USESO 2021

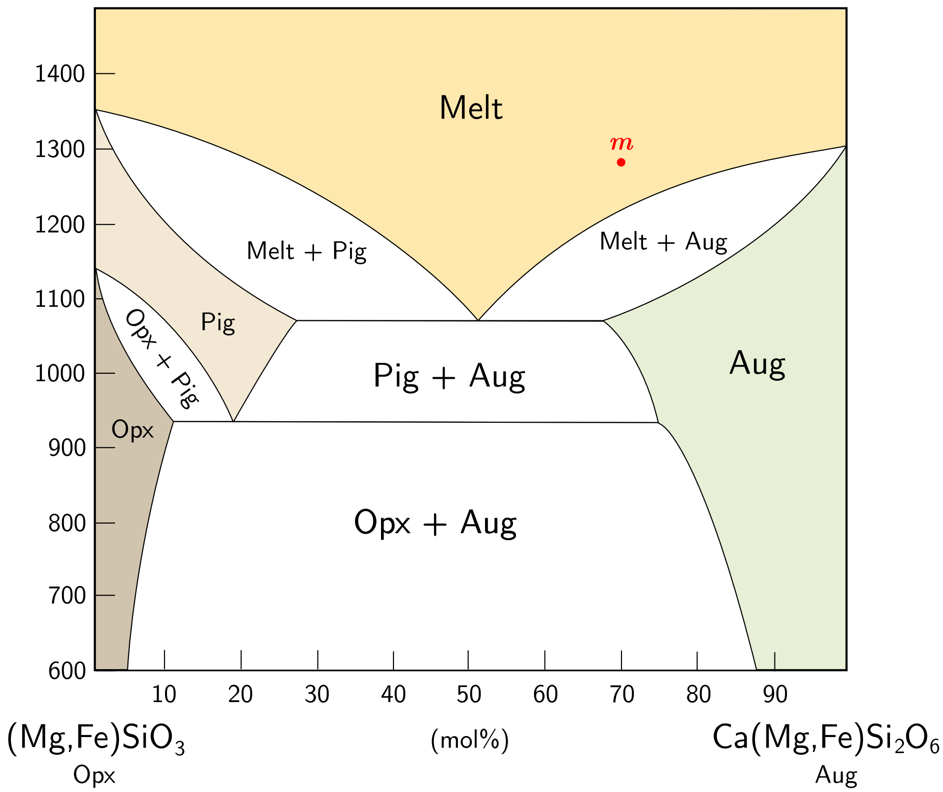
Rocks & Minerals KEY

Instructions:

- There are free response questions and multiple choice questions. There is no penalty for guessing.
- Questions marked with (*) may have 1 or more correct answers.
- A non-graphing, non-programmable calculator is allowed; show work for calculations unless otherwise directed.

Problem 1

Below is a simplified psuedobinary phase diagram of orthopyroxene (Opx), (Mg, Fe)SiO_3, and augite (Aug), Ca(Mg, Fe)Si_2O_6. Pigeonite (denoted Pig) is a high-temperature pyroxene mineral. Here, the percentages on the x axis denote the mole percent of Ca.



1. (2 points) A pyroxene melt of a bulk composition of 70% Aug, 30% Opx (marked m) cools slowly (assume chemical equilibrium is maintained throughout crystallization) until all the melt is crystallized. At the moment immediately after the melt completely solidifies, which of the following best approximates the composition of the augite phase?

   A. 27% Aug

   B. 52% Aug

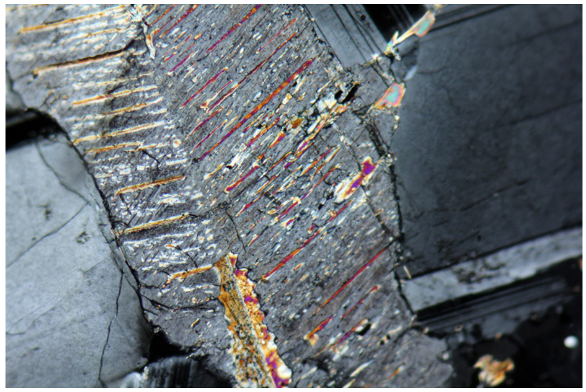
   C. 60% Aug

   D. 70% Aug

   E. 87% Aug

Solution: The only solid phase after crystallization is augite. Hence the augite phase will have the same composition as the original bulk composition, or 70%.

