Modelling mantle geodynamics in the Ethiopian Rift and Afar through olivine thermometry and rare-earth element distributions

Kevin Wong[1], David Ferguson[1], Dan Morgan[1], Simon Matthews[2], Amdemichael Tadesse[3], and Gezahegn Yirgu[4]

[1]University of Leeds
[2]University of Iceland
[3]Université Libre de Bruxelles
[4]Addis Ababa University

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Abstract

The Ethiopian sector of the East African Rift system (the Main Ethiopian Rift, MER) and Afar rift showcase advanced stages of continental breakup. Here the interplay between active continental rifting and rift-induced volcanism poses key questions regarding the mantle geodynamics of late-stage rift development. A particular subject of interest is the presence of hot mantle upwellings in the sub-rift mantle, which are inferred from geophysical imaging. Magma generation in the sub-rift asthenosphere depends on the temperature, lithology, and composition of the upwelling mantle material. Geophysical observations of the sub-rift mantle must therefore be supported by petrological studies aimed at understanding the physico-chemical conditions of melt production. In this study we investigate melt generation beneath the MER and Afar using a mantle melting model constrained by olivine crystallization temperatures and rare-earth element (REE) concentrations, both observed in rift zone lavas. Olivine crystallization, a proxy for magma liquidus temperature, is directly related to the thermodynamic and geochemical conditions of the melting mantle. Through application of an olivine-spinel aluminium exchange thermometer, we provide the first petrological olivine crystallization temperatures for MER and Afar basalts (1177±16°C and 1263±43°C respectively). A multi-lithology mantle melting model subsequently allows for inversion of our olivine crystallization temperatures and observed REE concentrations of rift magmas to estimate the temperature, lithology, and composition of the Ethiopian mantle. Our results suggest that the crystallization temperatures and REE distributions measured at the MER and Afar necessitate elevated mantle temperatures (T_p [?] 1450 degC) relative to ambient mid-ocean ridge mantle. A thick mantle lithosphere (~60 km) is also required to provide deep garnet-field mantle melting inferred from REE distributions. We additionally conclude that an enriched and fusible pyroxenitic mantle component is necessary to match crustal melt thicknesses and observed REE concentrations. The composition of this pyroxenitic lithology is further explored through our inversions, and the contributions of enriched pyroxenitic melts to rift volcanism in the MER and Afar are subsequently compared.

Email: eekw@leeds.ac.uk
Twitter: @GeoKevW

UKRI Natural Environment Research Council

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Kevin Wong

UNIVERSITY OF LEEDS

Email: eekw@leeds.ac.uk
Twitter: @GeoKevW

Natural Environment Research Council

Supervisors and collaborators

David Ferguson and **Daniel Morgan** (University of Leeds),
Simon Matthews (University of Iceland),
Amdemichael Zafu Tadesse (Université Libre de Bruxelles),
Yared Sinetebeb (Ethiopian Electric Power),
and **Gezahegn Yirgu** (Addis Ababa University)

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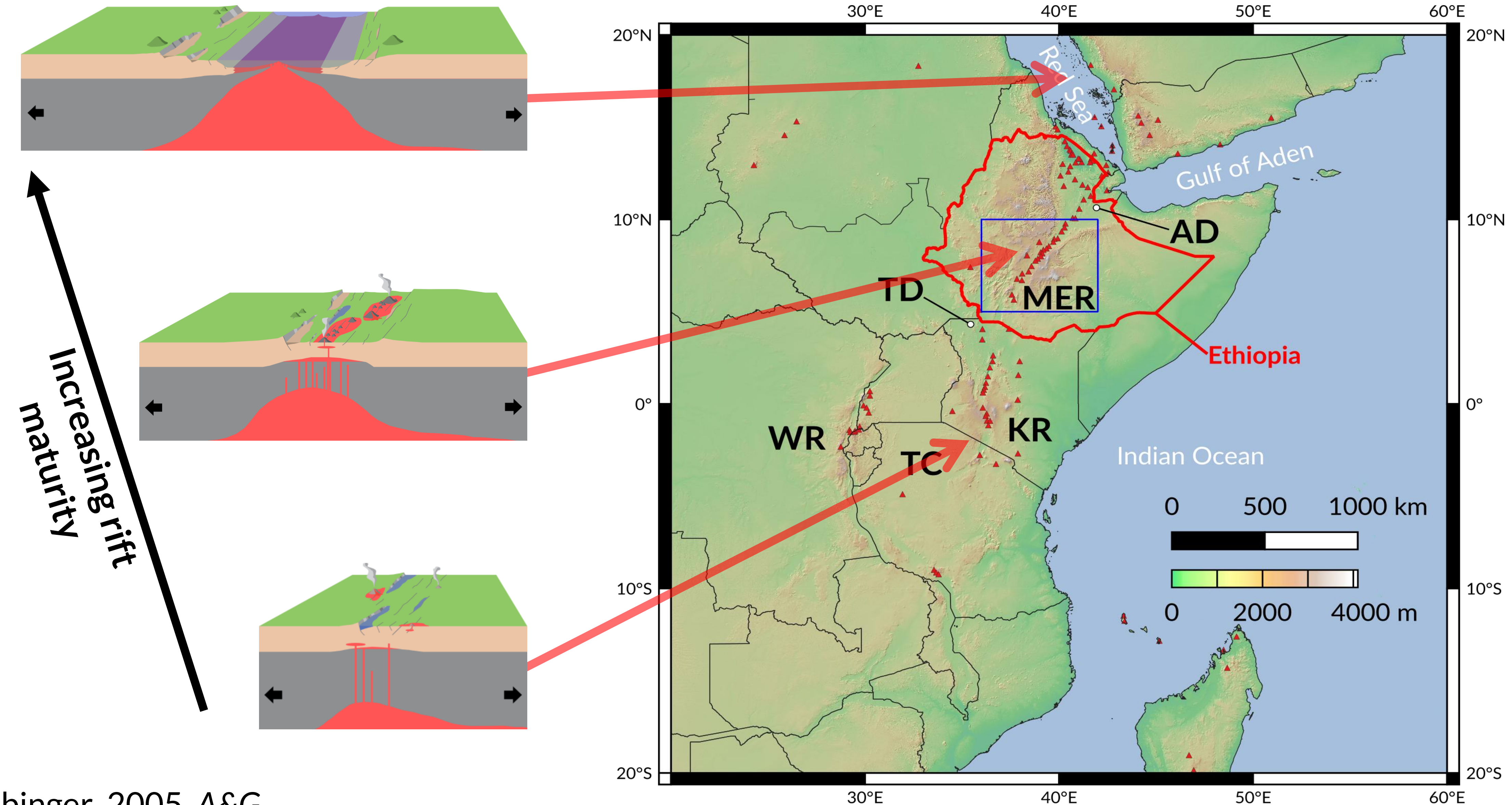
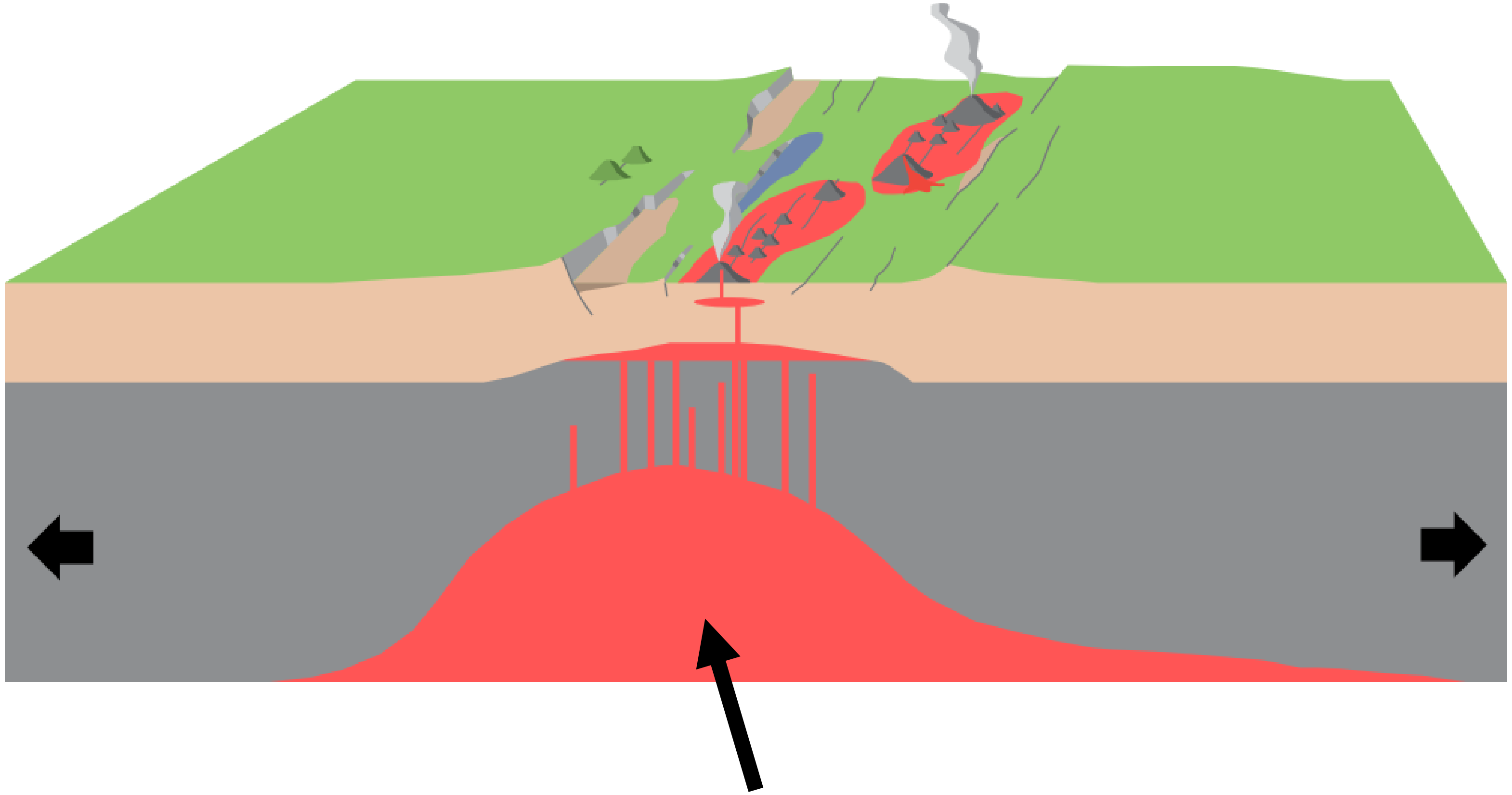
Continental rifts and rift volcanism evolves temporally and spatially. One such example is the East African Rift system.



