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

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EGU2020 GMPV8.4
4th May 2020

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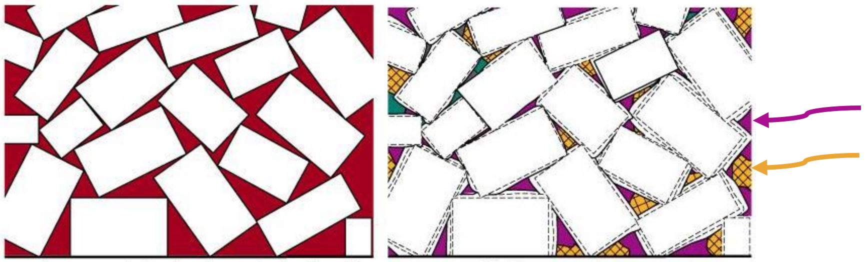
Overview

- *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*

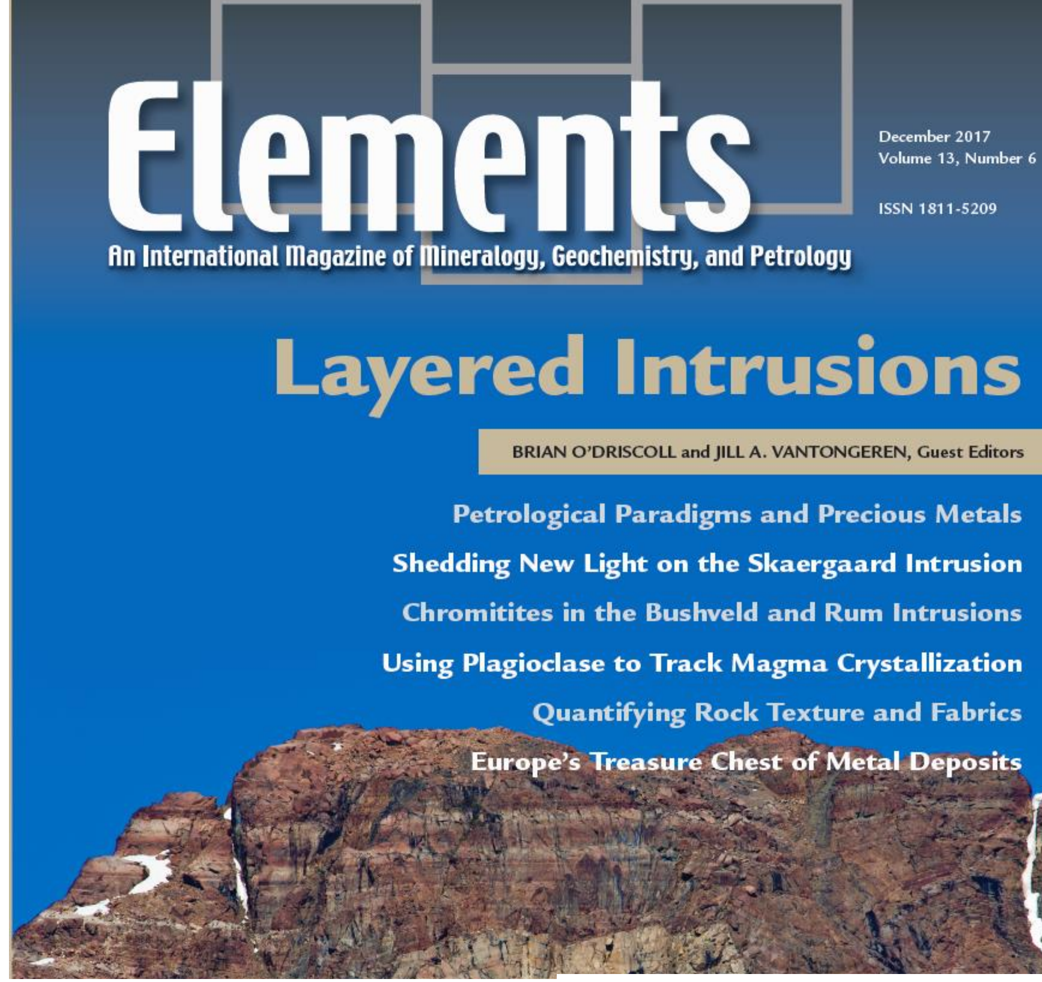
Recent studies of layered basic intrusions reveal importance of incremental pluton assembly

(repeated small intrusions – not vast magma chambers)

*open, **not** closed systems*



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. Hepworth[1]*, Brian O'Driscoll[1,2]*, Ralf Gertisser[1], J. Stephen Daly[3,4] and C. Henry Emeleus[5]

Received 8 Jan 2016 | Accepted 29 Sep 2016 | Published 14 Nov 2016 DOI: 10.1038/ncomms13385 OPEN

U-Pb geochronology documents out-of-sequence emplacement of ultramafic layers in the Bushveld Igneous Complex of South Africa

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James E. Mungall[1], Sandra L. Kamo[1] & Stewart McQuade[2]

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

Earth and Planetary Science Letters

Samuel J. Robb*, James E. Mungall

JOURNAL OF PETROLOGY

Journal of Petrology, 2018, Vol. 59, No. 1, 153–190
doi: 10.1093/petrology/egy024
Advance Access Publication Date: 28 February 2018
Original Article

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. Wall[1,2]*, James S. Scoates[1], Dominique Weis[1], Richard M. Friedman[1], Marghaleray Amini[1] and William P. Meurer[3]

Contributions to Mineralogy and Petrology (2020) 175
https://doi.org/10.1007/s00410-019-1652-9

Braided peridotite sills and metasomatism in Scotland

Luke N. Hepworth[1] · Felix E. D. Kaufmann[2] · Lutz Hecht[2] · Ralf Ger

JOURNAL OF PETROLOGY

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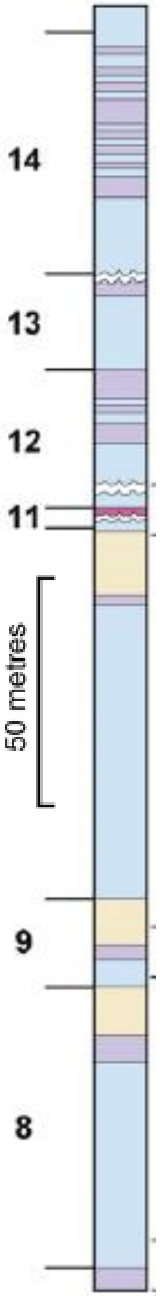
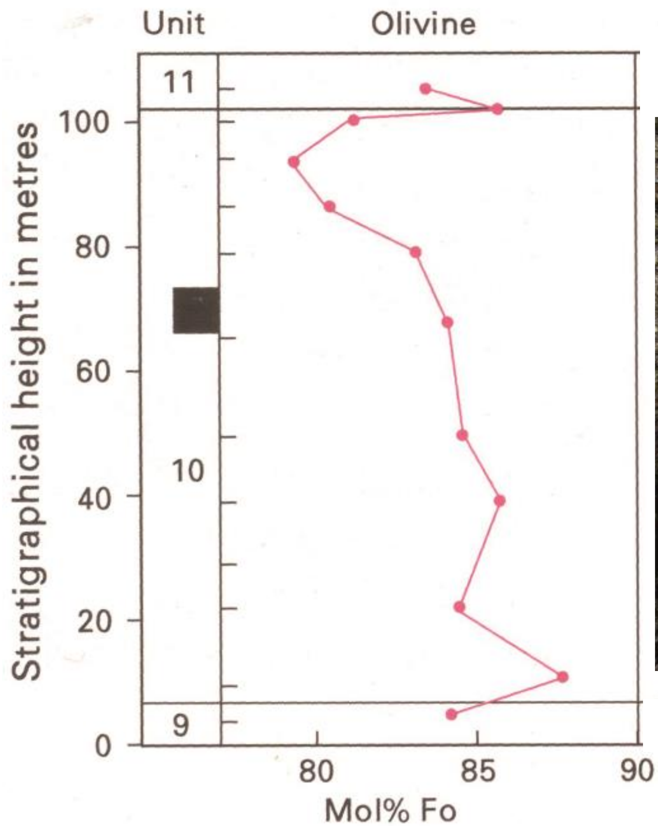
Linking *In Situ* Crystallization and M Replenishment via Sill Intrusion in t Western Layered Intrusion, NW Scot

