



HAL
open science

A dynamic mid-crustal magma domain revealed by the 2023 to 2024 Sundhnúksgígar eruptions, Iceland

Simon W Matthews, Alberto Caracciolo, Enikő Bali, Sæmundur Halldórsson,
Olgeir Sigmarsson, Guðmundur Guðfinnsson, Gro B M Pedersen, Jóhann
Gunnarsson Robin, Edward W Marshall, Araksan A Aden, et al.

► To cite this version:

Simon W Matthews, Alberto Caracciolo, Enikő Bali, Sæmundur Halldórsson, Olgeir Sigmarsson, et al.. A dynamic mid-crustal magma domain revealed by the 2023 to 2024 Sundhnúksgígar eruptions, Iceland. *Science*, 2024, 386 (6719), pp.309-314. 10.1126/science.adp8778 . hal-04732737

HAL Id: hal-04732737

<https://uca.hal.science/hal-04732737v1>

Submitted on 12 Nov 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

A dynamic mid-crustal magma domain revealed by the 2023-24 Sundhnúkgígar eruptions, Iceland

Authors: Simon W. Matthews^{1*}, Alberto Caracciolo¹, Enikó Bali¹, Sæmundur A. Halldórsson¹, Olgeir Sigmarsson^{1,2}, Guðmundur H. Guðfinnsson¹, Gro B. M. Pedersen¹, Jóhann Gunnarsson Robin¹, Edward W. Marshall^{1,3}, Araksan A. Aden¹, Bryndís Ýr Gísladóttir¹, Chantal Bosq², Delphine Auclair², Heini Merrill¹, Nicolas Levillayer¹, Noëmi Löw¹, Rebekka Hlín Rúnarsdóttir¹, Sóley M. Johnson¹, Sveinbjörn Steinþórsson¹

Affiliations:

¹Nordic Volcanological Centre, Institute of Earth Sciences, University of Iceland; Reykjavík, Iceland.

²Laboratoire Magmas et Volcans, Université Clermont Auvergne; Aubière, France.

³GeoZentrum Nordbayern, Friedrich-Alexander-Universität Erlangen-Nürnberg; Erlangen, Germany

*Corresponding author. Email: simonm@hi.is

Abstract: Mid-crustal magma domains are the source of many basaltic eruptions. Lavas from individual eruptions are often chemically homogeneous, suggesting they derive from single well-mixed magma reservoirs. The 2023-2024 eruptions at Sundhnúkgígar in the Svartsengi volcanic system, Iceland, provide an opportunity to observe the behavior of a mid-crustal magma domain at high spatial and temporal resolution by detailed sampling and geochemical characterization. Substantial mantle-derived geochemical variability is observed in the products erupted in the first hours of the December 2023, January, and February 2024 eruptions, indicating the eruptions derived from multiple magma reservoirs, which mineral-melt equilibration pressures place in the mid-crust. The unusual presence of geochemical heterogeneity in the mid crustal magma domain provides an insight into how dynamic and complex mid-crustal magma domains can be.

One-Sentence Summary: Chemical variability in consecutive eruptions at Svartsengi, Iceland, reveals a complex and dynamic mid-crustal magma domain

Main Text:

Between December 2023 and February 2024 three volcanic eruptions occurred along the Sundhnúksígárgar crater row in the Svartsengi volcanic system on Iceland's Reykjanes Peninsula. These eruptions were preceded by volcanic and tectonic unrest across the peninsula, including earthquake swarms and inflation beginning in 2020 (1-3), three eruptions in the neighboring Fagradalsfjall complex between 2021 and 2023 (4-7), and a major dike event in Svartsengi in November 2023 (8). The events have had a devastating impact on the Icelandic population; the residents of Grindavík (a town within the Svartsengi fissure swarm) have been displaced and critical infrastructure for Reykjanes, including geothermal powered central heating and electricity, has been extensively damaged. Geophysical observations have been used to monitor the accumulation and movement of magma in the subsurface (8) and are the basis on which hazard is assessed (9), but petrological and geochemical observations can help significantly with their interpretation and are the only means by which the behavior of the deepest parts of the system can be inferred (4, 10).

Here we report the geochemical and petrological characterization of the lava and tephra erupted in the eruptions beginning on 18th December 2023, 14th January 2024, and 8th February 2024, including major and trace element concentrations, ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd isotope ratios, and mineral compositions. Using these observations, we constrain the depth, configuration, and changing behavior of the magma domain underlying Svartsengi (8). Our results both characterize the subsurface behavior of a magmatic system driving an ongoing volcanic crisis and provide new insights into the dynamics of mid-crustal magma domains, which are the source of many large eruptions globally (11-13).

Volcanic unrest on Reykjanes since 2020

Following a hiatus of ~780 years (14, 15), volcanic and tectonic unrest on Reykjanes began with seismicity close to Svartsengi in January 2020, accompanied by inflation at ~4 km beneath the Svartsengi and Krýsuvík geothermal fields (2) (Fig 1A). Inflation continued episodically at Svartsengi until continuous inflation started in late 2023 (8). Following a dike intrusion beneath the Fagradalsfjall complex in early 2021, a volcanic eruption began there in March 2021 (1). This eruption continued until September 2021 (5), and was followed by two shorter eruptions in 2022 and 2023 (6, 7).

The composition of the material erupted during the first 40 days of the 2021 Fagradalsfjall eruption displayed a shift in mantle-derived parameters (e.g., K₂O/TiO₂, La/Yb, and radiogenic isotopes) from depleted to enriched values, corresponding to magmas generated at relatively shallow and deep pressures, respectively (4). The rest of this eruption (16), and the two subsequent eruptions, were dominated by enriched magmas (7). Magma equilibration pressures, melt inclusion CO₂ saturation pressures, and the CO₂/SO₂ ratio of the emitted volcanic gas all pointed towards magma transport directly from near the Moho (4). The eruption of such large amplitude mantle-derived heterogeneity in a single event was unique, but consistent with the presence of diverse mantle melts in near-Moho magma reservoirs as inferred from the melt inclusion and mineral record (17, 18).

Inflation resumed beneath the Svartsengi geothermal field in late 2023, centered on a depth of ~5 km (8). On 10th November, a large dike intrusion occurred beneath the Sundhnúksígárgar crater row (last active ~2400 years ago) (19), propagating beneath Grindavík, and off the southern coast (8). Inflation continued beneath Svartsengi, and an eruption began on 18th December 2023 lasting until 21st December 2023, along the northern part of the

Sundhnúksígígar crater row (Fig. 1B). A second eruption occurred on the 14th of January 2024 along the southernmost part of the Sundhnúksígígar crater row, and a second fissure opened a few hours later further to the South, close to the edge of Grindavík (Fig. 1C). The eruption ended on 16th January 2024. A third eruption occurred on 8th February 2024 along a fissure slightly offset from the December fissure (Fig. 1D) and ended after one day. Inflation beneath Svartsengi then resumed.

Rapid changes in the composition of erupted magmas

Samples of lava and tephra were obtained throughout the eruptions and further material was collected after the end of each eruption, ensuring a good spatial and temporal coverage (Fig. 1). All the erupted material is tholeiitic basaltic and contains a variable crystal assemblage of olivine, plagioclase, clinopyroxene, and chromian spinel. In the glassy lava crusts, there is a microlite assemblage dominated by olivine and plagioclase, while the tephra is microlite-poor (fig. S1). The samples show a large range in their major oxide element concentrations (Fig. 2A, fig. S2), and form a linear array between a low-MgO and -K₂O (depleted) endmember and a high-MgO and -K₂O (enriched) endmember. The scatter in composition about this array is consistent with variable proportions of accumulated crystals. Since the crystallizing assemblage does not contain significant K₂O and TiO₂ (fig. S3), the K₂O/TiO₂ ratio is not affected by either fractional crystallization or crystal addition and resolves the two compositional endmembers clearly (Fig. 2B). The utility of K₂O/TiO₂ as a tracer insensitive to crystallization is further confirmed by the coincident variability in ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd isotope ratios (Fig. 2C, fig. S4) and incompatible trace element ratios (fig. S4). The greatest variability in K₂O/TiO₂ is seen in the December and January products, while in the February products the range in K₂O/TiO₂ is much suppressed (Figs. 2B, D-F), though still analytically resolvable (fig. S5).

