Theoretical

Q1 - Zoning of Plagioclase



Ab-An bands

Shown in the figure is a thin section of a zoned plagioclase crystal, with anorthite-rich bands denoted with An and albite-rich bands denoted with Ab. Use the figure above for the next three questions.

Identify the type of zoning exhibited by this plagioclase crystal. (1 pt)

Oscillatory zoning

Identify all of the following statements that are true about the crystallization of this sample. (*)

Anorthite bands mark areas of relatively lower crystallization temperature

The transition from the crystallization of anorthite to the crystallization of albite involves a coupled substitution of Ca²⁺ for Na⁺ and Al³⁺ for Si⁴⁺

The temperature of the local magma body in which this plagioclase crystal crystallized shifted relatively rapidly

The starting composition of the magma body had little effect on the zoning of the plagioclase crystal shown

The plagioclase crystal stayed in chemical equilibrium with its parent magma for the entirety of its crystallization

Briefly describe any possible environment (e.g. tectonic environment, etc.) in which this zoning could have developed, and explain why it would develop in that environment. (4)

- Subduction zone/volcanic arc (2)
- Lots of magma mixing/new injections of fresher, hot magma -> quick changes in composition
- Also possible convection within magma bodies -> varying local crystallization temperature over time, which may cause oscillatory zoning

(2)

Explanation:

<u>Part (a)</u>: concentric bands of anorthite and albite rich plagioclase is characteristic of an oscillatory-zoned crystal. The common presence of intermediates (e.g. 50% Ab) hints that this is not a sample of exsolution lamellae

<u>Part (b)</u>: the first three options are simple application of knowledge of the plagioclase solid solution series; the starting composition of the magma marks the bulk composition, which does impact the overall zoning; lastly, by definition, equilibrium crystallization means that the entirety of the crystal maintains a chemical equilibrium with the melt - thus, zoning cannot develop.

<u>Part (c)</u>: oscillatory zoning of plagioclase is characterized by rapid changes in temperature. Though this may occur in various tectonic environments, it is most commonly associated with subduction zones, where new influxes of magma drive quick changes in crystal composition

Q2 - Magma Evolution

Consider a subducting oceanic slab that leads to partial melting of the mantle under a continental arc. The composition of the eutectic melt **M** formed is given in **Figure 1** below as the red dot. As the magma body **M** ascends and cools, rocks **A**, **B**, and **C** are formed, shown as thin sections in **Figure 2**.



Figure 1: Shows an AFM diagram with the eutectic melt **M** and four other points, labeled 1 through 4.





Rock A

Rock **B**



Rock C

Figure 2: Shows thin sections (field of view = 7 mm) of three rocks, **A**, **B**, and **C**. Rock **A** contains aegirine (a pyroxene with formula NaFe(SiO₃)₂ abbreviated Ae) and xenotime (a phosphate with formula YPO₄ abbreviated Xe) in a matrix of orthoclase. Rock **B** contains Al_{70} (70% albite, 30% anorthite plagioclase) and magnetite (Fe₃O₄, abbreviated Mt) crystals in a fine-grained orthopyroxene matrix. Lastly, rock **C** contains Al_{20} (20% albite, 80% anorthite plagioclase) crystals in a matrix of fine-grained olivine, clinopyroxene, and magnetite.

Determine the order of crystallization (first to last) of rocks **A**, **B**, and **C** from melt **M**, giving your answer as three letters separated by no spaces (e.g. ABC). (2 pts) **CBA**

Given enough time for melt \mathbf{M} to fully evolve, indicate the number on the AFM diagram where the composition of a fully-evolved melt \mathbf{M} will end up. (2 pts) 2

Identify all of the following statements regarding the evolution of **M** that are likely **true**. (*) **Magnesium-rich orthopyroxenes (e.g. enstatite) crystallize at higher temperatures than iron-rich orthopyroxenes (e.g. ferrosilite)**

The presence of magnetite in rocks B and C indicates that M is relatively oxidized M was more reduced during the crystallization of B than during the crystallization of A Latent heat of crystallization drives the melting and assimilation of crust into M

M evolves along the tholeiitic magma series

Water catalyzes the polymerization of silica and destabilizes amphiboles in **M** The relative concentrations of the CaO + MgO components of **M** remain mostly constant over time

Explanation:

