Giant Dykes & Deep Time Tectonics; the Role of Dyke Swarms in Shaping the Early Earth

In partnership with University of Leeds and Durham University

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Overview

Magma plumbing systems are commonly dominated by vertical dykes, which deliver magma from depth into shallow-level reservoirs or to be erupted at the surface (Magee et al., 2018a). In active volcanic settings, we track subsurface dyke intrusions to monitor and assess volcano hazards. We also analyse the petrology and chemistry of erupted rocks to shed light on the processes within magma reservoirs that control eruption and hazard style; these processes can also drive the formation of economically important ore deposits. However, within these systems, dykes are typically assumed to be relatively simple pathways that link areas of magma storage to eruption sites. Yet there is a growing awareness that physical and chemical magma processes within dykes can vary over small-scales in time and space, giving rise to domains within dykes where magma behaves differently (e.g., Magee et al., 2016; Holness et al., 2017). For example, dykes may be expected to convect, focusing magma ascent in some areas (Holness et al., 2017), whereas other parts of dykes may stagnate and allow layering to occur (Upton & Thomas, 1980). Magma processes within dykes are therefore more complex than many previous studies and models consider. Critically, we do not know how such complexity within dykes could impact the location of eruption sites, the distribution of minerals (including ore deposits), or the evolution and rheology of magma during transport. Addressing this knowledge gap in our understanding of dyking will provide fundamental insights crucial to volcano hazard assessment and mineral exploration.

This project will examine the ~1.1 billion year old Tugtutôq Giant Dykes of SE Greenland (Fig. 1), which represents a voluminous phase of Proterozoic rift magmatism (Upton & Blundell 1978).

Fig. 1 Excellent 3D exposure of the Younger Giant Dyke in SE Greenland offers excellent opportunities to assess the structure of sheeted intrusions.

Giant dykes, like those in Tugtutôq, are extremely wide (10's–100's m) and often contain zones of mineral layering (e.g., Upton & Thomas, 1980), which are known to form important mineral and metal ore deposits (e.g., Chaumba & Musa, 2020). These giant dykes represent an excellent natural laboratory to study magma processes within dykes because they contain discrete domains (e.g., layered pods and areas of presumed flow), where magma behaved differently, which can be easily sampled. Previous mineralogical and geochemical studies provide a broad understanding of the Tugtutôq Giant Dykes petrogenic history and associated Ti-Fe deposits (see Steenfelt et al. 2016). However, the mechanics of dyke injection, the formation of pristine mineral layering, and the interaction between domains within these intrusions remains unstudied.

This PhD will specifically examine physical and chemical records of magma movement and crystallisation within the Tugtutôq Giant Dykes, in order to determine controls on the: (1) localisation of magma flow, which may represent a key influence on the location and distribution of eruption sites; and (2) accumulation and evolution of minerals within stagnating magma, which will shed light on how magma chemistry is modified during dyking and formation of associated ore deposits. The resulting data will help the community to pinpoint how magma moves through and stalls within dykes, and how these processes impact magma evolution, mineralisation, and eruption style.

Fig. 2 Fantastic expires of modal layering in mafic sheet intrusions, SE Greenland.

Methodology

This project will integrate a variety of field and laboratory techniques to help understand the composition and structure of the Tugtutôq Giant Dykes. The three broad areas of investigation include:

<u>Fieldwork</u>

Fieldwork will consist of a substantial expedition to SE Greenland that will involve detailed structural mapping using airborne drone (UAV) and tablet mapping methods. Mapping will focus on the identification of magma flow indicators, i.e. small-scale structures formed during dyke propagation (e.g. intrusive steps; Magee et al. 2018b), and the architecture of mineral layering. Geological mapping will also be used to direct targeted rock core sampling campaigns; this will be supplemented by more than 200 samples already collected from the Tugtutôq Giant Dykes and at St Andrews.

<u>Composition</u>

Mineralogy and chemistry provide important clues to where magma is sourced from, how it interacts with the country rock, and the crystallisation processes that drive layering and ore mineralisation. The composition of the Tugtutôq Giant Dykes will be analysed through standard petrography and the PhD candidate will also have access to cutting-edge geochemical facilities in the University of St Andrews and at Durham University. LA-ICP-MS and probe analysis will initially be used provide textural and compositional context for rock magnetic data and to map mineral compositional variation in magma layers.