Luke N. Hepworth[1]*, Brian O'Driscoll[2], Ralf Gertisser[1], J. Stephen Daly[3,4] and C. Henry Emeleus[5†]

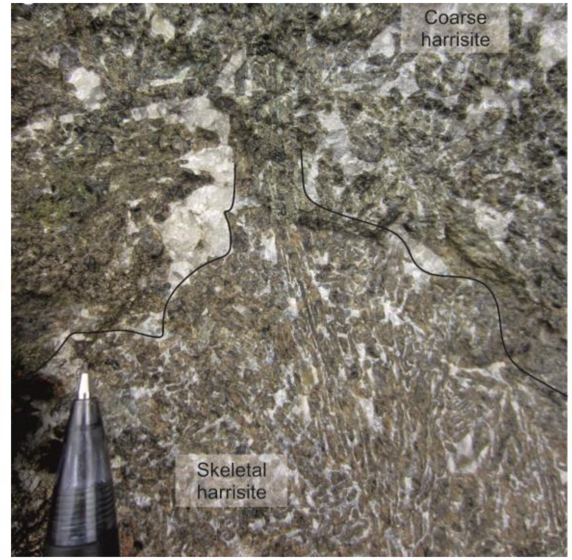
Rum Eastern Layered Intrusion Unit 10



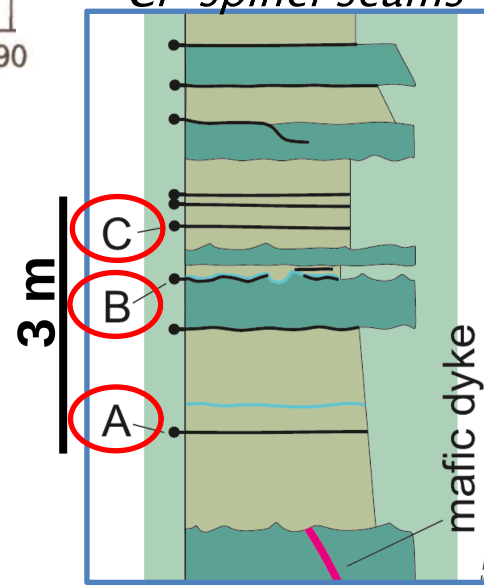
Emeleus, 1997

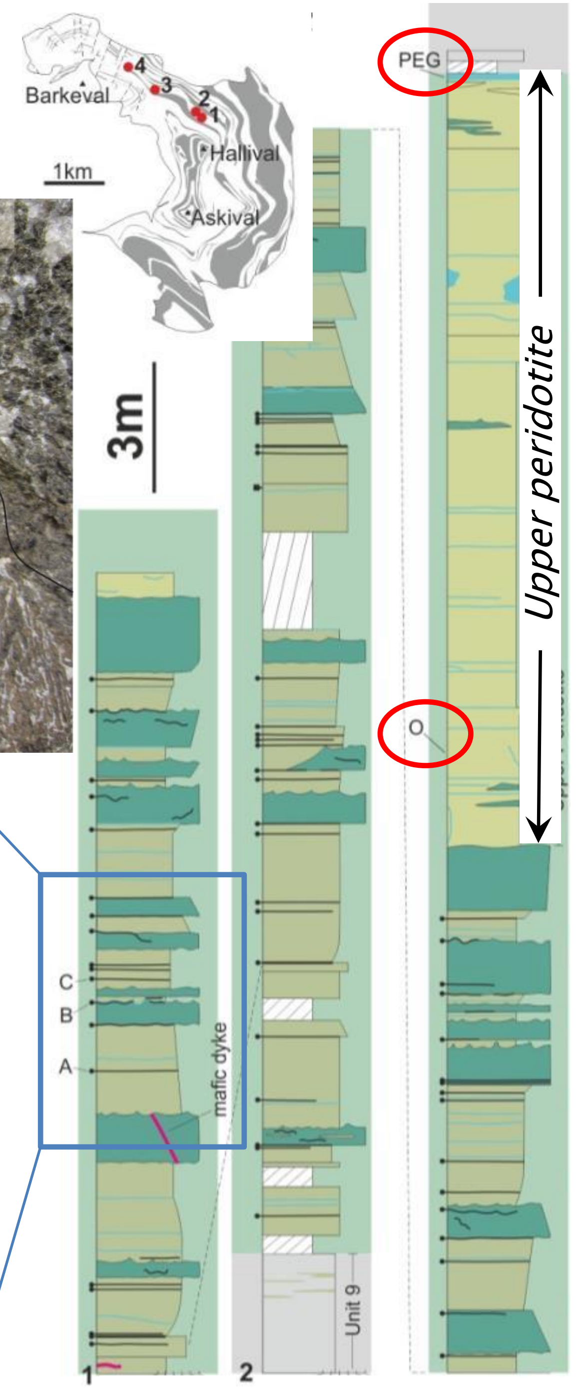


Harrisite

