Sr isotopes indicate millenial-scale formation of metal-rich layers by reactive melt percolation in an open-system layered intrusion

J. Stephen Daly¹, Luke N. Hepworth², Brian O'Driscoll³, Chris Johnson³, Ralf Gertisser² and C. Henry Emeleus⁴†

¹ UCD School of Earth Sciences, University College Dublin, Ireland (stephen.daly@ucd.ie) and Irish Centre for Research in Applied Geosciences (iCRAG: icrag-centre.org)
² School of Geography, Geology and the Environment, Keele University, Keele, UK
³ Department of Earth and Environmental Sciences, University of Manchester, Manchester, UK
⁴ Department of Earth Sciences, Durham University, Durham, UK, † deceased

Rum, ~60 Ma, western Scotland
Overview

- Several cyclic units in the Rum intrusion exhibit a close association between Cr-spinel seams and PGE enrichment
- Ubiquitous mineral zoning associated with Cr spinel seams due to reaction with invading picritic melts
- Use Sr isotopes to test open system models and calculate time-scale
- Preservation of Sr isotopic zoning => very rapid ($10^3$ yr) formation of metal-rich layers by reactive melt percolation in the Rum intrusion

Rum, ~60 Ma, western Scotland
Recent studies of layered basic intrusions reveal importance of incremental pluton assembly
(repeated small intrusions – not vast magma chambers)

So, if open systems are the norm, how do the invading melts interact with the cumulate framework?

Incremental Construction of the Unit 10 Peridotite, Rum Eastern Layered Intrusion, NW Scotland

Luke N. Hepworth1, Brian O’Driscoll1,2, Ralf Gertisser1, J. Stephen Daly3,4 and C. Henry Emelius5

Testing emplacement models for the Rustenburg Layered Suite of the Bushveld Complex with numerical heat flow models and plagioclase geospeedometry

Samuel J. Robb, James E. Mungall

Contributions to Mineralogy and Petrology

Braided peridotite sills and metasomatism in Scotland

Luke N. Hepworth1, Felix E. D. Kaufmann2, Lutz Hecht3, Ralf Gertisser1

The Stillwater Complex: Integrating Zircon Geochronological and Geochemical Constraints on the Age, Emplacement History and Crystallization of a Large, Open-System Layered Intrusion

Corey J. Wall1,2, James S. Scoates1, Dominique Weis1, Richard M. Friedman1, Marghalay Amini3 and William P. Meurer5

Linking In Situ Crystallization and Melt Replenishment via Sill Intrusion in the Western Layered Intrusion, NW Scotland

Luke N. Hepworth1, Brian O’Driscoll2, Ralf Gertisser1, J. Stephen Daly3,4 and C. Henry Emelius5
Rum Eastern Layered Intrusion Unit 10

Emeleus, 1997

Cr-spinel seams

Harrsite

Olivine

Unit

Olivine

Stratigraphical height in metres

50 metres

Upper peridotite

Lower peridotite

3 m

PEG

Barkeval

Harrval

Askival
1–5 mm thick Cr-spinel seams in Lower Peridotite, laterally continuous for 10–100s m often associated with coarse-grained (harrisitic) peridotite intrusions.

Diffuse (with olivine) or discrete seams of chromitite; enriched in Platinum Group elements (PGE), both in sulphides and Platinum Group minerals (PGM).

Interpreted as forming by reactions in picritic melt percolation zones.
QEMSCAN® image showing a Cr-spinel seam with associated sulphides and Platinum-Group minerals (PGM e.g. at white circles) including Pt-arsenides/tellurides, Pd-antimonides, Ru-Ir alloys and Pt-Ir sulphosalts, and electrum (Au-Ag) grains.
QEMSCAN® image of a diffuse Cr-spinel seam with associated sulphides and PGM

Adapted from Hepworth et al 2017
Intercumulus plagioclase associated with PGM-mineralized Cr-spinel seams is ubiquitously chemically zoned.
Method:
Use Sr isotopes (measure $^{87}\text{Sr}/^{86}\text{Sr}$) to test if external (picritic) melts have interacted with the cumulate framework to form the Cr-spinel seams and associated PGE enrichment.

Closed system fractionation $\Rightarrow$ constant $^{87}\text{Sr}/^{86}\text{Sr}$; open system melt percolation could introduce variable Sr isotopes (variable source of melt, assimilation of rocks with variable $^{87}\text{Sr}/^{86}\text{Sr}$).

Analyse selected parts of plagioclase and clinopyroxene crystals, that (very low Rb/Sr ratios – no age-correction needed).

Do the chemically zoned plagioclase and clinopyroxene exhibit Sr isotopic heterogeneity? Answer: yes

Using experimentally determined diffusion rates for Sr, how long can these isotopically-zoned crystals remained hot and still retain their zoning?