Consider the same melt. It cools until its closure temperature, T_c, at which chemical equilibrium is no longer maintained between the crystals, and diffusion effectively stops. The thin section below shows an augite crystal (grey) with pigeonite exsolution lamellae (colored).



2. (2 points) Given that the augite host crystal has a composition of 73% Aug, estimate T_c. (Assume equilibrium is perfectly maintained until the closure temperature).

Solution: As the system cools, we expect the exsolved phases to follow the compositions at phase boundaries until T_c (in reality, deviations occur, and solvus lines may be inaccurate, so this is impractical). Hence, $T_c \approx 980\,°C$ (see the blue dashed lines in figure 1). A range of answers from 950 - 1050 °C are accepted.

The method used above is known as *solvus thermometry* (we determine the temperature using the composition of exsolved phases). Unfortunately, it is not very accurate for practical purposes.

3. (2 points) Which of the following factors presents a source of error for the estimate above?

I) The pyroxene phase equilibria are also dependent on pressure, and crystallization is not necessarily isobaric

II) The pyroxene phase equilibria are also dependent on the Mg-Fe solid solution

A. I only

B. II only

C. I and II

D. Neither I nor II

Solution: In solvus thermometry, we rely on the accuracy of the solvus line in estimating T_c. Exsolution, like all phase equilibria, is a function of temperature, pressure, and composition. The given phase diagram does not account for possible variations in pressure and composition (of the Mg-Fe solid solution), so the best answer is $\boxed{\text{C}}$.

4. (2 points) Briefly explain how the slope of the solvus line (the line separating two exsolved solid phases) affects the accuracy of solvus thermometry.

Solution: A very steep solvus line means that the composition of exsolved phases is not particularly sensitive to changes in temperature. Slight errors in measuring composition will likely lead to large errors in T_c. As such, there will be greater error in estimating T_c with steeper solvus lines.

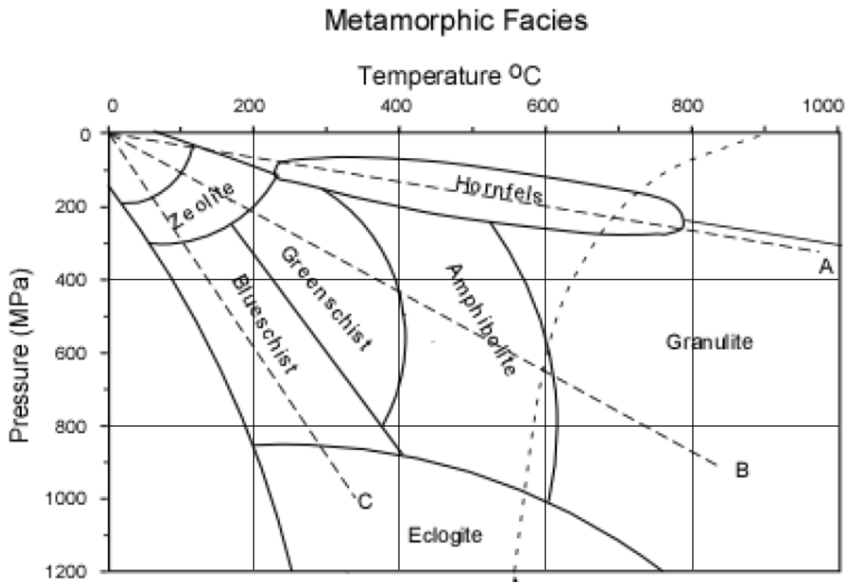
5. (3 points) The closure temperature is also dependent on the cooling rate. Briefly explain what the presence of pigeonite indicates about the cooling rate of the crystal.

Solution: Pigeonite is not thermodynamically stable below temperatures of $\sim$900 C. This indicates that the cooling rate was relatively fast; otherwise, the pigeonite would have converted to the stable orthopyroxene phase. Indeed, pigeonite is essentially never present in slowly-cooled magma bodies.

(Note that even faster crystallization may result in no exsolution of pigeonite at all; students that accounted for this also earned points)

Problem 2

A metamorphic complex in Northwest China has been of particular interest since its discovery in the 1980s because of its implications for tectonics. For this problem, we'll call it the IMC (interesting metamorphic complex). By analyzing the mineral assemblage and through careful phase calculations, it was determined that the peak P-T conditions range from 650 - 800 MPa and 310 - 380 deg C.