<u>Part (a)</u>: notice that rock **A** contains xenotime and aegirine, both of which occur in evolved alkali granites. Further, xenotime contains both yttrium and phosphorus, which are both considerably incompatible elements that hint to crystallization from a highly evolved melt. From the thin section and composition, rock **B** can be classified as an andesitic porphyry. Finally, from both the thin section and the composition, rock **C** can be classified as a basalt. It follows that the order of crystallization is **CBA** <u>Part (b)</u>: it is useful to realize that **M** evolves along the calc-alkaline series; this can be deduced from both the petrogenic environment as well as the compositions of the rocks. Thus, **M** will become more alkali-rich and less Mg and Fe rich (Mg-rich mafic minerals tend to crystallize before Fe-rich mafic minerals)

<u>Part (c)</u>: the second and third options may be reasoned through a survey of the oxidation states of iron throughout the minerals provided in rocks **A**, **B**, and **C**. Generally, iron silicates are ferrous (i.e. iron is 2+), while in magnetite, there are two iron 3+ with one iron 2+, indicating the host rock is relatively oxidized. Finally, it can be realized that the latent heat of crystallization is always negative (releases heat), thus, it provides a source of heat for the melting and assimilation of crust into M

Q3 - Evaporites



Halite, sylvite, aragonite, and anhydrite are four important evaporite minerals. A deposition sequence of evaporites is shown in the figure above.

Identify all of the following statements regarding evaporite deposition that are likely true: (*)

Halite precipitates from water before the precipitation of sylvite

Aragonite precipitates from water after the precipitation of halite

The water from which B was precipitated was sulfate-poor

A experienced dehydration following precipitation

The density of the water from which B was precipitated is less than the density of water from which A was precipitated (assuming temperature of the water for A and B are equivalent)

Explanation:

Aragonite, a carbonate, is the least soluble out of the evaporite minerals shown. It follows from the deposition sequence that the sequence in terms of increasing solubility is aragonite, anhydrite, halite, then sylvite. Anhydrite, calcium sulfate, was skipped during the crystallization of B; it is reasonable to conclude that B was sulfate poor. Calcium sulfate is almost always precipitated as a hydrate (in the form of gypsum); as it dries, the water is lost and the gypsum converts to anhydrite. Finally, since T and P are constant, the density of the water is solely dependent on the salinity, which is higher for A than for B.

Q4 - Glomeroporphyritic Basalt



Shown in the figure is a sample of glomeroporphyritic basalt, which contains aggregates, called glomerocrysts, of plagioclase phenocrysts in a groundmass of fine-grained clinopyroxene. Assuming complete equilibrium crystallization (unlikely), identify all of the following statements regarding this sample that are likely true. (*)

There is distinct zoning within the plagioclase glomerocrysts

The bulk composition of the parent magma is more enriched in plagioclase relative to the plagioclase-clinopyroxene eutectic

The bulk composition of the parent magma is equal to the composition of the plagioclase-clinopyroxene eutectic

The bulk composition of the parent magma is more enriched in clinopyroxene relative to the plagioclase-clinopyroxene eutectic

The aggregation of plagioclase phenocrysts into glomerocrysts led to rapid crystal settling

Explanation:

A critical fact that must be kept in mind is that the sample crystallized in complete equilibrium. Thus, there cannot be distinct zoning or rapid crystal settling. Finally, because there are plagioclase phenocrysts (crystallized first) within a fine-grained clinopyroxene matrix, the bulk composition of the parent magma must be more enriched in plagioclase relative to the eutectic.

Q5 - Mica Fish



Shown in the figure is a cross-polarized light (XPL) thin section of a mica fish, which are common microscale structures present in mylonites. Two shear stress vectors are shown and denoted τ_1 (parallel to the striations within the mica) and τ_2 .

Which shear vector, τ_1 or τ_2 , likely dominated the formation of this mica fish? (1 pt)

 $\tau_1 \\ \tau_2 < ANSWER$

Which of the following statements regarding mica fish is true? (2 pts)
The majority of mica fish form below the brittle-ductile boundary
Mica fish form as a result of ultra-high temperature (UHT) metamorphism
Mica fish are common within most muscovite schists
Mica fish are common within granitic intrusions
The mineral grains surrounding mica fish mostly grow in size as a result of metamorphism

Explanation:

- Part (a): τ_2 is a more reasonable option - most foliation within the surrounding mica crystals hint that τ_2 was the direction of the dominant shear force.

- Part (b): mica fish are common in mylonites (i.e. similar to faults, but deformation is mostly plastic). Thus, it is reasonable to assume that the majority of mica fish form below the brittle-ductile boundary.



