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IGNEOUS PETROLOGY

GEOLOGICAL PHASE DIAGRAMS

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Most magma are silicate melts containing as main elements oxygen, silica, calcium, iron, magnesium, aluminium, sodium and potassium. When magma crystallizes (due to a drop in temperature below its freezing point, these elements combine into crystals, mainly silicates which are the rock-forming minerals. Over the past decades, laboratory experiments on silicate melts have become technically more and more sophisticated. It must be realized that it is complicated to imitate the pressures and temperatures that reign in the interior of the earth, but obviously the most complex factor is the amount of time available to a researcher; in nature, magmas may take 10,000 years or more before they are completely crystalline. Nevertheless, nowadays it is possible to melt existing rocks or to predict the cooling history of magma. A large amount of new data has become available concerning the behavior of silicate melts and the information is still increasing. The crystallization behavior of melts of a certain composition can be best shown in a so-called **phase diagram**, which illustrates the relation between composition and the pressures and temperatures of crystallization.

This chapter discusses the interpretation of the most important phase diagrams used by petrologists. In order to understand these diagrams, it is necessary to be familiar with some of the standard terminology which is derived from physical chemistry.

The Phase Rule

The term **system** is used for any chemical substance that can be isolated from its surroundings. A system may be a liquid in a beaker, a magma in a magma chamber or even an entire planet.

A system may be either at **equilibrium** or at **nonequilibrium**. A system at equilibrium is in its lowest energy state at the prevailing conditions. It has no tendency to change spontaneously. It can be called a **stable** system. When a system is **unstable**, it is not in equilibrium, which means that it is either changing or has a tendency to change. A system in an intermediate state between stability and unstability is called a **metastable** system, which is a system that may appear to be at equilibrium (i.e. not changing), but in fact is not in its lowest energy state.

Obviously, there exists in nature a relationship between the composition of an igneous rock and the composition of the magma from which it crystallizes. This is in accordance with a simple rule of physical chemistry, the rule which says:

In a system at equilibrium

$F + P = C + 2$ or $\underline{F = C - P + 2}$

In which P = number of phases

C = number of components

F= degrees of freedom (number of externally imposed variables)

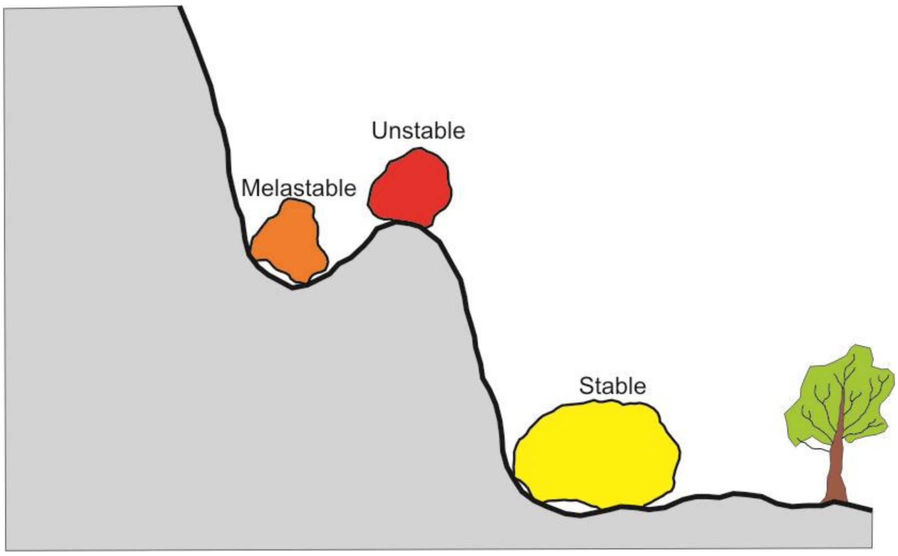

Figure 1 The various states of equilibrium, assuming ground level to represent the most stable state (from Ehlers, 1972).

A **phase** is any part of a system with a particular chemical composition that is physically distinct from other parts of the system. Phases may exist in the solid, liquid or gaseous state. Considering magma as a system, it usually consists of several phases: one gas phase (as gases are completely miscible with each other), usually one liquid phase (but sometimes more when immiscible fluids occur), and the solid phase (s) are represented by crystals which are floating in the magma, each different type is regarded as one phase. In rocks, the various mineral types represent the phases, in some cases accompanied by a liquid phase or gas phase (intergranular water, fluid inclusions and so on).

