Investigating mantle melting temperatures on Earth, Mars and the Moon using Al-in-olivine thermometry

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Introduction

Background

Whilst mantle thermal anomalies are moderately well-understood on Earth, relatively little is known about the melting conditions in the mantles of the Moon and Mars that led to the production of Maria basalts and Martian surface basalts and associated volcanic activity.

Al-in-olivine thermometry is based upon the temperature-dependent solubility of Al in olivine in equilibrium with spinel [1], and has become a widely adopted method to investigate the crystallisation temperatures of primitive mantle melts on Earth [2].

The thermometer should access near-liquidus temperatures of mantle melts, thereby constraining minimum mantle melting temperatures. This thermometer has been used to demonstrate that terrestrial CFB-associated primitive melts had mantle sources with thermal anomalies of >200 °C [3].

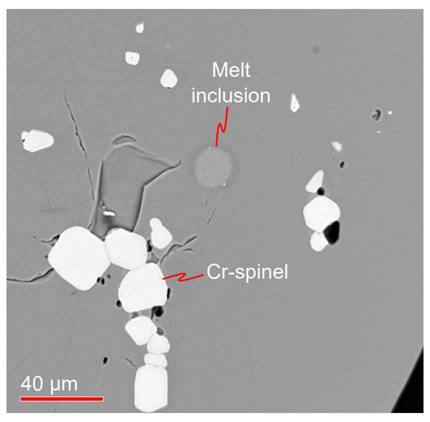
Several samples returned from the Moon and basaltic meteorites from Mars (shergottites) are primitive and rich in both olivine and spinel, so appear ideal samples for the application of Al-in-olivine thermometry to unravel their respective mantle melting conditions and the thermal structures of those planetary interiors.

We present the results of preliminary investigations into the crystallisation temperatures and associated mantle potential temperatures of primitive samples from Mars and the Moon.

Approach

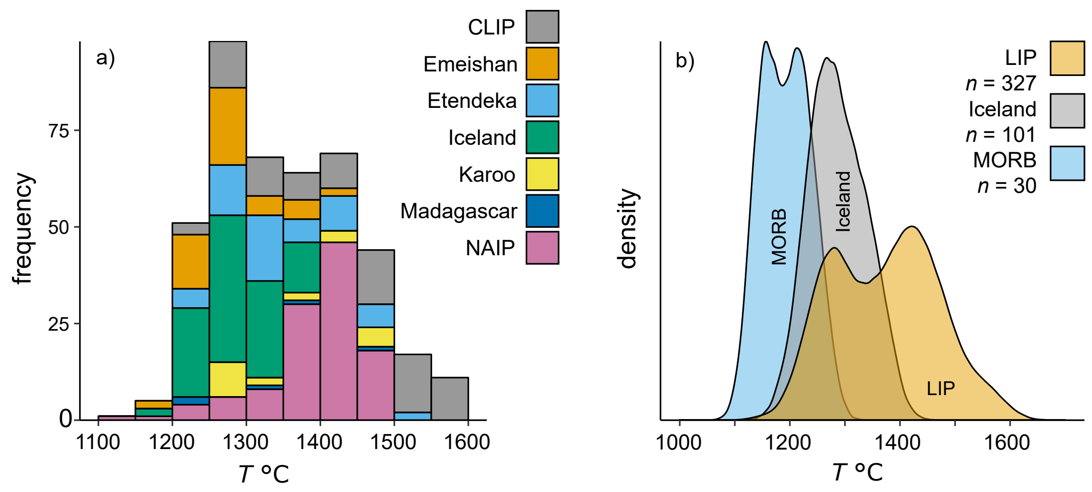
1) Apply Al-in-olivine thermometry from EPMA investigation to a) five Apollo 12 primitive lunar basalts, and b) two olivine-phyric shergottites. Al is fairly immobile, so this thermometer is robust to subsolidus resetting. Maximum olivine T_{cryst} in near-primary melts constrains minimum mantle melting T.

2) Back-calculate the mantle T for a given lithospheric thickness. For this thermal model, we derive thermodynamic parameters and create a new parametrisation for solidus, liquidus and melt productivity using an ultramafic melt model [4] of in THERMOCALC and PERPLEX.



