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

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Datum: 07-11-2007, 13:00-16:00, C.108 & C.110

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

Use the following where needed:

Avogadro's Constant, $N_A = 6.022 \times 10^{23}$ mol $^{-1}$,
Planck's constant, $h = 6.626 \times 10^{-34}$ J s,
Rest mass of electron, $m_e = 9.10956 \times 10^{-31}$ kg,
Charge on electron, $e = 1.60219 \times 10^{-19}$ C,
1 electron volt (eV) = 1.602×10^{-19} J,
Universal Gas Constant, $R = 8.314$ J mol $^{-1}$ K $^{-1}$,
Boltzmann's constant, $k = 1.381 \times 10^{-23}$ J K $^{-1}$
$\log_a x = \log_b x / \log_b a$ and $\log_{10} e = 0.43429448$

Questions:

1.

M122

a) What is a reconstructive phase transformation?

b) Describe what would happen to the mineral Olivine $(Mg,Fe)_2SiO_4$ if it were to sink through the Earth's mantle from a depth of 100 km in the upper mantle, through the transition zone to a depth of 750 km in the lower mantle. Illustrate you answer with a sketch of a phase diagram with corresponding pressures of 0-150 kbar (upper mantle), 150-250 kbar (transition zone) and >250 kbar (lower mantle).

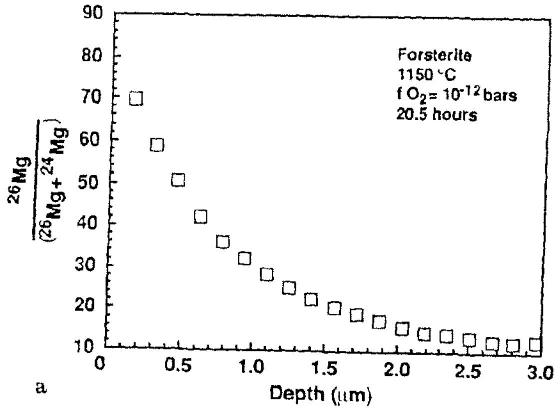
2.

In a study of high temperature diffusion of magnesium in olivine, experiments were carried out using oriented single crystals of pure forsterite (Mg_2SiO_4) in contact with a layer of isotopically labeled magnesium oxide (MgO, which was enriched with at least 98atom% ^{26}Mg). The layer was sufficiently thick to allow a constant ^{26}Mg source concentration (C_1) boundary condition. The mathematical solution of Fick's second law that describes the diffusive process into the semi-infinite half space occupied by the forsterite crystal with an initial concentration of ^{26}Mg = C_0 at time, $t = 0$, gives the concentration $C_{(x,t)}$ at positive distance x, into the crystal after time t, as:

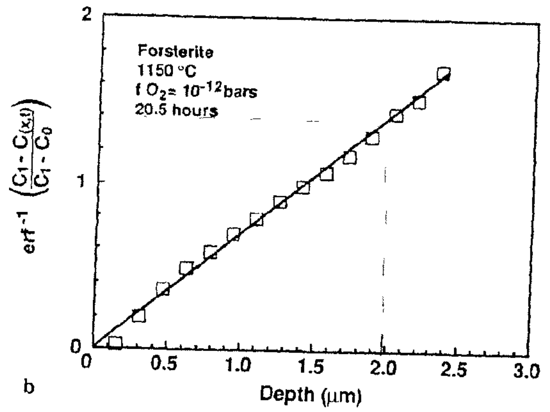
$$\frac{C_1 - C_{(x,t)}}{C_1 - C_0} = \mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$$

Where **erf** is the Gaussian error function (tabulated below for reference).

The experiments were carried out for 20.5 hours at 1150°C under a controlled oxygen atmosphere of 10^{-7} Pa. Diffusion took place in the [001] direction of the forsterite single crystal and the penetration profile of ^{26}Mg was measured with a secondary ion mass spectrometer, after the diffusion experiment. These results are given in the figure below as a ^{26}Mg penetration curve as plot (a) and a graph of the inverse error function, " **erf** $^{-1}$ ", of $\left(\dfrac{C_1 - C_{(x,t)}}{C_1 - C_0}\right)$ as plot (b).



a



b

What is the diffusion coefficient for ^{26}Mg in forsterite given that the inverse error function value at 2.0 micrometre depth is 1.4, taken from plot (b)?

Table of the error function and its compliment:

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.

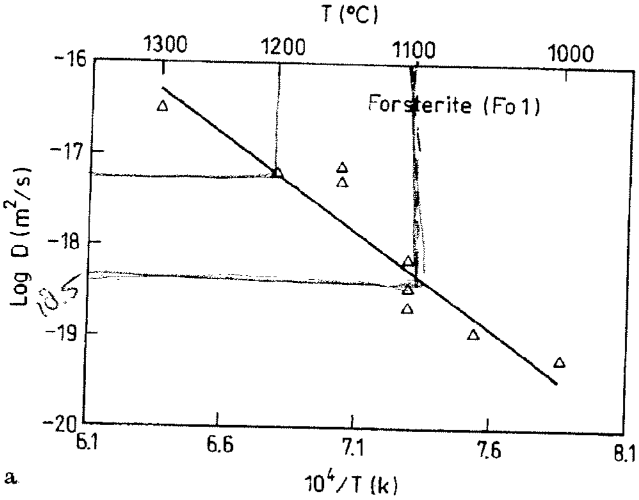
a) Give the formula that relates Gibbs free energy to enthalpy and entropy.
b) How does the Gibbs free energy of a mineral vary with temperature?
c) Describe how and why a gradient in Gibbs free energy is required to drive a mineral transformation from a phase α to a phase β, where α is most stable at low pressure and low temperature. If the transformation is reversed, would you expect to see the same magnitude of change in Gibbs free energy, and if not, why not?