After Ebinger, 2005, *A&G.*

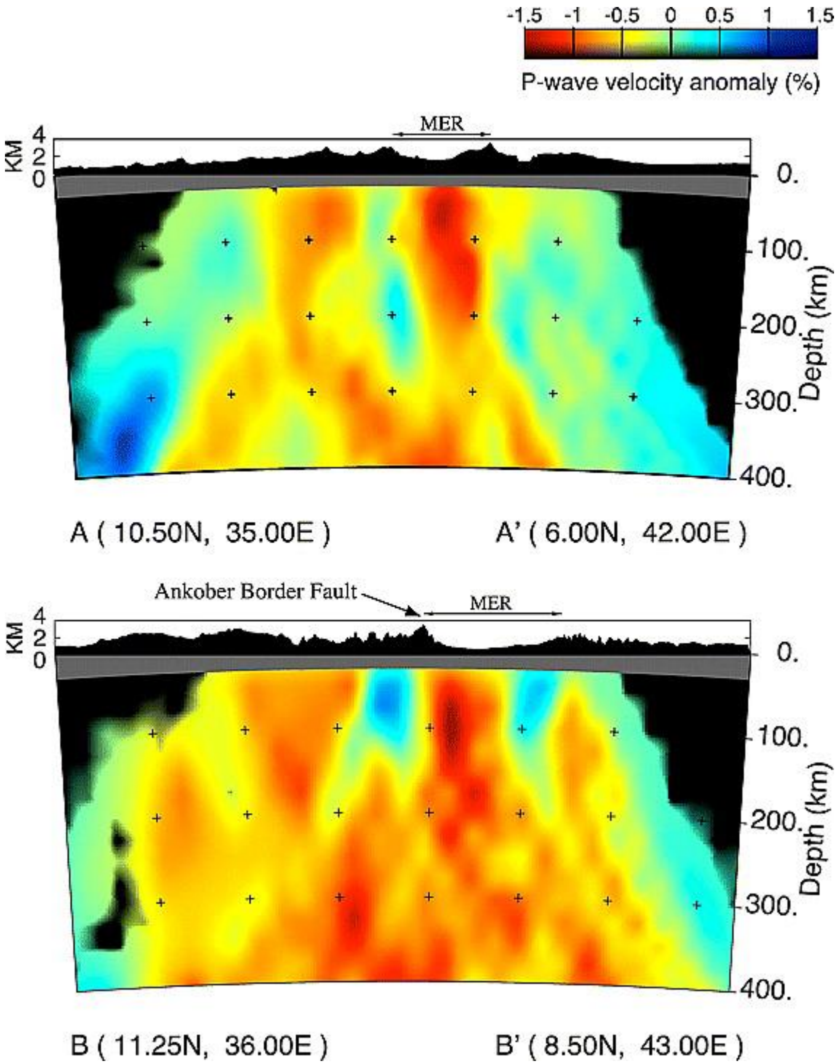
The Main Ethiopian Rift (MER) bridges large fault-bound grabens in Kenya with incipient oceanic spreading at Afar.

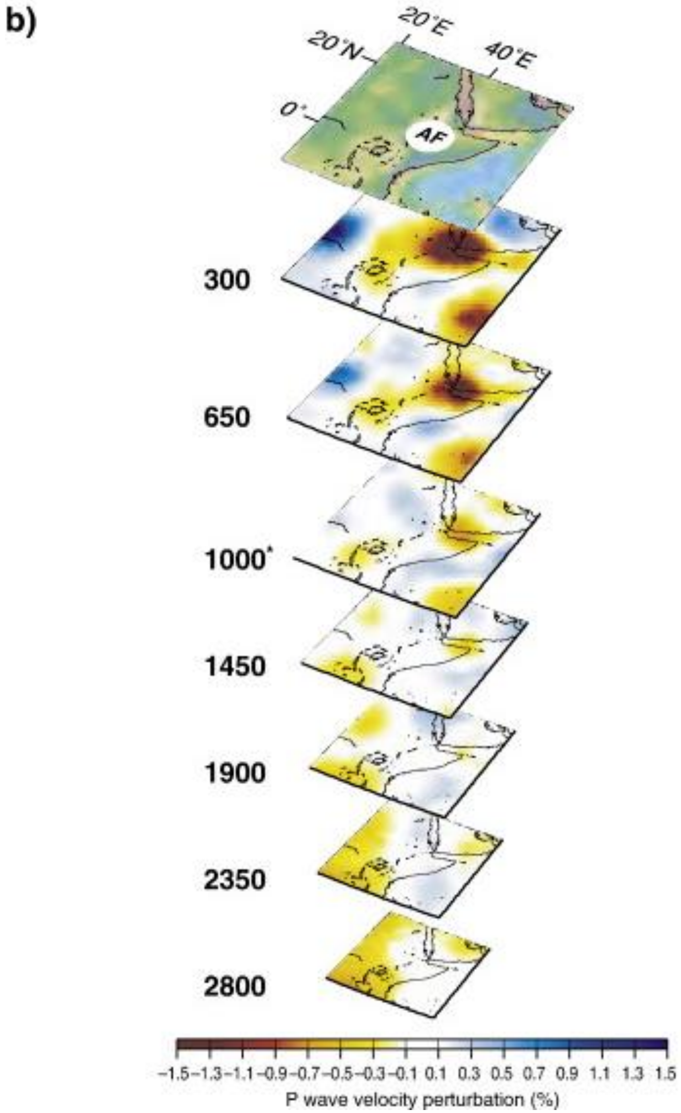


So what's going on here?

After Ebinger, 2005, A&G.

Seismic tomography highlights a thermo-chemical deviation of Ethiopian mantle from normal mid-ocean ridge mantle.

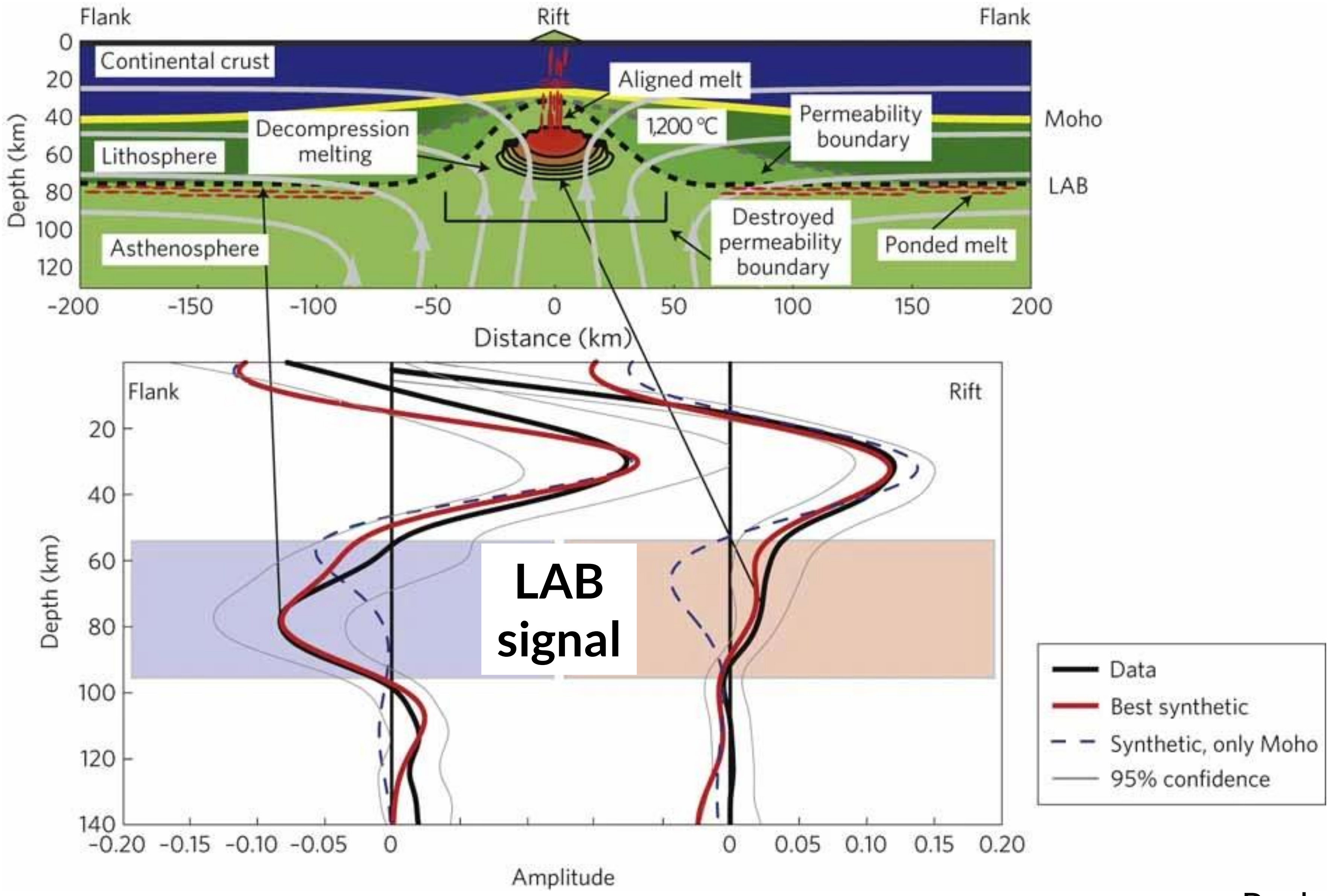




Bastow+, 2008, *Geochem. Geophys. Geosyst.*

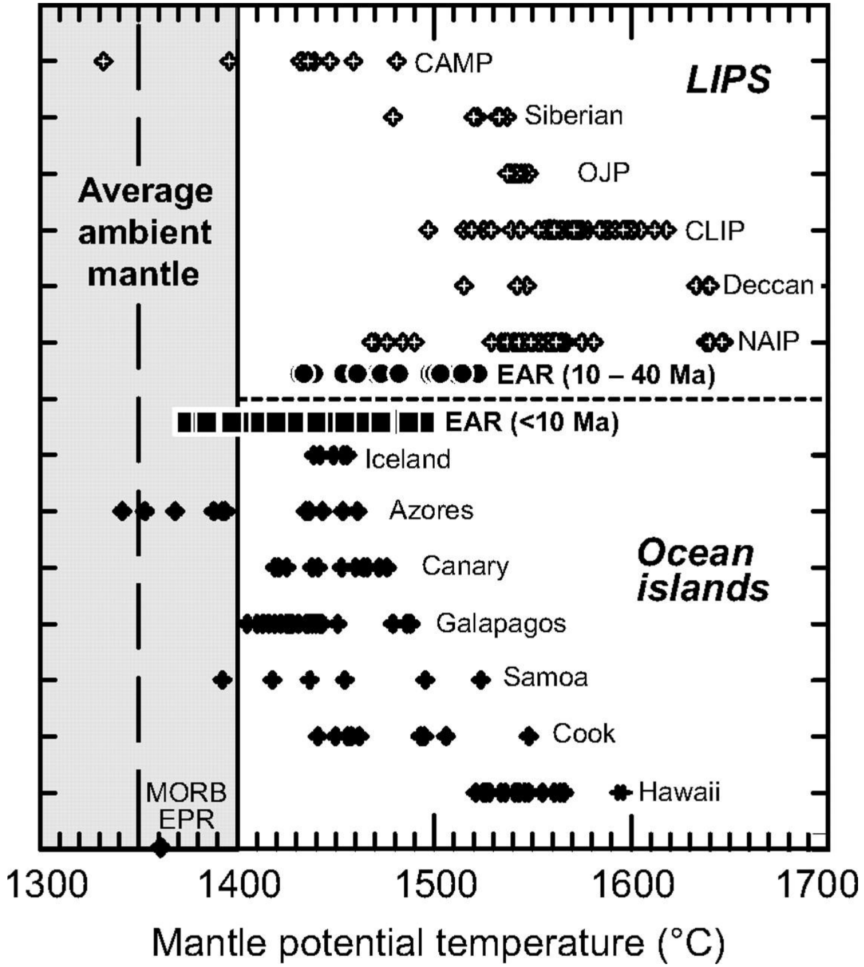
Corti, 2009, *Earth-Sci Rev*; after Montelli+, 2004, .

S-to-P receiver functions suggest that the LAB under the rift is absent, and melting in the mantle is mid-ocean ridge-like.



