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Phase changes in the earth's crust—the record of crustal geophysics

W. S. Fyfe

The chemical and structural features of minerals preserve parts of the record of geological events: age, T *and* P *of formation, thermal gradients, magnetic field, etc. The correct use of such mineral memory units requires an exact knowledge of the possible equilibrium states of minerals in rocks and the kinetics of attainment of such states.*

1. Introduction

Geologists spend most of their time describing things on the surface of the earth. Occasionally they obtain a tiny view of deeper events by drilling holes and sinking mine shafts, but these rarely exceed a few kilometres in depth. What do they describe? In general the most important things include: the minerals present in a rock, the chemistry of the rocks and minerals and their fabric; the structure of the rocks, the geometrical arrangement of recognizable layers (faults, folds, etc.), the orientation of mineral grains, slip surfaces, etc.; the organic features of rocks (fossils, coal beds, organic debris). All these bits and pieces go together to form a geologic map which should tell what you will find at point X on the surface, and, if the structure is simple and topography cooperative, often a good idea of what may be encountered at depth. The geologist then continues by trying to reconstruct the history of the given part of the earth's crust. What I would like to try and show in this essay is how modern techniques may assist in the final analysis. It is an unfortunate fact of geological life that the parts of the earth we ever see form only a thin film making up no more than about 0·2 per cent of the total mass of the system. We want to know how the entire system works and to do this we must extract every possible drop of information from the processes we observe in this film. The scale of our problem is vast and the type and detail of information we may seek will be highly variable depending on whether we are collecting information about continental drift or the formation of gold deposits.

Dr Fyfe is Royal Society Professor of Geochemistry, Department of Geology, The University, Manchester.

2. Minerals have a memory

When we want to understand the dynamics of the crust the following types of question arise. When did this event happen? At what depth did this deposit form? How hot was the crust at 40 km when these rocks melted? Was the thermal gradient in the crust the same 4×10^9 years ago as it is today? How can we begin to answer such questions? It rapidly becomes apparent that if the information can be obtained, a memory of events must be frozen into the rocks themselves and their constituent minerals. There are some obvious examples.

Radiometric dating is now well known. Reactions involving radioactive decay are used in answering almost all questions about when and how fast. For example, a very common mineral in rocks is potash feldspar, $KAlSi_3O_8$. Natural potassium is a mixture of the three isotopes ^{39}K, ^{40}K and ^{41}K. The proportion of the isotopes is nearly constant in crustal materials. The isotope ^{40}K decays to argon (^{40}A) by electron capture and the half life $1{\cdot}3 \times 10^9$ years is appropriate for geological dating. If we examine an old crystal of $KAlSi_3O_8$, it will contain a small quantity of ^{40}A and if this can be accurately measured and if we know that leakage from the crystal has been zero since its time of formation, we can date the growth of the crystal. Clearly, what is dated is a time relative to the assumption of zero argon loss. We know that feldspars leak rapidly at high temperatures so in fact we date the last rather cool event in the history of that crystal. If we date another potassium-bearing mineral in the rock with different diffusion characteristics we may get a different age, timing a different thermal or chemical event. Thus even with the simple dating process, interpretation is required. But at the same time, once the parameters of the processes are known a single rock may allow the timing of more than one event. In this case as in many others, we need to understand the conditions under which the mineral has a good or a faulty memory.

Today there is convincing evidence that the polarity of the earth's magnetic field has reversed many times during earth history. Studies of paleomagnetism have provided important evidence relating to such processes as continental drift and ocean floor spreading. Again, the record of the earth's magnetic field is locked up in the spin orientation of paramagnetic ions (Fe^{++}, Fe^{+++}) in minerals such as magnetite (Fe_3O_4). Again, the memory unit is temperature dependent and will only act at temperatures below the Curie or Néel temperature of the material. We must know that the mineral is chemically stable for if recrystallization occurs, the memory may be fuzzy. Techniques are available sometimes to clarify the memory by eliminating the weak components.

There are many ways by which temperature memories may be left in a mineral. Let us imagine that we are growing crystals in hot liquid water (note that the critical temperature of water is 374°C). When most crystals grow, they contain some holes filled with liquid. When we examine the crystal at low temperatures,