High magma effusion rates and intense fountaining occurred in the first hours of the December eruption, meaning that much of the areal extent of the lava was emplaced within this time (fig. S6), including flows that represent both enriched (high K₂O/TiO₂) and depleted (low K₂O/TiO₂) compositions. This timescale is orders of magnitude shorter than the 40 days over which a similarly large change in composition was observed at Fagradalsfjall in 2021 (4) (Fig. 2B,C). Tephra deposited early in the eruption has the most enriched composition, and the last lava lobes emplaced at the edge of the flow were depleted (supplementary text, figs. S6C, S7A). Likewise, there was a general change from enriched to depleted compositions with time during the January and February eruptions (fig. S7B,C).

Petrological constraints on pre-eruptive melt storage conditions

The depleted and enriched products contain distinct populations of clinopyroxene microphenocrysts, distinguished by their Mg# (fig. S10B), but the crystals are close to being in equilibrium with the glass compositions. Pressure estimates derived using the clinopyroxene-liquid barometer (20) with the microphenocryst core compositions give mean pressure estimates of 2.6 ± 1.4 kbar (8.8 ± 4.7 km) for crystals in the enriched products and 2.1 ± 1.4 kbar (7.1 ± 4.7 km) for crystals in the depleted products (Fig. 3A). Similar pressures are estimated from the crystal rims, and small glomerocrysts (Fig. 3B, C). The presence of glomerocrysts containing olivine, plagioclase, and clinopyroxene (fig. S1E,F), suggests the magmas were three-phase saturated during pre-eruptive storage, a necessary condition for applying the OPAM geobarometer (21-23). The mean OPAM pressure estimate for the tephra glass is 1.24 ± 1.13 kbar (4.1 ± 3.8 km), distinct from the mean pressure estimated from the

glassy lava crusts: 0.25 ± 1.13 kbar (1.2 ± 3.8 km), which represents re-equilibration at surface pressures by microlite growth during eruption (Fig. 3D, fig S8). The clinopyroxene-liquid and tephra OPAM equilibration pressures are all within mutual uncertainty and point towards pre-eruptive magma storage in the mid-crust.

The mean OPAM temperature estimate for the tephra glass is $1166 \pm 10^\circ\text{C}$ (fig. S8), $\sim 60^\circ\text{C}$ lower than the OPAM temperature calculated from the 2021 Fagradalsfjall tephra (4), consistent with the lower MgO concentrations in the Sundhnúksgígar lavas (Fig. 2). Little change is seen in the MgO concentrations in the whole rocks and glasses between eruptions (Fig. 2, fig. S2), nor in the liquidus temperatures (fig. S9). This suggests the pre-eruptive storage region is not cooling substantially over the timescale of these eruptions; it is likely that the magma storage region is at thermal equilibrium with the surrounding crust, with hotter intruding magmas quickly losing heat. Indeed, the high temperature geothermal field present in the shallow crust above the magma domain indicates a long-lived high temperature anomaly in the mid-crust (2).

Magma supply to the Svartsengi mid-crustal magma domain

The Sundhnúksgígar magmas define tight arrays in plots of incompatible trace element (ITE) ratios and radiogenic isotope ratios (Fig. 2C, fig. S4), consistent with variable amounts of mixing between depleted and enriched endmember magmas. Relative to the Fagradalsfjall 2021 magmas, the Sundhnúksgígar magmas have slightly more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ (Fig 2C), and their ITE ratios are offset to more enriched values (figs. S4, S12). The offset in both ITE ratios and radiogenic isotopes requires that the mixing endmembers for the Sundhnúksgígar magmas have compositions distinct from Fagradalsfjall 2021 (supplementary text). Magmas erupted at Fagradalsfjall in 2022 and 2023 have $^{87}\text{Sr}/^{86}\text{Sr}$ intermediate between the enriched endmembers of Fagradalsfjall 2021 and Sundhnúksgígar (Fig. 2C). If the magmas erupted at Fagradalsfjall in 2022 and 2023 represent melt supply from near-Moho depths following the end of the eruption in 2021, this implies the composition of the enriched melt supplied is generally becoming more enriched (more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$) with time. This would suggest the enriched magmas erupted at Sundhnúksgígar were delivered to the mid-crust in 2023, probably corresponding to the inflation late that year.

The composition of the Sundhnúksgígar depleted endmember sits between those of the enriched endmember and the lavas erupted at Svartsengi in previous eruptive cycles (24), and is similar, but not identical, to the depleted endmember seen at Fagradalsfjall (Fig. 2). It is therefore difficult to distinguish whether the depleted endmember corresponds to magmas resident in the crust since the last eruptive cycle (800-1240 AD) or represents a new influx of magma from near-Moho depths since unrest started in 2020. There is seismic evidence for the presence of magma in the mid-crust beneath Svartsengi before unrest started in 2020 (25), and the inferred volume of the November 2023 dike intrusion was larger than the cumulative volume increase associated with inflation between 2020 and 2023 (8), which might suggest the involvement of magmas accumulated long before 2020. On the other hand, depleted magmas were erupted almost directly from a near-Moho magma reservoir at Fagradalsfjall in 2021 (3, 4), a clear indication that depleted melts were present at depth and could ascend to shallower levels, at least in 2021.

Though the Sundhnúksgígar magmas were not derived directly from the more primitive magmas erupted at Fagradalsfjall, the higher concentrations of K_2O , TiO_2 , and the ITEs in the endmember melts at Sundhnúksgígar (Fig. 2A, figs. S4, S12) are most likely due to fractional crystallization of the magmas, with concentrations in the parental melts being only subtly

different. Based on this, the depleted endmember at Sundhnúksíggar underwent ~46% additional crystallization relative to the depleted endmember at Fagradalsfjall (supplementary text), and the enriched endmember underwent an additional ~35% crystallization. A greater extent of crystallization in the depleted endmember than the enriched endmember, despite storage under similar thermal conditions, is consistent with experiments and modelling performed on Reykjanes Peninsula magma compositions (26). The Sundhnúksíggar magmas being more evolved than the Fagradalsfjall magmas is consistent with the ~60°C lower OPAM temperature estimated from the Sundhnúksíggar tephra than the Fagradalsfjall tephra (4).

A dynamic magma domain beneath Svartsengi

When two basaltic magmas are present in a convecting reservoir, magma mixing and homogenization is expected to be rapid, within hours to days (27, 28). In the Sundhnúksíggar products, the presence of crystals that are close to being in equilibrium with the matrix glass, or are more primitive (fig. S10), suggests crystallization, and therefore cooling coupled with convective circulation, was occurring in the pre-eruptive storage region. It is therefore likely that prior to the December and January eruptions the endmember magmas were isolated from each other (in the mid-crust) until immediately before eruption (Fig. 4). This is further supported by the distinct populations of clinopyroxene core compositions in the depleted and enriched material (fig. S10B). The eruption of lava and tephra with intermediate K_2O/TiO_2 within the first hours of eruption (fig. S7) is consistent with rapid mixing during transport to the surface (Fig. 4).

The lava and tephra erupted in February have a much tighter range of K_2O/TiO_2 (Fig. 2F), consistent with this eruption being fed from a single almost-homogeneous magma reservoir. The small variability in K_2O/TiO_2 that is present (fig. S5) suggests that magma mixing may have occurred in the days or weeks prior to the eruption (28). Whether mixing took place in the same reservoirs that supplied the December and January eruptions, or this was a separate, but nearby, reservoir is unclear. Together, the observations from the three eruptions suggest that a minimum of two isolated reservoirs were present in the mid-crust beneath Svartsengi and were able to contribute magmas to the eruptions (near) simultaneously. Furthermore, the different amplitude of geochemical variability present in the February eruption demonstrates either that successive eruptions may not be derived from the same reservoir(s), or that the reservoirs are dynamic and are not in a steady state.