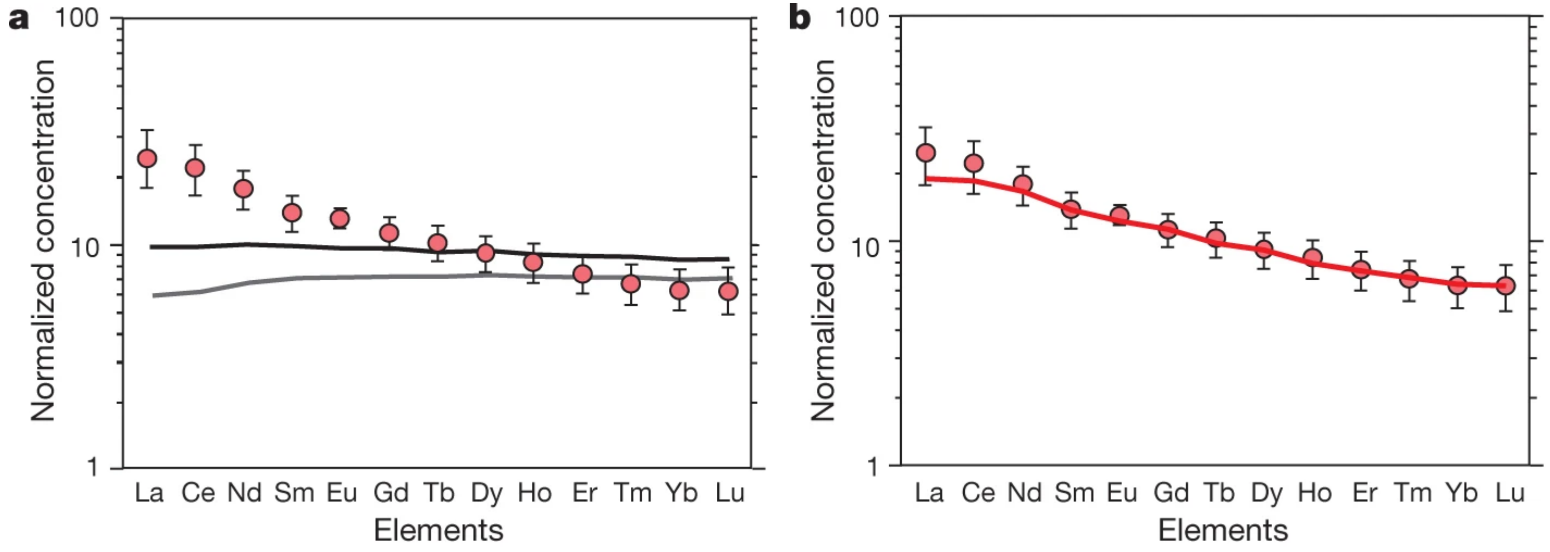
Rychert+, 2012, *Nature*.

Geochemical approaches necessitate elevated mantle temperatures and deep mantle melting.



Mid-ocean ridges ~1350 °C

light → medium → heavy



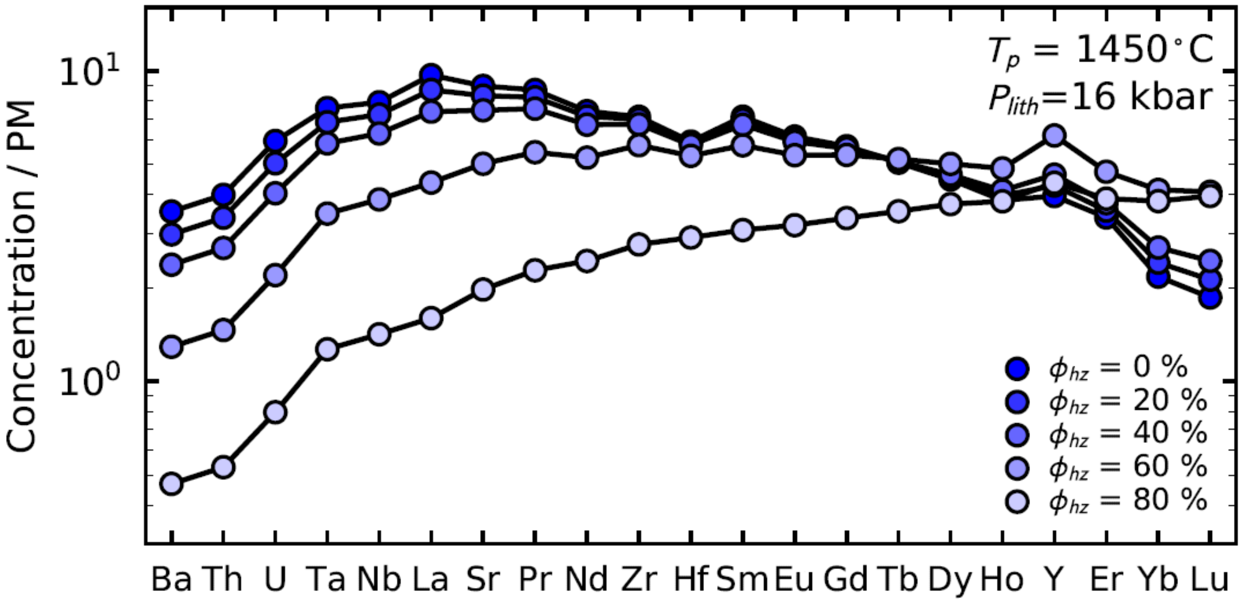
Shallow melting models can't fit Afar Rift data

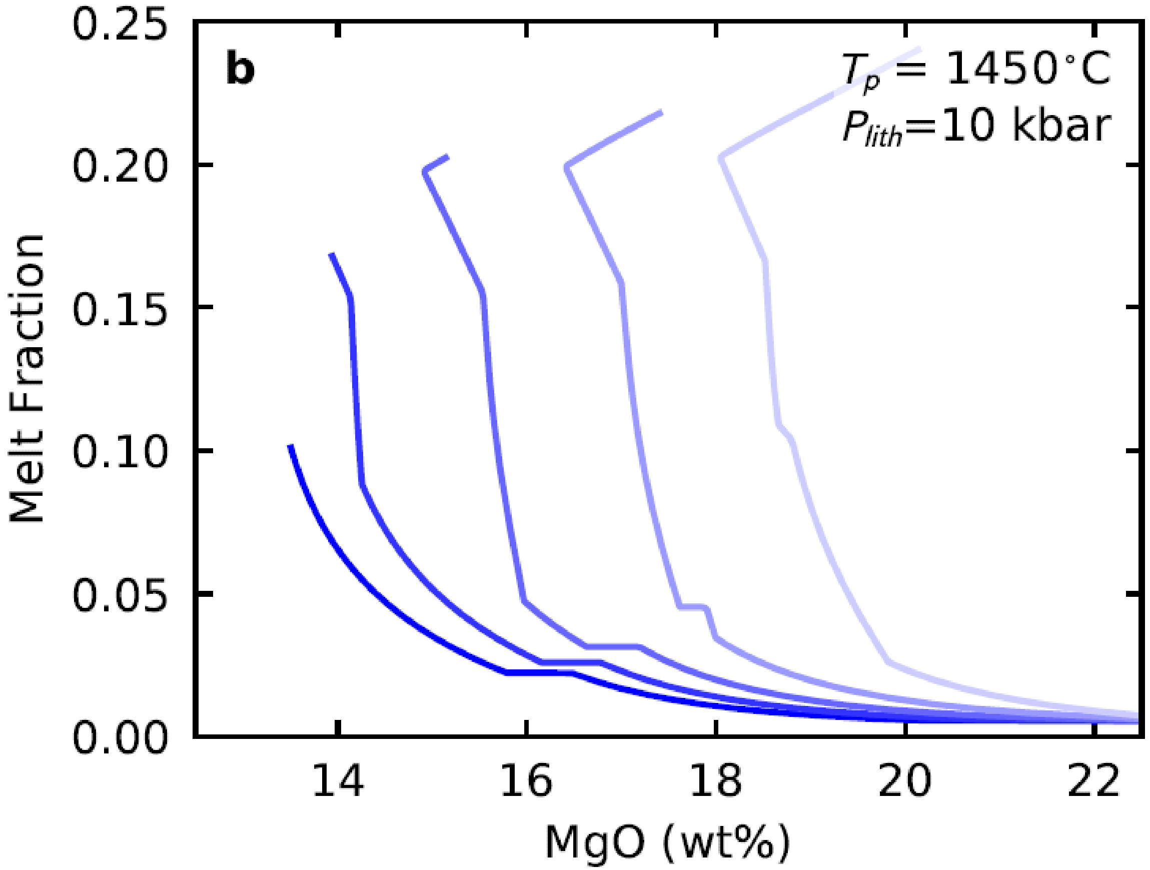
Hot and deep melting models can

Rooney+, 2012, *Geology*.

Ferguson+, 2013, *Nature*.

A mantle of multiple melting and non-melting components will affect the chemistry of erupted lavas.

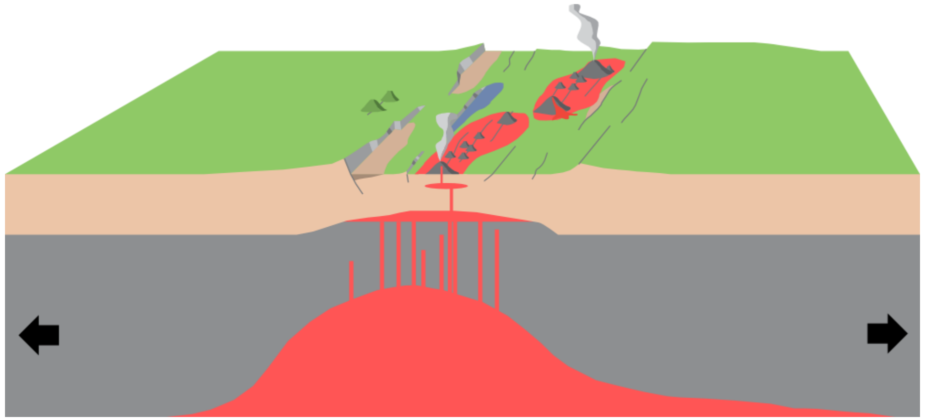




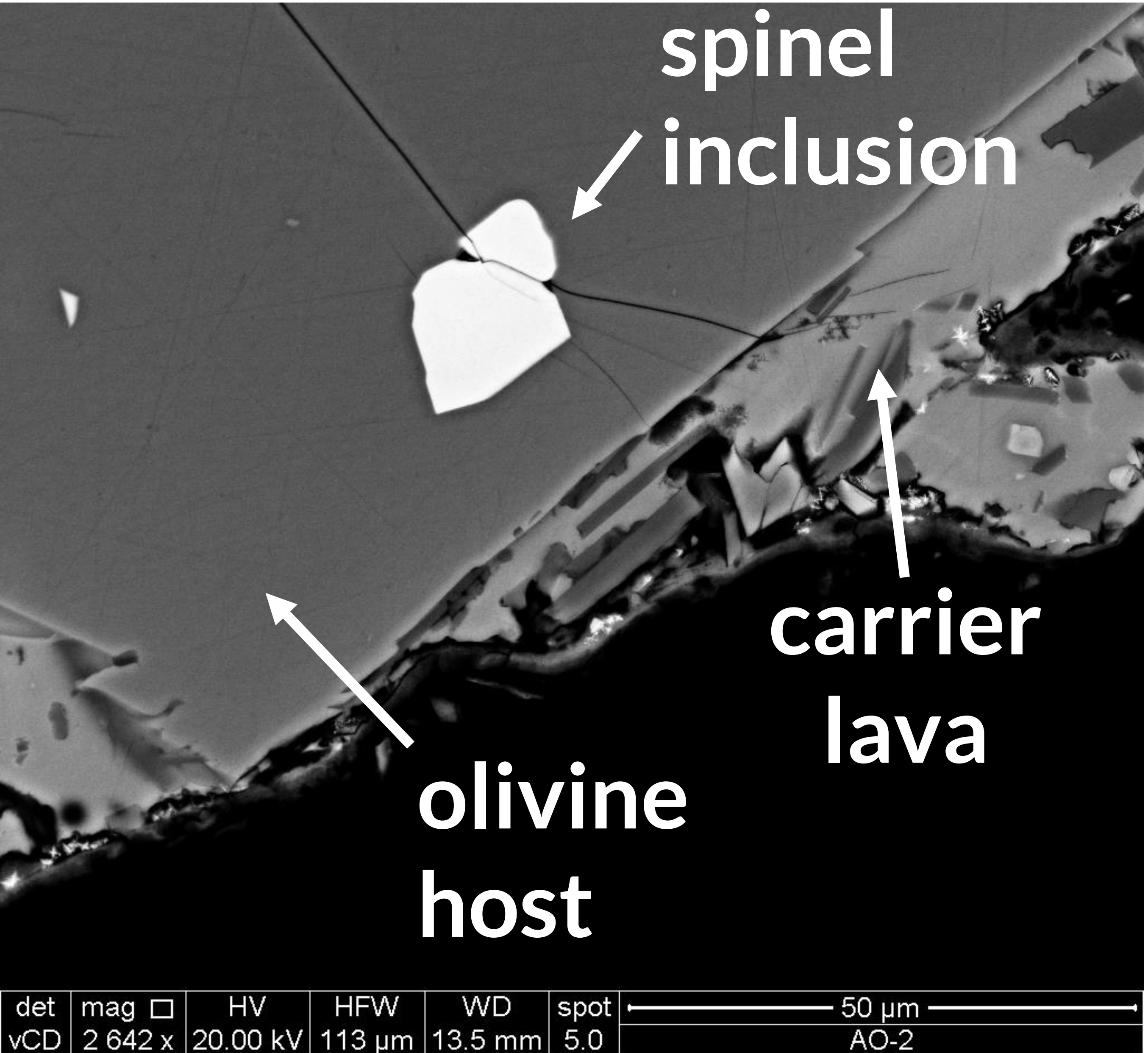
Matthews+, 2021, *Geochem. Geophys. Geosyst.*

