The Granulite Facies, Partial Melting and the Archaean Crust

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The granulite facies, partial melting and the Archaean crust

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Introduction

As chairman of a session of the meeting I would like to add a few comments concerning some of the problems discussed. During the discussions certain important conclusions have appeared. The detailed descriptions presented of the oldest known samples of the Earth indicate that at that time the crust had already a remarkably similar structure and chemistry to that of more modern times. It has also been made clear that rocks of the granulite facies make a massive contribution to the base of the ancient crust and logically could make a large contribution to modern regions under batholith zones of mobile belts, where the crust has been thickened by tectonic events. It also seems possible that the mantle processes controlling tectonics in the Archaean, while having some features in common with the present régime, were unique.

Most models of the Earth's thermal history (Birch 1965) suggest a very hot initial stage and it is difficult to see how the general geochemical equilibrium state of the Earth could be achieved without a very large degree of melting at some period of Earth history. If a large molten fraction is assumed, it would be difficult to preclude very complex convective structures. Crust will appear when surface temperatures approach 800 °C which could be at a very early stage indeed. When liquid water appears on the surface at 100 °C or less, a crust a few kilometres thick would rapidly form. Some present models (Finale 1971) indicate that formation of a hydrosphere might be an early event and this process itself would accelerate initial cooling.

It might well be expected that the earliest semi-stable crustal fragments would be granitic. Such materials would be capable of floating on basalt liquids while solid basalt would be rapidly engulfed. This crust would also concentrate radioactive species (see Heier, this volume). When an aqueous phase is present, weathering would be intense partly on account of the supply of acids from intense volcanism and also from the supply of glassy volcanic debris. Early geochemical separation processes associated with a hydrosphere would thus be intense and synchronous with thicker crust formation. The initially radioactive crust could well have been associated with thermal gradients of the order of 100 °C $\mathrm{km^{-1}}$ and could hardly be thicker than 10 km before belting would occur at the base with the occurrence of igneous overturn of the material.

It is now also abundantly clear that the appearance of simple life forms and the hydrosphere were separated by a very brief period so that bio-geochemical precipitates and bio-geochemical separations might also operate on the primitive surface at a very early stage.

Initially, when only a thin granitic skin was present, it seems possible that convective motion in the upper mantle might be little influenced by the skin. Convective flow of basic liquids under the crust could occur, a motion not present today on any large scale. The skin would tend to pile up in regions of descending currents and these proto-subduction zones would be zones of intense crust-mantle mixing. Modified magma types such as andesites could appear in such regions.

From the observations of McGregor & Moorbath (this volume) it is clear that igneous and tectonic processes were highly evolved by 3900 Ma. It seems impossible that some form of crust did not exist before 4000 Ma. It is also difficult to see that early skins would not be widespread unless heat generation was highly asymmetric, a possibility not to be dismissed if core formation was asymmetric (Elsasser 1963).

We can thus perhaps approach our Archaean problem by considering an Earth, partly molten with thin accumulations of granitic and sedimentary rocks. Massive basaltic volcanism would be widespread at positions of rising convection cells and intermediate to acid volcanism in down flow regions. The thickness of the more acid crust would be controlled by radioactivity and plutonic overturn. Basaltic liquids could well have flowed under the thin skins, partly consolidating and underplating with less radioactive material. Between granitic crust and basaltic underlayer, the first granulites could well appear as a fusion residue.

Formation of granulites

The granulite facies of metamorphism is characterized by suites of rocks dominated by a pyroxene-feldspar mineralogy. Many other phases, garnets, aluminium silicates, scapolites and the like may also be important. The striking feature of granulites is their lack of hydrated phases. Basically the granulite problem is that of producing the dry mineralogy without the formation of related amphibole-bearing rocks. Considering this problem it must be remembered that hornblendes have very low vapour pressures and are thermally stable into regions of magma production and crystallization. Thus, in considering the conditions of formation of granulites one must carefully define the relations between the variables fluid pressure, water pressure, load pressure and temperature. In general, eclogite formation as contrasted to amphibolite formation from basic rocks, presents the same problems and certainly in some high-pressure regions the eclogite and granulite facies must overlap.

No problem is involved in the formation of granulites (or eclogites) from rocks once at or near the surface if they never contained sufficient water to form hydrates such as amphiboles or micas. In this instance, their fields of stability lie well within normal geothermal gradients. There may be some examples (intrusive diorites, gabbros, etc.) which could illustrate such processes where the metamorphic rock is formed essentially by solid state reactions. But inspection of the stratigraphy of granulite terrains indicates that the materials of many granulites did not originate in anhydrous environments. They were formed by dehydration processes. A most efficient high-temperature dehydration process involves the partial formation of a silicate melt where water is effectively diluted and removed in solution by a silicate fluid.