Table

The number of **components** of a system is the minimum number of chemical constituents necessary to define the composition of all the phases in the system. Most igneous rocks contain 10 to 12 components, which are usually written in the form of oxides. The oxides are the building stones of the rock-forming minerals.

The **degrees of freedom** of a system (also called "variance" or "mode of variation") are equal to the number of externally imposed variables on the system. In the case of igneous rocks and magmas, the variables may be represented by a change in the composition of the system (for example, due to an influx of water into the system). Hence F equals commonly one, two or three.

When we consider the above phase rule again, we can see how it defines the relation that exists between magma composition and the number of minerals that can be formed from it at certain P and T conditions. The phase rule applies to any chemical system, not only to magmas and rocks. The simplest example is the system H_2O. It has only one component (H_2O). The variables T and P determine the state in which this component occurs: solid (ice), liquid (water) or gas (water vapour). The phase rule says: F=C-P+2=1-P+2. When F=2 (the variables being temperature and pressure) then P=1, i.e. only one phase can be stable: either ice or water or vapour.

Phase diagrams are constructed on the basis of experimental studies and show the stability conditions of the various phases in a system in terms of system H_2O shows the stability fields of water, ice and vapour with regard to T and P. it is possible to read the freezing point of water (obviously identical to the melting point of ice) at a certain pressure from the diagram. The diagram is valid for pure water. As soon as another chemical component is added to the system, the boundary curves between the three stability fields will shift. A simple example: adding water lowers its boiling point and also its freezing point.

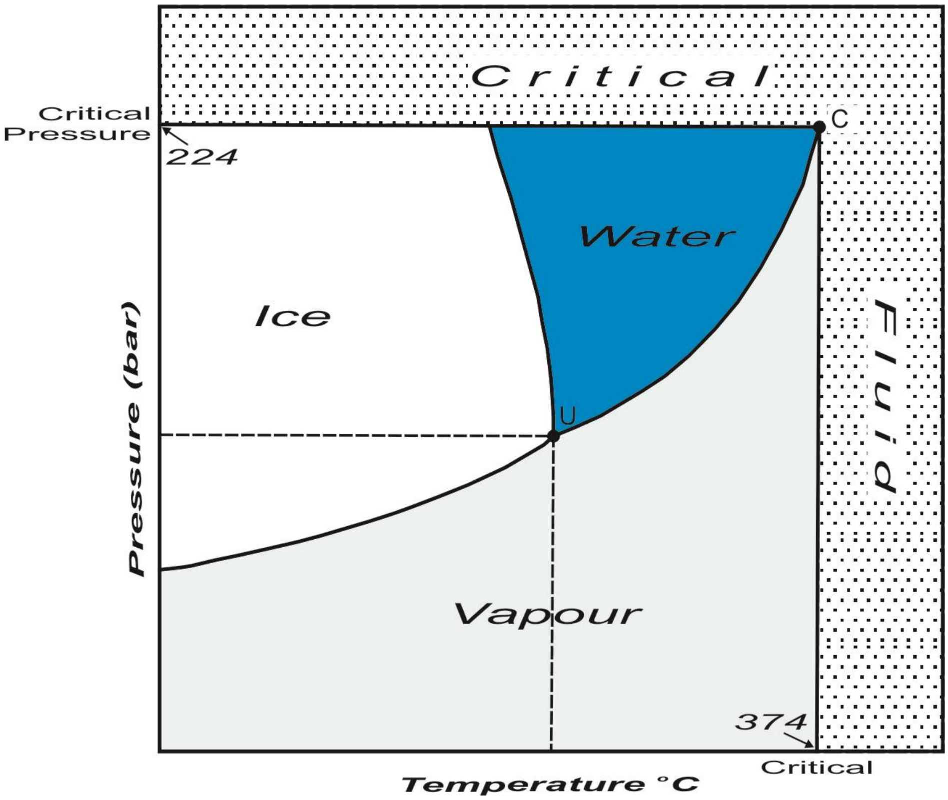

Figure 2 *The one-component system H_2O.*

Unary Phase Diagrams

Systems that contain one component are called **unary** or **one-component systems**. An example which we have already seen is the system H_2O. Another one component system which is very important for petrologists is the system SiO_2. A phase diagram of this unary system explains the stability relations between the various SiO_2 polymorphs. The stability field of a α-quartz, β-quartz, coesite, stishovite, cristobalite and tridymite are shown in relation to P and T conditions.