Principal research questions

- Can we confidently determine Ethiopian mantle temperature and composition using petrology to complement geophysical observations?
- What is the depth of melting?
- How does the Ethiopian mantle compare to ambient mantle?



The olivine-spinel Al-exchange thermometer is used to determine olivine crystallization temperature.



$$T\ (K) = \frac{10{,}000}{0.575 + 0.884\ Cr\# - 0.897\ \ln(k_d)}$$

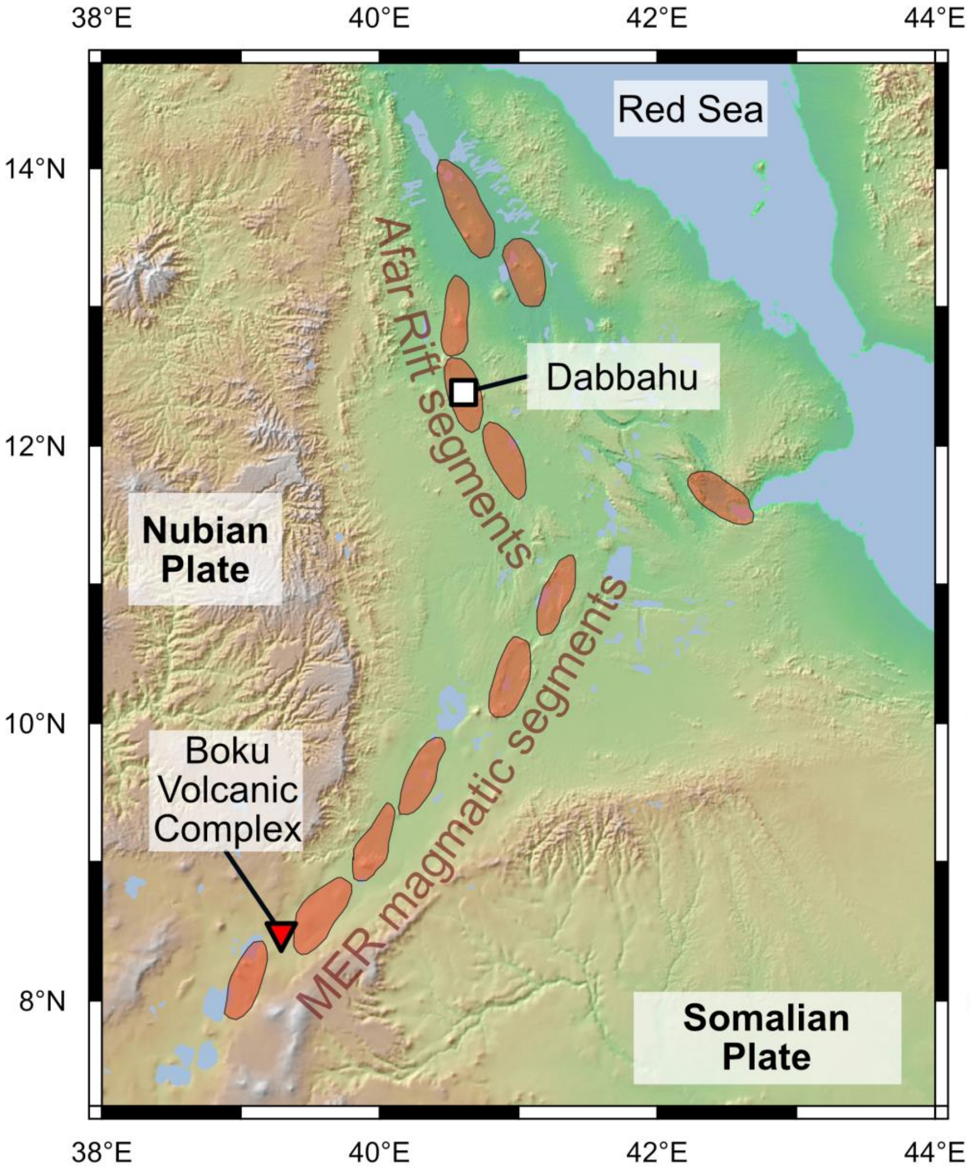
$$k_d = \frac{{Al_2O_3}^{olivine}}{{Al_2O_3}^{spinel}}$$

$$Cr\# = \left(\frac{Cr}{Cr + Al}\right)$$

Coogan+, 2014, *Chem. Geol.*

Our samples are collected from the MER and Afar.

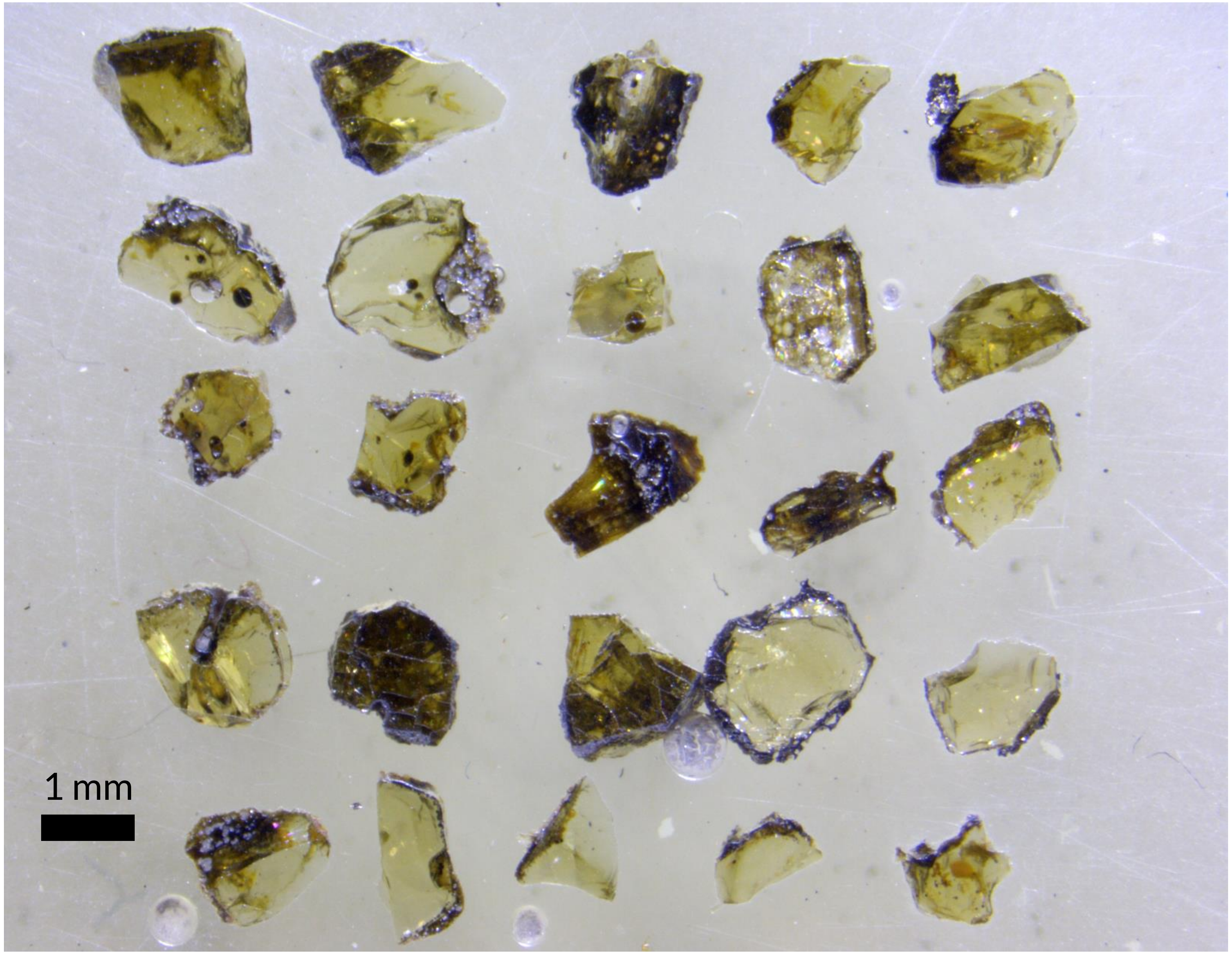
Boku Volcanic Complex
(Photo credit: D. Ferguson)