Q6 - Phase Diagram Fun

Consider the isobaric equilibrium crystallization of a 1100 °C melt, x, containing an alkali feldspar composition of ~23% Or. Shown in the figure is a phase diagram of a hydrated system of albite (abbreviated Ab) and orthoclase (abbreviated Or), with the composition and temperature of the melt x plotted at the red point. Identify all of the following statements regarding the crystallization of x that are true. (*)

The composition of the liquid from which *x* crystallizes approaches a composition of 70% albite before solidifying

As x is cooled to below 500 °C, the major phase is an alkali feldspar with a composition of about 23% orthoclase

As x is cooled from 975 °C to about 950 °C, the composition of the melt generally becomes more sodic

As x is cooled from 800 $^{\circ}$ C to about 700 $^{\circ}$ C, the bulk composition becomes more potassic

When x is cooled to 750 °C, exsolution lamellae of orthoclase are present in albite, which is the dominant phase

The albite-orthoclase solid solution is unstable at low temperatures due to differing substituent cation charges

As pressure increases, and the system remains hydrated, the liquidus and solidus lines will fall If all water is removed from the system, the liquidus and solidus lines will rise

Explanation:

The minimum point (i.e. the minimum of the liquidus and solidus) represents the final composition of the melt - thus, the first option is correct. Option B can be eliminated by realizing that the solvus separates the two solid solution (Ab and Ksp) phases - no alkali feldspar with bulk composition is formed. Options C and D may be eliminated by a tracing of the phases as temperature is lowered within the ranges given. Option E is an application of the lever rule - the composition two phases must average out to the bulk composition. It follows that albite is the dominant phase (closer composition to bulk) with exsolution lamellae of orthoclase. Option F can be eliminated by looking at their respective chemical formulae. The fact that this system is hydrous is critical for the last two options. In a hydrous system, increasing pressure actually increases dissolved water fugacity, which lowers melting point (contrary to an anhydrous system).

Q7 - Metamorphic Petrology

Consider the epitodization of calcite and chlorite, which can be represented by the equation:

Calcite + Chlorite group \rightarrow Epidote group + Actinolite + H2O + CO2. (reaction **R**)

Occasionally, if the parent metabasalt is enriched in rare earth elements (REEs) or other incompatible elements, the REE-containing allanite group may form as the dominant epidote phase. The general formula of the allanite group is $A_2M_3(Si_2O_7)(SiO_4)O(OH)$, where A sites may contain large, incompatible cations, and where M sites contain two trivalent (i.e. +3) cations and one divalent (i.e. 2+) cation, which are generally small and compatible.

THE CRYSTALLOBLASTIC SERIE	HE	CRY	STAL	LOBI	ASTI	C S	ERIE	S
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Most Euhedral

Titanite, rutile, pyrite, spinel Garnet, sillimanite, staurolite, tourmaline Epidote, magnetite, ilmenite Andalusite, pyroxene, amphibole Mica, chlorite, dolomite, kyanite Calcite, vesuvianite, scapolite Feldspar, quartz, cordierite

Least Euhedral

Identify all of the following statements regarding epitodization and the formation of allanite that are **true**. (*)

Reaction R is a retrograde reaction and generally occurs from the exhumation of metabasalts

The surface free energy of epidote is higher than that of calcite

The water released in the reaction is derived from chlorite-group minerals

The presence of internal radiation in allanite crystals signifies the incorporation of uranium and thorium in the M site

The solid products of reaction R are completely anhydrous

Two trivalent REEs may be incorporated into the A site of allanite

Explanation:

The release of volatiles is generally a sign that the reaction is prograde, not retrograde. Option B can be deduced from the crystalloblastic series - minerals with higher SFE will tend to crystallize in bigger, more euhedral crystals to minimize free energy. Chlorite minerals are hydrous; it is reasonable to conclude that the water released in reaction \mathbf{R} came from the chlorite. While U and Th may provide alpha particles to create metamictization, they are big, highly charged, and thus quite incompatible; any U and Th present will fit in the A site rather than the M site. The last option may be reasoned from an analysis of the oxidation states - it follows that the elements in the A site must have a total oxidation number of 5+ to maintain charge balance (pedantically, it is likely possible for two trivalent REEs to be incorporated into the A site if charge balance is maintained elsewhere).