Contributions from multiple magma reservoirs to the flux out of the mid-crustal magma domain may also explain the difference in the geometry of geodetic signals before and after the November 2023 diking event. While the inflation was well matched by a sill-like source, the deflation was best modelled with a spherical source, likely a result of magma extraction from multiple reservoirs at different depths (8). Rather than being driven primarily by magma chamber overpressure, the November 2023 diking event is thought to have been precipitated by tectonic stress (8), aiding the contribution of multiple magma reservoirs. It is possible that residual tectonic stress continued to play a role in the December, January, and perhaps February eruptions, enabling them to tap multiple magma reservoirs simultaneously. However, pressure changes arising within individual magma reservoirs can cause magma to be mobilized from nearby reservoirs (29).

It is now clear that the inflation events at Svartsengi since 2020 were caused by intrusion of magma in the mid-crust. It also seems likely that significantly more magma is present in the Svartsengi mid-crustal magma domain than implied by inflation alone (8). Inflation at the

neighboring Krýsuvík volcanic system in 2020 (2) was, therefore, probably caused by magma accumulation in the mid-crust as well. Based on the observations at Svartsengi, there might also be greater amounts of eruptible melt present than indicated by inflation. Previous lava flows originating in the Krýsuvík system have reached what are now the outskirts of the capital area in Hafnarfjörður (19). Continued eruptions on Reykjanes will continue to have significant consequences for the Icelandic population.

Implications for mid-crustal magma domains

The geochemical heterogeneity in the Sundhnúksígígar lavas and tephra demonstrates the magmas derived from multiple compositionally distinct reservoirs in the mid-crust. While pre-eruptive storage in the mid-crust is common for basaltic eruptions in Iceland (23), these mid-crustal reservoirs are generally devoid of geochemical heterogeneity (17, 28), erupting melts that are relatively homogeneous (12, 30-33). This has led to the assumption that the last stage of magma accumulation before eruption likely occurs in a single magma reservoir (11, 15, 21), which in turn has influenced physical modelling of volcanic behavior (34-36).

Elsewhere, the presence of substantial mantle-derived geochemical heterogeneity has been inferred for the shallow magma reservoirs beneath Kīlauea and the East Pacific Rise (EPR). At Kīlauea, lavas erupting between 1971 and 1982 defined bimodal trends in radiogenic Pb isotope ratios, corresponding to different parts of the eruptive fissure (37). Though this was indicative of two distinct shallow reservoirs contributing to the eruptions, the magmas remained separated from each other, unlike Sundhnúksígígar where they could partially mix during ascent. At a fast-spreading segment on the EPR, high-resolution sampling has revealed mantle-derived heterogeneity within a single mapped unit (38), albeit with a smooth variation occurring on a much larger wavelength than at Sundhnúksígígar (> 10 km). Though it is likely the chemical diversity was erupted during different events (39), the persistence of axial magma reservoirs (40) means that the heterogeneity is most likely present within the shallow magma domain. Despite their differences to Sundhnúksígígar, both of these examples demonstrate that mantle-derived heterogeneity can be present in the mid-crust and multiple magma reservoirs can contribute to single eruptive episodes.

In contrast to basaltic eruptions, it is well established that eruptions involving more silicic magmas are often sustained from multiple magma reservoirs, whose configuration can change throughout the course of an eruption (10, 41, 42). Like the rare examples from basaltic eruptions above, the contribution of multiple magma reservoirs has been identified from geochemical variability in the erupted material. However, this variability is seldom mantle-derived, rather it is generated *in situ* by variable extents of cooling and assimilation of country rock (43, 44). If the contribution of multiple basaltic reservoirs is only revealed on the occasion that mantle-derived heterogeneity escapes homogenization at depth and propagates to the mid-crust, it follows that the role of multiple reservoirs has been underestimated in basaltic eruptions derived from mid-crustal magma domains.

Finally, the observations at Sundhnúksígígar provide further constraints on how the signal of mantle compositional heterogeneity is modulated and diminished by the crust, i.e., the “crustal filter” (40). In magmatic systems in Iceland, basaltic melts are largely homogenized in near-Moho magma reservoirs, before ascending to shallower levels (17, 28). Where mantle-derived heterogeneity has been seen in single flow units or eruptions in Iceland, the magmas have been derived directly from the near the Moho (4, 31, 45). As discussed above, observations at mid-ocean ridges (38, 40), Hawai‘i (37), and now Sundhnúksígígar, demonstrate that occasionally this heterogeneity can propagate into shallower magma

domains. In some cases (e.g., the reservoir feeding the February eruption) this heterogeneity may be homogenized in the mid-crust, but it seems that basaltic magmas are in general unlikely to continue homogenizing here, and instead reside in largely isolated magma reservoirs.

References and Notes

1. F. Sigmundsson *et al.*, Deformation and seismicity decline before the 2021 Fagradalsfjall eruption. *Nature* **609**, 523-528 (2022).
2. Ó. G. Flóvenz *et al.*, Cyclical geothermal unrest as a precursor to Iceland's 2021 Fagradalsfjall eruption. *Nat. GeoSci.* **15**, 397-404 (2022).
3. T. Greenfield *et al.*, Deep long period seismicity preceding and during the 2021 Fagradalsfjall eruption, Iceland. *Bulletin of Volcanology* **84**, (2022).
4. S. A. Halldorsson *et al.*, Rapid shifting of a deep magmatic source at Fagradalsfjall volcano, Iceland. *Nature* **609**, 529-534 (2022).
5. G. B. M. Pedersen *et al.*, Volume, Effusion Rate, and Lava Transport During the 2021 Fagradalsfjall Eruption: Results From Near Real-Time Photogrammetric Monitoring. *Geophysical Research Letters* **49**, (2022).
6. M. Parks *et al.*, Deformation, seismicity, and monitoring response preceding and during the 2022 Fagradalsfjall eruption, Iceland. *Bulletin of Volcanology* **85**, (2023).
7. A. Caracciolo *et al.*, in *EGU General Assembly 2024*. (Vienna, Austria, 2024).
8. F. Sigmundsson *et al.*, Fracturing and tectonic stress drives ultrarapid magma flow into dikes. *Science*, eadn2838 (2024).
9. S. Barsotti *et al.*, The eruption in Fagradalsfjall (2021, Iceland): how the operational monitoring and the volcanic hazard assessment contributed to its safe access. *Natural Hazards* **116**, 3063-3092 (2023).
10. C. Gansecki *et al.*, The tangled tale of Kilauea's 2018 eruption as told by geochemical monitoring. *Science* **366**, (2019).
11. D. A. Neave, E. Passmore, J. Maclennan, G. Fitton, T. Thordarson, Crystal–Melt Relationships and the Record of Deep Mixing and Crystallization in the ad 1783 Laki Eruption, Iceland. *JPet* **54**, 1661-1690 (2013).
12. S. A. Halldórsson *et al.*, Petrology and geochemistry of the 2014–2015 Holuhraun eruption, central Iceland: compositional and mineralogical characteristics, temporal variability and magma storage. *CMP* **173**, (2018).
13. K. V. Cashman, R. S. Sparks, J. D. Blundy, Vertically extensive and unstable magmatic systems: A unified view of igneous processes. *Science* **355**, (2017).
14. K. Sæmundsson, M. Á. Sigurgeirsson, G. Ó. Friðleifsson, Geology and structure of the Reykjanes volcanic system, Iceland. *Journal of Volcanology and Geothermal Research* **391**, (2020).
15. A. Caracciolo *et al.*, Magma plumbing architectures and timescales of magmatic processes during historical magmatism on the Reykjanes Peninsula, Iceland. *EPSL* **621**, (2023).
16. I. N. Bindeman *et al.*, Diverse mantle components with invariant oxygen isotopes in the 2021 Fagradalsfjall eruption, Iceland. *Nat Commun* **13**, 3737 (2022).
17. J. Maclennan, Concurrent Mixing and Cooling of Melts under Iceland. *JPet* **49**, 1931-1953 (2008).
18. D. A. Neave, O. Shorttle, M. Oeser, S. Weyer, K. Kobayashi, Mantle-derived trace element variability in olivines and their melt inclusions. *EPSL* **483**, 90-104 (2018).

