

more significant results. Minerals are notorious for being impure. Most minerals form part of solid-solution series. This is true for almost all common rock forming minerals except quartz. Let us imagine we have two minerals A and B which can form a complete range of solid solutions under appropriate conditions. Let us further consider the case where A is a high pressure mineral while B is quite stable at low pressures. Mineral B forms C at low pressures. The phase diagram for the system A-B at a constant temperature will then appear as in Fig. 2. There is a field where only the solid solution is present and another field where a solid solution of given composition coexists with C. If in a rock we find a mixture of solid solution + C, then if we can find the temperature of formation (say by oxygen isotopes) we can say that for composition of solution x to coexist with C,

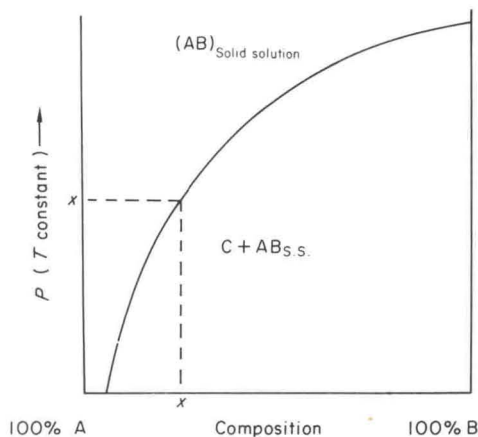


Fig. 2. Phase relations in a system A-B where A and B form one solid solution at high pressures but B is unstable at low pressures. At pressure x , the solid solution coexisting with C has composition x . The diagram is drawn for constant temperature.

the pressure must be P_x . The pressure is unique for a given temperature if chemical equilibrium is attained. Such equilibria abound in rocks and now we are beginning to use such solid-solutions to trace pressure history; in most cases this is equivalent to tracing the history of depth below the surface.

Many minerals which are members of solid-solution series, when examined chemically (as by the electron micro-probe) are found to be chemically zoned. The content of A and B will change from core to rim. The appearance of zoning indicates the very sluggish kinetics of diffusion of atomic species in many minerals. If this is the case, it is even possible that a single zoned crystal can more or less continuously record P - T events during its growth. Some day, we may have instruments for measuring the isotopic zoning as well as the chemical zoning.

It is very clear from the discussion above, that the mineral memory depends

Phase changes in the earth's crust

on an equilibrium process which is assumed to occur at some stage and the freezing in of this information. Interpretation thus depends on knowing the significant equilibrium states and knowing how fast these states may change. History shows that workers tend to ignore the rate factors until anomalies accumulate to such an extent that a more cautious approach becomes essential.

Most equilibrium states are achieved more rapidly in response to rising temperatures than the reverse process in response to cooling. It is this fact that saves the day. Moreover, as we shall see below, certain catalysts tend to be more active when we heat rocks than when we cool rocks. The most important catalyst is water in the liquid or vapour state.

Certain information on processes can also be obtained from minerals. Consider that we find a quartz vein with a small amount of gold. We may wish to know how this material was transported into the vein. In general, we would expect aqueous solutions to have been active for we know that quartz is quite soluble in hot water. The oxygen isotopes of water from various sources are rather characteristic. Thus gases flowing from a very hot volcanic source would differ from those resulting from deep circulating surface water. If we know the temperature of formation of the vein system, and the fractionation coefficients of O^{16}/O^{18} between quartz and water, we may be able to say something about the source of the water and the quantities of water involved in the process. Understanding how geochemical processes occur is one of the most important aspects of economic geology.

3. The metamorphic cycle

In many active parts of the crust of the earth a very important series of events tends to be repeated, time after time. Continental rocks are eroded and transported to the oceans as sediments. As the sediment pile thickens, the sediments are depressed. As the sediments are depressed they go through a series of chemical processes and become metamorphic rocks. If the process continues long enough, the lower levels may become hot enough for melting to commence and igneous rocks are formed. These same igneous rocks may form parts of new mountain ranges which in turn become eroded to continue the process. Most geologists now believe that convective forces in the underlying mantle drive these spectacular processes. The margins of some continents are the situations where today we see these processes in operation. A complete cycle involves a time span of the order of 10^8 or more years. Understanding the cycle in modern situations and in older, now stable regions of the crust where remnants of past activity are to be found, is one of the most important aspects of all geological research. These processes record the thermal, dynamic and geochemical history of the earth, of the crust and mantle.

Let us look in a little detail at the materials and reactions involved in this