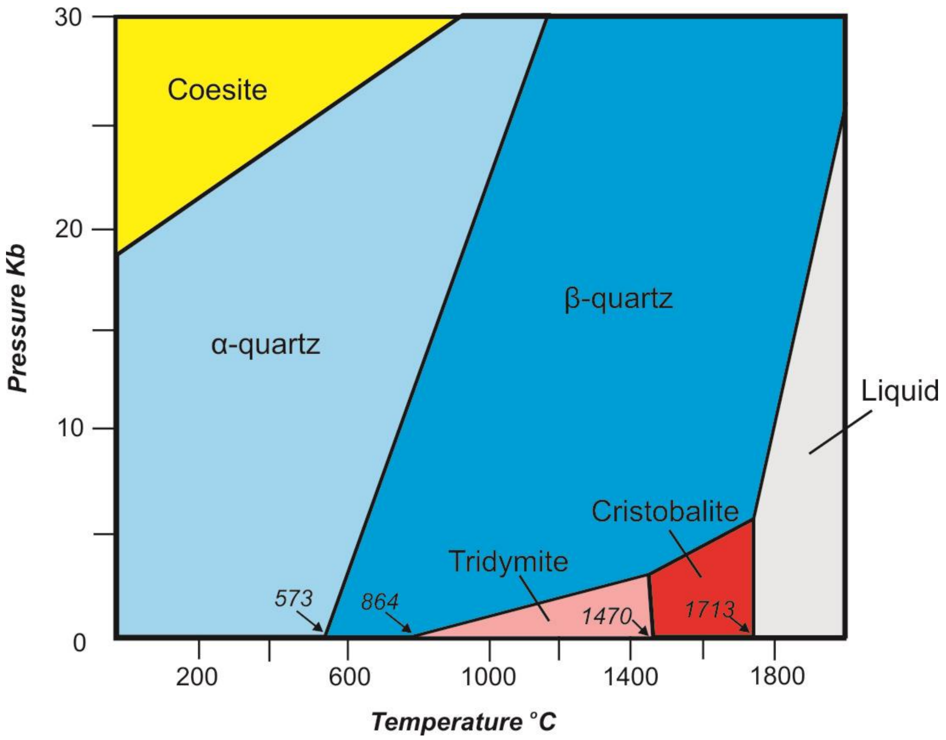

Figure 3 The one-component system SiO_2.

The **liquidus line** is the temperature line above which the system is completely liquid. The **solidus line** represents the temperatures below which the entire system is solid. In the case of the system SiO_2 the liquidus and solidus coincide: it is the boundary line which separates the crystal fields form the field in which the system is in the liquid state.

In the stability fields of the six SiO_2 polymorphs equilibrium is said to be **divariant** because the number of degrees of freedom is two, as we can calculate from the phase rule: F= 1-1+2 = 2. What does that mean? The stability of the polymorph will not be affected by a change in P or T or both as long as they do not cross the boundaries of the field. As soon as the conditions change in such a way that they fall outside the P-T field of the polymorph under consideration, the polymorph will convert into another which is stable at those conditions. The boundary curves between the divariant fields represent the Ps and Ts under which two polymorphs are stable at the same time (e.g. during the conversion of a α-quartz to β-quartz both phases are present). That implies that P=2 in such a case, and by application of the phase rule we find that F=1. Therefore, the boundary curves are called **univariant lines**, because there is only one degree of freedom which can vary independently. α-quartz to β-quartz can only be stable at the same time along the line a-b. a change in T would require also adjustment of P in order to remain on that line. In other words: there is only one variable that can change independently from the other. The points where the univariant lines intersect are called **invariant points**. Three polymorphs may coexist (occur stably together) only at the fixed temperature and pressure of those points. This situation is expressed by the phase rule as F=0, because C-P+2=1-3+2=0