19. K. Sæmundsson, H. Jóhannesson, Á. Hjartason, S. G. Kristinsson, M. Á. Sigurgeirsson, "Geological Map of Southwest Iceland, 1:100 000," (Iceland GeoSurvey, 2010).
20. D. A. Neave, K. D. Putirka, A new clinopyroxene-liquid barometer, and implications for magma storage pressures under Icelandic rift zones. *American Mineralogist* **102**, 777-794 (2017).
21. M. E. Hartley, E. Bali, J. Maclennan, D. A. Neave, S. A. Halldorsson, Melt inclusion constraints on petrogenesis of the 2014-2015 Holuhraun eruption, Iceland. *Contrib Mineral Petrol* **173**, 10 (2018).
22. H.-J. Yang, R. J. Kinzler, T. L. Grove, Experiments and models of anhydrous, basaltic olivine-plagioclase-augite saturated melts from 0.001 to 10 kbar. *CMP* **124**, 1-18 (1996).
23. R. J. M. Baxter, J. Maclennan, D. A. Neave, T. Thordarson, Depth of Magma Storage Under Iceland Controlled by Magma Fluxes. *G3* **24**, (2023).
24. D. W. Peate *et al.*, Historic magmatism on the Reykjanes Peninsula, Iceland: a snapshot of melt generation at a ridge segment. *CMP* **157**, 359-382 (2009).
25. J. E. Martins *et al.*, 3D S-wave velocity imaging of Reykjanes Peninsula high-enthalpy geothermal fields with ambient-noise tomography. *Journal of Volcanology and Geothermal Research* **391**, (2020).
26. D. A. Neave, O. Namur, O. Shorttle, F. Holtz, Magmatic evolution biases basaltic records of mantle chemistry towards melts from recycled sources. *EPSL* **520**, 199-211 (2019).
27. H. E. Huppert, R. S. J. Sparks, J. A. Whitehead, M. A. Hallworth, Replenishment of magma chambers by light inputs. *Journal of Geophysical Research: Solid Earth* **91**, 6113-6122 (1986).
28. J. Maclennan, Mafic tiers and transient mushes: evidence from Iceland. *Phil. Trans.* **377**, 20180021 (2019).
29. J. Tarasewicz, R. S. White, A. W. Woods, B. Brandsdóttir, M. T. Gudmundsson, Magma mobilization by downward-propagating decompression of the Eyjafjallajökull volcanic plumbing system. *Geophysical Research Letters* **39**, (2012).
30. E. Passmore, J. Maclennan, G. Fitton, T. Thordarson, Mush Disaggregation in Basaltic Magma Chambers: Evidence from the ad 1783 Laki Eruption. *JPet* **53**, 2593-2623 (2012).
31. J. Sinton, K. Grönvold, K. Saemundsson, Postglacial eruptive history of the Western Volcanic Zone, Iceland. *G3* **6**, Q12009 (2005).
32. D. E. Eason, J. M. Sinton, Lava shields and fissure eruptions of the Western Volcanic Zone, Iceland: Evidence for magma chambers and crustal interaction. *Journal of Volcanology and Geothermal Research* **186**, 331-348 (2009).
33. O. Sigmarsson, M. Condomines, K. Grönvold, T. Thordarson, Extreme magma homogeneity in the 1783–84 Lakagigar Eruption: Origin of a large volume of evolved basalt in Iceland. *Geophysical Research Letters* **18**, 2229-2232 (1991).
34. M. T. Gudmundsson *et al.*, Gradual caldera collapse at Barðarbunga volcano, Iceland, regulated by lateral magma outflow. *Science* **353**, aaf8988 (2016).
35. F. Galetto, V. Acocella, A. Hooper, M. Bagnardi, Eruption at basaltic calderas forecast by magma flow rate. *Nat. GeoSci.* **15**, 580-584 (2022).
36. F. Sigmundsson *et al.*, Unexpected large eruptions from buoyant magma bodies within viscoelastic crust. *Nat Commun* **11**, 2403 (2020).
37. A. J. Pietruszka, D. E. Heaton, J. P. Marske, M. O. Garcia, Two magma bodies beneath the summit of Kīlauea Volcano unveiled by isotopically distinct melt deliveries from the mantle. *EPSL* **413**, 90-100 (2015).

38. E. C. Bergmanis, J. Sinton, K. H. Rubin, Recent eruptive history and magma reservoir dynamics on the southern East Pacific Rise at 17°30'S. *G3* **8**, n/a-n/a (2007).
39. J. Sinton *et al.*, Volcanic eruptions on mid-ocean ridges: New evidence from the superfast spreading East Pacific Rise, 17°–19°S. *Journal of Geophysical Research: Solid Earth* **107**, (2002).
40. K. H. Rubin, J. M. Sinton, J. Maclennan, E. Hellebrand, Magmatic filtering of mantle compositions at mid-ocean-ridge volcanoes. *Nat. GeoSci.* **2**, 321-328 (2009).
41. O. Sigmarsson *et al.*, Remobilization of silicic intrusion by mafic magmas during the 2010 Eyjafjallajökull eruption. *Solid Earth* **2**, 271-281 (2011).
42. B. V. Alloway, N. J. Pearce, G. Villarosa, V. Outes, P. I. Moreno, Multiple melt bodies fed the AD 2011 eruption of Puyehue-Cordon Caulle, Chile. *Sci Rep* **5**, 17589 (2015).
43. O. Sigmarsson, M. Condomines, S. Fourcade, A detailed Th, Sr and O isotope study of Hekla: differentiation processes in an Icelandic Volcano. *CMP* **112**, 20-34 (1992).
44. E. Martin, O. Sigmarsson, Crustal thermal state and origin of silicic magma in Iceland: the case of Torfajökull, Ljósufjöll and Snæfellsjökull volcanoes. *CMP* **153**, 593-605 (2007).
45. J. Maclennan, D. McKenzie, F. Hilton, K. Gronvöld, N. Shimizu, Geochemical variability in a single flow from northern Iceland. *Journal of Geophysical Research: Solid Earth* **108**, ECV 4-1-ECV 4-21 (2003).
46. P. Wieser *et al.*, Thermobar: An open-source Python3 tool for thermobarometry and hygrometry. *Volcanica* **5**, 349-384 (2022).
47. F. A. Darbyshire, R. S. White, K. F. Priestley, Structure of the crust and uppermost mantle of Iceland from a combined seismic and gravity study. *EPSL* **181**, 409-428 (2000).
48. J. Jenkins *et al.*, Crustal Formation on a Spreading Ridge Above a Mantle Plume: Receiver Function Imaging of the Icelandic Crust. *Journal of Geophysical Research: Solid Earth* **123**, 5190-5208 (2018).
49. A. Caracciolo, E. Bali, E. Ranta, S. A. Halldórsson, G. H. Guðfinnsson, Medieval and recent SO₂ budgets in the Reykjanes Peninsula: implication for future hazard. *GPL*, (Accepted.).
50. J. T. Armstrong, in *Electron probe quantitation*. (Springer, 1991), pp. 261-315.
51. E. Jarosewich, Smithsonian microbeam standards. *Journal of research of the National Institute of Standards and Technology* **107**, 681 (2002).
52. C. Pin, A. Gannoun, A. Dupont, Rapid, simultaneous separation of Sr, Pb, and Nd by extraction chromatography prior to isotope ratios determination by TIMS and MC-ICP-MS. *J. Anal. At. Spectrom.* **29**, 1858-1870 (2014).
53. R. J. M. Baxter, J. Maclennan, Influence of magma flux on magma storage depths along the Reykjanes Ridge. *EPSL* **631**, (2024).
54. H.-J. Yang, R. J. Kinzler, T. L. Grove, Experiments and models of anhydrous, basaltic olivine-plagioclase-augite saturated melts from 0.001 to 10 kbar. *CMP* **124**, 1-18 (1996).
55. E. Bali, M. E. Hartley, S. A. Halldórsson, G. H. Gudfinnsson, S. Jakobsson, Melt inclusion constraints on volatile systematics and degassing history of the 2014–2015 Holuhraun eruption, Iceland. *CMP* **173**, (2018).
56. P. Wieser *et al.*, Thermobar: An open-source Python3 tool for thermobarometry and hygrometry. *Volcanica* **5**, 349-384 (2022).
57. K. D. Putirka, Thermometers and Barometers for Volcanic Systems. *Reviews in Mineralogy and Geochemistry* **69**, 61-120 (2008).

