Barringer Family Fund 2026

Student and PostDoc Project Research Grant

A Phase Heritage and Modelling Approach for Resolving the Crystallisation Mechanisms of Impact Melt Sheets

Ari J. Guest

*University of Portsmouth**

** Institute of the Earth and Environment,*

University of Portsmouth, Portsmouth, UK.

ari.guest@myport.ac.uk

+44 7935 824566

arijguest.com

Recommendations from J. R. Darling & H. Moreira

Abstract

Large meteorite impacts generated extensive impact melt sheets during Earth's early history, yet the processes by which they crystallised remain poorly constrained. The 1.85 Ga Sudbury Structure in Ontario, Canada, contains the best-preserved record of large impact melt sheet evolution on Earth, but competing hypotheses for its differentiation include fractional crystallisation of homogeneous melts or segregation of immiscible melts generated from different target rocks. The identification and origin of potential roof sequence rocks are key to Sudbury melt evolution models. Recent studies propose that the Upper Contact Unit (UCU) and/or melanorite groups represent preserved roof material, though the petrogenesis and relationship between these units is not resolved.

This project aims to investigate the origin of melanorite and the UCU within the Sudbury impact melt sheet. Geological mapping will target existing melanorite occurrences and the granophyre–UCU interface, supported by in-situ pXRF and pVisNIR for rapid geochemical discrimination of mafic and ultramafic bodies. Geochemistry, accessory mineral phase-heritage analysis, and thermodynamic modelling will be used to constrain crystallisation sequences, extreme thermal histories, and melt evolution.

The primary goal is to evaluate competing models of impact melt sheet crystallisation and provide broader insights into crust formation on Earth and other rocky planetary bodies.

Plain Language Summary

Meteorites once bombarded the primitive Earth, forming vast lava lakes that solidified into rocky crust. We investigate the best-preserved terrestrial example, the Sudbury impact structure, to better understand how impacts changed Earth's earliest crust.

Introduction

Competing hypotheses remain for the differentiation of impact melt sheets. One model proposes fractional crystallisation of initially homogeneous impact melts **(1,2)**, whereas another suggests segregation of immiscible melts from a viscous emulsion **(3)**. Each carries major implications for early crust formation. Fractional crystallisation would generate new felsic crust and ultramafic cumulates, supporting models of early continent formation and crust–mantle exchange, whereas viscous emulsion would largely recycle pre-existing crustal heterogeneity, causing disequilibrium that inhibits widespread fractional crystallisation through rapid cooling and mixing **(3)**.

The Sudbury impact structure **(Figure 1)**, Earth's only surviving large, differentiated impact melt sheet is central to resolving this debate, yet it presents its own enigma. Most impact melt sheets and layered intrusions preserve a fine-grained roof unit formed by rapid cooling at the melt-sheet roof, but no such unit has been conclusively identified at Sudbury **(1,2)**. Such units may be key to resolving if fractional crystallisation or viscous emulsion **(Figure 2)** is the mechanism for impact melt sheet differentiation **(1,4)**.

Anders et al. (2015) interpret the Upper Contact Unit (UCU) as preserved roof material, citing its transitional contact with granophyre, skeletal quartz–feldspar intergrowths, depth-dependent textural trends, and shocked clasts indicative of an impact melt lithology. In contrast, **Latypov et al. (2019)** propose that melanorite bodies preserved as lenses and autoliths within granophyre, norite, and quartz gabbro represent fragments of an early roof cumulate that crystallised rapidly before foundering into the melt sheet. Such melanorite bodies require high-precision in-situ geochemical methods to identify, owing to very subtle textural differences between adjacent units in the field **(1)**.

This study therefore aims to investigate these models for roof formation via in-situ and laboratory geochemical, textural, and phase-heritage analysis **(Figure 4)**. New constraints on melt sheet geometry and temperature allow thermodynamic modelling to investigate if fractional crystallisation or viscous emulsion is the differentiation mechanism for impact melt sheets.

