

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 *Leptothrix*, *Siderocapca* and *T. ferroxidans*¹, use ferrous iron as an electron (energy) source, oxidizing it to ferric iron while respiring O₂. 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 CO₂ while reducing hydrous ferric oxide to magnetite, Fe₃O₄. 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 Fe₃O₄ presumably occurs extracellularly after the export of ferrous ions into the medium, where they subsequently interact with unreduced hydrous ferric oxide. Fe₃O₄ 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. Fe₃O₄ 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 Fe₃O₄ per 10 grams of biomass³. Of course, actual Fe₃O₄ 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 Fe₃O₄ 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 Fe₃O₄ 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 Fe₃O₄ 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 Fe₃O₄ in the banded-iron deposits during the Precambrian.

To investigate the chemistry of this

process, Tamaura *et al.*⁵ and Mann⁶ have produced Fe₃O₄ *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 Fe₃O₄ 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 Fe₃O₄ formation in the bacterium *A. magnetotacticum*⁷.

Lowenstam has distinguished⁸ between biologically induced mineralization (BIM) and matrix-mediated, or boundary-organized, biomineralization (BOB)⁶. 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, Fe₃O₄ production by GS-15 and *A. magnetotacticum* is biologically induced and matrix-mediated, respectively. In the former, Fe₃O₄ 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, Fe₃O₄ 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, Fe₃O₄ 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. Fe₃O₄ 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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