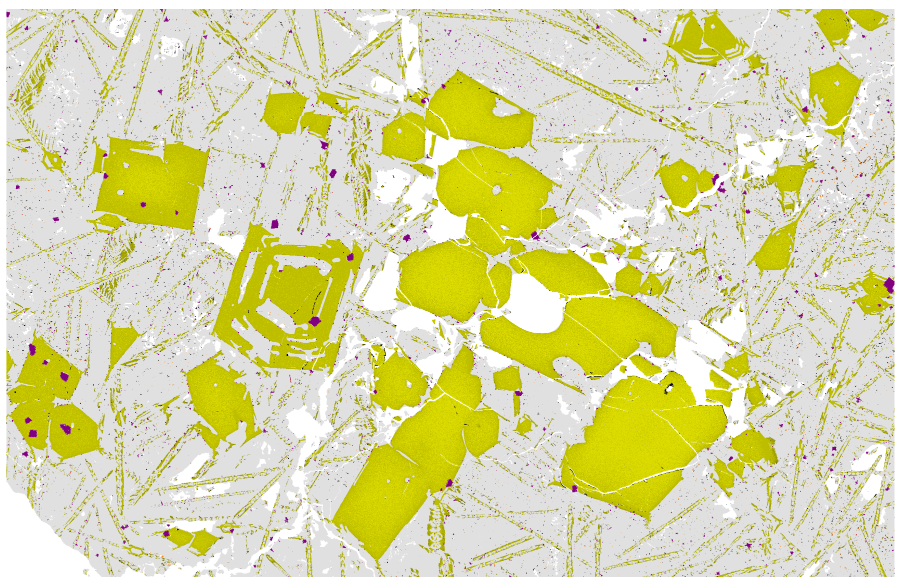
Spinel inclusions in olivine phenocryst from Etendeka CFB; long-count Al-in-olivine measurements by EPMA of olivine around co-existing inclusions [3]

Al-in-ol thermometry example: Earth (CFBs: Parana-Etendeka)



a) Frequency distribution of published and new olivine temperatures from various LIPs; b) probability density function of olivine temperatures comparing results from LIPs to MORB. Figures published in [3]; data references in [3].

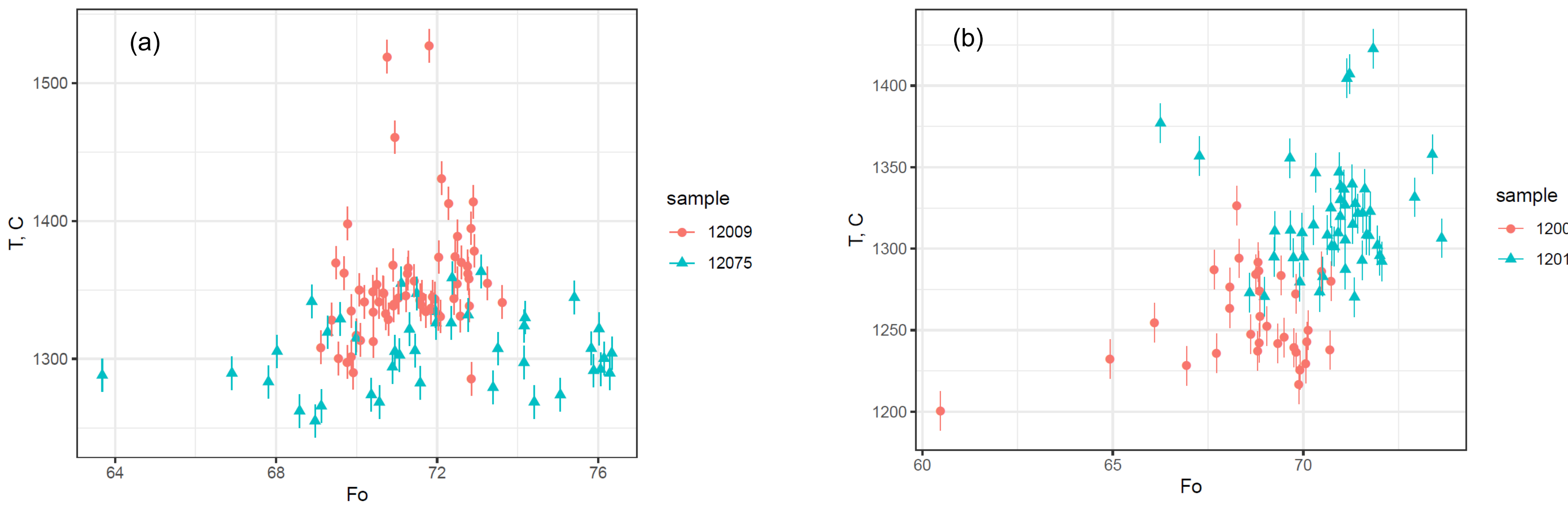
Al-in-ol thermometry: Moon (Apollo 12 Mare basalts)