Goals of the Study

Investigate Newly Proposed Roof-Series Units:

The primary goal is to investigate and compare the geochemical and textural properties of the Upper Contact Unit (UCU) identified by **Anders et al., (2015)** and the newly proposed roof-proximal melanorite series identified by **Latypov et al., (2019)**. The latter identify melanorite bodies in close stratigraphic proximity to the Upper Contact Unit, so this project will also involve geological mapping at Sudbury **(Figure 1)** complemented by in-situ geochemical analysis given it is needed to discriminate melanorite **(1)**.

Geochemical analysis is required to conclusively identify melanorite **(1)**, with strong TiO_2 and K_2O depletion relative to quartz gabbro and granophyre, and elevated Mg/(Fe, Al, Ca) ratios relative to main-mass norite. Typically, characterisation requires sample return for lab petrographic and geochemical analysis **(1)**. However, developments using pXRF (portable X-Ray Fluorescence) and pVisNIR (portable Visible & Near Infrared Spectroscopy) for mafic/ultramafic rock discrimination **(5)** allow rapid in-situ identification of melanorite. This approach improves geological mapping by allowing analysis/discrimination of complex geological interactions and features invisible at the macro scale.

Geochemical and Phase-Heritage Analysis:

Samples returned from this fieldwork will undergo a wide programme of geochemical analysis. Whole-rock major- and trace-element compositions will be determined to place each sample within established Sudbury differentiation trends and to assess compositional variability within and between UCU and melanorite (both main-mass and sublayer) following established approaches **(1,6)**. These data will also test whether newly sampled melanorites plot near the least evolved end of a single liquid line of descent, consistent with formation as early cumulates from a homogeneous impact melt sheet. In parallel, electron microprobe (EPMA) data for major mineral phases will provide key petrological constraints for later thermodynamic modelling (detailed below). Targeted isotopic and crystallographic analyses of accessory phases will constrain the thermal evolution of the melt sheet. Baddeleyite phase-heritage analysis **(Figure 4)**, informed by microstructural characterisation, offers unique potential to trace extreme temperature histories of impact melts, thereby providing quantitative constraints on conditions within the early Sudbury impact melt sheet which will inform thermodynamic modelling and resolve simple crystallisation from reincorporation into the superheated impact melt sheet **(7)**.

Modelling the Crystallisation of the SIC:

Phase-equilibria modelling will test if the observed assemblages and mineral compositions can crystallise from the Sudbury impact melt under pressure–temperature conditions informed by phase-heritage and geochemical analysis. Representative bulk compositions constrained by Onaping Formation impact glasses and Main Mass geochemistry **(6)** will be modelled across realistic pressure–temperature conditions (<2 GPa **(7)**). Models will also be run with a two-layer viscous-emulsion scenario and a single homogeneous melt composition (**Figure 2**). Simulations will track phase assemblages, melt chemistry, density evolution, and mineral compositions under both equilibrium and fractional crystallisation conditions. Emphasis is placed on the stability and timing of orthopyroxene–plagioclase–dominated assemblages characteristic of melanorite and the UCU **(1, 2)**. Calculated phase assemblages will be compared with established geochemical trends to evaluate whether melanorite can form as an early roof cumulate from a single homogeneous melt sheet **(Figure 2)** or instead requires melt stratification or heterogeneous starting compositions **(1)**. This provides a test of competing models for melt sheet differentiation and complements phase-heritage and geochemical constraints.

Geological Background

The Sudbury Igneous Complex (SIC; 1.85 Ga **(6)**) formed when a ~12–15 km chondritic meteorite impacted Paleoproterozoic continental crust, generating a superheated, compositionally homogeneous impact melt sheet several kilometres thick **(6,8)**. The melt was derived from Archean Superior Province gneisses and the Proterozoic Huronian Supergroup **(Figure 3)**, was granodioritic in bulk composition, and contains only a minor mantle contribution **(6)**. After impact, the melt sheet ponded within the crater and was rapidly overlain by fallback breccias and pyroclastics of the Onaping Formation, forming strong thermal gradients between roof and insulated interior **(8)**.