Answer: Must be short implying very rapid ($10^3$ yr) formation of metal-rich layers by reactive melt percolation in an open-system.
Intercumulus plagioclase and clinopyroxene sampled (by Luke Hepworth) using the Micromill guided by SEM imaging.
intracrystalline $^{87}\text{Sr}/^{86}\text{Sr}$ variation in Unit 10 intercumulus plagioclase (left) and oikocrystic clinopyroxene (right)

Total range in clinopyroxene $^{87}\text{Sr}/^{86}\text{Sr}$ ~0.0098; in plag. ~0.0006

Overall higher An% plagioclase has more radiogenic Sr
Cr-spinel seams

- Peridotite
- Troctolite ± olivine gabbro
- Chromitite

- Granular-textured peridotite
- Coarse-grained intrusive peridotite
- Foliated peridotite
- Troctolite
- Cpx oikocrystic peridotite

- Western Layered Intrusion peridotite (HAR-1)
- U8 Peridotite

- U9 cpx
- U9 plag rims
- U9 plag cores

- U8 Plagioclase

- U7 Plagioclase

- U6 Plagioclase

- U5 Plagioclase

- U4 Plagioclase

- U3 Plagioclase

- U2 Plagioclase

- U1 Plagioclase

- U0 Plagioclase

- 87Sr/86Sr

This study

- Plagioclase
- Clinopyroxene

- Mafic hornfels dyke

- Gabbroic pegmatite

- Cr-spinel seam
Potentially the incoming picrite acquired radiogenic Sr by assimilating early formed feldspathic cumulates that had been contaminated with country rocks (e.g. picrite melt + ~7% Lewisian gneiss)

Generally Cr-spinel is associated with more An-rich plagioclase and Cr-spinel is absent when plagioclase is more sodic. As interstitial picritic melt flows through, olivine and Na-plagioclase dissolve and Cr-spinel precipitates.
Reactive throughflow of picritic melt was facilitated by high intercumulus porosity (30–40% olivine). High throughflow required to mass balance the observed PGE concentrations.
**Results of Sr diffusion calculations**

Characteristics diffusion distance as a function of temperature for plagioclase (An

\[ An_{100} \text{ and } An_{50-70} \] and Diopside (cpx)

\[ \Rightarrow \text{Over } 1 \text{ Ma (the max. timeframe to crystallize the Rum intrusion), 10–100μm scale Sr zoning would not be preserved in the } T \text{ range shown} \]

**Calculated diffusion length-scale for Sr for plagioclase (An}_{50-70} \] versus time for different cooling rates. Suggests cooling was > 1 °C per year and cooling to diffusive closure for Sr within < 1000 years**
Conclusions

Significant proportion (~20%) of the Unit 10 cumulate pile of the Rum layered intrusion was intruded late

Numerous chromite seams attest to repeated late-stage infiltration of picritic melt and melt-rock reaction events. These are intimately associated with PGE mineralization

Intercumulus plagioclase associated with chromite seams exhibit significant mineral chemical and Sr isotopic ($^{87}$Sr/$^{86}$Sr) heterogeneity (disequilibrium)

Length-scales (10–100 µm) of preservation of Sr isotopic heterogeneities suggest rapid cooling to below diffusion closure temperatures on ~1000 year timescale
Rapid crystallization of precious-metal-mineralized layers in mafic magmatic systems

Luke N. Hepworth1,2, J. Stephen Daly3,4, Ralf Gertisser1, Chris G. Johnson5, C. Henry Emeleus6,7 and Brian O’Driscoll2

The solidified remnants of mafic magmatic systems host the greatest concentrations of platinum-group metals in the Earth’s crust. Our understanding of precious-metal mineralization in these intrusive bodies is underpinned by a traditional view of magma chamber processes and crystal mush solidification. However, considerable uncertainty remains regarding the physical and temporal controls on concentrating these critical metals, despite their importance to modern society. We present high-precision 87Sr/86Sr analyses of plagioclase and clinopyroxene from within centimetre-thick precious-metal-enriched layers in the Palaeogene open-system Rum layered intrusion (northwest Scotland). Isotopic heterogeneity is present between plagioclase crystals, between clinopyroxene and plagioclase and within plagioclase crystals throughout the studied section. On the basis of these observations, we demonstrate that platinum-group element mineralization formed by repeated small-volume reactive melt percolation events. The preservation of strontium isotope heterogeneities at 10-100μm length scales implies cooling of the melts that formed the precious-metal-rich layers occurred at rates greater than 1°C per year, and cooling to diffusive closure within tens to hundreds of years. Our data highlight the importance of cyclic dissolution-recrystallization events within the crystal mush and raise the prospect that precious-metal-bearing mafic intrusions may form by repeated self-intrusion during cooling and solidification.