

Geology

The origins of granites

R. Stephen J. Sparks and Herbert E. Huppert

GRANITIC rocks represent 70 per cent of the exposed surface of the continental crust and many sedimentary and metamorphic rocks are derived from granite by various physical and chemical processes. Between 1785 and 1787 James Hutton of Edinburgh (Fig. 1) made several critical observations on the geology of granite which demonstrated its igneous origin and the intrusive relationship of granites to surrounding rocks. Hutton recognized that these rocks had been melted within the Earth, which was a basis of his seminal book *Theory of the Earth* (1788). This publication initiated modern igneous geology, and how knowledge has progressed since then was the central question at a recent conference* which celebrated the bicentenary of Hutton's book.

It is sobering to reflect that several currently fashionable ideas were anticipated by nineteenth-century geologists, although they often did not have the techniques to validate them (W. Pitcher, Liverpool University). Granite cannot be extracted directly from the mantle by a one-stage process because the mantle generates basalt when it melts. Granite is a product of repeated melting and differentiation in the crust which, over geological time, has concentrated the most fusible and lowest-density components at the Earth's surface (Fig. 2). Some granites form from the melting of metamorphic rocks that have a sedimentary origin, for example, the spectacular leucogranites of the Himalayas that seem to have formed by melting of pelitic schists and gneisses in the hot Tibetan thrust slab during the collision of India and Eurasia 18 million years ago (P. Le Fort, CNRS, Nancy).

Another example is a Peruvian ignimbrite that is essentially an erupted, partially molten pelite with primary igneous muscovite, andalusite, sillimanite and cordierite (M. Pichavant, CNRS, Nancy). The granites of the Lachlan fold belt in south-east Australia reflect the source-rock compositions, either sedimentary (S type) or igneous (I type), that melted and then ascended (B. Chappell, ANU; A. White, La Trobe University). The latter interpretation is supported by ion-probe data (I. Williams, ANU) from inherited zircons with ancient cores that are much older than the granite emplacement, and which record the metamorphic and igneous history of the source rocks.

Different kinds of granites are formed in other situations. Geochemical data from

the Cordilleran batholiths of the western United States indicate there were systematic variations of isotopes, trace elements and mineralogy across these ranges, with rocks becoming increasingly radiogenic inland towards the old Precambrian craton (L. Silver and H. Taylor, Caltech). Attention was drawn to the difficulty of distinguishing young, lower crust as a source of granites from mixtures of mantle-derived magmas and older continental crust (A. Halliday, Michigan University).

Is there an empirical link between the composition of granites and tectonic environment (J. Pearce, University of Newcastle)? Certain trace elements (niobium, rubidium and yttrium) produce very impressive discrimination between granites from syn-collisional environments, arcs, mid-ocean ridges and within-plate environments. Pearce also gave plausible explanations of petrogenetic processes that could be responsible for the different behaviour of these elements.

Although there is agreement on many aspects of granite genesis, there are still some fundamental differences of opinion and perspective. One such issue is the debate on the relative importance of deep-versus shallow-level processes on the petrogenesis of granite and associated volcanic rocks. On the one hand, there are adherents to the US Geological Survey (USGS) standard magma-chamber model who hold that most of the processes dominating the geochemistry and petrological characteristics of silicic igneous rocks occur in large, long-lived, shallow magma chambers. Various geological and geochemical observations on ash-flow tuff caldera systems can be interpreted in

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Fig. 1 James Hutton, MD 1726–1797, by Sir Henry Raeburn in about 1780.

terms of this magma-chamber model (P. Lipman, USGS; R. MacDonald, University of Lancaster). At the other end of the spectrum of opinion are those who interpret many rocks in terms of deep-level processes in the source region. The Australian granite school, for example, considers that many granitic magmas involve the mobilization and ascent of partially molten source regions. These regions are emplaced in the upper crust as a mixture of restite crystals and melt, where they freeze as high-level granites or erupt as volcanic rocks. According to this view, the deep-level partial melting processes are much more important. This is not now simply a debate between plutonists and volcanists, as the argument about the petrogenesis of the Fish Canyon Tuff demonstrates (see Stormer, J.C. *et al. J. Petrol.* **28**, 747; 1987).

The physical mechanisms of magma generation and emplacement were addressed in rather few contributions, reflecting the great emphasis on geochemistry in modern granite research, rather than the wider implications of granites for large-scale geodynamic processes. Indeed, there are even some philosophical differences between groups about what is actually meant by 'origin'. The work of the Australian school, for example, has the objective of identifying the age and composition of the deep crustal source regions that melt to generate granites. The identification of the characteristics of the source is one important element of the origin. The cause of the melting, which must have required

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Fig. 2 Basalt dykes cutting the Golmud granite, which was emplaced 260–195 million years ago during the collision of the Qiantang terrane of central Tibet with the Kunlun terrane along the Jinsha suture. (Photograph by C. Lewis.)

* *The Origin of Granites* Heriot-Watt University, Edinburgh, 14–16 September 1987. Organized by the Royal Societies of Edinburgh and London.

large amounts of heat transfer into the crust for the generation of the south-east Australian granites, for example, and the tectonic environment in which this happened, could be argued to be more fundamental to the concept of origin.

What are the emplacement mechanisms of granites? In thermal and fluid-dynamical models of diapir ascent (M. Harrison, State University of New York, Albany), the surrounding rocks are heated to high temperature in a thin skin which then flows around the ascending diapir. Harrison's calculations make it hard to envisage a diapiric rise through the cold upper crust; the diapirs simply ascend too slowly and freeze. Studies of the effect of structural environment on granite emplacement (D. Hutton, Durham University) show that the crust is not just a passive medium through which granites pass, but deviatoric stress conditions and local structural factors can have a major influence on how magmas are emplaced.