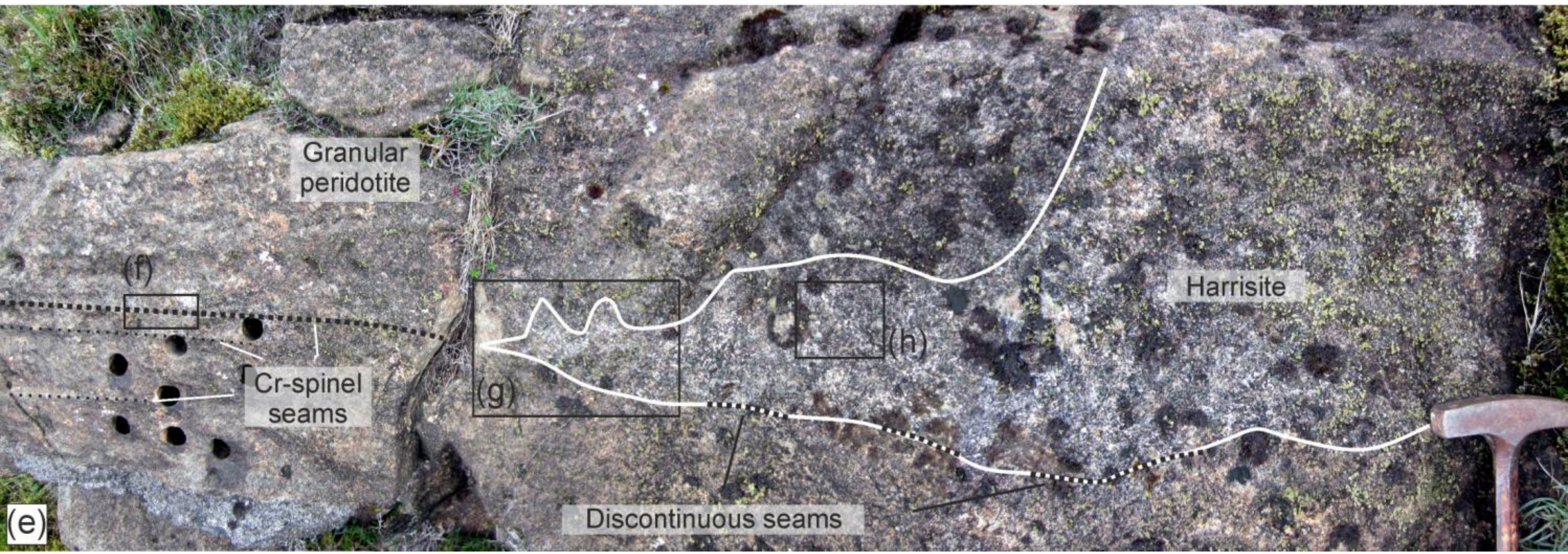


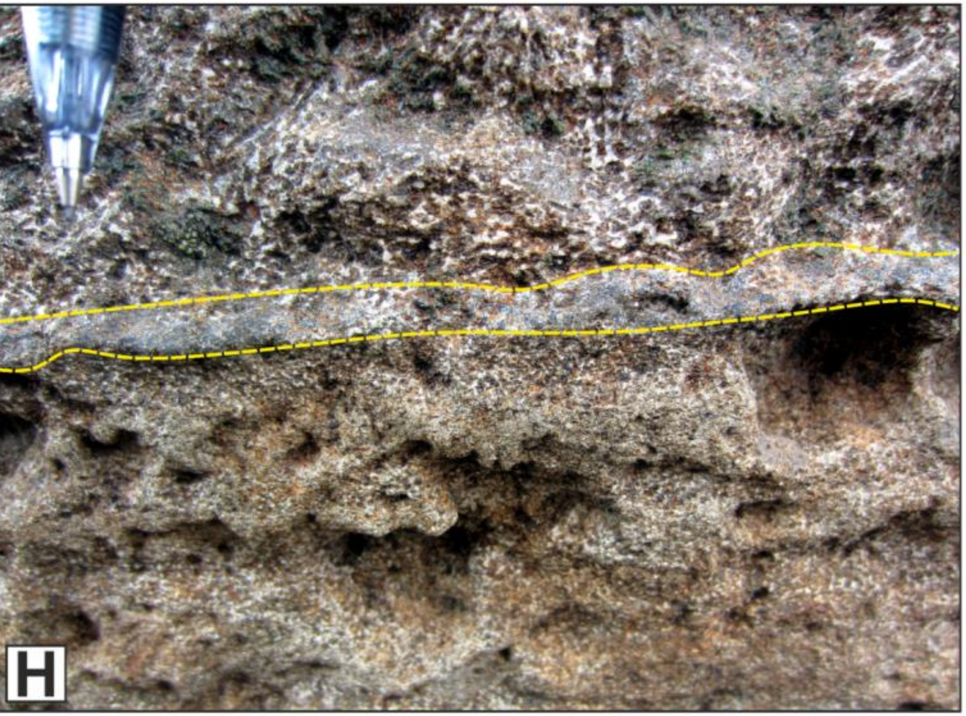
Cr-spinel seams





Lower peridotite



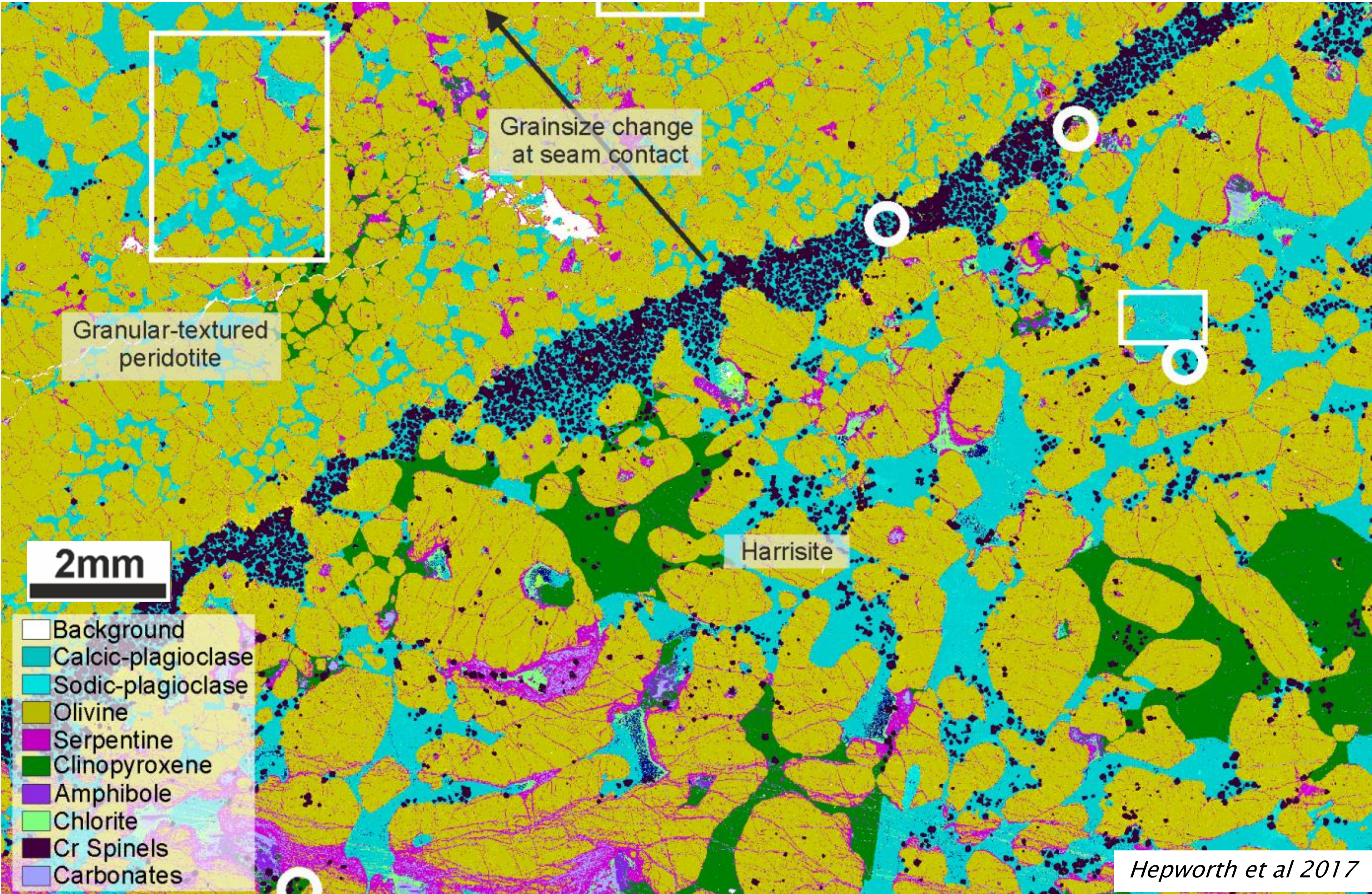


1–5 mm thick Cr–spinel seams in Lower Peridotite, laterally continuous for 10–100s m often associated with coarse-grained (harrisitic) peridotite intrusions