As the melt sheet cooled, it crystallised inward from the roof and floor, producing the characteristic norite–quartz gabbro–granophyre stratigraphy of the SIC through fractional crystallisation, as seen in **Figure 2 (6)**. An alternative interpretation suggests that the superheated melt initially behaved as an emulsion of felsic and mafic melt parcels inherited from the heterogeneous target **(Figure 2)**, which rapidly segregated before significant crystallisation **(3)**. Cooling drove intense hydrothermal systems within both the SIC and overlying breccias, causing extensive metasomatism **(9)**.

These magmatic and hydrothermal processes ultimately generated globally important Ni–Cu–PGE sulphide resources **(10)**. Immiscible sulphide melts segregated from the impact melt and accumulated along the basal contact of the melt sheet within, embayments and offset dykes, where they interacted with footwall lithologies. Later hydrothermal activity further redistributed metals and modified ore assemblages, forming numerous deposits across the basin **(9,10)**.

Methods

Investigate Newly Proposed Roof-Series Units:

- Conduct geological mapping at Sudbury near known UCU occurrences **(4)** and roof-proximal melanorite bodies while collecting paired samples to ground-truth pXRF/pVisNIR analysis against SEM-EDS, EPMA, and LA-ICP-MS analysis **(1)**.
- Apply pXRF elemental ratios to discriminate mafic and ultramafic lithologies, targeting elevated Mg# (Mg/(Mg+Fe)), Cr/Zr and Ti/Zr, together with diagnostic TiO_2–K_2O depletion, while using Ca/Si to distinguish orthopyroxene-dominated assemblages and Fe/Mn ratios to monitor plagioclase contribution and alteration **(1,5,6)**.
- Analyse drill core samples containing melanorite or UCU material **(1,4)**.

Geochemical and Phase-Heritage Analysis:

- Use SEM (BSE, EDS, SE, CL) and optical analysis for petrology and accessory targeting.
- Acquire whole-rock major- and trace-element geochemistry via ICP-OES and ICP-MS, along with mineral chemical data by EPMA to place samples within established Sudbury differentiation trends and quantify compositional variability among the UCU and melanorite **(6)**.
- Use electron backscatter diffraction (EBSD) for phase-heritage analysis to characterise temperature-sensitive microstructural states and to identify domains suitable for geochronology **(7)**. See **Figure 4**.

Modelling the Crystallisation of the SIC:

- Apply geochemical constraints and thermal constraints from baddeleyite phase-heritage analysis to refine pressure-temperature inputs for phase-equilibria modelling in THERMOCALC v3.51 **(11)**.
- Model crystallisation of representative bulk melt compositions constrained by impact melt glasses and geochemistry at derived pressure-temperature conditions **(12)**.
- Evaluate if opx–plag–dominated assemblages are stable at the indicated conditions.
- Model conditions expected for viscous emulsion **(3)** and fractional crystallisation **(12)**.

Proposed Reporting of Results

This project will lead to the production of a primary paper, targeted for release in **MaPS** *(Meteoritics and Planetary Science)* or **GCA** *(Geochimica et Cosmochimica Acta)*. This paper will test whether melanorite bodies and the Upper Contact Unit represent components of a preserved Sudbury roof sequence, and the implications this may have for impact melt sheet differentiation and Hadean crustal formation. Additional papers related to the use of the in–situ geochemical methods outlined in this proposal may be produced.

Timeframe

Fieldwork will commence in September 2026. Primary thin section preparation and characterisation using optical and SEM methods will be completed by January 2027. Detailed SEM analysis, baddeleyite targeting, and isotopic analysis will be completed by May 2027. Thermodynamic modelling efforts will be completed by July 2027, ready to be presented orally at **MetSoc** and/or **Goldschmidt** (July 2027). By March 2028, all research outputs are complete, and papers are in review. Additional conference presentations of the research outputs are scheduled for March 2028 **(LPSC)**, April 2028 **(EGU)**, and June 2028 **(BPSC)**, alongside regional events which have yet to be announced.