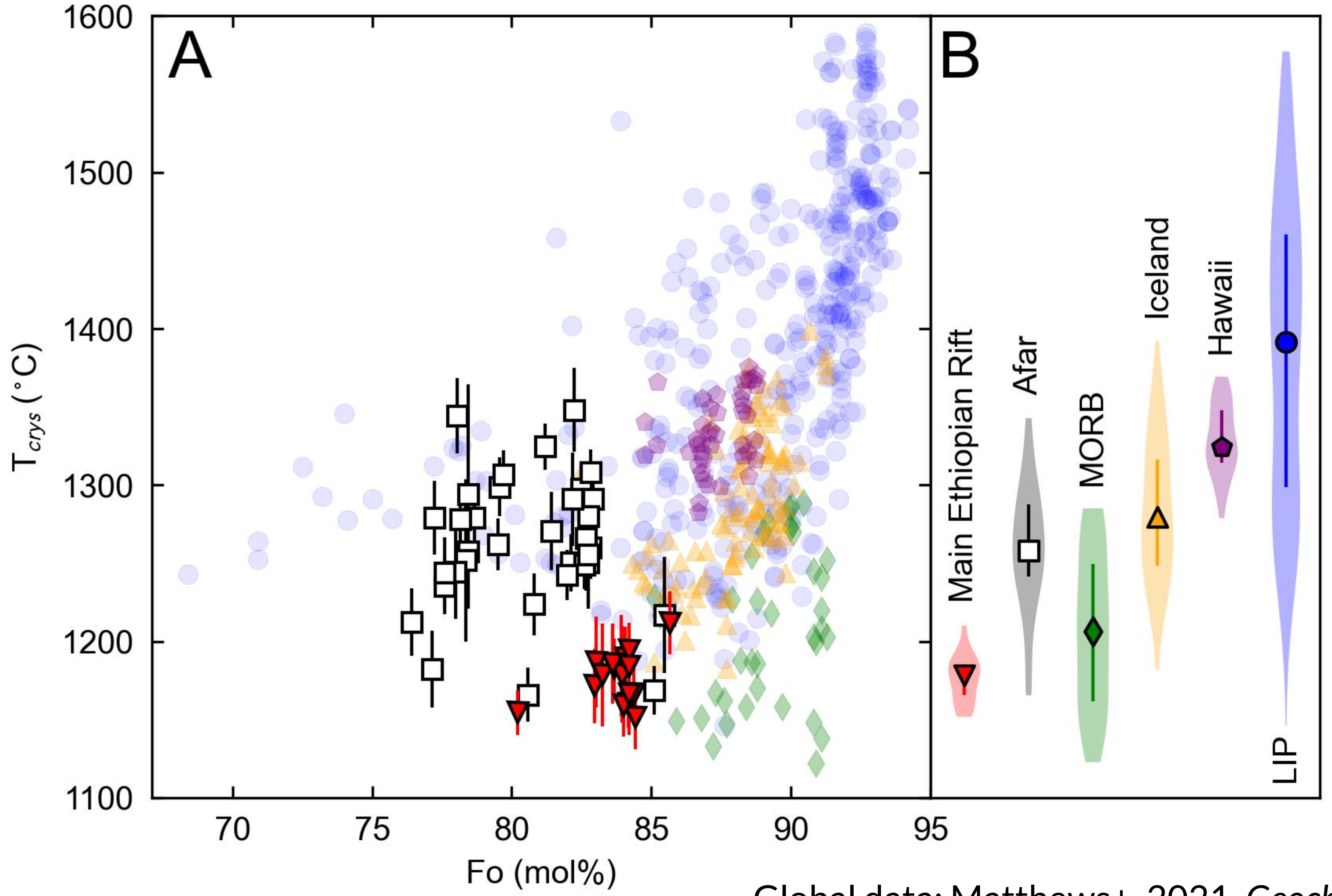
Dabbahu rift segment
(Photo credit: D. Pyle)

After Hayward and Ebinger, 1996, *Tectonics*.

Our olivine crystals are mounted, polished, and analysed by probe.

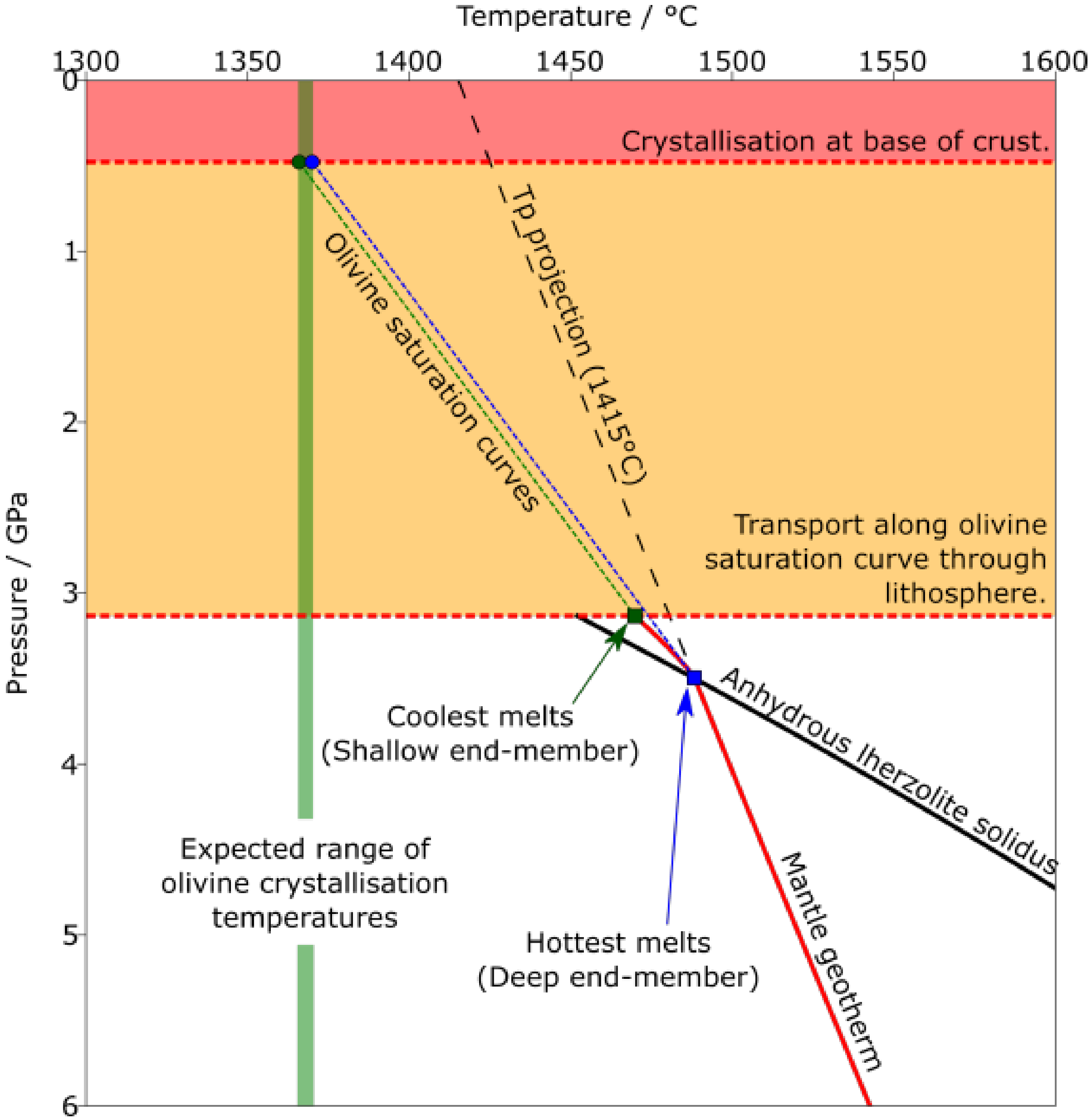


Olivine crystallization temperatures measured by olivine-spinel Al-exchange thermometry are shown here.



Global data: Matthews+, 2021, *Geochem. Geophys. Geosyst.*

Olivine crystallization temperatures by themselves cannot be used to estimate mantle temperature.



Matthews, Wong, and Gleeson
Software: pymelt.readthedocs.io

Our mantle melting library, *pyMelt*, generates data from user-defined model parameters describing mantle conditions.

Model parameters

Ethiopian mantle temperature

+

Crustal thickness
(depth of crystallisation)

+

Lithospheric thickness
(depth where melting stops)

+

Mantle lithology composition

Forward model (pyMelt library) →

Data

Primary olivine crystallisation temperature

+

Rare-earth element concentrations

+

Melt thickness
(amount of melt produced)

Through Bayesian inversion (MULTINEST) we match the results of several thousand model runs to our data to find a best fit.

Model parameters

Ethiopian mantle temperature

\+

Crustal thickness
(depth of crystallisation)

\+

Lithospheric thickness
(depth where melting stops)

\+

Mantle lithology composition

Forward model (pyMelt) →

← **Inverse model (MULTINEST)**

Data

Primary olivine crystallisation temperature

\+

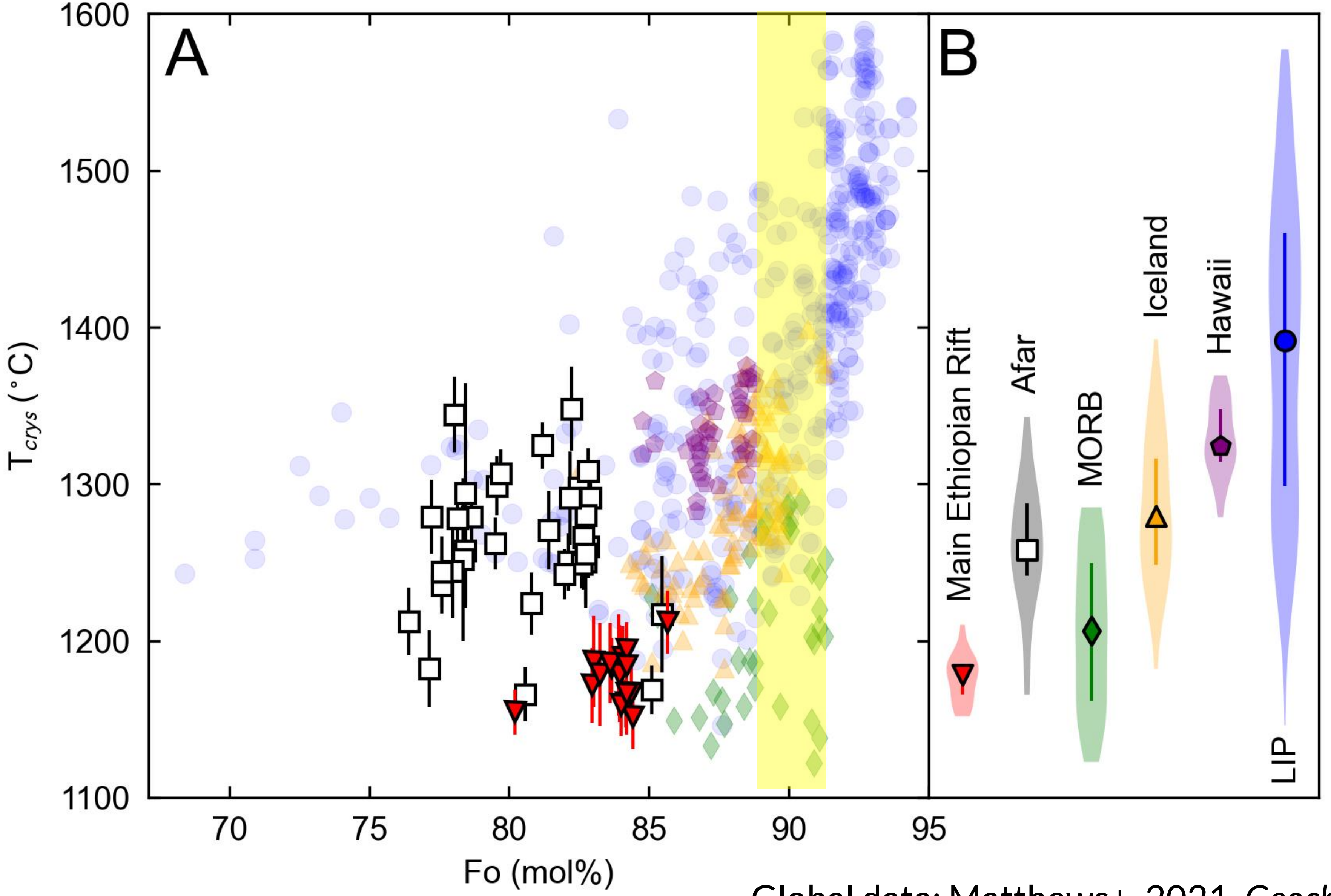
Rare-earth element concentrations

\+

Melt thickness
(amount of melt produced)