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

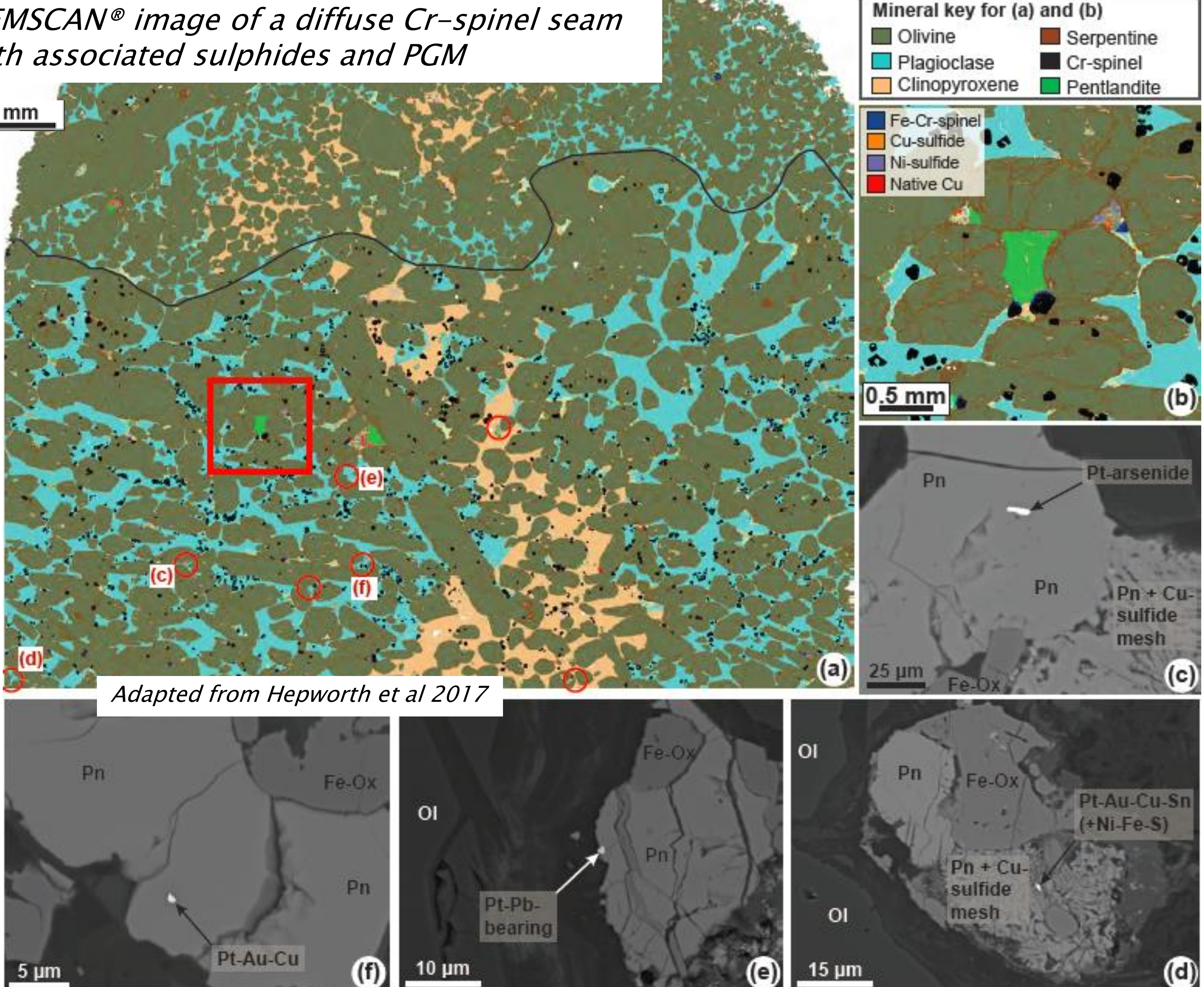
Interpreted as forming by reactions in picritic melt percolation zones