Visibility of Barringer Family Fund Support

This project will produce academic articles acknowledging the Barringer Family Fund (BFF). BFF-supported research will be presented at international **(LPSC, EGU, Goldschmidt)** and regional **(BPSC, UKPF, GGRiP)** conferences with clear acknowledgement. Support will also be highlighted via **University of Portsmouth** IEE social media, the applicant's LinkedIn, and IEE outreach events, including the annual Stargazing event **(~800 attendees)**, recognising BFF's role in enabling research, sample acquisition, and outreach.

Figures

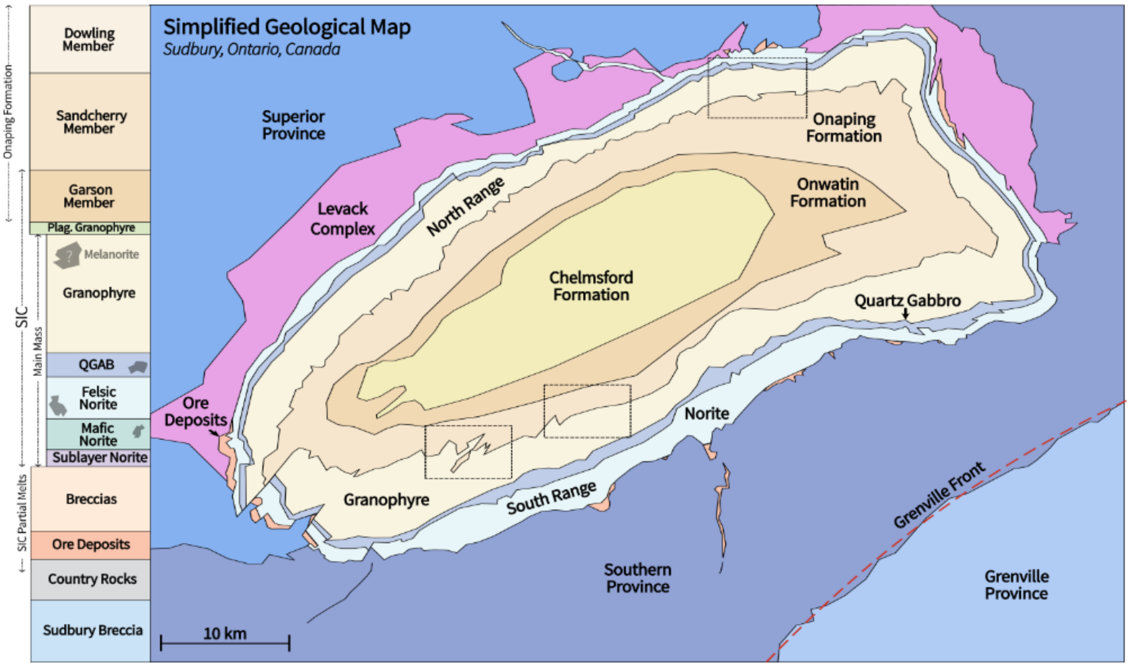

__Figure 1__ — Simplified geological map and stratigraphic column for the Sudbury impact structure in Ontario, Canada. Dashed black boxes indicate target regions for geological mapping and sample acquisition in September 2026 targeting known occurrences of the Upper Contact Unit (UCU) __(4)__ and roof-proximal melanorite __(1)__.