Q8 - Metakomatiites

Komatiites are geologically important rocks that provide information about ancient magmatism and primitive mantle geochemistry. Unfortunately, almost all komatiites are altered by weathering or metamorphism, which complicates their study. The metamorphism of komatiites may take two main "facies", depending on the fugacity (i.e. partial pressure) of CO_2 . When CO_2 fugacity is high, carbonation occurs, which produces an assemblage of minerals that includes talc. When CO_2 fugacity is low, hydration occurs. Given this, and using the distinct geochemical characteristics of komatiites, identify all of the following that are likely **true** regarding the formation of metakomatiites. (*)

When CO2 fugacity is high, the metakomatiite formed will likely contain significant serpentine minerals Komatiite carbonation occurs in large scale at mid-ocean ridges from volcanic volatile release Komatiite hydration occurs in large scale at mid-ocean ridges from hydrothermal circulation

The carbonation of komatiites produces phyllosilicates

The carbonation of komatiites produces significant magnesite (MgCO3)

The carbonation of komatiites produces significant calcite (CaCO3)

Explanation:

Serpentine minerals are formed from the hydration of mafic rocks and thus will not form if CO2 fugacity is high. Komatiites are strictly precambrian and thus will not occur at mid-ocean ridges. Lastly, it is

helpful to know that komatiites are characteristically high in Mg. It is reasonable to conclude that carbonation will produce magnesium carbonate, or magnesite.

Q9 - A Colorful Assemblage



Refer to the figure above for following three questions:

Identify the red mineral shown in the sample. (1 pt)

Pyrope (garnet is acceptable, other garnet minerals are also acceptable)

Identify the **primary constituent** (mineral) of the green matrix shown in the sample. (1 pt)

Omphacite (**pyroxene** is acceptable, other pyroxene minerals like **jadeite** are also acceptable)

Identify all of the following statements that are likely **true** regarding this sample (*):

The red mineral crystallized from magma before the crystallization of the green mineral The green mineral crystallized from magma before the crystallization of the red mineral **This rock was formed under high pressure conditions that may be found in subduction zone environments**

Wollastonite (CaSiO₃) may be associated in large quantities with this rock

Orthoclase $(KAlSi_3O_8)$ may be associated in large quantities with this rock Both the red and green mineral present in the sample are silicates

Explanation:

Once this sample is recognized to be an eclogite, a high T and P metamorphic rock, the part (c) multiple choice follows in a straightforward manner.

Q10 - Mysterious Vug



Refer to the figure above for the next three questions. Mineral **A** is a whitish-pink mineral that effervesces weakly upon treatment with cold dilute HCl. When **A** is powdered and treated with hot dilute HCl, it effervesces strongly.

Identify mineral **A** and give its mineral group. If **A** is a silicate, give the name of the structure of the silicate (e.g. phyllosilicate, inosilicate) **or** describe the structure of the silicate (e.g. sheets, chains). (2 pts)

Dolomite; carbonate (CaMg(CaCO₃)₂)

If HCl was not available in the field, what is a possible characteristic of mineral **A** that could be used to identify it and distinguish it from other minerals? (Multiple answers possible) (1 pt)

- Saddle-shaped crystals (accept anything reasonable describing crystal habit)

When samples of the rock surrounding A are analyzed with XRD in the laboratory, it is determined that mineral **A** is the main constituent of the greyish matrix rock surrounding **A**. Considering this, give a **brief** description of the formation of the structure shown in the figure. (3 pts)

- Dolomitization of limestone via hydrothermal processes
- Formation of the vug occurred through dissolution of the matrix and replacement with larger crystals in a second crystallization event (likely also hydrothermal)

1.	Basalt - Yuchen
2.	Chalcedony 🖌
3.	Copper ✓
4.	Kaolinite 🖌
	• Precursor mineral(s)
5.	Bauxite 🗸
	 Economic importance
6.	Barite
7.	Sulfur 🗸
8.	augite
9.	Apophyllite 🗸
10.	Fluorite - google
11.	Gneiss - google
12.	Schist - google
13.	Pyrite 🗸
	• Chemical formula (since it's in Ben's guide I believe)
14.	Amethyst 🗸
15.	Quartz 🗸
16.	Tourmaline 🗸
17.	Muscovite 🖌
18.	Biotite ✓
19.	Selenite 🗸
20.	Garnet✔
21.	Corundum
22.	Kyanite 🗸
	 Something metamorphic
23.	Pegmatite
24.	Malachite 🖌
	• How formed/precursor mineral
25.	Labradorite
26.	Calcite
27.	Granite
28.	Sandstone
29.	Calcite hex
30.	Limestone
31.	Scoria
32.	Arkose V
22	• what indicates about environment of formation
<i>33</i> .	
34. 25	Shale V
<u>35.</u>	chert/lint
36.	Mıgmatite

37. Topaz