58. A. R. L. Nichols, M. R. Carroll, Á. Höskuldsson, Is the Iceland hot spot also wet? Evidence from the water contents of undegassed submarine and subglacial pillow basalts. *EPSL* **202**, 77-87 (2002).
59. D. Tian *et al.*, PyGMT: A Python interface for the Generic Mapping Tools (2024); <https://doi.org/10.5281/zenodo.10578540>.
60. P. Wessel *et al.*, The Generic Mapping Tools Version 6. *G3* **20**, 5556-5564 (2019).
61. J. D. Hunter, Matplotlib: A 2D graphics environment. *Computing in Science & Engineering* **9**, 90-95 (2007).
62. The pandas development team, pandas-dev/pandas:Pandas (2020); <https://doi.org/10.5281/zenodo.3509134>.
63. W. McKinney, in *Proceedings of the 9th Python in Science Conference*. (2010), pp. 56-61.
64. C. R. Harris *et al.*, Array programming with NumPy. *Nature* **585**, 357-362 (2020).
65. B. J. Wood, J. D. Blundy, A predictive model for rare earth element partitioning between clinopyroxene and anhydrous silicate melt. *CMP* **129**, 166-181 (1997).
66. O. Namur, B. Charlier, M. J. Toplis, J. Vander Auwera, Prediction of plagioclase-melt equilibria in anhydrous silicate melts at 1-atm. *CMP* **163**, 133-150 (2011).
67. H. Palme, H. S. C. O'Neill, in *Treatise on Geochemistry*. (2014), pp. 1-39.

Acknowledgments: We gratefully acknowledge help with sample collection by Celine Mandon, and Elisa Piispa. Freysteinn Sigmundsson and Halldór Geirsson are thanked for helpful discussions. The geographic information provided by Landmælingar Íslands and Vincent Drouin (at the Icelandic Meteorological Office) was extremely valuable for constraining the relative timing of lava emplacement and planning the field sampling campaigns.

Funding:

Icelandic Research Fund Grant of Excellence 228933-053 (EB, SAH)
Icelandic Research Fund Grant 206755-052 (GBMP)

Author contributions:

Conceptualization: SWM, AC, EB, SAH, OS, GHG

Methodology: SWM, AC, EB, SAH, OS, GHG, GBMP, JGR, EWM

Investigation: SWM, AC, EB, SAH, OS, GHG, GBMP, JGR, AAA, BYG, CB, DA, HM, NL, NL, RHR, SMJ, SS.

Visualization: SWM

Funding acquisition: EB, SAH

Project administration: EB, SAH, OS

Writing – original draft: SWM

Writing – review & editing: SWM, AC, EB, SAH, OS, GHG, GBMP, JGR, EWM, AAA, BYG, HM, NL, NL, RHR, SMJ, SS.

Competing interests: Authors declare that they have no competing interests.

Data and materials availability: All data are available in the main text or the supplementary materials.

Supplementary Materials

Materials and Methods

Supplementary Text

Figs. S1 to S24

Tables S1 to S7

References (49-67)

Data S1 to S5

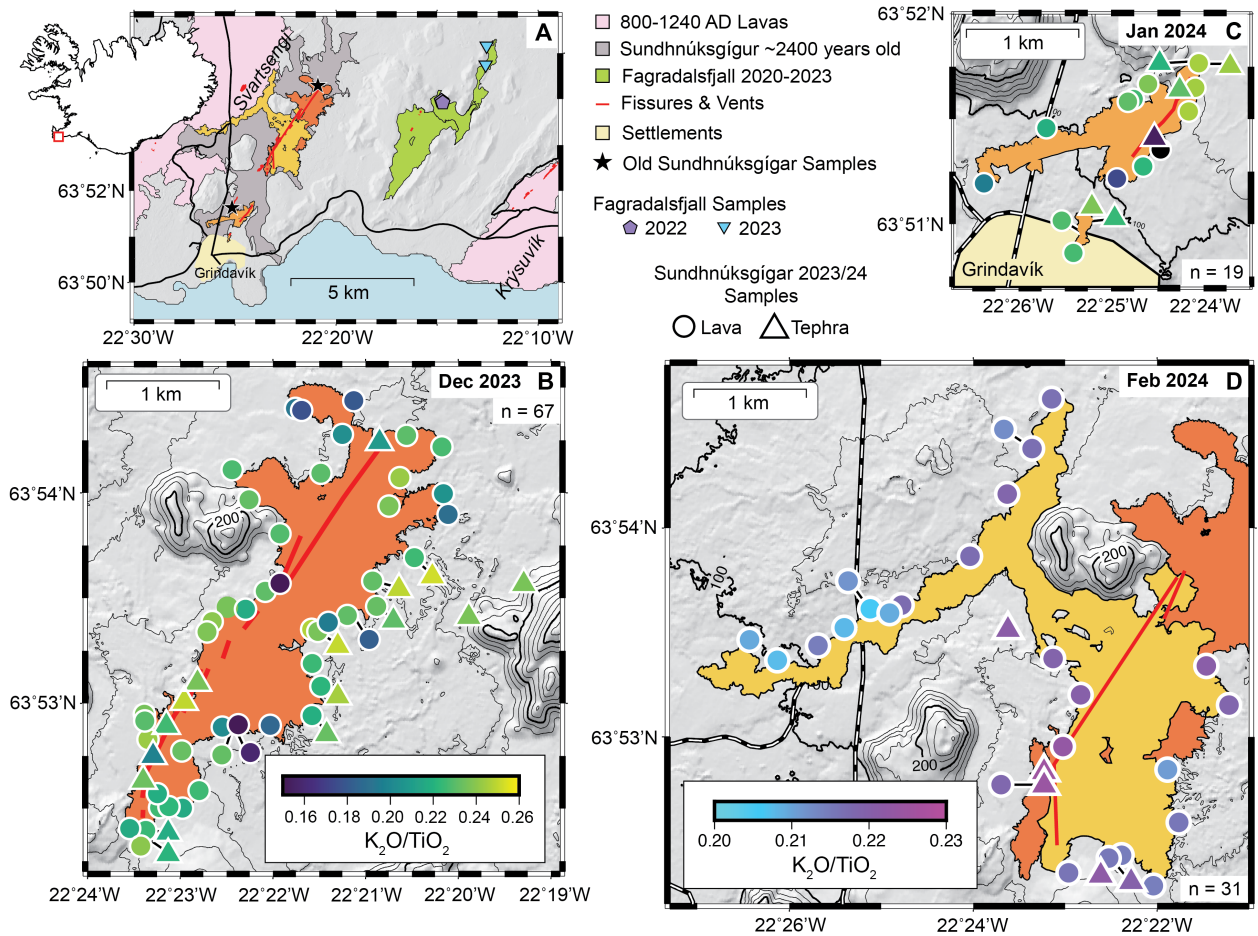


Fig. 1. The locations of the lava flows, fissures, and where lava and tephra samples were collected. (A) The locations of the recent lava flows, lava flows emplaced in the 800-1240 AD fires, and the extent of the lava last erupted at Sundhnúsgígur (~2400 years ago). Italic text indicates the Svartsengi, and Krýsuvík volcanic systems. Sampling locations for the 2400 year old Sundhnúsgígur tephra and the 2022 and 2023 Fagradalsfjall material are indicated. The inset shows the location of the map area within Iceland. (B) The locations from which samples were collected from the December 2023 lava and tephra. The shading indicates the whole rock K_2O/TiO_2 . (C) The same for the January eruption, the color scale is the same as in (B). (D) The same for the February eruption. A different color scale is used so that the smaller range in K_2O/TiO_2 can be resolved. The number of samples collected from each eruption are given in the corner of (B), (C), and (D). The geological data are provided by the Iceland GeoSurvey (ÍSOR) (19), and the geographic data are provided by Landmælingar Íslands.