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



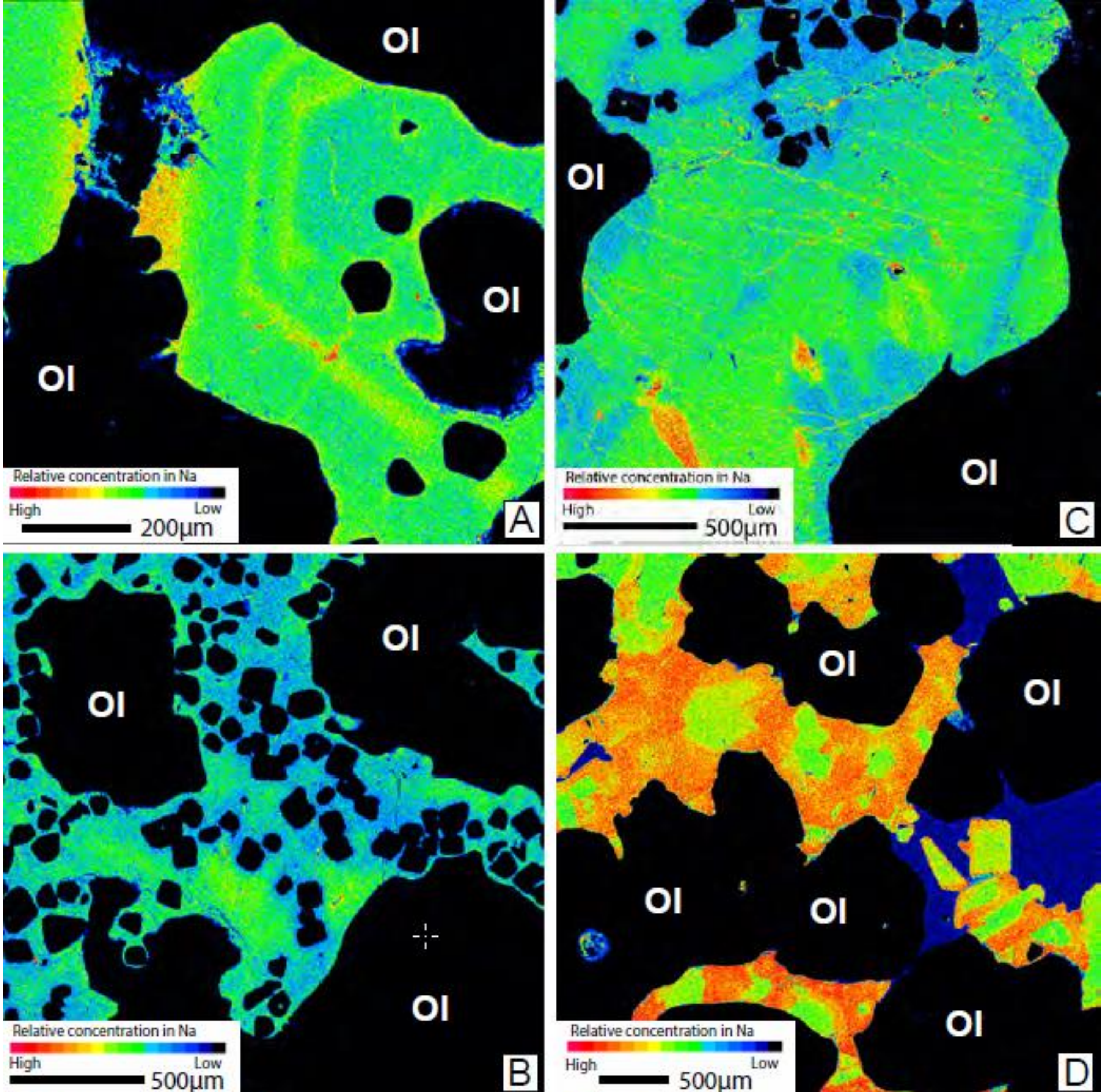
Hepworth et al 2017

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



Hepworth et al 2017

Method:
Use Sr isotopes (measure $^{87}Sr/^{86}Sr$) 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 => constant $^{87}Sr/^{86}Sr$;
open system melt percolation could introduce variable Sr isotopes (variable source of melt, assimiliation of rocks with variable $^{87}Sr/^{86}Sr$)

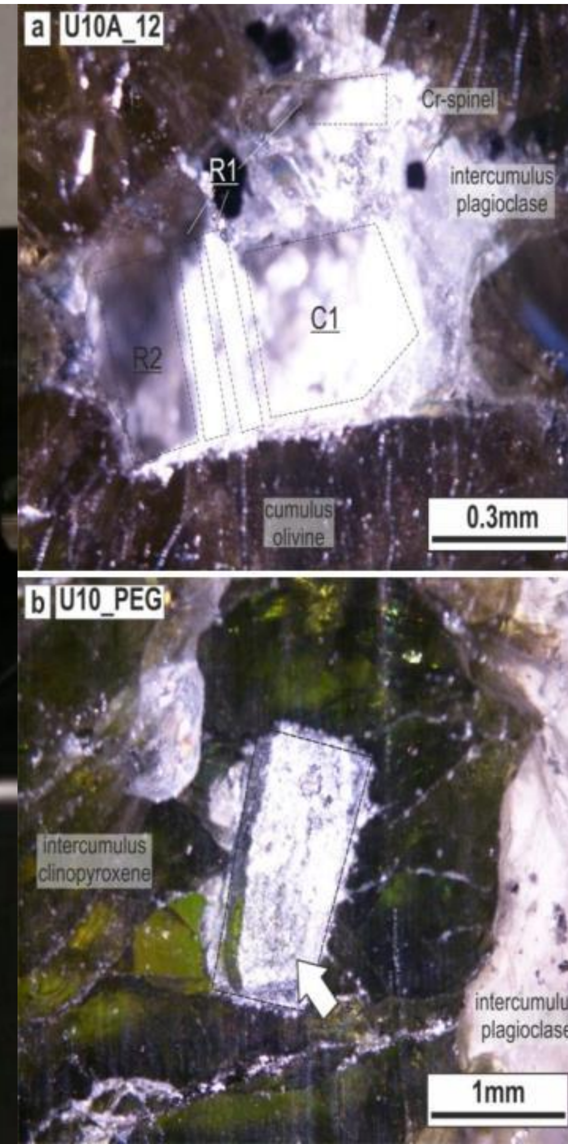
Analyse selected parts of plagioclase and clinopyroxene crystals, that (very low Rb/Sr ratios – no age-correction needed)

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

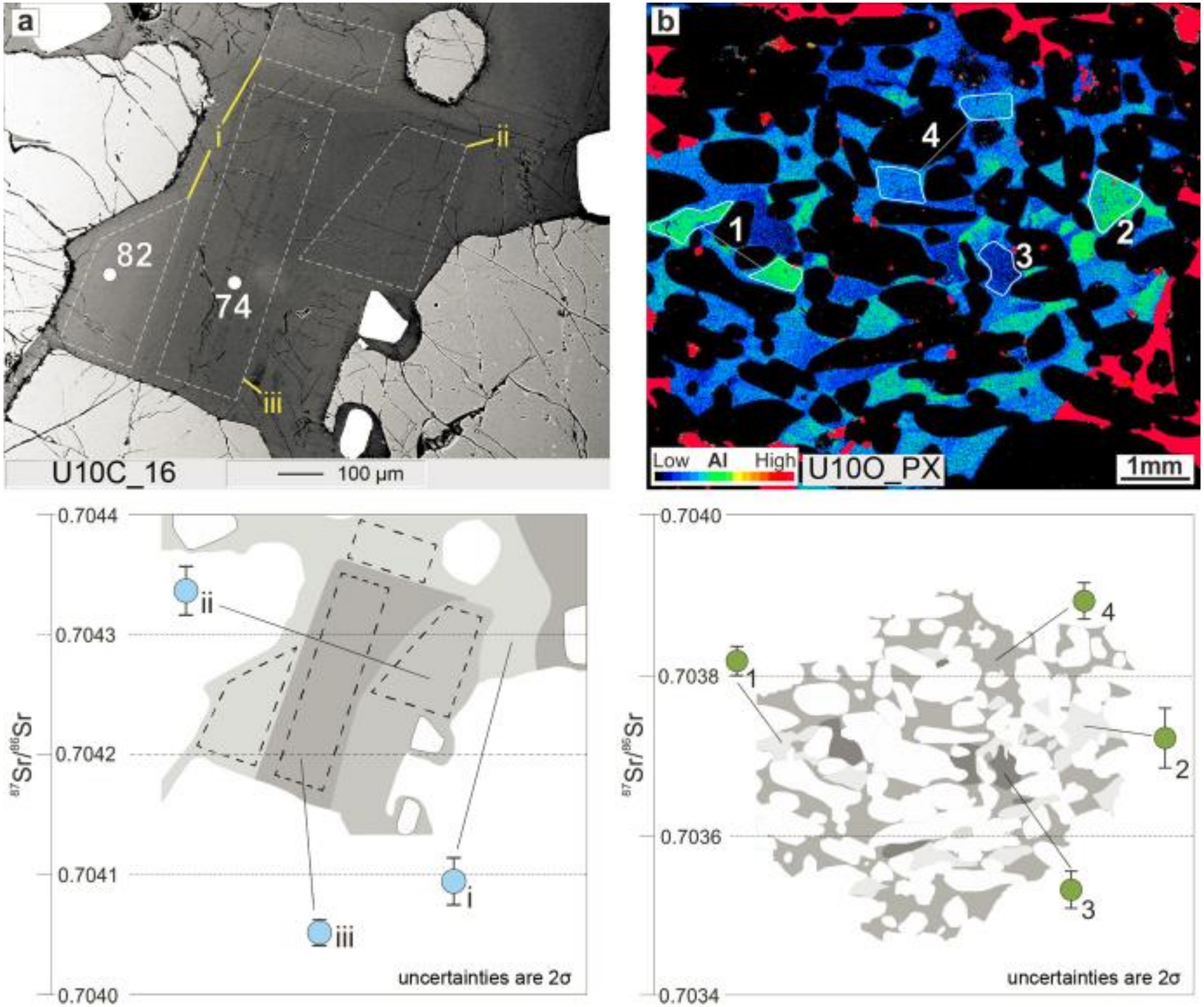
Intercumulus plagioclase and clinopyroxene sampled (by Luke Hepworth) using the Micromill guided by SEM imaging