When considering the genesis of granite, a fundamental problem is how continental crust is heated sufficiently to generate large amounts of magma. Two main mechanisms have been proposed: first, thickening of crust in collision zones

is followed by conductive heating from below which can be accentuated by deep burial of rocks rich in radioactive elements, a suggestion supported by thermal models in which thickening is accomplished by the stacking of several thrust sheets (E-an Zen, USGS, Virginia); and second, basalt underplating, which brings thermal energy directly into the crust. This second mechanism is attractive as all the main tectonic processes (subduction, extension and plume activity) can involve substantial melting of the mantle and emplacement of basalt beneath or through the crust. We presented a fluid-dynamical model of the emplacement of basalt sills into the crust which predicts that this situation provides a very efficient mechanism for transferring heat between the mantle and crust and for generating substantial volumes of granite. Phenocrysts form in the source region during melting and the resulting granite magma is a mixture of phenocrysts and restite, satisfyingly consistent with the Australian school. □

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Microbial metabolism

Anaerobes pumping iron

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SEVERAL microorganisms, including the bacteria *Leptethrix*, *Siderocapca* and *T. ferrooxidans*¹, use ferrous iron as an electron (energy) source, oxidizing it to ferric iron while respiring O_2 . Some bacteria can use ferric iron at the other end of the electron-transport chain as the terminal electron acceptor. But there have been no indications that the latter is an important process *in vivo*. Now, Lovley and co-workers, on page 252 of this issue², report the isolation and growth of a bacterium from anaerobic mud in the Potomac River basin that oxidizes organic acids to CO_2 while reducing hydrous ferric oxide to magnetite, Fe_3O_4 . This finding has geochemical, evolutionary and palaeomagnetic implications.

The organism described by Lovley *et al.*, cryptically designated GS-15, reduces 8 moles of ferric iron per mole of acetate consumed. The ferric iron in the culture medium is present as an amorphous hydrous iron-oxide precipitate resulting from the hydrolysis of ferric chloride. The production of Fe_3O_4 presumably occurs extracellularly after the export of ferrous ions into the medium, where they subsequently interact with unreduced hydrous ferric oxide. Fe_3O_4 is composed of two ferric and one ferrous iron per formula unit, and apparently cannot be further

reduced by the organism. Hence, only one-third of the ferric iron in the medium is available for respiration. Fe_3O_4 production is nevertheless copious, potentially reaching 1 kilogram per 10 grams of biomass! By comparison, magnetotactic bacteria that use nitrate or oxygen as electron acceptors produce about 0.2 grams Fe_3O_4 per 10 grams of biomass³. Of course, actual Fe_3O_4 production by GS-15 *in vivo* could vary depending on the concentrations of anions such as carbonate, phosphate or sulphide that compete for ferrous ions. Whether the exported ferrous ions are incorporated into Fe_3O_4 or into other iron minerals, it is clear that GS-15 and its relations can have a significant impact on the chemistry of iron in anaerobic sediments. Moreover, because the Fe_3O_4 particles are in the single-magnetic-domain size range, they can have a large effect on the palaeomagnetic intensity of those sediments. Karlin *et al.* recently reported⁴ magnetic evidence for Fe_3O_4 production in suboxic marine sediments, and attributed it to iron reduction by microorganisms. Lovley *et al.* now point out² that ancestors of GS-15 could have played a major role in the formation of Fe_3O_4 in the banded-iron deposits during the Precambrian.

To investigate the chemistry of this

process, Tamaura *et al.*⁵ and Mann⁶ have produced Fe_3O_4 *in vitro* by adding ferrous ions to hydrous ferric-oxide precipitates. The process is thought to involve a solution reprecipitation sequence that begins with the binding of the ferrous ions on the surface of the iron-oxide particles. On the other hand, Lovley *et al.*² did not obtain Fe_3O_4 when they added ferrous ions to their uninoculated medium. This may result from inhibition by acetate or something else, either by chelating the ferrous ions or preventing binding to the surface of the oxide. In viable cultures, acetate would be consumed; that and other changes, such as in pH, could allow the process to proceed. Amorphous hydrous ferric oxide and ferrous ions are known to be precursors to intracellular Fe_3O_4 formation in the bacterium *A. magnetotacticum*⁷.

Lowenstam has distinguished⁸ between biologically induced mineralization (BIM) and matrix-mediated, or boundary-organized, biomineralization (BOB)⁹. In BIM, cellular export of metabolic products leads to extracellular mineral formation with materials in the environment. In BOB, the mineral phases are deposited in preformed organic matrices produced by the organism. Thus, Fe_3O_4 production by GS-15 and *A. magnetotacticum* is biologically induced and matrix-mediated, respectively. In the former, Fe_3O_4 particles have a broad size distribution and do not seem to be associated with an organic matrix, whereas in the latter the particles have a narrow size distribution, definite morphologies and are enveloped by a membrane⁹. Even in the BIM process the dimension of the particles is less than 50 nanometres.

In magnetotactic bacteria, Fe_3O_4 serves as an aid to magnetic orientation and navigation, helping the motile cells to find and remain in the preferred microaerophilic zone¹⁰. For GS-15, Fe_3O_4 could just be a metabolic by-product and have no other biological significance. But these non-motile cells seem to grow in intimate contact with the precipitates in the culture vessel and not in the water column above, which is sensible considering the very low solubility of hydrous ferric oxides and the very high iron requirement of the organism. Fe_3O_4 has a density of 5 and *in vivo* could serve as an anchor for the cells in the habitat where their physiology gives them an advantage over other bacteria. □

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