<u>Rock texture</u>

The arrangement and geometry of crystals within igneous rocks record how magma was emplaced (e.g., sticks align with flow in a stream; Magee et al. 2016), crystallised, and evolved. The state-of-the-art M^{3}Ore rock magnetics lab at the University of St Andrews harnesses magnetic susceptibility and remanence techniques to quantitatively map rock fabrics (e.g. McCarthy et al. 2015); these magnetic fabric analysis techniques can be used to reconstruct magma flow patterns and the mechanics of layering. Other textural analyses, including crystal size distribution, allow the cooling history and equilibration of the Tugtutôq Giant Dyke magma to be studied.

Fig. 3 The M3Ore Lab is equipped with (left) a KLY-5a Kappabridge with CSL cryostat and CS4 Furnace, (bottom right) a 3D automated rotator, and a selection of lab based and hand-held susceptibility meters, two impulse magnetisers, two isothermal tumbler demagnetisers (top right), two spinner magnetometers and a super cooled thermal demagnetiser housed in our new palaeomagnetic shielded room.

A set of objectives and an example timeline are provided below:

Objectives

1) Conduct new, high-resolution mapping and structural analysis of the Tugtutôq Giant Dykes, using drone, satellite and digital field mapping techniques, to efficiently record structural data from the dykes and host rocks and to identify structures related to magma flow;
2) Analyse rock fabrics, identified through petrography and magnetic techniques, to interpret magma flow patterns and layering processes;
3) Acquire new, high-resolution geochemical data for the dykes to constrain magma evolution;
4) Integrate data to produce a conceptual model describing dyke emplacement and evolution,

highlighting their role in driving mineralisation and tectonics.

The PhD is designed to be flexible and the successful candidate will be encouraged to pursue their own exciting ideas using the wide range of state-of-the-art analytical facilities available at St Andrews and Durham (see our School Facilities Website).

Timeline

Year 1
Familiarisation of the project through background reading and induction from supervisors. A reconnaissance field campaign, accompanied by supervisors, to dykes in Scotland for training in the field skills to be employed (e.g., digital & drone mapping, sampling strategies). Commence rock magnetic & petrological analyses on existing samples. Identify prime target localities for upcoming field season.
Year 2
Extensive field campaign to the Tugtutôq Giant Dykes in Spring, digital mapping and sample collection. Ongoing rock magnetic experiments and petrography. Geochemical training and analyses. Write-up of first paper with tutelage from supervisors.
Year 3
Completion of data analysis. Write-up of second paper on Greenland data.
Year 3.5
Write-up and submission of thesis and additional papers.

Training & Skills

This project benefits from advisors who have specific skill sets in key aspects of the proposed project. Primary advisor Will McCarthy focuses on rock magnetics and the architecture of igneous. External collaborator Madeleine Humphreys (Durham) specialises in using petrology and chemistry to understand magma storage and migration. Craig Magee (Leeds) is a specialist in sill and dyke intrusion mechanics. Adrian Finch is an applied mineralogist with more than 20 years of experience working in the Gardar province of South Greenland.

You will receive bespoke training in: (1) digital (i.e. tablet-based) and traditional (i.e. pen and paper) mapping techniques (all supervisors); (2) rock magnetic techniques (McCarthy and Magee); (3) transmitted light petrography (all supervisors); and (4) probe and LA-ICP-MS analyses (Humphreys). Training will be largely one-to-one, working closely with supervisors. Over the course of the PhD you will gain many transferable skills such as scientific writing, statistics and data analysis, problem-solving, as well as time management and developing independent research planning skills. Formal, delivered training courses, as part of the fulfilment of DTP transfer requirements, will also be undertaken. At the end of the PhD, you will become a confident and independent researcher with transferable skills applicable to both academic and non-academic jobs. We will also provide training and support in moving your career beyond the PhD.

References & Further Reading

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Further Information

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