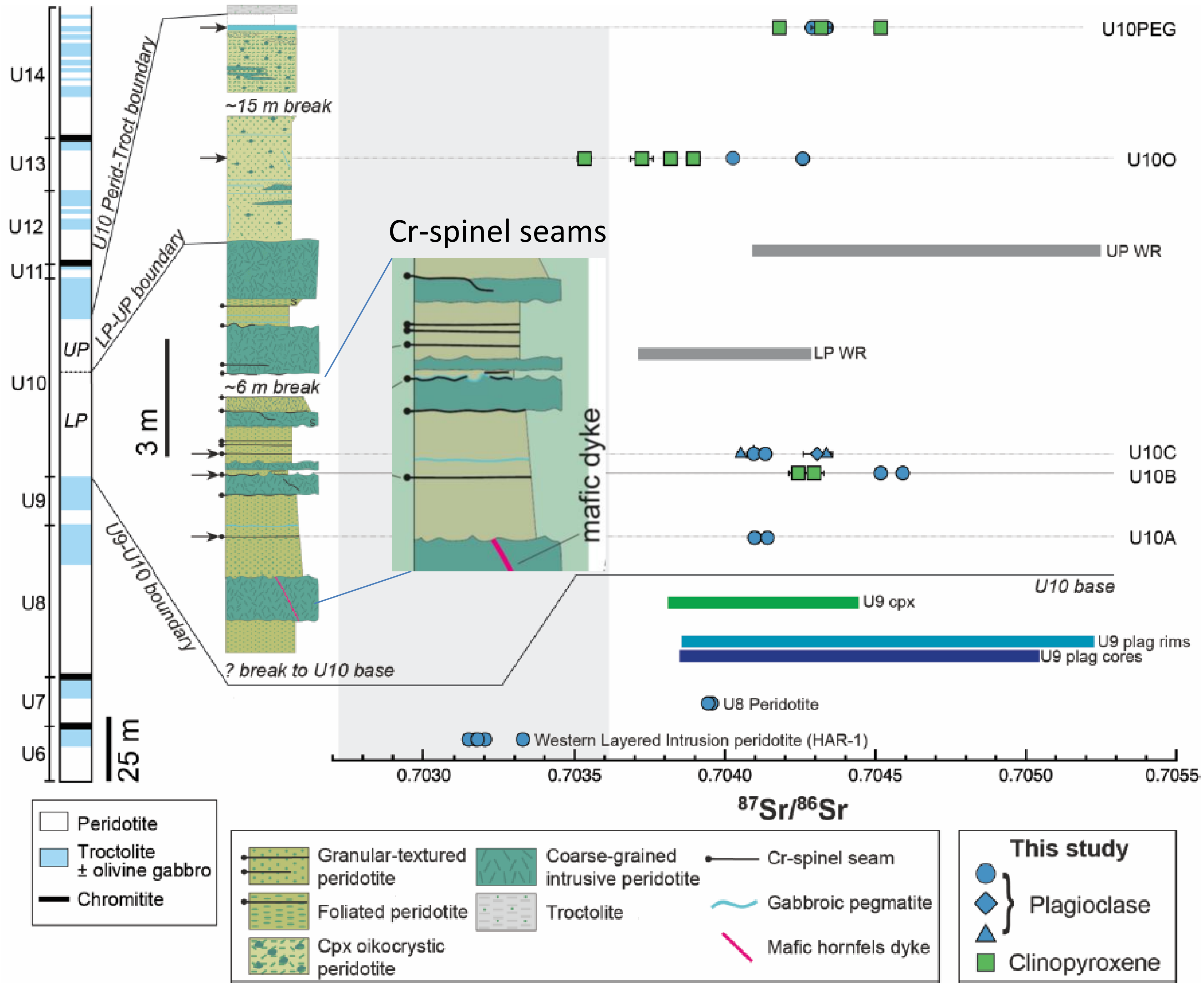


intracrystalline $^{87}Sr/^{86}Sr$ variation in Unit 10 intercumulus plagioclase (left and oikocrystic clinopyroxene (right)

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

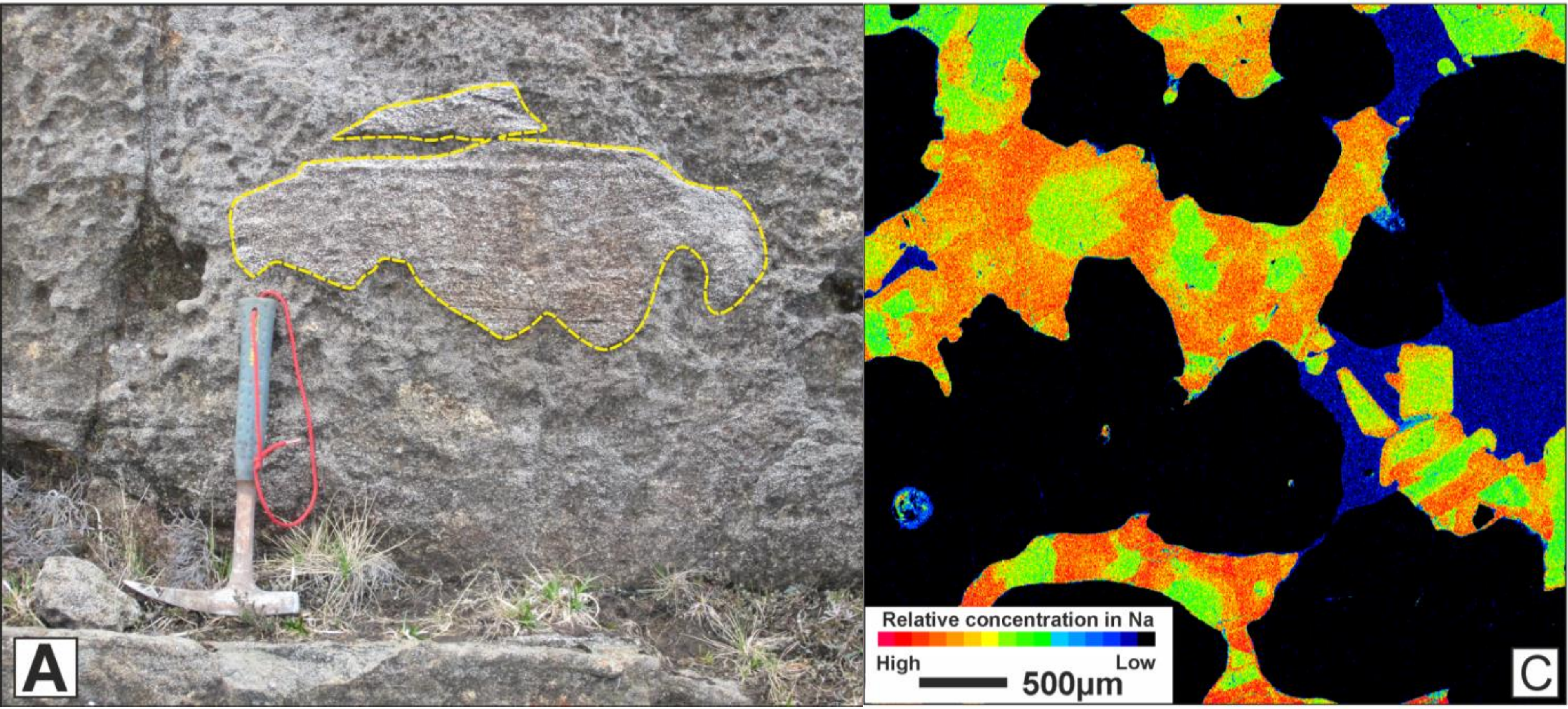
Overall higher An% plagioclase has more radiogenic Sr