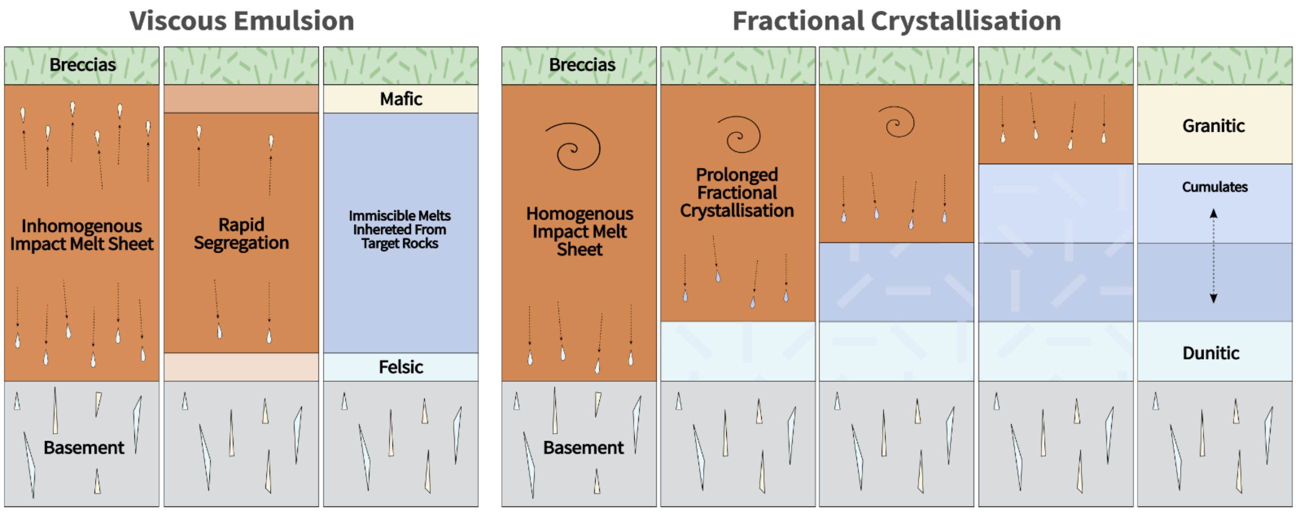

__Figure 2__ — Competing models for impact melt sheet crystallisation of Hadean primitive crust; viscous emulsion __(3)__ and fractional crystallisation __(1)__. The former involves the segregation of immiscible melts inherited from target lithologies and only recycles existing crustal heterogeneity (or lack thereof). The latter instead forms a new stratigraphy of mafic and felsic cumulates, contributing to widespread crustal differentiation __(1,3)__.