Melting phenomena near the Earth's surface may follow three distinct patterns. These are illustrated in figure 1. With dry rocks (figure 1*a*) melting temperatures normally increase with pressure. When excess water is present and the total pressure on the system is similar to water pressure, melting temperatures are depressed by water pressure (figure 1*b*), at least over the range of pressures in the crust. When water is present only in hydrated phases with a well defined vapour pressure, the melting region will be as shown in figure 1*c*. When crustal melting processes are considered, this third type of melting behaviour is probably dominant. The phases which carry water into the deeper parts of the crust are mainly micas and amphiboles. Studies by Brown & Fyfe (1970) and others have shown the general regions of stability of hydrates in crust of average composition. During ultrametamorphism of the crust, hornblende may break down forming a granodioritic melt and a pyroxene rich residue, granulite. The conditions of reaction are:

$$P_{\text{total}} \approx P_{\text{fluid}} \approx P_{\text{melt}} > P_{\text{water}}.$$

For hornblende breakdown, temperatures near 900 °C are involved and such a figure is in good agreement with observations of the temperature of formation of liquids of the granite family.

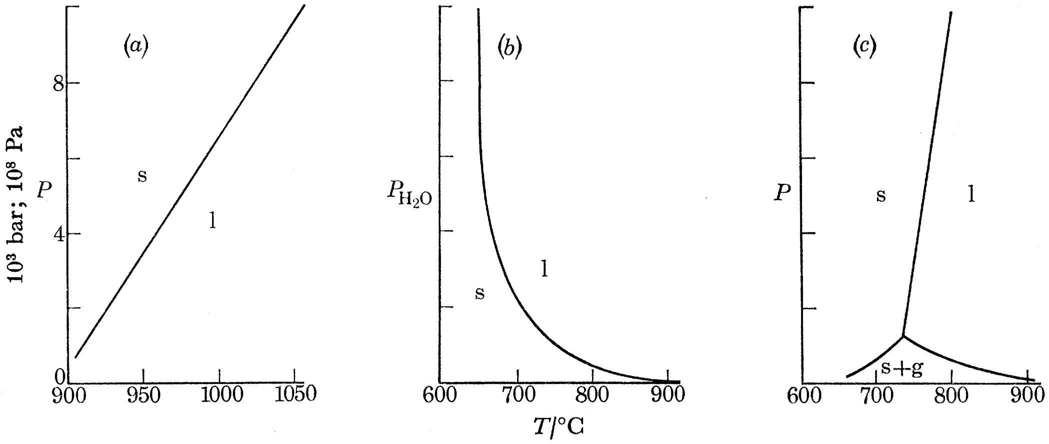

FIGURE 1. Form of melting relations illustrated for granitic compositions: (*a*) dry melting; (*b*) melting with excess water; (*c*) melting where biotite provides the water. s, solid; l, liquid; g, gas.

It can be proposed that partial melting is a necessary process in the formation of most common granulites. The geochemical results presented in this volume by Heier support such an observation. It should be noted that where extensive melting, and hence granulite formation occurs in a given stratigraphic column, may be quite sensitive to the detailed geochemistry of the column. Massive basaltic amphibolite layers (with a small granitic component) may survive as amphibolities while thin interlayers of amphibolitic–granitic composition may be melted. The granitic component is acting as the desiccant.

Heier (this volume) has pointed out the presence of carbon dioxide rich fluid inclusions in granulite facies minerals. This suggests another possible factor to be considered in granulite formation. Amphibole can break down to pyroxene at lower temperatures if water is diluted by carbon dioxide and fluid pressures depart significantly from water pressure. In this context it should be noted that pure calcite in massive layers can be quite stable in regions where more normal silicate assemblages would melt. Such melts could attack calcareous rocks liberating large quantities of carbon dioxide with the formation of calc-silicate rocks. But perhaps, too, one should sound a note of caution. After a granulite is formed, the anhydrous assemblages can consume water by a host of retrograde reactions. These reactions could concentrate carbon dioxide from original H_2O–CO_2 mixtures and the enriched phase could appear in late fluid inclusions.