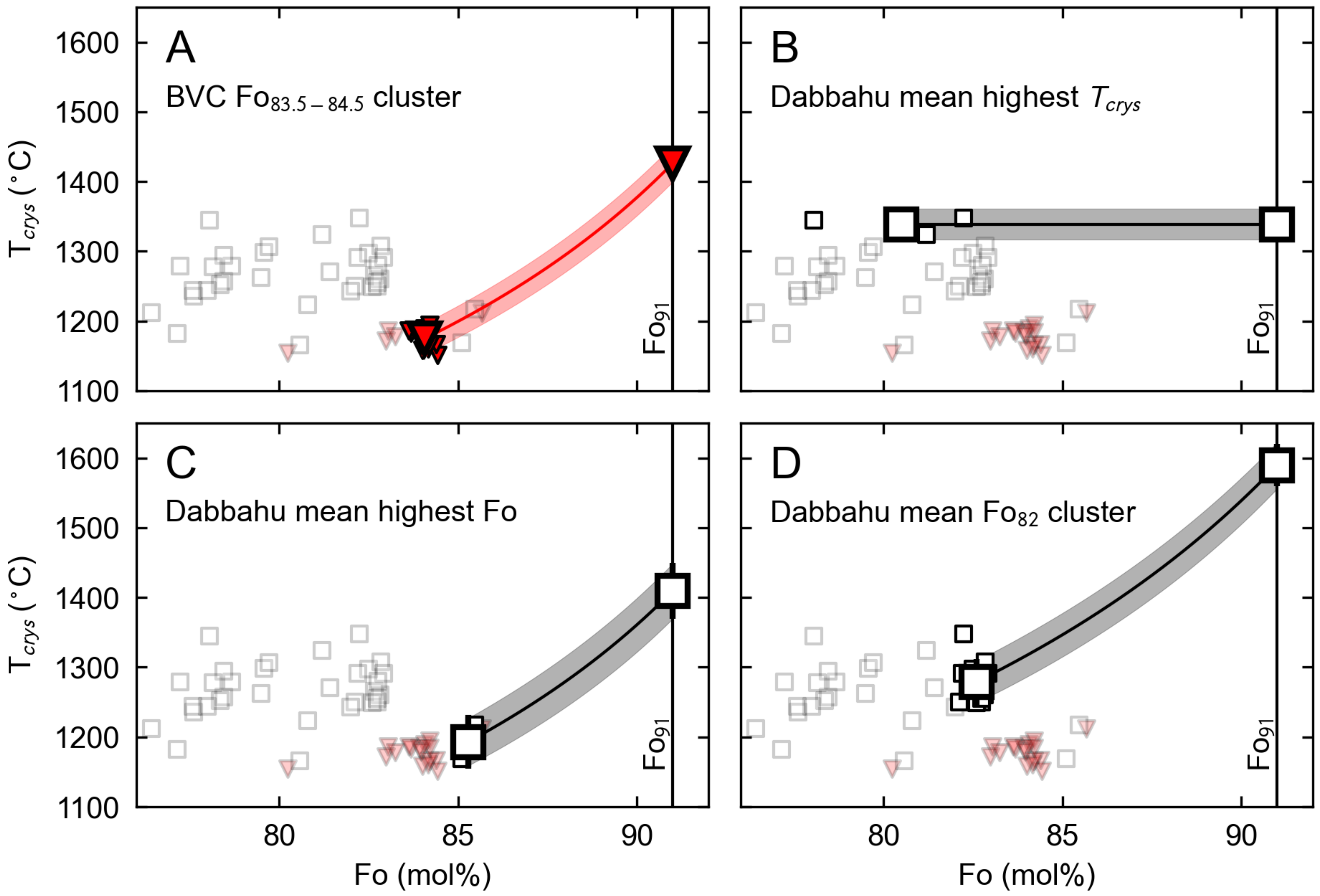
MULTINEST: Feroz+, 2009, *Mon. Notices Royal Astron. Soc.*

We must establish whether olivines have crystallized from a primary mantle-derived melt. First olivines are normally ~Fo90.

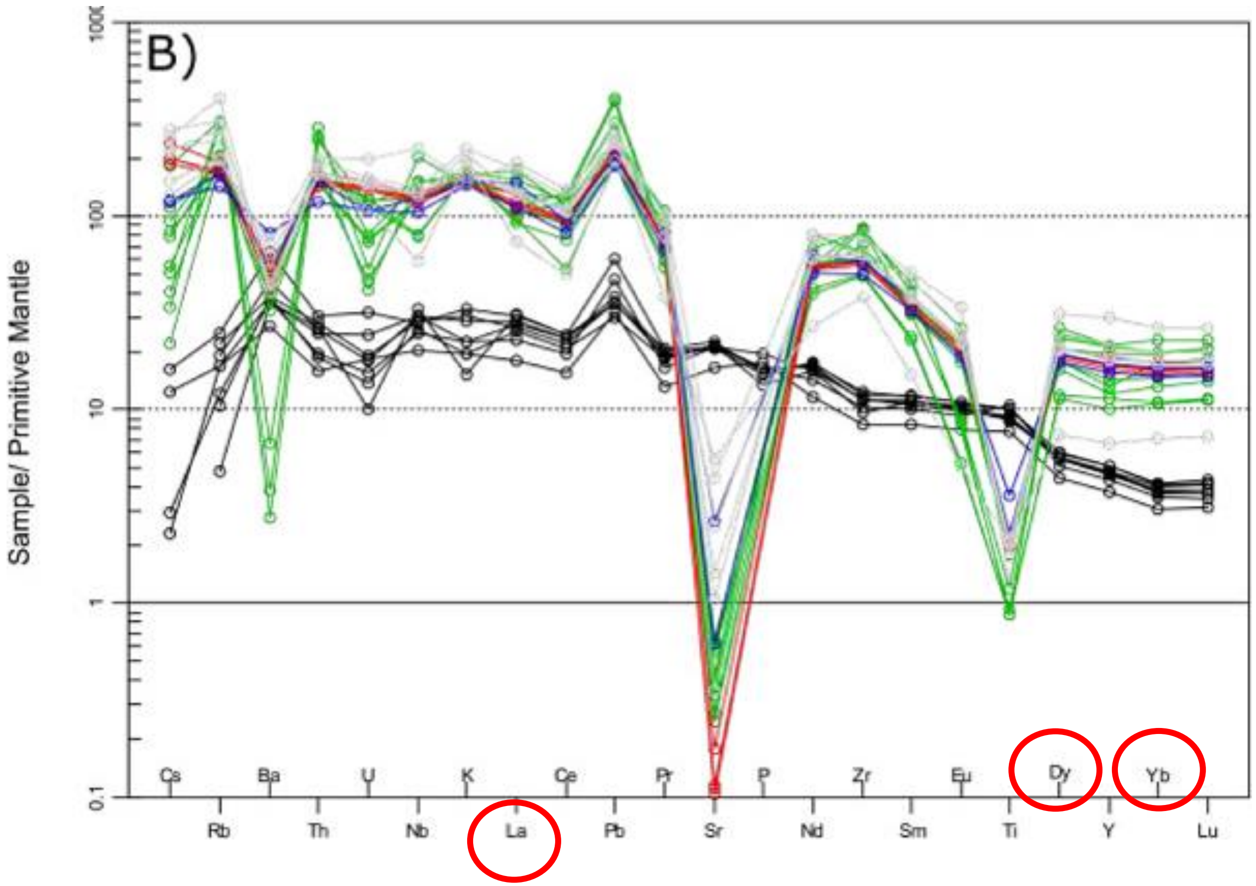


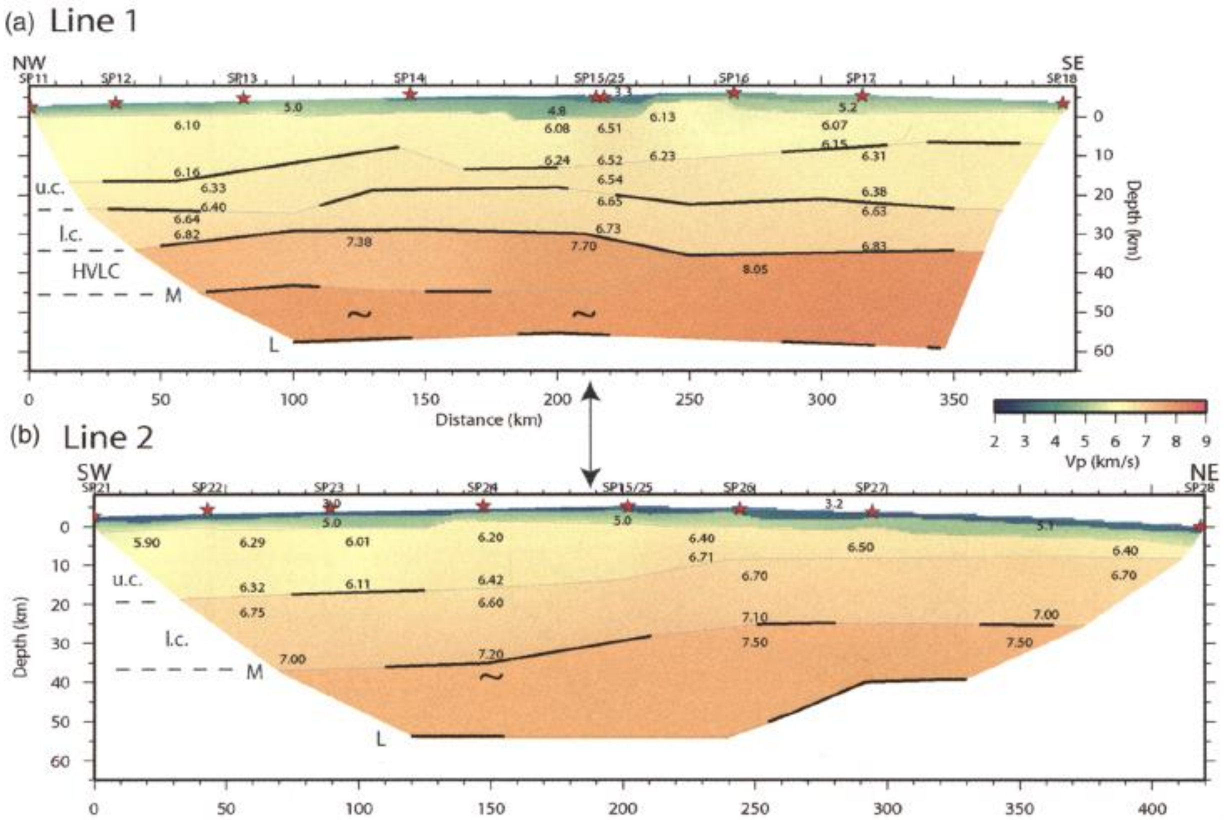
Global data: Matthews+, 2021, *Geochem. Geophys. Geosyst.*

We determine the temperature of the first-crystallizing olivines by calculating basalt liquid lines of descent.



Further constraints to our inversion are provided by rare-earth element ratios and melt thickness estimates.