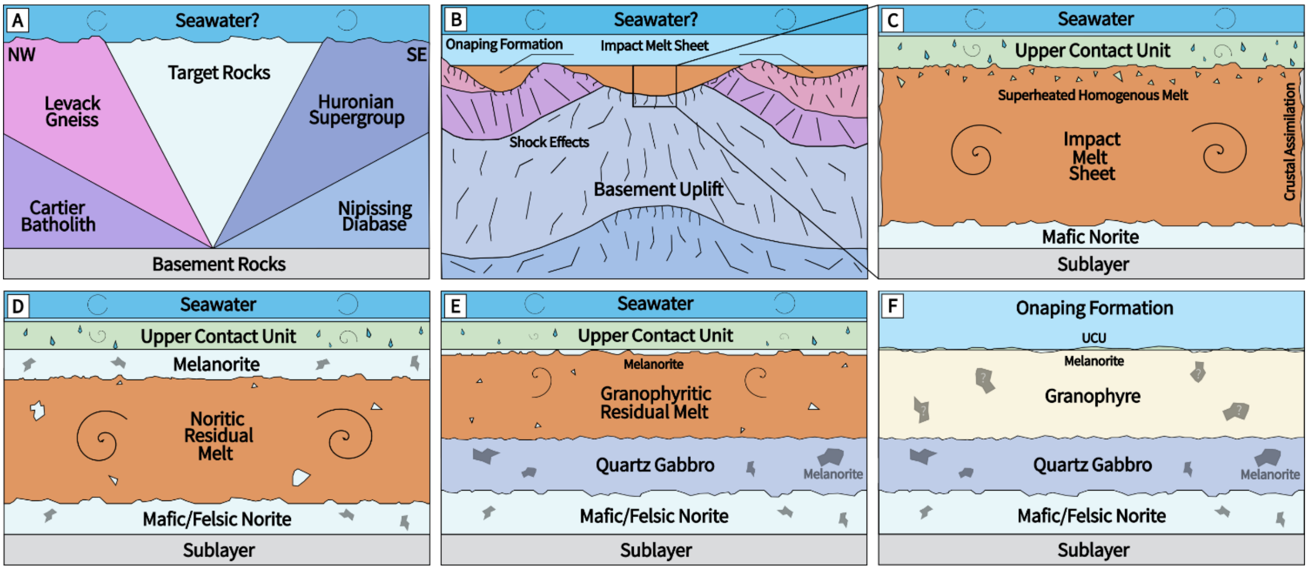

***Figure 3** — Proposed formation mechanism for the Upper Contact Unit (UCU) and melanorite at Sudbury, adapted from **Anders et al., (2015)** and **Latypov et al., (2019)**. **A)** The target rocks for the Sudbury impact. **B)** Initial melt sheet geometry. **C)** Initial melt sheet crystallisation to form mafic norite and UCU material falling into and cooling the melt sheet. **D)** Continued crystallisation of felsic norite and melanorite to form a roof layer underlying the UCU. **E)** Quartz gabbro crystallisation with melanorite autoliths incorporated after foundering from the melt sheet roof. **F)** Proposed final geometry of the crystallised melt sheet, with melanorite autoliths within quartz gabbro and felsic/mafic norite.*

