Magmatic mass transfer through deep crust: Field relationships, chemistry and rheology

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Project partner(s): ARC Centre of Excellence "Core To Crust Fluid Systems", Department of Earth and Planetary Sciences, Macquarie University, Australia

This exciting project aims to shed light on the long standing problem of how melt is transferred through the crust by a combination of field studies in Greenland and Central Australia, combined with lab-based microstructural and geochemical analyses. Depending on student's interests investigations will be augmented by a choice of high temperature or analogue experiments and/or numerical modelling. The student will be part of an international research group involving partners and students based in Greenland, Australia and Italy. Throughout the studentship, the student will have the opportunity to visit partners.

Fluids are instrumental in the evolution of Earth's crust and mantle; they facilitate chemical exchanges that change basic rock properties and are important for crustal differentiation at the large scale. Fluid advection of heat and mass is central to nuclear waste storage, CO_2 sequestration, geothermal systems, and the formation of ore deposits.

The motivation for examining transfer of melt in the lower crust is rooted in a fundamental gap in our knowledge. It is poorly understood how magmatic mass transfer occurs through the deep crust. This project builds on observations that significant migration of melt and mass transfer at the kilometre-scale can occur in localized areas resulting in significant changes to both the melt and the host through which melt migrates (Daczko, Piazolo et al. 2016) (Fig. 1).

This project aims to achieve a new level of understanding and quantification of the underlying principles governing *magmatic mass transfer* through deep crust. Three main questions will be addressed:

1) *Processes*: What physiochemical processes are involved in magmatic mass transfer through deep crust?
2) *Recognition*: How can geologists recognize prior magmatic mass transfer in natural rocks? What is the physical and chemical fingerprint at micro- to meso-scales? Do rock units commonly mapped as metasediments in fact represent such melt transfer zones which developed through extreme metasomatism?
3) *Effect*: How does magmatic mass transfer affect the chemistry, geochronology, melt fertility and rheology (strength) of the crust it transfers through as well as the crust it forms at higher levels?

Figure 1. Field example of melt transfer zone in the lower crust, Fiordland, New Zealand. It shows a gabbroic gneiss (light grey) which has changed due to fluxing of a hydrous melt to an ultrabasic granofels rock (hornblendite, dark) in a channel of melt-rock interaction (~40m wide). The melt channel is inferred to be a

zone of significant mass transfer on the basis of the change in rock chemistry and mineral assemblage. For scale see geologists in the foreground (modified after Daczko, Piazolo et al. 2016).

Objectives:
In this project, you will work with leading scientists at Leeds, UK, and the Centre of Excellence, (Macquarie University, Australia), together with experts on the geology of the field areas to develop an in-depth understanding of how melt moves through the crust and how such melt flux influences the chemical make-up of both the transgressing melt and the material that the melt passes through. Special emphasis will be given to the feedback between deformation and melt migration.

The studentship will involve

(1) field work in remote areas of W. Greenland, and/or Central Australia (Fig. 2).
(2) In-depth analysis of samples from the chosen two field areas. This will include chemical analysis including major and minor elements, bulk rock geochemical analysis, quantitative microstructural analysis (e.g. Smith et al. 2015) and high resolution trace element analysis using synchrotron analysis (Fig. 3).

Figure 2 *Field relationships of melt related structures. (Upper) Melt flux zone in a high strain zone in the lower crust of W. Greenland. (Lower) Melt rock interaction Central Australia; note the local abundance of garnet, biotite forming a "metapelitic composition" interpreted to be due to melt-rock interaction.*

In order to develop an in-depth understanding of the processes involved, the student will be able to utilize additional tools, the choice made depending on the student's individual background and interests:

1. Numerical modelling of reactive flow
2. High temperature- high pressure experiments
3. Analogue modelling with real-time analysis (see for example Bons et al. 2001, 2008)
4. Trace element analysis using laser ablation and synchrotron techniques (Stuart et al. 2016)
5. Analysis of "nanogranitoids" – crystallized melt inclusions (e.g. Bartoli et al. 2016)

Potential for high impact outcome
Geochemical signatures in upper crustal magmatic and volcanic rocks suggest that they are sourced from lower crustal or even mantle environments (e.g. Bourdon et al. 2002; Gray and Kemp 2009; Vigneresse 2006). However, we do not fully understand the mechanisms responsible for magmatic mass transfer through the lower and middle crust; these are widely debated [Brown, 2004; Petford, 1996; Weinberg, 1996] and the recognition of these processes in the rock record is poor.
We are in a unique position at Leeds in collaboration with the Australian Research Council Centre of Excellence "Core to Crust Fluid Systems" (CCFS, http://www.ccfs.mq.edu.au/, Macquarie University, Australia) to answer important unresolved questions about how magma moves through the crust.