1. Determine the possible metamorphic facies that correspond to the peak P-T conditions calculated for IMC. (*)
   A. Zeolite
   B. Blueschist
   C. Greenschist
   D. Granulite
   E. Hornfels

2. (2 points) Using a linear approximation (like the ones shown in the facies diagram), give an estimate for the geothermal gradient. Use the mean of the P and T ranges.

Solution: The mean P-T is 725 MPa and 345 deg C. Assuming linear approximation with surface conditions being zero, this corresponds to a geothermal gradient of about 0.476 deg C/MPa, or 476 deg C/GPa.

To constrain the age of this metamorphic complex, U-Pb analysis was conducted on two zircon populations called Gab and Det. ^{238}U decays to ^{206}Pb with a half-life of $4.468 \cdot 10^9$ years. It can be assumed that there has been no loss of parent or daughter isotopes from the zircons and that all ^{206}Pb is radiogenic. Calculations are often performed using isotopic ratios; in this case, we use the $^{206}\text{Pb}/^{238}\text{U}$ ratio.

3. (2 points) Which expression correctly gives the age t of a sample in terms of half-life (λ) and the isotopic ratio of $^{206}\text{Pb}/^{238}\text{U}$?

   A. $t = \lambda \log_2 (1 + {}^{206}\text{Pb}/{}^{238}\text{U})$

   B. $t = 2^{{}^{206}\text{Pb}/{}^{238}\text{U}} \lambda$

   C. $t = \frac{1}{\lambda} \log_2 (1 + {}^{206}\text{Pb}/{}^{238}\text{U})$

   D. $t = -\lambda \log_2 (1 + {}^{206}\text{Pb}/{}^{238}\text{U})$

   E. $t = \lambda \log_2 ({}^{206}\text{Pb}/{}^{238}\text{U})$

Solution: Begin with the general exponential decay equation.

$$\begin{aligned} {}^{238}\text{U}_t &= {}^{238}\text{U}_0 2^{-\lambda/t} \\ {}^{238}\text{U}_t &= ({}^{238}\text{U}_t + {}^{206}\text{Pb}_t) 2^{-\lambda/t} \end{aligned}$$

Next, dividing both sides by ^{206}Pb and rearranging, we have:

$$\begin{aligned} {}^{238}\text{U}/{}^{206}\text{Pb} &= ({}^{238}\text{U}/{}^{206}\text{Pb} + 1) 2^{-\lambda/t} \\ 2^{\lambda/t} &= 1 + {}^{206}\text{Pb}/{}^{238}\text{U} \\ t &= \lambda \log_2 (1 + {}^{206}\text{Pb}/{}^{238}\text{U}) \end{aligned}$$

Thus, the answer is $\boxed{\text{A}}$.

4. (2 points) Gab zircons were collected from a gabbro dike intruding into IMC. The dike shows little to no signs of metamorphism. Given that the average isotopic ratio $^{206}\text{Pb}/^{238}\text{U} = 0.126$, calculate the age of the Gab zircons. Showing work is not necessary.

Solution: Using the formula from above, $t = 4.468 \cdot 10^9 \cdot \log_2 (1.126) = \boxed{765\,\text{Ma}}$.

5. (3 points) Det zircons were collected from within the metamorphic rock itself, where they were identified to be detrital zircons originating from sedimentary processes. Det zircons had a minimum age of 805 Ma. Keeping in mind the petrogenic (rock-forming) processes, justify how these two ages (the youngest Det age and the average Gab age) constrain (i.e., provide the bounds for) the age of the metamorphism.

Solution: Ages of detrital zircon grains represent the depositional age of the protolith of the blueschist. The youngest grains in Det thus represent the maximum bound of the age of the metamorphism. The dike from which Gab zircons were extracted intruded after the metamorphism, so Gab ages represent the minimum bound of the age of metamorphism. Indeed, Gab is younger than Det.

6. (2 points) Which of the following statements is true?