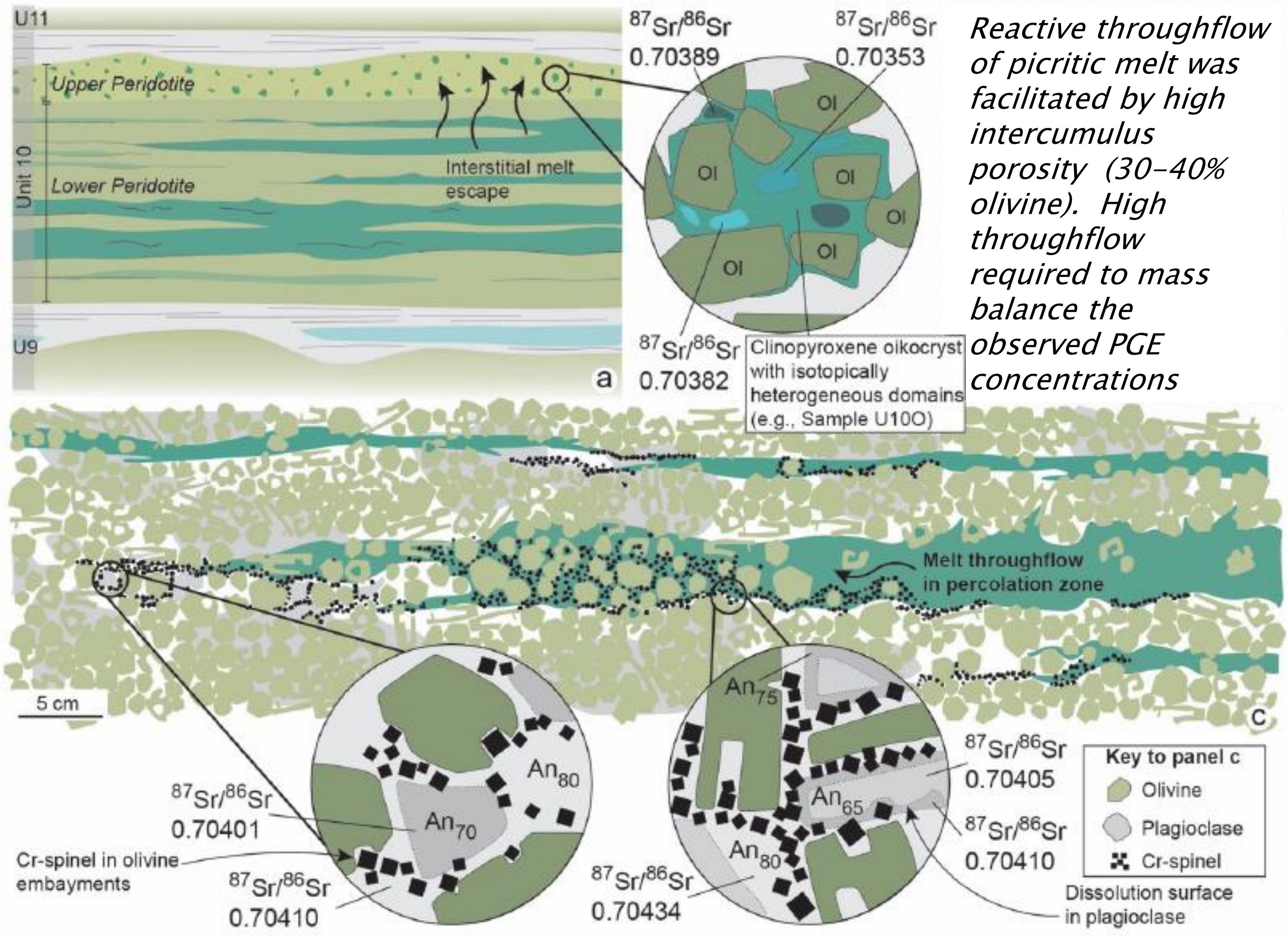


U14
U13
U12
U11
U10
UP
LP
U9
U8
U7
U6
25 m
3 m
U10 Perid-Troct boundary
LP-UP boundary
U9-U10 boundary
~15 m break
~6 m break
? break to U10 base
Cr-spinel seams
mafic dyke
U10PEG
U10O
UP WR
LP WR
U10C
U10B
U10A
U10 base
U9 cpx
U9 plag rims
U9 plag cores
U8 Peridotite
Western Layered Intrusion peridotite (HAR-1)
0.7030
0.7035
0.7040
0.7045
0.7050
0.7055
$^{87}Sr/^{86}Sr$
Peridotite
Troctolite ± olivine gabbro
Chromitite
Granular-textured peridotite
Foliated peridotite
Cpx oikocrystic peridotite
Coarse-grained intrusive peridotite
Troctolite
Cr-spinel seam
Gabbroic pegmatite
Mafic hornfels dyke
This study
Plagioclase
Clinopyroxene