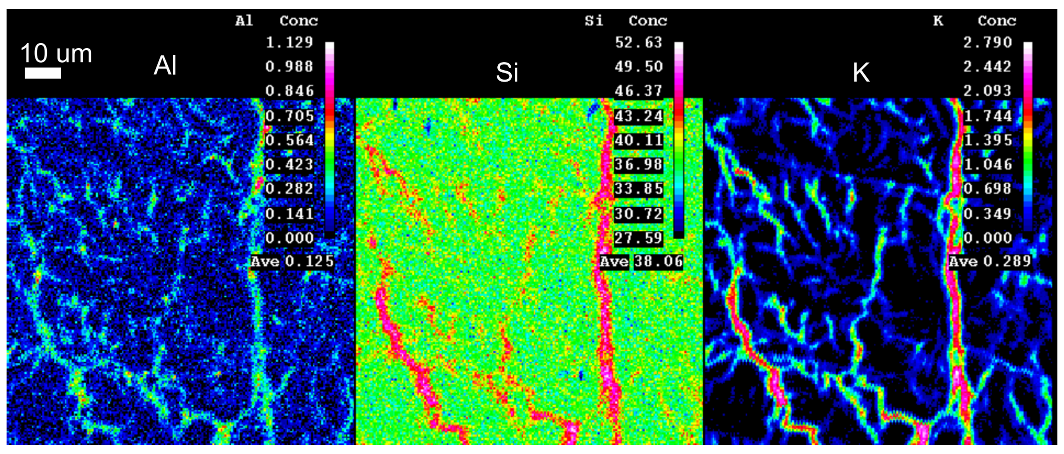
- **Lunar mare** samples are **suitable** for Al-in-olivine thermometry, containing pristine olivine and spinel
- Set includes most primitive samples known from moon (max. Fo 76); spinifex olivine in groundmass
- Max. T_{cryst} around 1400 °C
- Correlation between T_{cryst} and Fo weak

← QEMSCAN of sample 12015. Olivine in green-yellow, where brighter colours indicate higher Fo content. Magenta specks are spinel. Several olivine morphologies from multiple cooling stages.

↓ Al-in-ol T_{cryst} as a function of olivine Fo from mare basalts. (a) samples 12009 and 12075, which both have doleritic textures and equant olivine macrocrysts. (b)12002 and 12015 (right), which both have glassy groundmasses with spinifex olivine, with some hopper crystals and equant macrocrysts.

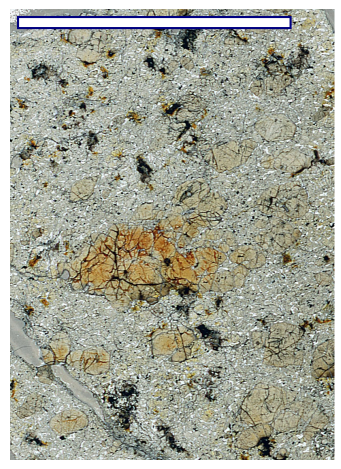


Al-in-ol thermometry: Mars (olivine-phyric shergottites)

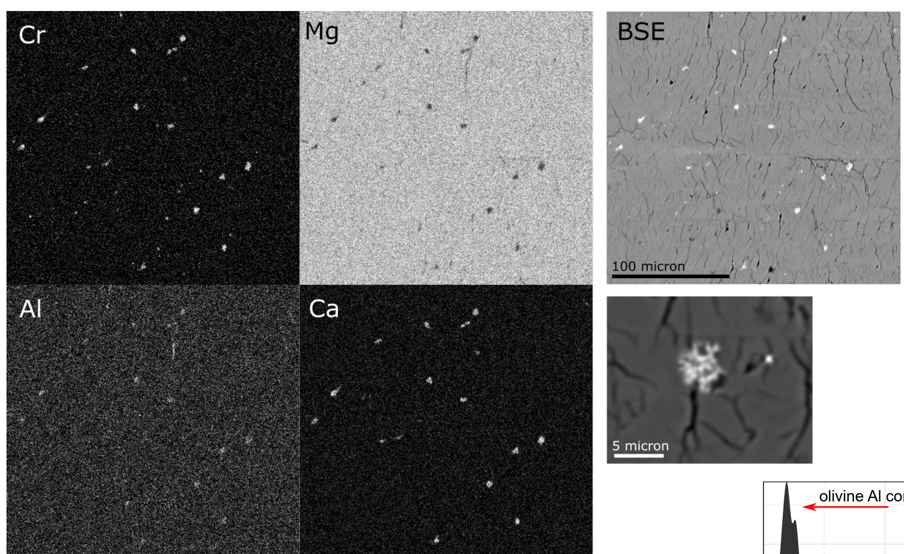


← WDS map of central portion of olivine phenocryst from DaG476; colour scale is quantified Al (left), Si (central) and K (right) element wt.%.