I) The geothermal gradient was greater in the past because there was greater residual internal heat from Earth's formation

II) The geothermal gradient was greater in the past because there was greater radioactive decay in Earth's interior

III) Precambrian-aged blueschists are rare

A. I only

B. III only

C. I and II

D. I and III

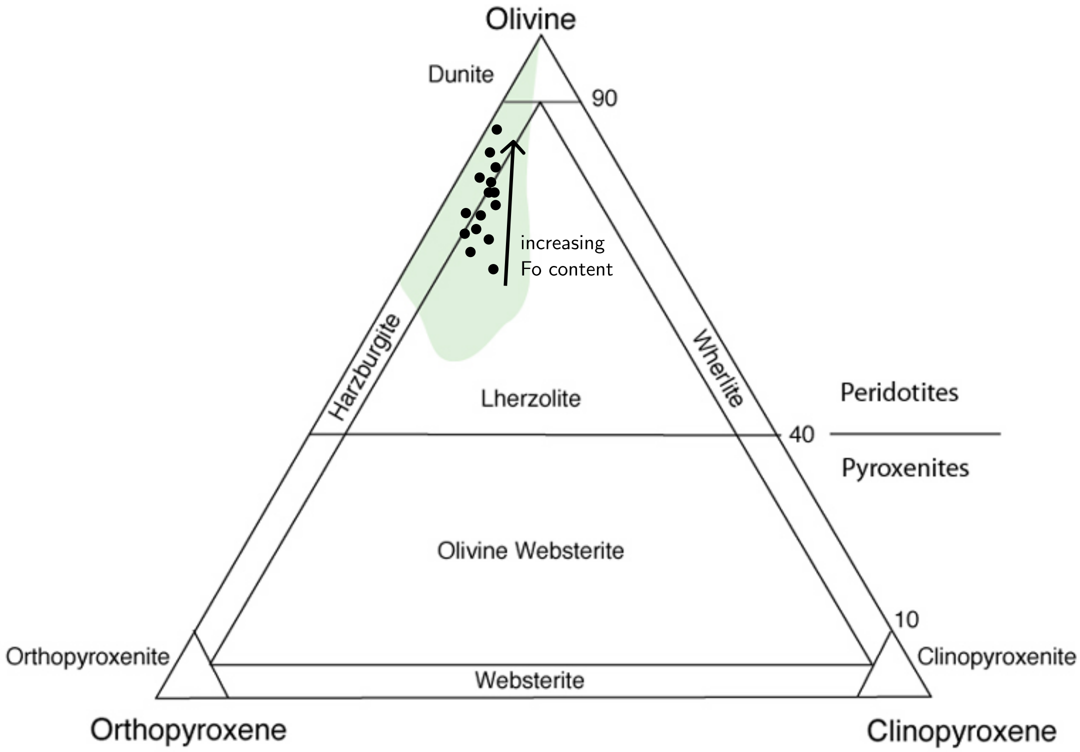
E. II and III

F. I, II, and III

Solution: We know I and II are true because as Earth has aged, its interior has cooled through outward heat transfer (e.g., mantle convection) and slowdown of radioactive decay. III can thus be inferred to be true. Blueschist metamorphism requires low T, high P conditions that are associated with low geothermal gradients, which are considerably rarer in Earth's past. Indeed, the Aksu metamorphic complex, which this problem is based around, is notable because it is a Precambrian blueschist.

Problem 3

Mid-Ocean Ridge Basalts, or MORBs, are the most common type of igneous rock on Earth.



Above shows a population of peridotites, with the composition of individual samples plotted as dots. Olivine, $(\mathrm{Fe},\mathrm{Mg})_2\mathrm{SiO}_4$, is a solid solution between forsterite ($\mathrm{Mg}_2\mathrm{SiO}_4$, melting point = 2160 K) and fayalite ($\mathrm{Fe}_2\mathrm{SiO}_4$, melting point = 1478 K). The arrow shows increasing forsterite content in olivine crystals.

Considering the implications of the diagram, answer the following true/false questions:

1. (1 point) T/**F**: The arrow denotes a decreasing trend in the degree of partial melting

   Solution: The peridotite samples represent the composition of the mantle body from which MORBs form. Because Fo-rich (Mg-rich) olivine melts at higher temperature than Fa-rich (Fe-rich) olivine, the trend of increasing Fo content in the parent peridotite corresponds with a trend of *increasing* partial melting.

2. (1 point) **T**/F: Fast spreading ridges like the East Pacific Rise are associated with harzburgite in the upper lithospheric mantle

   Solution: As we see in the ternary diagram, harzburgites are associated with high degrees of partial melting. Indeed, fast spreading ridges have high partial melting and a large magma chamber associated with depleted harzburgite mantle.