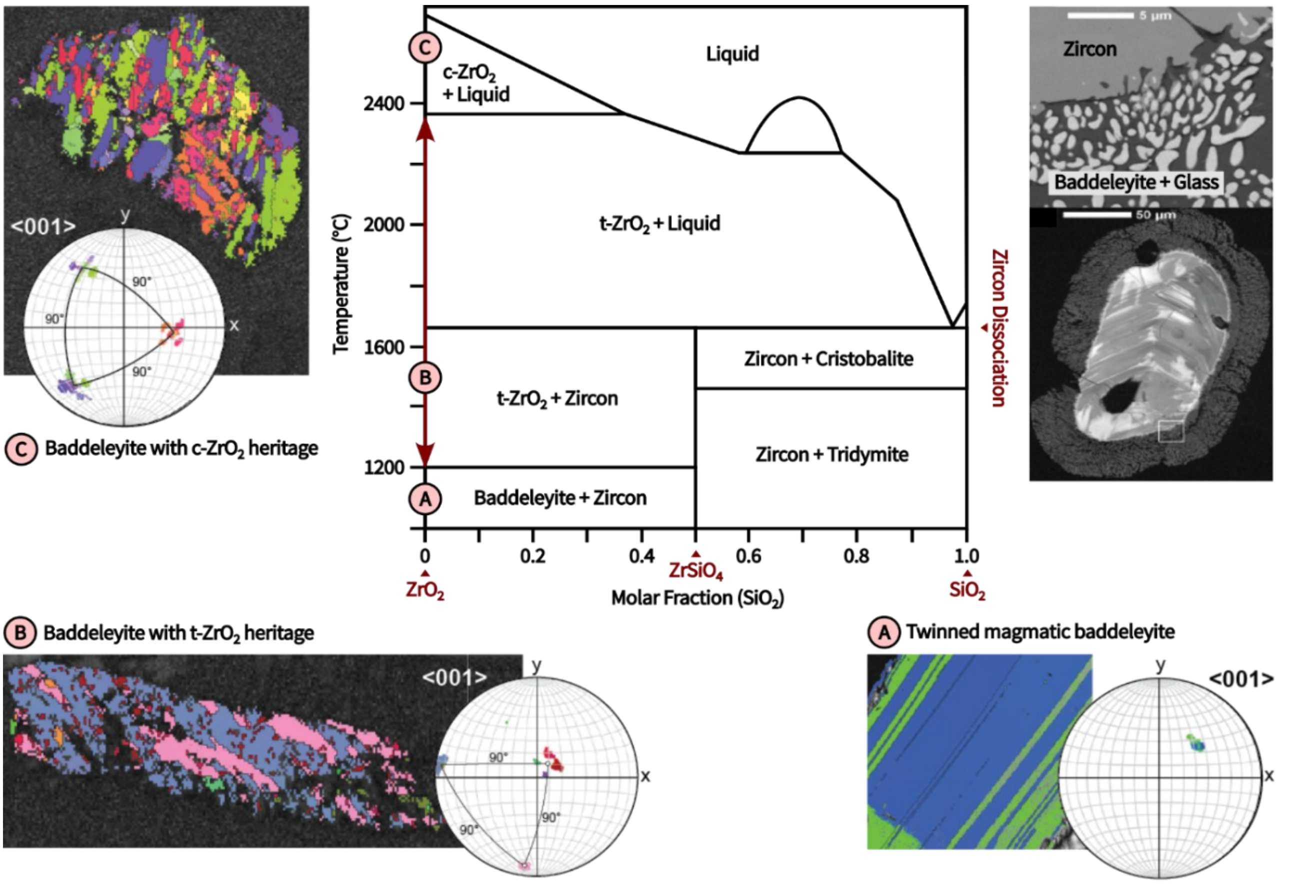

***Figure 4** — Diagram showing the phase-heritage approach using Electron Backscatter Diffraction (EBSD) to analyse crystallographic misorientation **(7)**. **A)** Monoclinic baddeleyite formed at temperatures below ~1200 °C. **B)** Baddeleyite with tetragonal heritage formed between ~1200 °C and ~1650 °C. **C)** Baddeleyite with cubic heritage formed above 2370 °C; a unique thermochronometer of extreme temperature histories.*

Budget

Table of Expenses:

Expense	Budget (USD)
Sustenance (21 days)	200
Fuel (~1500 km travel)	200
London–Toronto Return Flight (Economy)	800
Car Hire (4x4)	1500
Accommodation (20 nights @ ~$115/night)	2300
Total	**5000**

Justification:

The requested funding is solely to support three-weeks of fieldwork at the Sudbury impact structure, Ontario, Canada, and directly underpins the scientific objectives of this project. All analytical and conference costs are supported by the applicant's existing doctoral grant.

Funds are requested to cover essential travel, car hire, fuel, accommodation, and sustenance. A return economy flight from London to Toronto enables access to the Sudbury field area from the UK. Local 4×4 hire is required to reach drill–core facilities and remote mapping sites where public transport is not viable, with fuel covering ~1500 km of travel between accommodation and field localities **(Figure 1)**, including the return journey from Toronto to Sudbury. Accommodation reflects modest lodging for 20 nights, while sustenance covers basic daily subsistence over the 21-day field campaign.

Additional Support

The applicant is a NERC–funded doctoral student with the TREES DLA. As a result, grants totalling £8,000 are available to cover research activities. This will cover all analytical usage as well as local, regional, and international conferences to present the results. Nevertheless, BFF support will permit a greatly expanded fieldwork and mapping campaign, enhancing science outcomes.

Curriculum Vitae

- **MEarthSci Planetary Science**; University of Manchester; 2:1 ***2020–2024.***
  - Dissertation: "Shattering Assumptions: A Fresh Perspective on the Shatter Cone Debate from Steinheim crater and the Santa Fe impact structure".
    - Supervised by Romain Tartèse.
    - Optical, SEM-BSE/EDS, micro-Raman, LA-ICP-MS, Fieldwork.
    - Available at: **arijguest.com**
  - Stellify Award, Departmental Awards.
- **PhD Student**; University of Portsmouth; TREES DLA ***2025–2029.***

Letters of Recommendation: James R. Darling & Hugo Moreira

References

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