→ DaG476 thin section scan; orange staining visible on all olivine phenocrysts. Scale bar 5 mm.

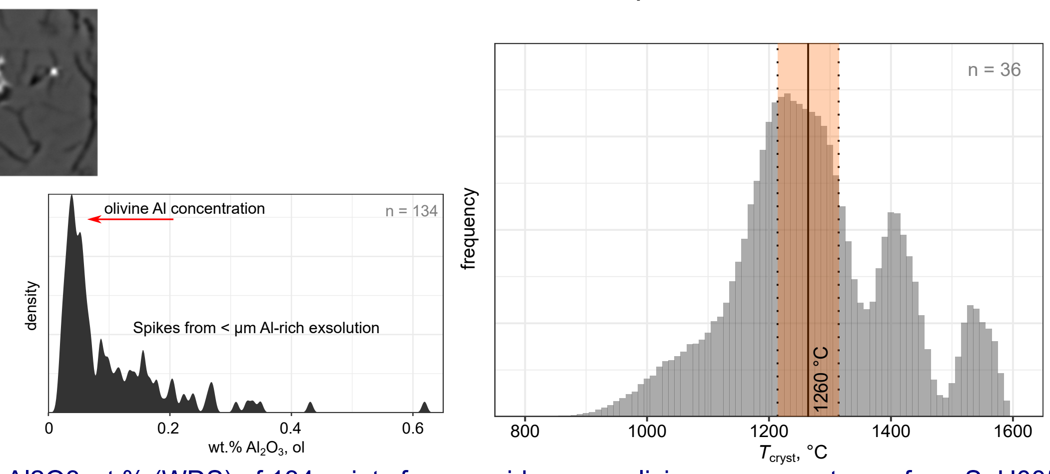


- **DaG476** is **unsuitable** for Al-in-ol thermometry because of sub-micron melt veining with evidence of hydrous mobilisation
- K- and Si-rich pervasive veining over different lengthscales; strong association between K_2O and Al_2O_3.



- **SaU005** is **suitable** for Al-in-ol thermometry because exsolution from impact damage is localised without widespread element mobility
- Exsolved cpx-spinel intergrowths
- Crystallisation temperature T_{cryst} **= 1260 °C** corrected to **1340 °C** at Fo77 to account for prior olivine fractionation
- Used to estimate mantle temperature

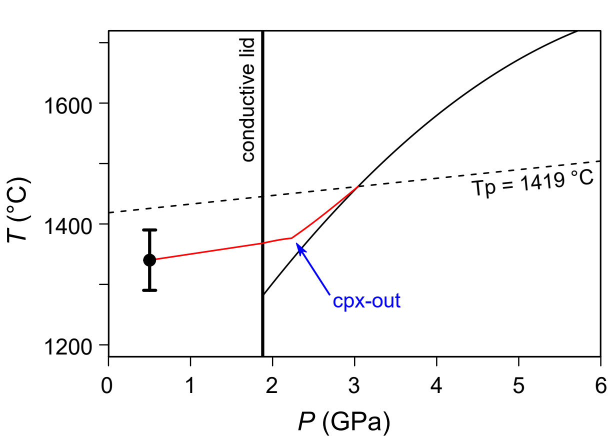
↑ EDS map of central portion of olivine macrocryst from SaU005; bright pixels have high concentrations. The fractures seen in BSE are not associated with chemical change. High Cr, Al and Ca concentration specks indicate micron-scale exsolution of spinel-cpx intergrowths

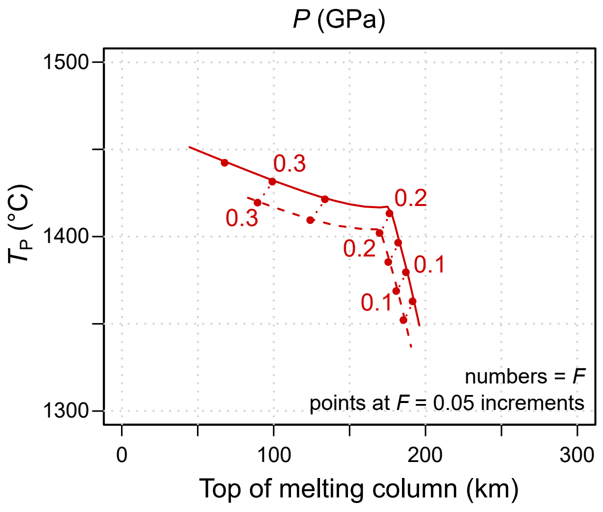


↑ Al2O3 wt.% (WDS) of 134 points from a grid on one olivine macrocryst core from SaU005. Most points are unaffected by exsolution.
→ T_{cryst} from 36 WDS olivine analyses from SaU005, with Monte Carlo resampling including analytical uncertainty. The main peak is interpreted as the "true" value; elevated peaks are affected by exsolution, at 1260 ± 50 °C (Fo_{max} = 73), that extrapolates to 1340 °C @ Fo77.

