# Physics of melts*

One of the most fundamental geodynamic processes to which can be traced a host of planetary structures and phenomena, each in its turn, central to several subdisciplines of earth and planetary sciences, is mediated by rock melting in planetary interiors and the subsequent deformation and relative movement of the melt and the matrix (two-phase flow). Earth scientists have long been aware of the implication of this process to the extent and composition of continental and sea floor volcanism that create the basic layout of the earth's surface. However, not much progress could be made until the mid-eighties in using the knowledge of the volcanic features of the globe (Deccan, Hawaii, Iceland, Indian Ocean) delineated from their geophysical (gravity and bathymetry/topography and seismics) and geochemical (trace element distribution) signatures to obtain the attendant conditions of their origin in terms of quantitative thermodynamical parameters, because of the difficulty in describing the fluid mechanical behaviour of the matrix and of the melt fraction separating from it.

A distinct advance in tackling this problem was made by Dan McKenzie of Cambridge who provided a basic mathematical framework constituted by four conservation principles: the conservation equations of mass, momentum, energy and of atomic species. These equations, however, are quite complicated especially the energy equation. For, it contains terms that account for the latent heat of melting, for the heat transport by the separate movement of the melt and the matrix, and for the heat generation by their deformation. Their complete solution is therefore not yet available. Yet, much enlightening insight can be gained by analysing their solutions under simplified conditions as in many a fluid dynamical problem. Specifically for example, the assumption of isentropic melting produced by upwelling, which is believed to be valid for the mantle both under the ridge axes and intraplate volcanoes, leads to fairly accurate estimates of the melt fraction generated during upwelling and of the volume of magma that would then erupt at the surface. Thus, proceeding from first principles, McKenzie and his colleagues showed how an oceanic crust of the observed thickness (7–8 km) would result from the partial melting of a mantle whose mean temperature is 1350°C and how localized hot jets with temperature of 1550°C can generate just the right amount of melt needed to produce the Hawaiian ridge, or how the trace element concentrations can provide constraints on the relative movements between the matrix and the separating melt.

Indeed, this approach has many other fruitful applications to the solution of a variety of important terrestrial processes involving two-phase flow, notably the movements of fluids during crustal metamorphism and in fluidized beds leading to mineral concentration and hydrocarbon migration, as well as environmental modification by dispersion and differential transport of solutes and suspended materials.

These exciting possibilities of understanding crucial earth processes through a more basic approach of mixed phase fluid flow have, in turn, spurred fruitful interdisciplinary collaboration between a few geophysicists, geochemists and fluid dynamicists towards developing a quantitative framework for studying geological phenomena of a remarkably fluid-like earth. Herbert Huppert (DAMTP, Cambridge) recently coined the word 'geological fluid dynamics' to underline the fact that the ideas of continuum and fluid dynamics are central to understanding almost every aspect of the earth. The Cambridge University graduate programme in Earth Sciences now has a core course in this subject, and a debate on the implications of this step to the content and structure of other geological courses has already begun.

A discussion meeting on 'Physics of Melts' was accordingly arranged in April this year during the visit of Dan McKenzie to Bangalore as Raman Professor of the Indian Academy of Sciences. It was felt that an approach to the new quantitative culture in earth sciences could be quite effective if it is launched from a somewhat familiar ground notably, the physicochemical aspects of rock melting which, howsoever qualitative, form a basic element of research in igneous petrology, and expose the expressive power of this paradigm for studies in hydrology, sediment compaction and hydrocarbon for-

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mation which keen scientists would not fail to notice.

Seventeen scientists, mostly young researchers and academics from the areas of petrology, isotope geochemistry and geophysics, selected after a wide consultation, attended the discussion meeting.

The meeting comprised of eight sessions including a final brainstorming session to discuss future initiatives – individual as well as national. Each of the other sessions began with a long exposition by Dan McKenzie – the first two on the mathematical formulation of the problem starting with the basic conservation principles through the concepts of scaling and dimensionless numbers and laboratory experiments, and drawing heavily from geological phenomena involving two-phase flow both at high Reynolds' number (aerosol and sediment transport, crystallization of magma, etc.) as well as low Reynolds' number (hydrology, sediment compaction, reservoir engineering and oil extraction). These sessions were of tutorial nature with active involvement of participants using both the lecture and the discussion mode.

The remaining six sessions also began with actual case analysis by McKenzie, of the Hawaiian and Icelandic volcanism and several other applications of the solution of conservation equations to special cases. In the latter part of the sessions, participants joined in drawing analogies with their own research problems and articulating new strategies and approaches.

The principal gain made by this discussion meeting was in terms of new intellectual insights in formulating geological problems quantitatively and with the possibility of testing hypotheses, and above all, a certain confidence in using the fluid dynamical approach. In fact, an overwhelming opinion voiced at the concluding session was that it would be highly desirable to re-examine earth science curricula in the country from this new viewpoint and introduce the subject of geological fluid dynamics in the core programme.

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