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

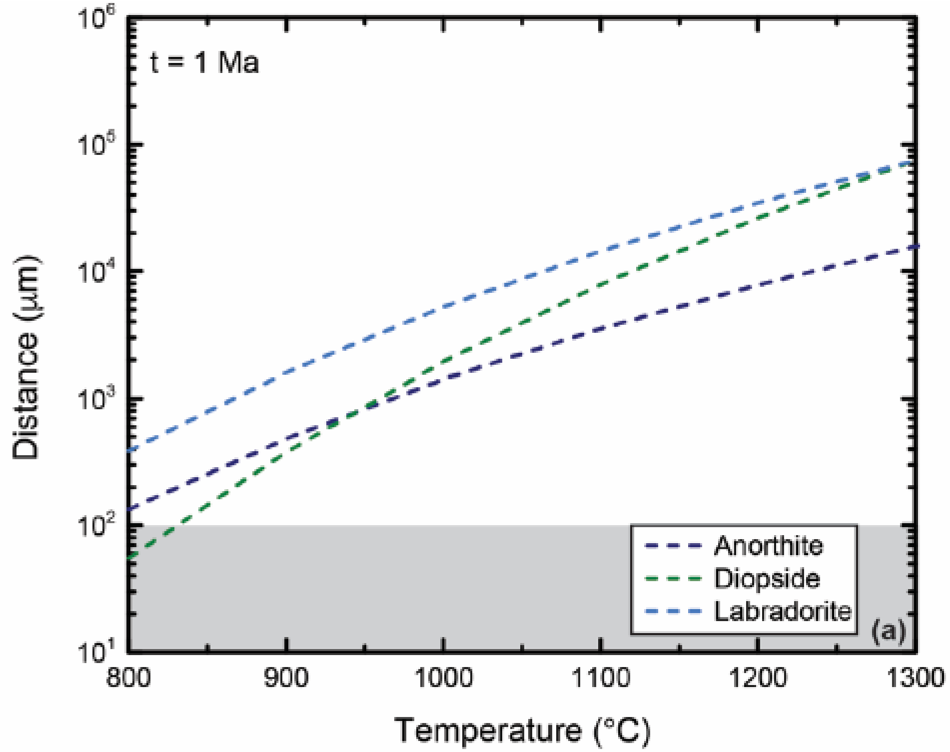


Potentially the incoming picrite acquired radiogenic Sr by assimilating early formed feldspathic cumulates that had been contaminated with country rocks (e.g. picrite melt + ~7% Lewisian gneiss



Reactive throughflow of picritic melt was facilitated by high intercumulus porosity (30–40% olivine). High throughflow required to mass balance the observed PGE concentrations

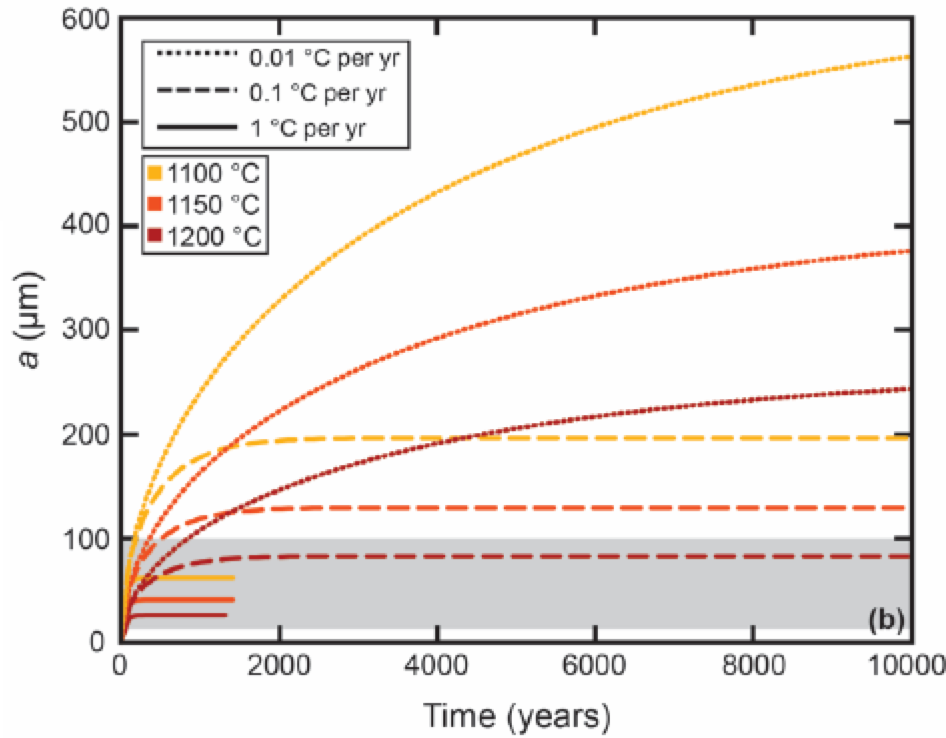
Results of Sr diffusion calculations



Characteristic diffusion distance as a function of temperature for plagioclase (An_{100} and An_{50-70} and Diopside (cpx)

⇒ *Over 1 Ma (the max. timeframe to crystallize the Rum intrusion), 10–100μm scale Sr zoning would not be preserved in the T range shown*

Calculated diffusion length-scale for Sr for plagioclase (An_{50-70}) versus time for different cooling rates.
Suggests cooling was > 1ºC per year and cooling to diffusive closure for Sr within < 1000 years



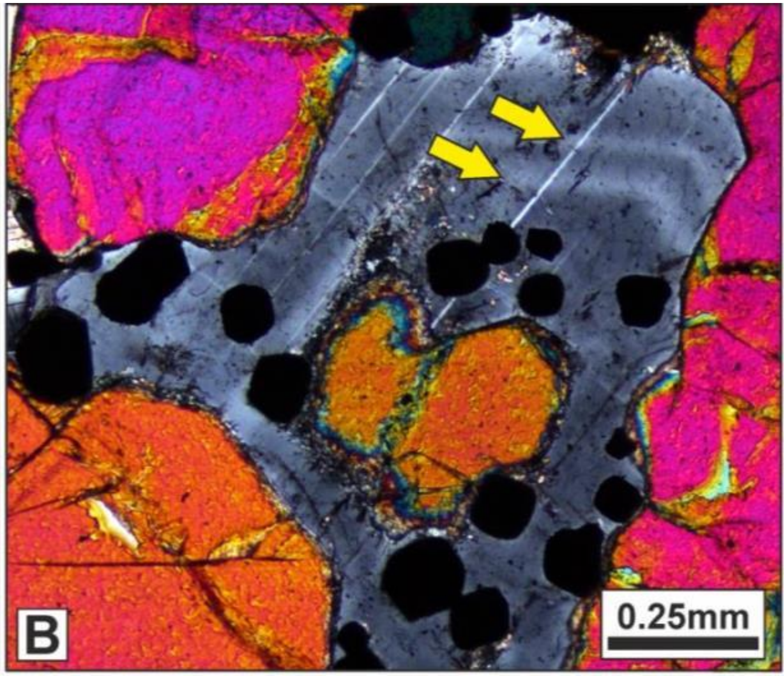
Conclusions

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



Published online 13 April 2020. Doi: 10.1038/s41561-020-0568-3

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https://doi.org/10.1038/s41561-020-0568-3

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Rapid crystallization of precious-metal-mineralized layers in mafic magmatic systems

Luke N. Hepworth[1,2], J. Stephen Daly[3,4], Ralf Gertisser[1], Chris G. Johnson[5], C. Henry Emeleus[6,7] and Brian O'Driscoll[2]✉

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 $^{87}Sr/^{86}Sr$ 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 10–100 μm 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.