
0.90	0.796908	0.203092
0.95	0.820891	0.179109
1.0	0.842701	0.157299
1.1	0.880205	0.119795
1.2	0.910314	0.089686
1.3	0.934008	0.065992
1.4	0.952285	0.047715
1.5	0.966105	0.033895
1.6	0.976348	0.023652
1.7	0.983790	0.016210
1.8	0.989091	0.010909
1.9	0.992790	0.007210
2.0	0.995322	0.004678
2.2	0.998137	0.001863
2.4	0.999311	0.000689
2.6	0.999764	0.000236
2.8	0.999925	0.000075
3.0	0.999978	0.000022

3. Why are superheating or undercooling often required to drive a mineral transformation? Explain in your discussion why minerals can be metastable.

4. (a). A freshly cleaved quartz crystal surface is gradually exposed to water vapour, increasing the humidity until finally submerged in liquid water. Describe the stages and physical processes involved in the evolution of such a surface.
(b) Mineral surfaces may also be charged, affecting their behaviour in aqueous solutions. Expand on this to explain the Gouy-Chapman electrical double layer?
(c) What is the "point of zero charge"?
(d) Why do suspensions of clay minerals and certain hydroxides increase their sedimentation rate when transported from fresh to salty water?

5. (a) What are the three main types of *solid solution* in minerals? Give examples of minerals which display solid solution in your answer.
(b) Describe the two main mechanisms by which exsolutions occur.

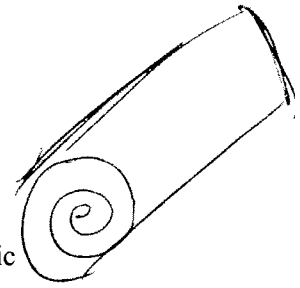
Nepheline
+ interstitial
+ substitution
+ omission
Olivine
Pyrrhotite
Pyrrhotite



6. (a) Mineral surfaces exhibit a wide range of interactions with other phases that are brought into contact with them. What is the main source of energy driving these interactions, and what is the physical reason for it?
(b) Why are meteorite chondrules spherical?
(c) What is the significance of grain boundaries, in a polycrystalline solid, meeting at 120°? —> equilibrium
(d) Explain the energy changes during adhesion and cohesion.

7. (a) Describe how the diffusion rate and crystallization rate interact to give different crystal forms during crystal growth.
(b) Give an example of how a mineral/fluid interaction can be beneficial or hazardous to the environment. Concentrate on the mineralogical processes during element incorporation or release.

8. (a) What physical steps are required for solid-state diffusion to take place?
(b) Explain what energies contribute to the activation energy for solid-state diffusion and what part does the Maxwell-Boltzmann distribution play?
(c) What has solid-state ionic electrical conductivity got in common with solid-state diffusion and what mathematical relation links the two processes?



9. What is asbestos? Sketch the crystal structure of an asbestiform mineral and describe how its properties make it hazardous to human health. In which tectonic setting might you find asbestos minerals if you wished to commercially exploit them?

10. (a) An Arrhenius graphical plot of electrical conductivity exhibits a kinked line with two slopes, both are negative but the lower temperature region has a smaller slope than the higher. Explain the possible reasons for the occurrence of two slopes in the two cases of (i) a polycrystalline rock and (ii) a monocrystalline mineral. Are these explanations exclusive?
(b) Estimate the thermal activation energy for the **intrinsic transport process** if the two slopes are –8000K and –4000K respectively, in a plot of **$\log_{10}$**conductivity versus reciprocal absolute temperature (K^{-1}). Give your answer in joules per mole, joules per atom and electron volts per atom.
(c) Suggest an equation for the temperature dependence of this conductivity.

Good luck!

References:

Ganguly, J., Chakraborty, S., Sharp, T. & Rumble, D., 1996, Constraint on the time scale of biotite-grade metamorphism during Acadian orogeny from a natural garnet-garnet diffusion couple., *Am. Mineral.*, **81**, pp1208-1216.

Crank, J., 1983, Mathematics of diffusion, *Oxford University Press.*