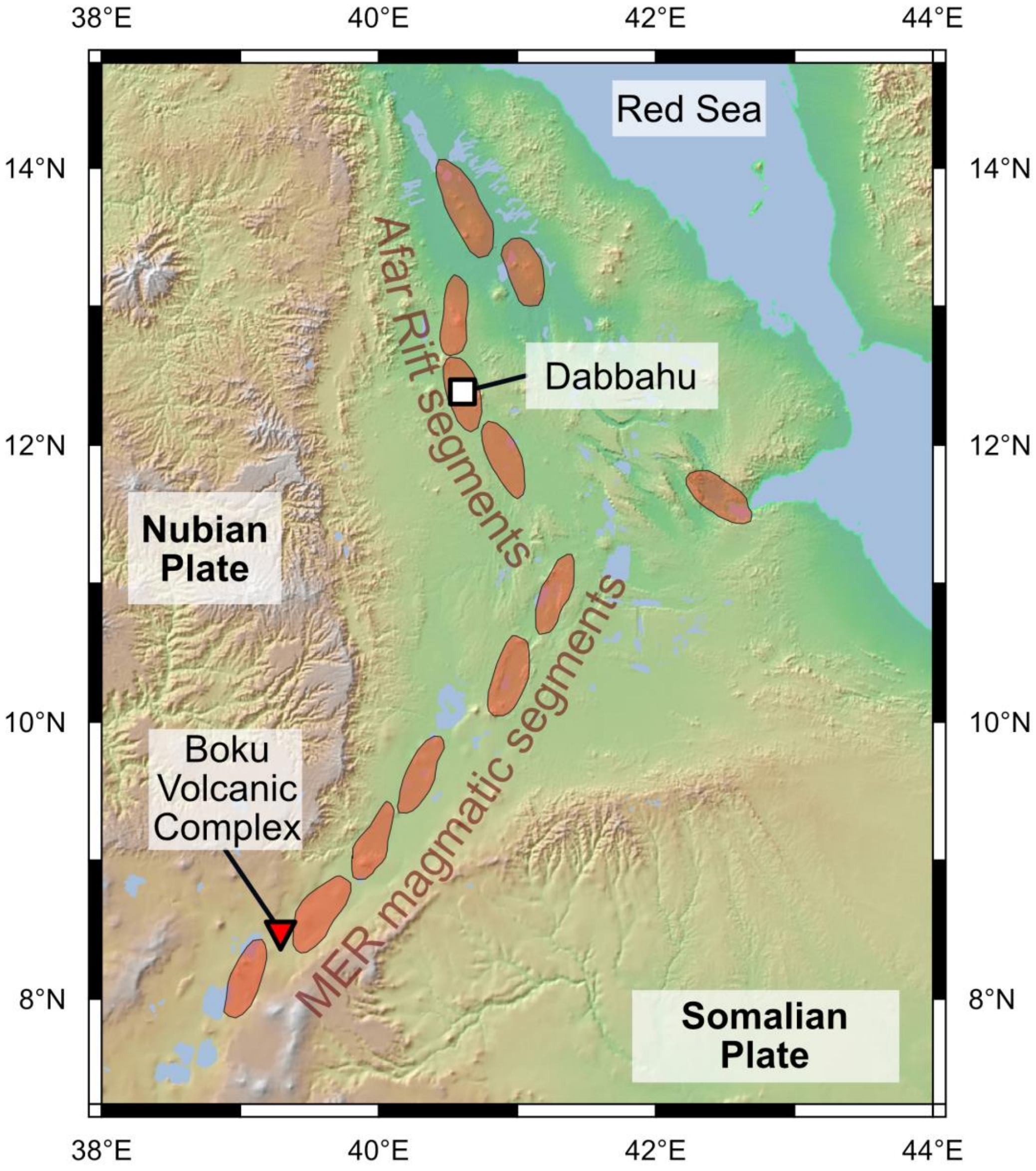


Tadesse+, 2019, *J. African Earth Sci.*

Maguire+, 2006, *Geol. Soc. London Spec. Pub. 259*

We will now consider the results of our inversions, firstly for the Boku Volcanic Complex in the MER, then the Dabbahu rift in Afar.

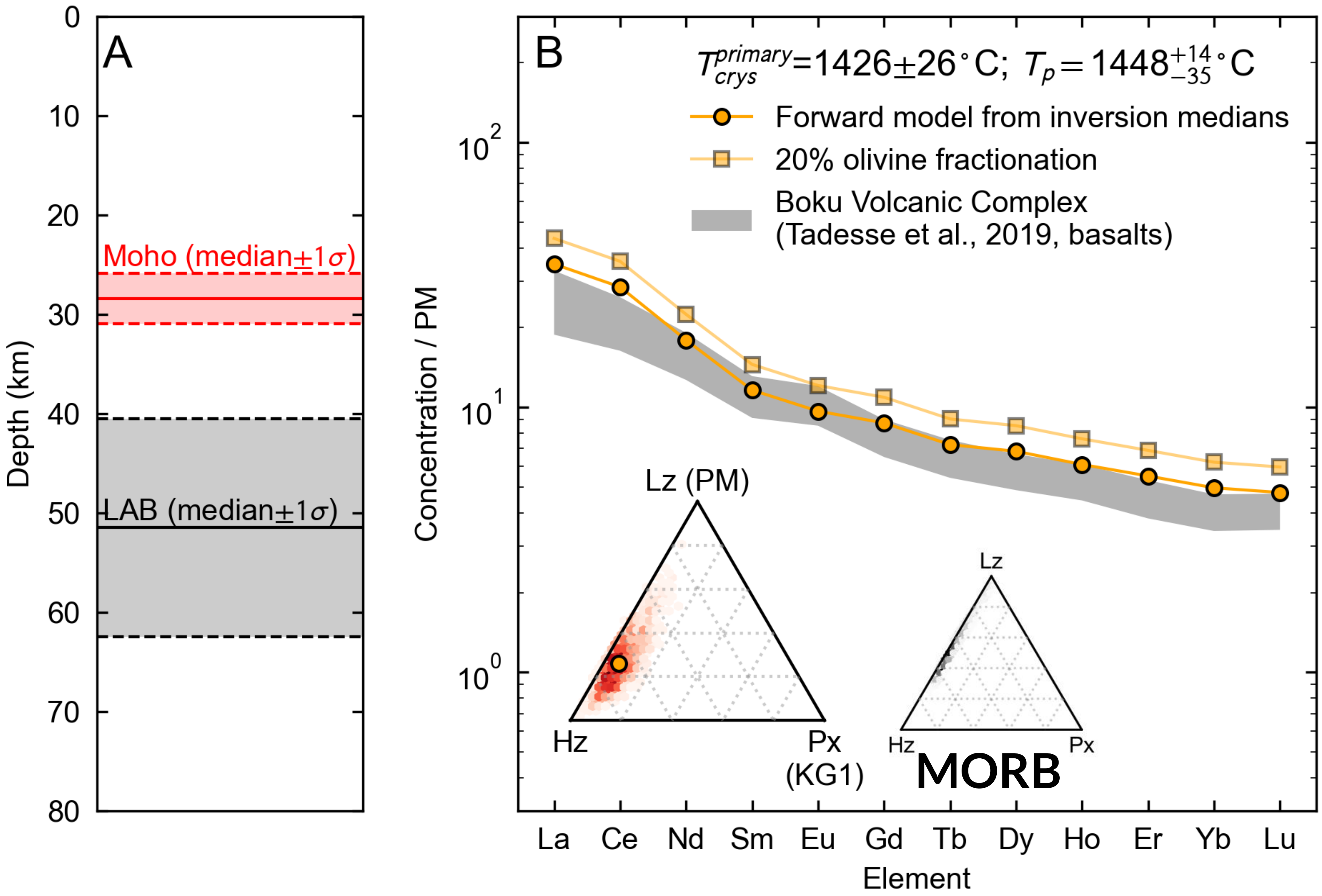
Boku Volcanic Complex
(Photo credit: D. Ferguson)



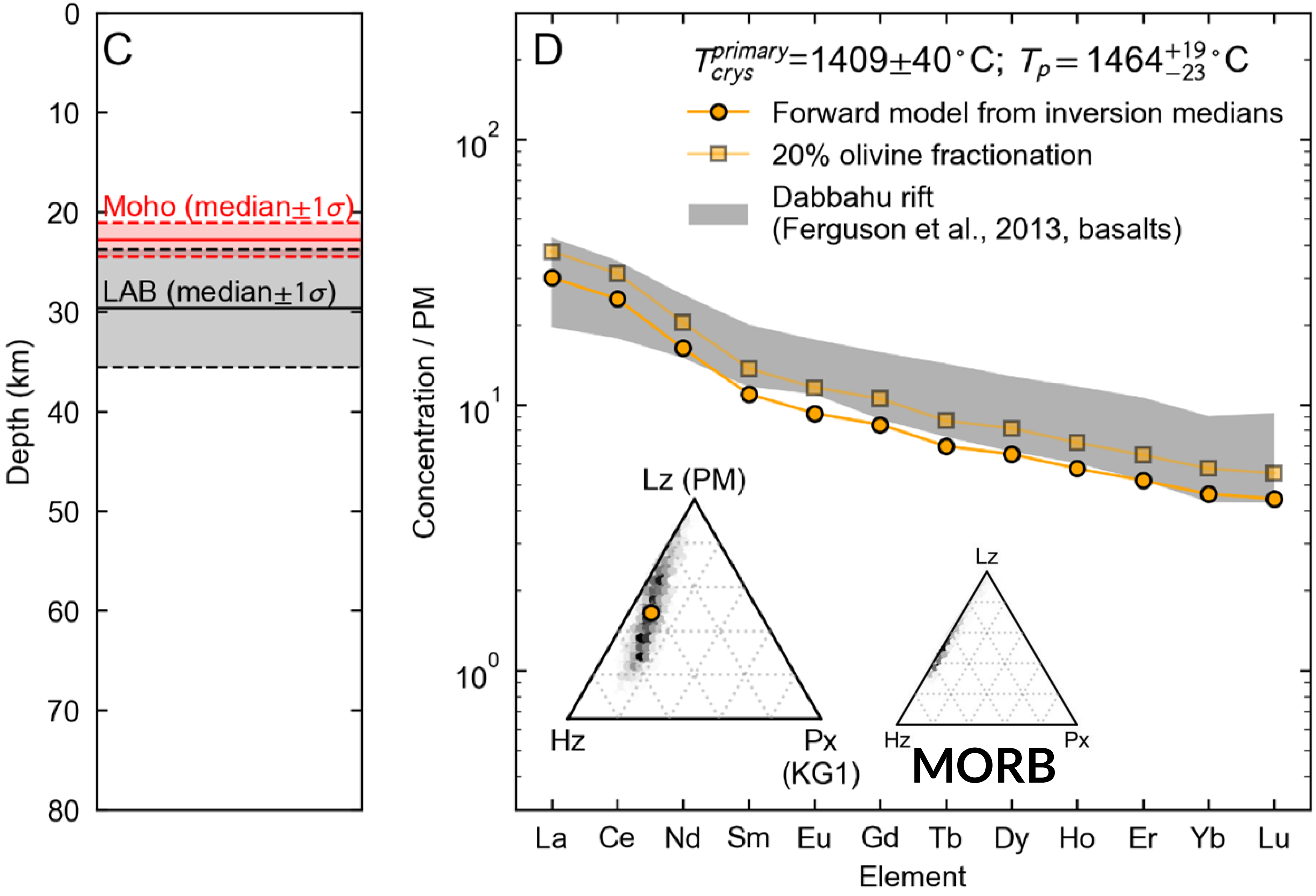
Dabbahu rift segment
(Photo credit: D. Pyle)

After Hayward and Ebinger, 1996, *Tectonics*.