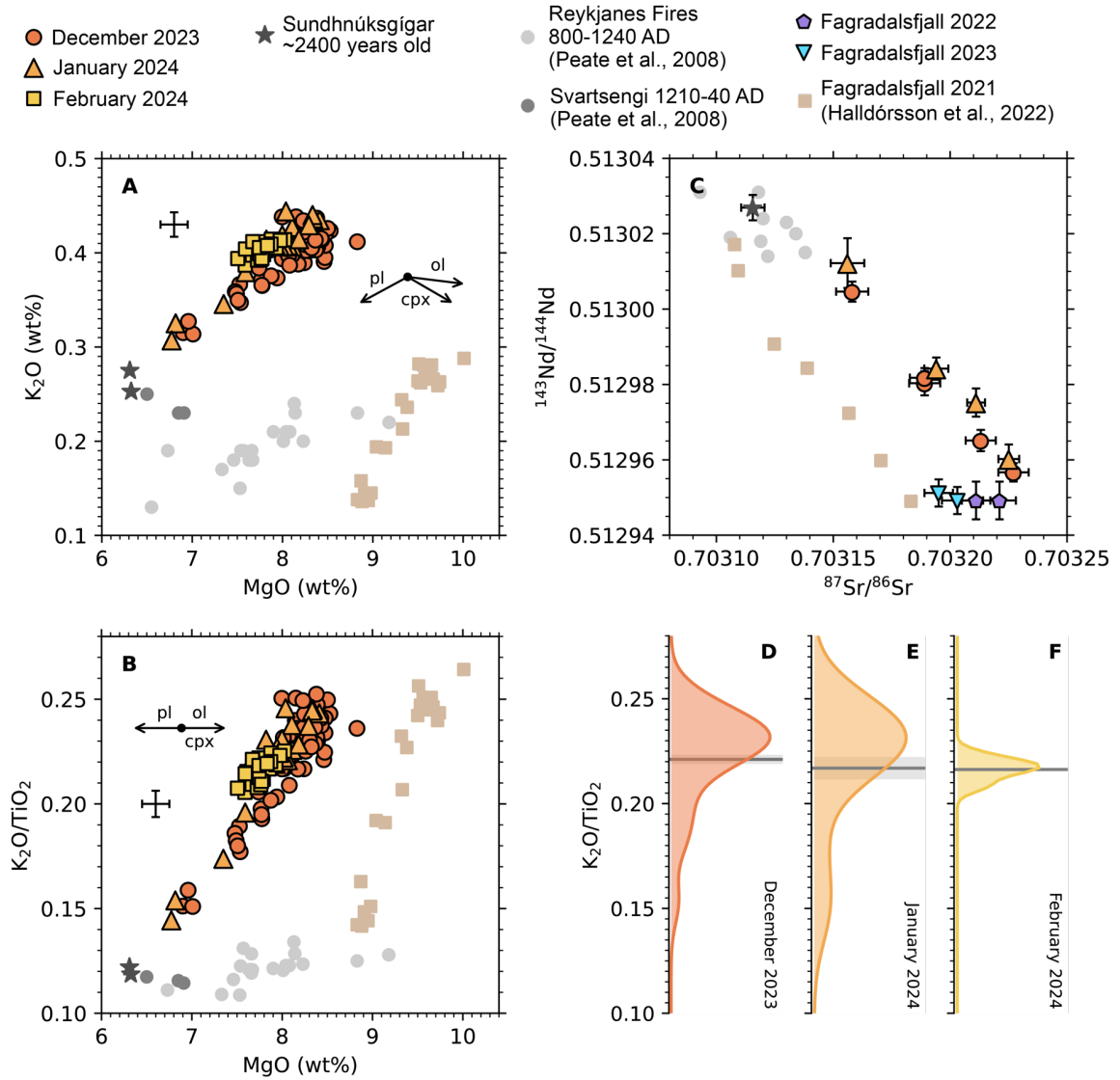


Fig. 2. Comparison of the geochemical variations in the erupted lava and tephra with other Reykjanes lavas. (A) Whole rock K_2O and MgO concentrations. **(B)** Whole rock K_2O/TiO_2 ratios vs MgO concentrations. The vectors in (A) and (B) show the effects of olivine (ol), clinopyroxene (cpx), and plagioclase (pl) accumulation on the whole rock composition. Crystal fractionation will result in the opposite sense of change. The error bars in (A) and (B) show representative 2σ on repeated standard analyses across all measurement sessions. The accuracy of the analyses was within this range. **(C)** Sr and Nd radiogenic isotope ratios from whole rocks and glasses. The error bars show 2 s.e. precision on the measurement. **(D, E, F)** show kernel density estimates of the K_2O/TiO_2 ratios of the material sampled in each eruption. The horizontal lines show the mean composition of the samples from each eruption and the 2 s.e. of the estimate. The Fagradalsfjall 2021 data is from (4) and the data from historical Reykjanes is from (24).

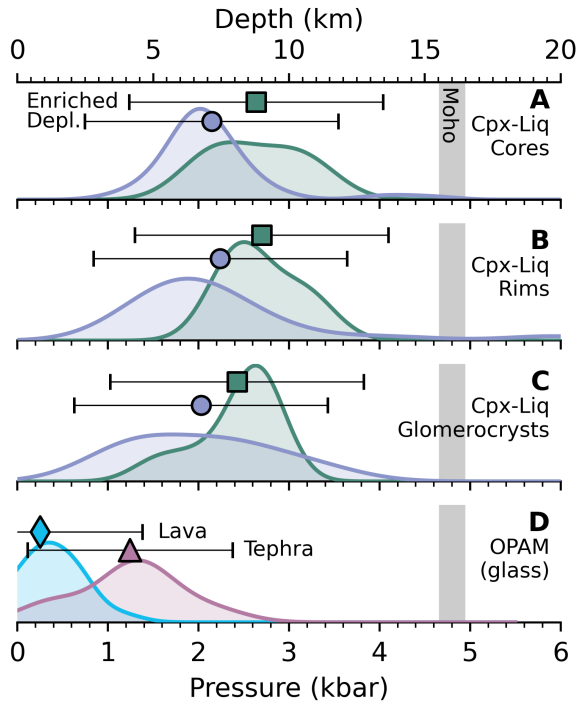


Fig. 3. Magma equilibration pressures derived from OPAM and clinopyroxene-liquid barometry. (A) shows the clinopyroxene-liquid (20, 46) equilibration pressures calculated from crystal core compositions in depleted and enriched whole rocks. (B) and (C) show the same for rims and glomerocrysts. (D) shows the OPAM (21-23) equilibration pressures for glass analyses where the probability of fit is 0.8 or greater. In all panels the symbols show the mean pressure estimate and the error bars the standard error of the estimate (20, 23). The depth scale is calculated assuming the density of the crust is 3000 kg m^{-3} (23, 47). A Moho depth appropriate for the Reykjanes peninsula is indicated (48).