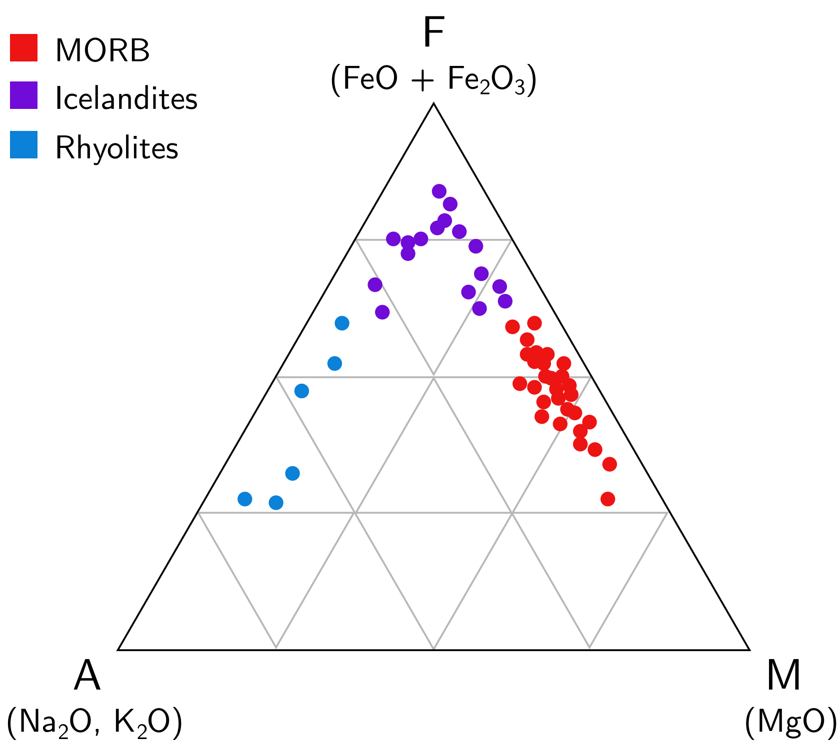
3. (1 point) **T**/F: MORBs formed from very slowly spreading ridges tend to have a greater concentration of incompatible elements like K and Rb than MORBs formed at fast spreading ridges

Solution: Incompatible elements do not fit well within the structure of crystallized minerals and hence preferentially enter melt. When there is limited melt production (e.g., at slow-spreading ridges), the concentration of these incompatible elements will be greater than when there is prolific melt production (e.g., at fast-spreading ridges).

4. (1 point) T/**F**: Normal MORBs have lower ^{143}Nd/^{144}Nd than bulk Earth

Solution: ^{143}Nd is a radiogenic isotope formed from the slow decay of ^{147}Sm. Nd is less compatible than Sm, so the mantle has a higher ^{143}Nd/^{144}Nd than bulk Earth. Thus, MORBs, which are formed from partial melting of the mantle, have a higher ^{143}Nd/^{144}Nd than bulk Earth.

Melt formed from mantle peridotite evolves on the tholeiitic magma series; MORBs are thus known as tholeiites. Iceland is a unique location where a mantle plume has significantly enhanced mid-ocean ridge magma production. Icelandic rocks also document a complete evolution along the tholeiitic series.



Rocks from Iceland were sampled and their (relative) compositions were plotted, shown in the AFM diagram above. The AFM ternary diagram plots alkali (A), iron (F), and magnesium (M).

5. (2 points) Briefly account for the iron enrichment trend as MORBs evolve to Icelandites.

Solution: Magnesian minerals are preferentially crystallized from the melt as they have higher melting points (e.g., forsterite vs fayalite, enstatite vs ferrosilite). This leaves the iron rich minerals behind in the melt.

6. (2 points) As a magma evolves from MORB $\longrightarrow$ Icelandite $\longrightarrow$ rhyolite, indicate whether the given quantity increases or decreases. (0.5 points each)

   (a) Silica content **increases**

   (b) Viscosity **increases**

   (c) Gas solubility **increases**

   (d) Percentage of incompatible elements in the melt **increases**

7. (3 points) Rhyolites are rarely formed at mid-ocean ridges, so Iceland is a special case. Propose one reason for why rhyolite may be formed in Iceland.

Solution: Iceland has a particularly large magma chamber associated with the mid-ocean ridge because of a mantle hotspot. This extra heat source may trigger partial melting of oceanic crust, leaving the resultant melt relatively enriched in silica.

(Note that the petrogenesis of Icelandic rhyolites is still debated. While the true reason is likely much more complex than partial melting or fractional crystallization, students were rewarded points for reasonable silica-enriching processes if they cited the mantle plume as an additional heat source)

END OF EXAM