Temp. of Mars shergottite-source mantle

- SaU005 primary melt T_{cryst} of ~1340 °C is best explained by melting of mantle with T_P **≈ 1400 °C** with thick lithosphere (120-170 km), corresponding to moderate- to high-fraction (F ≈ 0.15-0.25) melting.
- Thermal pathway of melt calculated using modified equations of [5] and thermodynamic parameters calculated in Perplex from model of [4]





↖**Fig.** Example showing how mantle T_P relates to T_{cryst}. Melt productivity decreases when cpx is exhausted.
←**Fig.** Combinations of T_P and depth to top of melting column that can produce a magma that is 1340 °C in the crust. Solid line for crystallisation at 0.5 GPa; dashed line at 1 GPa. T_P ≈ 1400 °C implies F (~ 0.15 to 0.25) with a conductive lid thickness of ~ 120-170 km
→**Table** Parameters used: newly-determined unless indicated otherwise. Calculated in Perplex with composition of Dreibus and Wänke [6]; bulk O for equilibrium with graphite.

New properties and melting model, Dreibus & Wänke [6] Mars composition

	Solid mantle	Melt	unit	notes
ρ	3500	3000	kg m^{-3}	
α	3.6×10^{-5}	5.4×10^{-5}	K^{-1}	
C_P	1220	1440	J $kg^{-1}K^{-1}$	
ΔS_{fus}	350		J $kg^{-1}K^{-1}$	
ρ(crust)	3100		kg m^{-3}	(from Baratoux et al., 2014)
$P_{solidus} = -15.43P^2 + 231.53P + 900.4$				*
$P_{lhz\text{-}liq} = 35.39P^2 - 131.70P + 1629.6$				*
$P_{liquidus} = -3.87P^2 + 60.99P + 1658.9$				*
$P_{cpx\text{-}out} = -3.58P^2 + 158.86P + 1039.7$				*
$\beta_{cpx\text{-}present}$	1.00			*melt function exponent
$\beta_{cpx\text{-}absent}$	1.50			*melt function exponent

*For use with equations of Katz et al. [5] with modification

Summary and next steps

- Al-in-ol thermometry may be viable for lunar maria samples with high T_{cryst} to 1400 °C. Next steps: 1) constrain effect of high spinel Ti contents on thermometer, as outside of calibration range; 2) create melting model for lunar low-Ti basalt source; determine temp. of lunar mantle during maria generation; implications for origin of Maria.
- Al-in-ol is difficult to use in olivine-phyric shergottite samples due to presence of shock features; importance of detailed microtexture characterisation.
- T_{cryst} of shergottite SaU005 ≈ 1260 °C, extrapolates to primary melt T of approx. 1340 °C, explained by moderate near-modern Mars mantle T_P = 1400 °C.

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References [1] Coogan, L. A., Saunders, A. D. & Wilson, R. N. Aluminum-in-olivine thermometry of primitive basalts: Evidence of an anomalously hot mantle source for large igneous provinces. Chem. Geol. 368, 1–10 (2014). [2] Trela, J. et al. The hottest lavas of the Phanerozoic and the survival of deep Archaean reservoirs. Nat. Geosci. 10, 451–456 (2017). [3] Jennings, E. S., Gibson, S. A. & Maclennan, J. Hot primary melts and mantle source for the Paraná-Etendeka flood basalt province: New constraints from Al-in-olivine thermometry. Chem. Geol. 529, 119287 (2019). [4] Jennings, E. S. & Holland, T. J. B. A simple thermodynamic model for melting of peridotite in the system NCFMASOCr. J. Petrol. 56, 869–892 (2015). [5] Katz, R. F., Spiegelman, M. & Langmuir, C. H. A new parameterization of hydrous mantle melting. Geochem. Geophys. Geosystems 4, 1073 (2003). [6] Dreibus, G. & Wänke, H. Mars, a Volatile-Rich Planet. Meteoritics 20, 367 (1985).