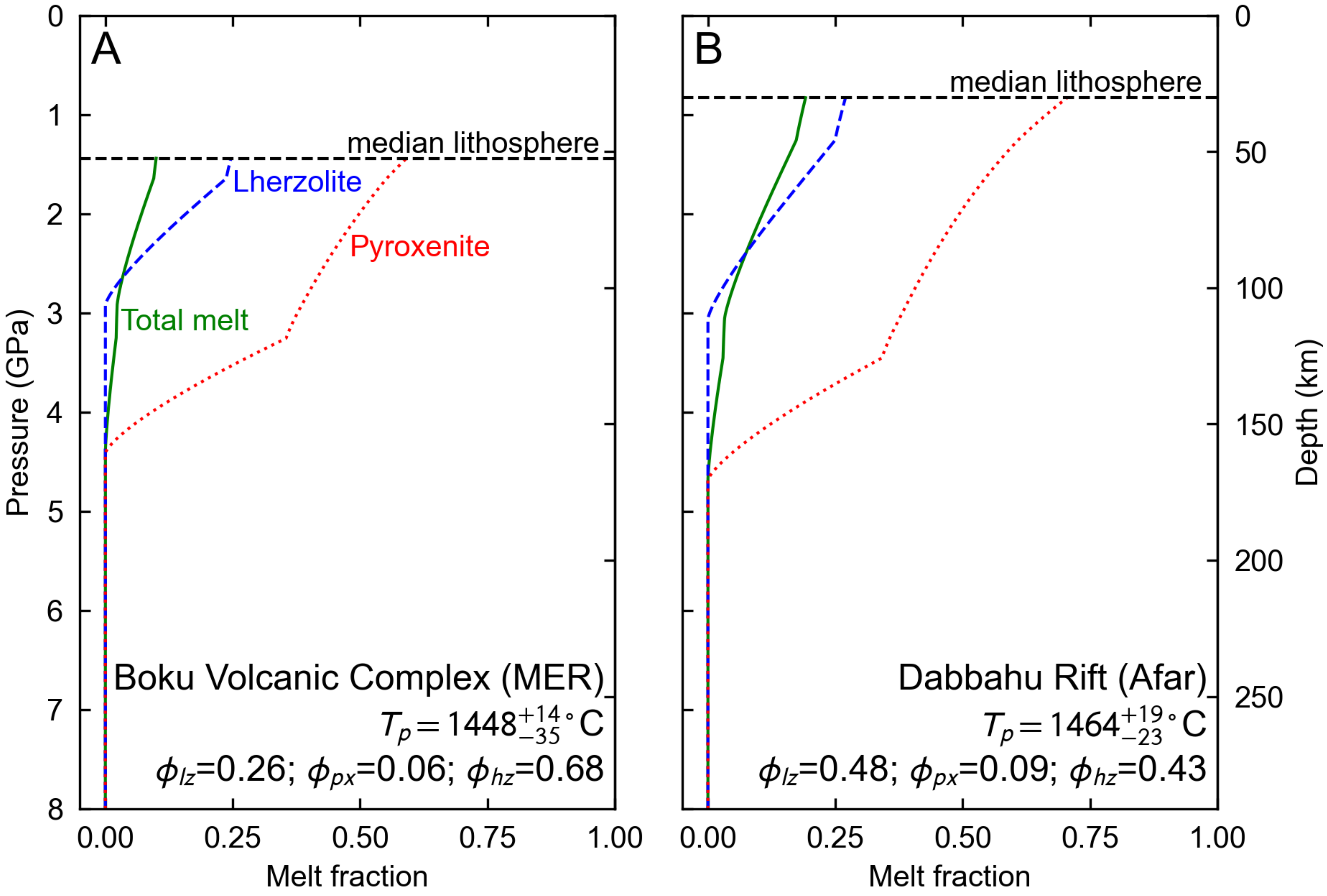
A: Cross section through the MER crust and uppermost mantle.
B: Median temperature and composition of the MER mantle.



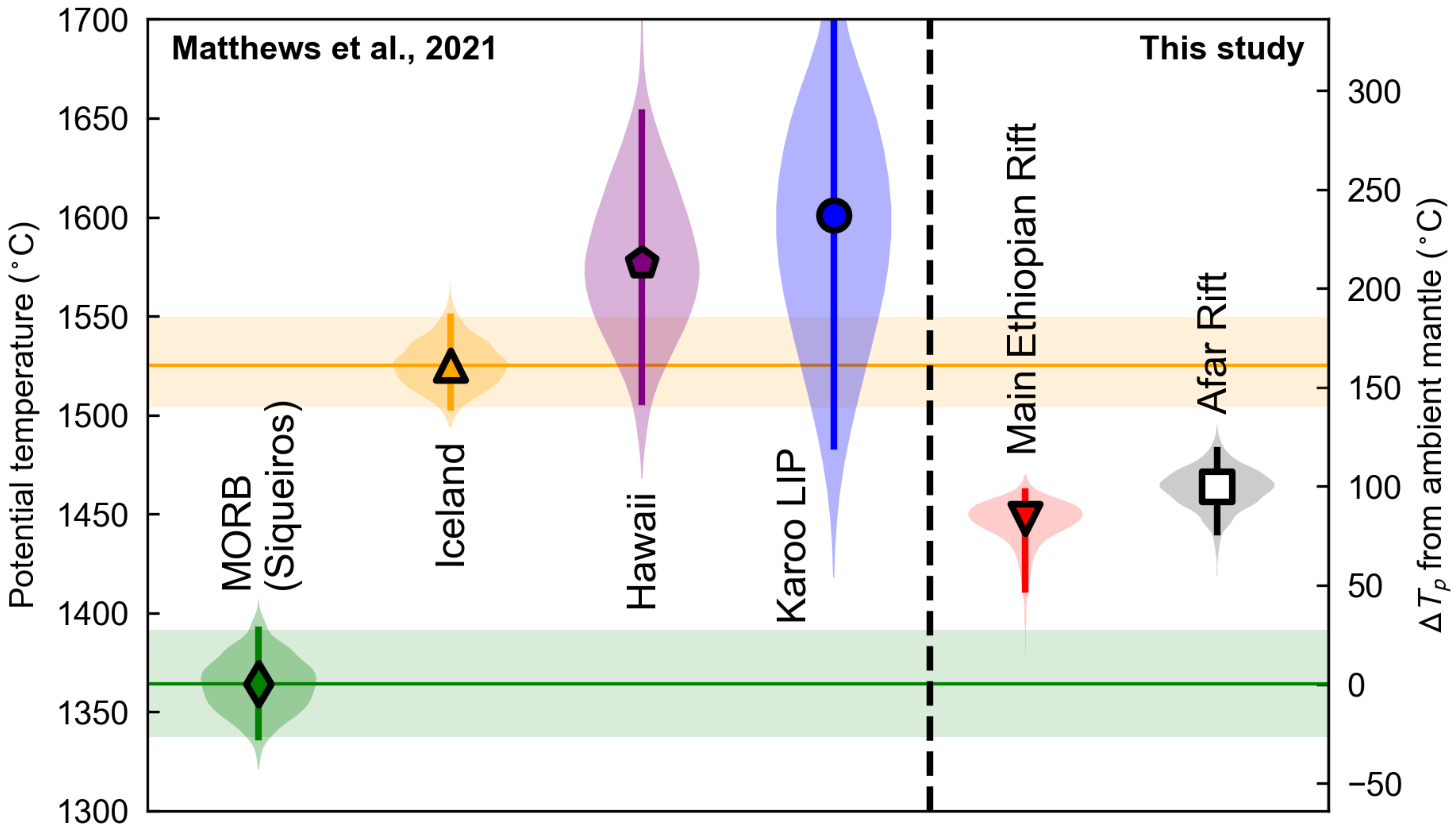
A: Cross section through the Afar crust and uppermost mantle.
B: Median temperature and composition of the Afar mantle.



Deep melting of enriched, fusible pyroxenites can replicate observed lava chemistry without necessitating a thick lithosphere.

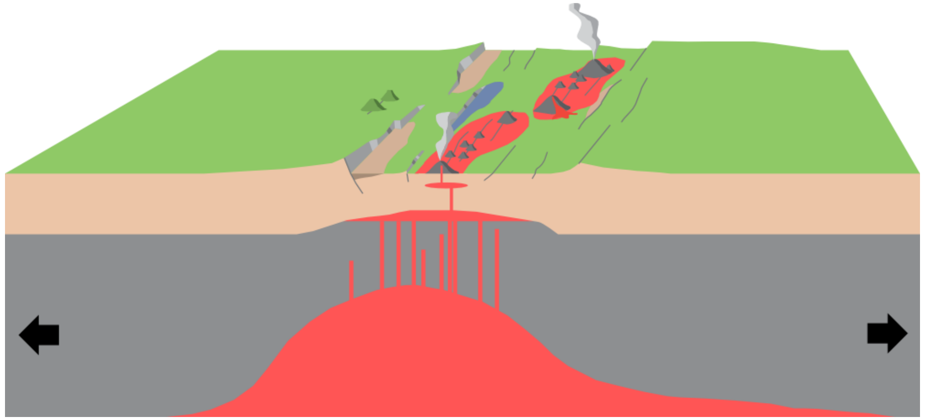


The Ethiopian mantle is consistent across the MER and Afar, and hot relative to MORB.

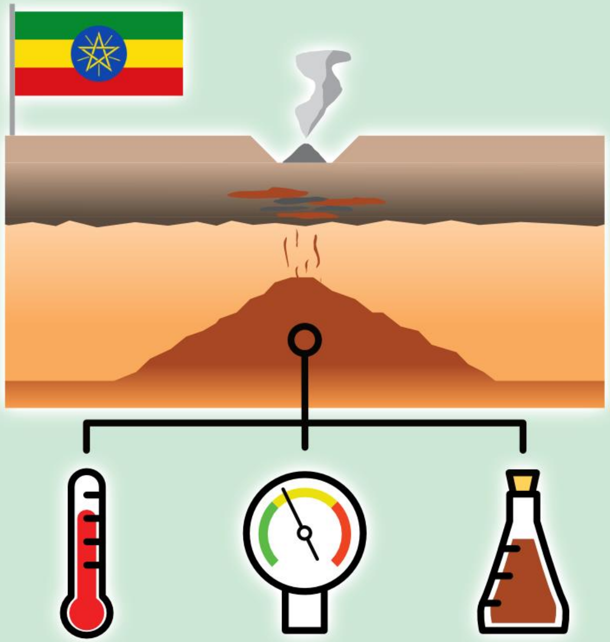


Conclusions

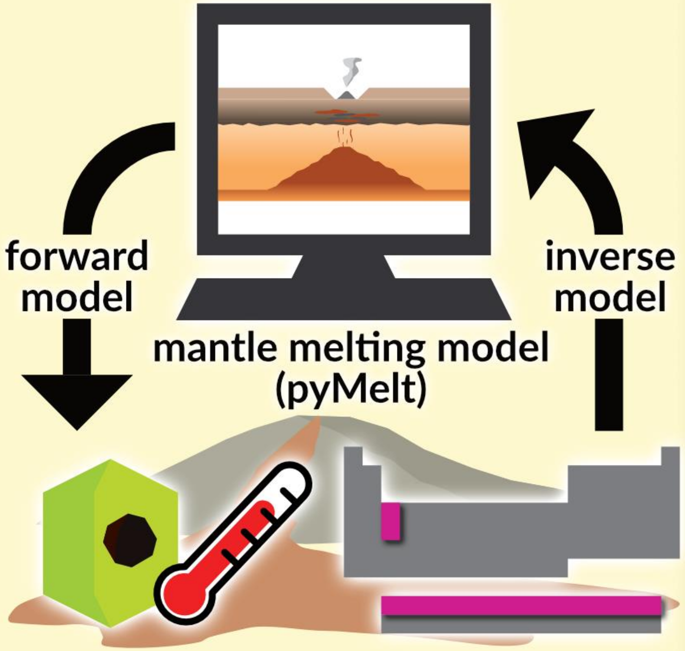
- We develop a model that can predict olivine crystallization temperatures, melt volumes, and rare-earth element concentrations from mantle conditions.
- Ethiopian mantle is ~1450°C, and consistently hot across Ethiopia. It is also likely to be more enriched in fusible pyroxenite than ambient mantle.
- The main differences in melt generation between the Main Ethiopian Rift and Afar can be attributed to comparative depth of melting and enrichment in mantle lithologies.



Exploring Ethiopian Rift and Afar mantle geodynamics through Al-in-olivine thermometry and rare-earth element distributions



Continental rifting in Ethiopia and Afar may be driven by the conditions of the melting rift mantle. We constrain these conditions through petrology.



We develop a mantle melting model to predict properties of rift lavas. Inversion for known lava chemistry allows for estimation of mantle properties.

	mid-ocean ridges	Ethiopian Rift and Afar
	AMBIENT Tp~1350°C	**HOT** Tp≥1450°C
	SHALLOW near-surface	**DEEP** ~60 km
	DEPLETED MORB-source mantle	**ENRICHED** with fusible lithologies

Our results highlight the physico-chemical differences in melting mantle conditions between the Ethiopian Rift and mid-ocean ridges.

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eekw@leeds.ac.uk   @GeoKevW

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