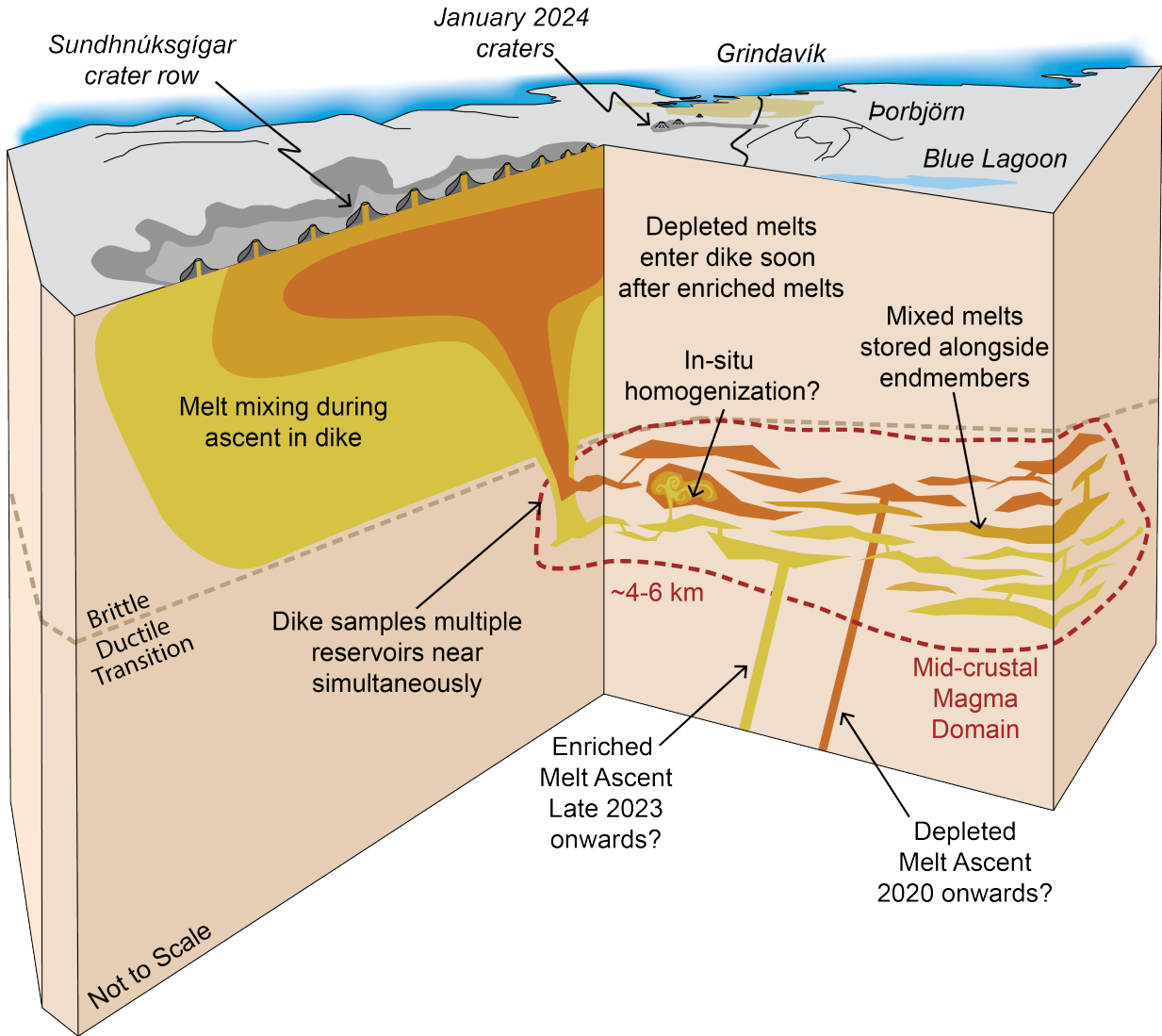


Fig. 4. The structure of the mid-crustal magma domain beneath Svartsengi and its evolution with time. The diagram is drawn looking towards the Southeast. Enriched magmas are indicated by lighter shading (yellow) than the depleted magmas (dark orange). The location of the Sundhnúksígígar crater row is indicated which was the location of the December 2023 and February 2024 fissures. The January 2024 fissures were further South, near Grindavík. The magma domain is indicated at ~4~6 km depth based on the overlap between the clinopyroxene-liquid and OPAM barometers (Fig. 3), as well as the modelled inflation depth (2, 8).

Supplementary Materials for

**A dynamic mid-crustal magmatic system revealed by the 2023-24
Sundhnúkgígur eruptions, Iceland**

Simon W. Matthews^{1*}, Alberto Caracciolo¹, Enikő Bali¹, Sæmundur A. Halldórsson¹, Olgeir Sigmarsson^{1,2}, Guðmundur H. Guðfinnsson¹, Gro B. M. Pedersen¹, Jóhann Gunnarsson Robin¹, Edward W. Marshall^{1,3}, Araksan A. Aden¹, Bryndís Ýr Gísladóttir¹, Chantal Bosq², Delphine Auclair², Heini Merrill¹, Nicolas Levillayer¹, Noëmi Löw¹, Rebekka Hlín Rúnarsdóttir¹, Sóley M. Johnson¹, Sveinbjörn Steinþórsson¹

Corresponding author: simonm@hi.is

The PDF file includes:

Materials and Methods
Supplementary Text
Figs. S1 to S24
Tables S1 to S2
References (49-67)

Other Supplementary Materials for this manuscript include the following:

Data S1 to S5

Materials and Methods

Sample collection

A small number of samples were collected during eruption, from recently solidified lava, recently fallen tephra, or by direct sampling of flowing lava followed by quenching in water. More extensive sampling campaigns were completed following the end of the eruption where we aimed to collect samples representing lava and tephra erupted from different parts of the fissure at different times throughout the eruption. Where possible, glassy crusts were collected in favor of the solidified middle of the lava flows. Dataset S1 includes GPS sample locations as well as brief descriptions of the unit sampled. Following sample collection, the material was catalogued and dried. The samples are currently housed at the Institute of Earth Sciences, University of Iceland, but will be deposited with the Institute of Natural History, Iceland. A total of 66 samples were collected from the December eruption, 18 samples from the January eruption, and 30 from the February eruption. In addition two samples (Sund-01 and SHA) were collected from the old Sundhnúksígur craters, erupted ~2400 years ago.

ICP-OES whole rock major element analysis

Representative portions of the samples were powdered using a shatterbox with a tungsten carbide grinding container. The container was cleaned with water and compressed air between samples and was pre-contaminated by powdering a smaller amount of sample material. A mixture of 100 mg of sample powder and 250 mg of LiBO₂ were fluxed at 1000°C in a graphite crucible for ~40 minutes. The cooled glass bead was then dissolved in 50 ml 5% nitric acid. Solutions of USGS standards BHVO-1, BIR-1 and W-2, in addition to in-house reference materials A-THO, B-THO, B-ALK and MSR161014-1 were prepared the same way. The concentrations of SiO₂, Al₂O₃, FeO, MnO, MgO, CaO, Na₂O, K₂O, TiO₂, and P₂O₅ were then determined by inductively coupled plasma optical emission spectroscopy (ICP-OES) using the ThermoFisher iCAP 7400 Duo instrument at the University of Iceland Plasma Center. The in-house standards A-THO, B-THO and B-ALK were used to calibrate the instrument, MSR161014-1 was run every 5 samples to monitor drift and repeated analyses of BIR-1, BHVO-1, and W-2 were used to assess accuracy and precision (figs. S13-S14, Dataset S2). B from the LiBO₂ was used as an internal standard.

The values for 2σ reproducibility on K₂O/TiO₂ across all OES sessions for BHVO-1 and W2 are 4.6% and 5.9%, respectively (fig. S15). The reproducibility for K₂O/TiO₂ is substantially worse for BIR-1, with a 2σ value of 37%, owing to the concentration of K₂O being an order of magnitude lower. However, the material erupted in the 2023 and 2024 eruptions at Sundhnúksígur have K₂O and TiO₂ concentrations of a similar order to BHVO-1 and W2, hence a 2σ intersession reproducibility of 5.9% is appropriate for K₂O/TiO₂ in these samples.

EPMA glass and mineral analysis

Major element compositions of groundmass glass (n=252), plagioclase (n=67), olivine (n=91), clinopyroxene (n=168) and spinel (n=69) were determined in grain mounts by electron probe microanalysis (EPMA) using the JEOL JXA-8230 SuperProbe at the Institute of Earth Sciences, University of Iceland. In addition, glass analyses from three samples (G20231220-1, G20240114-4, and G20240208-2) acquired in the same sessions, but published by (49), are included in the compilation and figures. To address the lack of glass in the depleted material erupted in December, analyses (n=6) were obtained from the microcrystalline matrix of G20231221-3 using a defocused beam, along with glass hosted in embayments, with the aim of constraining the matrix K₂O/TiO₂ ratio for comparison with the whole rock (fig. S3).