M3

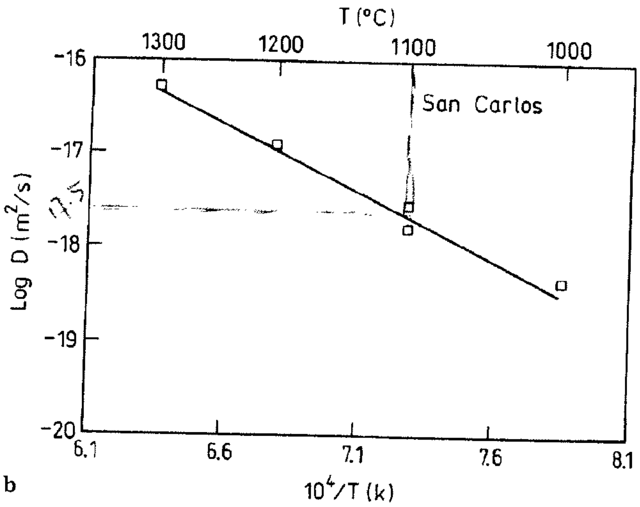
4.

The results of single crystal diffusion experiments for the diffusion of the tracer ^{26}Mg into two olivines, are given, below, as a function of absolute temperature. Both experimental sets were carried out under similar low oxygen atmospheres to prevent oxidation of the iron from Fe2+ to Fe3+. Melt-grown crystals of pure forsterite (Mg_2SiO_4) and natural single crystals of olivine with composition (Mg:92%,Fe:8%)$_2$SiO$_4$ picked from San Carlos peridotite nodules (xenoliths in a basalt), are represented in the two plots (a) and (b) respectively, below:

Ms



a



b

a) What kind of diagrams are these?

b) Write an equation relating diffusion coefficient to absolute temperature, based on these diagrams.

c) What does the slope of these plots represent?

d) At 1100°C, in which type of olivine is the diffusion of ^{26}Mg easiest?

e) In both materials, what is the significance of only a single slope being visible over the temperature range?

f) Estimate the activation energy for diffusion of ^{26}Mg, in each olivine type, based on the presented data.

g) Given that both crystals had similar crystallographic orientation for diffusion, then suggest what processes could be responsible for the difference in the measured slopes?

5.

M

Three different crystal structures have been described in detail during the course. Choose one out of Perovskite (ABO_3), Spinel (AB_2O_4) or Rutile (MO_2).

a) Sketch the unit cell of your chosen structure type.

b) Give the co-ordination numbers of the most important cations in this structure.

c) Where might you find a mineral that adopts this structure within the Earth and what would it be called?

d) **EITHER** - (*i*) How does this mineral reflect or respond to temperature and pressure conditions in the part of the Earth you just described in part (**c**) above?

OR - (*ii*) How does your chosen mineral help to create or remediate environmental problems?

Spinel ~~MgFe~~ $MgAl_2O_4$

6.

adhesion / cohesion

a) Explain the energy changes in bringing, ***i)*** two similar and ***ii)*** two dissimilar material surfaces, into permanent contact. What are these two processes called?

b) What two physical barriers to nucleation, of new solid phases in crystals, act in opposition to the Gibbs free energy that would otherwise drive the nucleation process forward?

c) What role does surface energy play in the determination of crystal form in polycrystalline rocks?

7.

M4

a) What are the three main types of *solid solution* observed in minerals? Give examples of specific minerals in each part of your answer.

b) How do the enthalpy and entropy of mixing in a solid solution interact to give *exsolution*? Sketch a diagram to show ΔH_{mix}, $-T\Delta S_{mix}$ and ΔG_{mix} vary in a binary system consisting of atoms A and B (i.e. over a composition from 100%A to 100%B). How can this information be used to construct a phase diagram with a solvus that gives two stable compositions at one temperature T?

8.

a) List 3 important physical properties of water that are different from those of most other compounds we commonly encounter, and explain what significant effect these properties have on the present state of our planet.

b) Explain how the physical properties of water make it a good solvent for ionic solids such as sodium chloride. Why does the solubility fall dramatically as water becomes a super critical fluid near 375°C and 20 MPa?

c) Most mineral surfaces are electrically charged, affecting their behaviour in aqueous solutions. Expand on this, using words and diagrams, to explain the Gouy-Chapman electrical double layer and its components?

9.

practical

a) Describe how a saturated solution of NaCl crystallizes at room temperature. What are the mineralogical and chemical controls on the shape of the crystals and how do the diffusion and crystallization rates interact to give their distinctive shape?

b) At which crystallographic sites would you expect dissolution to begin as a mineral breaks down in a solution? Describe how dislocations in the structure may play a role.

10.

P2

a) What is Bragg's law and how may it be used to understand crystal structure?

b) What are the advantages of neutron diffraction over x-ray and electron diffraction in the characterization of atomic structures?

c) The energy of an electron is related to its wavelength via the De Broglie relation: $\lambda = h/p$, where the momentum $p = (2m_e\ e\ V)^{1/2}$, and h = Planck's constant. What is the wavelength of electrons produced in a transmission 1MeV electron microscope? If a crystal has an atomic spacing of 200pm, then by what angle will such a beam of electrons be diffracted?

Good luck!