From figure 1*c* it is apparent that as geothermal gradients become steeper, granulites will form by partial melting at shallower depths. If Archaean gradients approached 100 °C km^{-1} granulites could form at the base of crust 8 to 9 km thick. Their chance of being exposed by later events would be large. If we consider modern gradients of say 20 to 30 °C km^{-1}, thicknesses of 50 to 30 km must be considered. The tectonic requirements for surface exposure are more severe. But it would be surprising if such rocks were not being formed in some modern region where granitic plutons are intruded at high levels in a tectonically thickened crust (e.g. the Andes).

Retrograde metamorphism of granulites

Once a dry rock is formed in the granulite facies at depth it is then subject to hydration to form greenschist or amphibolite facies mineralogy during its return to the surface. Observations on such retrograde hydration processes of granulites, eclogites, periodities and the like, illustrate that unless rocks are subjected to drastic tectonic disruption, the fundamental rate of water diffusion is slow. High-grade anhydrous rocks tend to be preserved. Further, if the hydration process is to occur in the crust, a source of water must be found. The essential fact to be considered is that the re-hydration of a massive section of granulite facies rocks involves a very difficult chemical and mechanistic problem. For example, imagine a column of granulite 5 km thick and 1 km^2 cross-section. The retrogressive transformation to greenschist would require access by almost 1 km^3 of fluid (density 0.6 g cm^{-3}). This water could come from the mantle by magma injection into the base of the crust. But I would like to suggest that a common mechanism could involve overthrusting of granulites onto wetter crustal rocks. Certainly the problem is one deserving considerable attention (Beach & Fyfe 1972).

Older crustal structures

Perhaps the most striking feature of Archaean terrains is the massive contribution by granitic rocks and the patterns of volcanic belts or schist belts and granites. I am personally most familiar with such features in the Rhodesian Craton. Such patterns seem rather similar in many Archaean terrains exceeding 3000 Ma. One of the outstanding problems of Archaean geology is to deduce from these patterns upper mantle processes at that time.

At the present time our views of modern tectonic processes are much focused on basalt production at ocean ridges, and plate subduction with its accompanying deep burial metamorphism, andesitic volcanism and granodioritic plutonism, both features occurring in vast linear belts. Today, we could use metamorphic or volcanic events to mark regions of plate destruction or regions of crust-mantle mixing. These would persist to some extent even if the driving force was relaxed. I would view the present situation as one of very large upper mantle convection cells.

In the same way in the past, one might view the ancient schist belts with their large contribution of andesite volcanism, as regions of subduction or mixing. But the scale is smaller and linearity less pronounced. Glaucophane schist-eclogite assemblages do not seem to be present (or preserved) which would not be surprising if geothermal gradients were much steeper. Thus a question that can be raised is, as to whether or not we can use andesites as markers of down-going convection cells. I think a second point must be remembered. If the geothermal gradient is steeper and the base of the more granitic crust is melting at shallow depth, heavy basaltic liquids may not penetrate but underplate and flow under continents. Such a process would itself lead to the large granitic areas. One is tempted to suggest that some igneous events such as the Great Dyke, the Bushveld complex and even anorthosites are related to such phenomena. Basic materials injected under a partially molten more acid crust would cool very slowly and fractionate perfectly.

It is possible to build models based on small-scale convection cells which could explain the granite dome-schist belt spacing of Rhodesia, i.e. dome separation pattern indicates the cell dimensions. It is tempting to postulate that the cell structure of the Earth has been quantized through time and that steady-state patterns leading to synchronous global events have been interspersed with turbulent periods, with the dimensions of the steady-state cells becoming progressively larger with time. It must be stressed, that what is observed in the old crust, is the relaxation pattern. It is too soon to carry such arguments far, but detailed studies of the age relations, structures and stratigraphy of granite domes and related schist belts and granulite terrains should provide the clues.

References (Fyfe)

Beach, A. & Fyfe, W. S. 1972 Fluid transport and shear zones at Scourie, Sutherland: evidence for overthrusting. *Contr. Miner. Petrol.* (in the Press).

Birch, F. 1965 Speculations on the Earth's thermal history. *Geol. Soc. Am. Bull.* **76**, 133–154.

Brown, G. C. & Fyfe, W. S. 1970 The production of granitic melts during ultra-metamorphism. *Contr. Miner. Petrol.* **28**, 310–318.

Elsasser, W. M. 1963 Early history of the Earth. In *Earth science and meteorites* (ed. J. Geiss and E. D. Goldberg), pp. 1–30. Amsterdam: North Holland.

Finale, F. P. 1971 A case for catastrophic early degassing of the Earth. *Chem. Geol.* **8**, 79–106.