This knowledge is fundamental to our understanding of Earths' evolution. At the same time, the understanding of reactive flow and tools to recognize, predict and model reactive flow is fundamental to many problems facing society (e.g. security of nuclear waste deposits, ore mineral formation). Hence, beside the advances in the fundamental understanding of crustal formation and evolution, the tools developed throughout this project have immediate policy-relevant implications. Consequently, we anticipate the project generating several papers being suitable for submission to high impact journals.

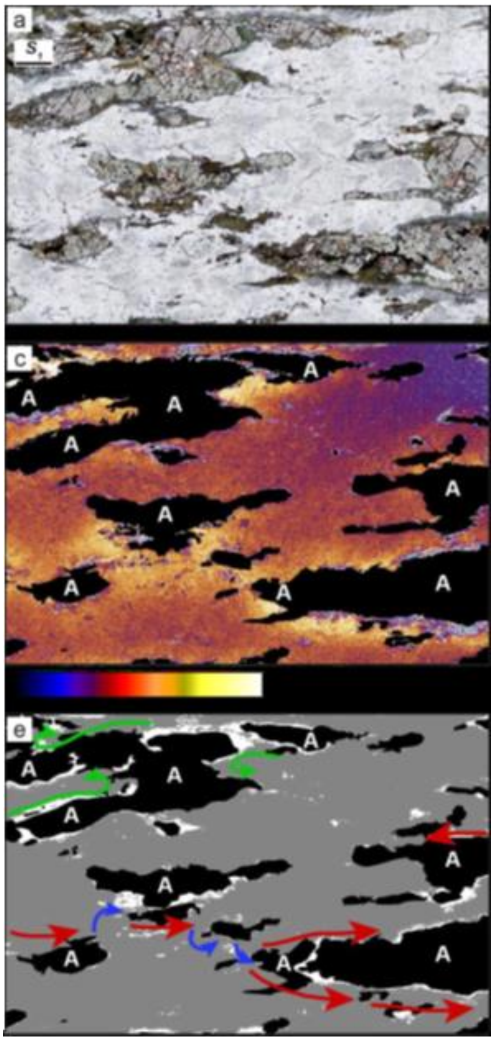

Figure 3: Trace element fingerprinting of melt flux using high end synchrotron analysis (Stuart et al. 2016). a: Overview photomicrograph of a fluxed gabbroic gneiss in plain polarized light showing pyroxenes with incipient coronas of hornblende and quartz intergrowths. FOV = 18 mm. c: Plagioclase Sr concentration (black low, white high concentrations) of same area as shown in (a); pyroxenes are marked in black. Sr is enriched next to replacement microstructures and in bands connecting individual coronas across samples. e: Schematic diagram illustrating the interpreted flow of melt as highlighted by the high Sr concentrations; grey areas are plagioclase rich domains. Melt is interpreted to have moved along pyroxene/corona boundaries parallel to foliation (red), accumulated and reacted in embayments (green), and moved along plagioclase-plagioclase boundaries forming 'bridges' (blue). Note that bands connect individual coronas across samples (modified after Stuart et al. 2016).

Training & Framework of the project

The student will work under the supervision of Prof. Sandra Piazolo and Dr. Thomas Mueller within the IGT "tectonics" and "rock, melt and fluids" group. This project provides a high level of specialist scientific training in: (i) Field work and targeted sampling in lower to mid crustal sections, (ii) state-of-the-art analytical techniques with special emphasis on both chemical and structural analysis of geomaterials; along with a selection of other skills including numerical modelling of reactive flow, high temperature and pressure experiments and analogue modelling. Co-supervision will involve regular meetings between partners and extended visits for the student to the Centre of Excellence "Core to Crust Fluid Systems" (CCFS, Macquarie University, Australia), where the student will work under the supervision of Assoc. Prof. Nathan Daczko. The later will be associated with field work in the remote outback of Australia.

The successful PhD student will have access to a broad spectrum of training workshops put on by the Faculty that include an extensive range of training workshops in numerical modelling, managing your degree, and preparing for your viva (http://www.emeskilltraining.leeds.ac.uk/). The student will not only benefit from the experts and facilities at Leeds University but also the ARC Centre of Excellence "Core to Crust Fluid Systems" located at Macquarie University.

The student will be part of a larger joint research effort currently under way both at Leeds University and CCFS (Macquarie University) involving at least 3 PhD students with collaborators within the School at Leeds and partners in Sydney and Padua. As such, the student will be part of an active group excited to unravel the processes and signatures involved in reactive fluid flow and mass transfer.

Student profile

The student should have a strong interest in structural geology, metamorphic geology and igneous processes, love for field work and thinking out of the box and a strong background in a quantitative science (maths, physics, chemistry). Willingness to work within an international research team is essential. A Masters of Research in a relevant area will increase the chances to get a scholarship.

CASE Partner

The proposal has been agreed as a "Partnership Project" - CASE project - with the Department of Earth and Environment, Macquarie University, providing extra funding additional to the NERC student stipend enabling a study stay of at least 3 months in Sydney, Australia.

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