The microprobe is equipped with five wavelength-dispersive spectrometers (WDS) and an energy-dispersive spectrometer. Analyses were acquired using a 15 keV accelerating voltage and a probe current of 10-20 nA. Groundmass glasses were analyzed with a defocused electron beam of 10 μm . To avoid Na loss in glasses, Na was always analyzed first on its spectrometer with a relatively short counting time (20 s on the peak, 10 s on the background). For all other elements, counting times were 30-40 s on the peak and 15-20 s on the background. All mineral phases were analyzed with a beam size of 5 μm . Counting times for olivine and clinopyroxene analyses were 30 s on peak and 15-30 s on background, while for plagioclase crystals the counting times were 40 s and 20-40 s on peak and background, respectively. The CITZAF correction program (50) was used for all analyses. Information on the standardization and counting times are given in Tables S1-S5.

Precision and accuracy were estimated by repeat measurements on secondary standard materials at the start and end of each session and are reported in Data S3. The accuracy of the $\text{K}_2\text{O}/\text{TiO}_2$ ratio measured in the glass was within the precision (2σ) of 5.5%. For most oxides measured in the glass standard, the session means are within 2 standard deviations of the accepted values (51) (fig. S16). For the other oxides they are within the range of values reported on GEOREM. The accuracy and precision on olivine Fo, clinopyroxene Mg#, spinel Mg#, and plagioclase An are all better than 2%. The full dataset is provided in Data S3.

ICP-MS trace element analysis

For each sample ~50 mg of cleaned and picked glass was digested in a mixture of distilled HF-HNO₃ in acid-cleaned Savillex Teflon beakers in the metal-free clean laboratory at the University of Iceland Plasma Center. Residual fluorides were removed by repeated reflux in 6M HCl acid until they could no longer be seen. They were then brought up in 6M HCl acid, before being further diluted in a 2% HNO₃ and 1% HCl solution (dilution factor of ~5000), acidified to about 0.05% HF and spiked with an In-Re solution, used as an internal standard. The samples were then transferred into acid-leached vials. Trace element concentrations were determined on the ThermoFisher iCAP RQ Quadrupole Inductively Coupled Plasma Mass-Spectrometer (ICP-MS) at the University of Iceland Plasma Centre, using a HF resistant inlet system. Powders of BIR-1, BCR-2, AGV-2, and W-2 standards were prepared in the same way and used for calibration. A solution of the BHVO-2 standard powder (also prepared in the same way) was used to assess accuracy. Most elements were within 1% of the GEOREM preferred values (Dataset S4), including La, Yb, Ce, and Y, which are used in fig. S4.

Sr and Nd radiogenic isotope analysis

Sr and Nd isotopes were analyzed at Laboratoire Magmas et Volcans at Université Clermont Auvergne using a Triton (ThermoScientific) thermal ionization mass spectrometer. Tephra and lava samples were crushed in a jaw crusher and powdered in an agate bowl using a planetary mill. A separate aliquot of crushed SHA was leached in ~1N HCl in an ultra-sonic bath for 30 minutes, with the leachate reserved and put through the following chemistry. The leached sample was then powdered. Approximately 100 mg of powder was dissolved in concentrated HF and HNO₃ acids in a 3:1 ratio, and the fluoride residue was reduced by repeated dissolution and evaporation in 6N HCl and 14N HNO₃. Isolation of Sr and Nd followed the protocol from (52), and their isotope ratios were measured by thermal ionization mass spectrometry. Strontium isotope ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and to the recommended value of the NIST 987 standard ($^{87}\text{Sr}/^{86}\text{Sr} = 0.710245$). International reference materials were used to ensure accuracy and precision, as described in (4). The data is reported in Data S5.

OPAM Geothermobarometry

Calculations were performed using the pyOPAM script (23, 53) which implements the parameterization by (54) and the filtering procedure of (55). Following (23, 55), we exclude results that have a probability of fit < 0.8 . Though this is an arbitrary cut off, Fig. S17 shows that this does not bias the predicted pressures. Where analyses have a probability of fit > 0.8 , other analyses from the same sample do not, which is likely caused by small scale compositional heterogeneity caused by partial re-equilibration during ascent or eruption (Fig. S17B). The uncertainties in the electron probe analyses are not directly propagated but are indicated by the scatter in pressure estimates (Fig. S8). When converting pressures to depth, a density of 3000 kg m^{-3} is assumed for the crust (23, 47). The results from applying the OPAM barometer (including the probability of three phase saturation) are given in Data S3.

Clinopyroxene-liquid barometry

Equilibration pressures for clinopyroxene and liquid were estimated using the cpx-liquid barometer (20). Calculations were performed with the ThermoBar python library (56). Equilibrium was tested between glass analyses (from all three eruptions) and clinopyroxene core, rim, and glomerocryst analyses. The criteria used for identifying equilibrium were the same as those used by (20). Following the suggestions of (20), low Al sectors were removed from the dataset, with a cut off of 0.125 Al on a 6O basis, identified by the scattered population of clinopyroxene analyses below this threshold (Fig. S18A). This removes a low (and negative) pressure population from the results (Fig. S18B). The clinopyroxene analyses from depleted (low $\text{K}_2\text{O}/\text{TiO}_2$) whole rocks match with both depleted and enriched glass compositions (Figs. S19-S21), but the pressure dependence of this is weak and well within the uncertainty of the barometer (± 1.4 kbar). Though the majority of the estimated equilibration pressures cluster around 2 kbar, a small number of clinopyroxene-liquid pairs return pressures up to ~ 6 kbar, with the highest two pressures associated with analyses of clinopyroxene rims (Fig. S11). These higher-pressure estimates are associated with a higher jadeite component in the clinopyroxene (Fig. S18c) and may represent locally higher Na_2O contents surround the growing clinopyroxene crystals. The uncertainty in the electron probe analyses are not directly propagated, but are indicated by the scatter in mean pressures estimates (Fig. S11). When converting pressures to depth, a density of 3000 kg m^{-3} is assumed for the crust (23, 47). The results of the clinopyroxene-liquid barometry are given in Data S3.

Liquidus temperature calculations

For estimating the liquidus temperatures two thermometers are used. The first is Eqn. 15 from (57) which is calibrated on experimental olivine-saturated liquids incorporating terms for the pressure, liquid Mg#, and MgO, FeO, Na_2O , K_2O and H_2O concentrations. The H_2O concentration for each sample was estimated using the correlation observed between K_2O and H_2O in minimally degassed Icelandic glasses (58), by scaling linearly between 0.45 wt% H_2O for 0.3 wt% K_2O and 0.8 wt% H_2O for 0.6 wt% K_2O . The uncertainty in the temperatures derived from this equation is $\pm 46^\circ\text{C}$ (56). The second thermometer is Eqn. 16 from (57) which is calibrated on experimental liquids saturated in olivine, plagioclase, and clinopyroxene. The calibration incorporates terms for pressure, and mole fractions of SiO_2 , Al_2O_3 , MgO, SiO_2 , and Al_2O_3 in the liquid. Temperatures estimated using this thermometer have an uncertainty of $\pm 19^\circ\text{C}$ (56). For both thermometers a pressure of 2 kbar was used, consistent with the results from clinopyroxene-liquid barometry. Calculations were performed using the ThermoBar python library (56).

Identifying timing of lava emplacement

A small number of the lava samples were collected from active flow fronts, meaning the timing of flow emplacement is defined precisely. For samples collected from cooled flows we estimated the timing of their emplacement by comparing the GPS coordinates of the sampling location with remote sensing data (made publicly available by Landmælingar Íslands) using the geographic information system software QGIS.

December 18th -21st, 2023 eruption: Online web camera data provided the times that particular segments of the fissure opened and then became inactive. Due to the bad weather during most of the eruption, the first map of the lava flow field was produced at the very end of the eruption on December 21st, based on orthomosaics and lava thickness maps from an aerial survey that day. At that time only one part of the lava field was active. Most of the lava field was emplaced during the night between December 18th 22:17 and December 19th 06:00. During this period two helicopter flights (December 18th 23:30- December 19th 00:30, and December 19th 04:30-05:30) were made to the area. On these flights, oblique photographs were taken covering the whole area, providing constraints on which lobes were active during these times. In addition, four ICEYE SAR amplitude images were acquired on December 19th at 03:57, 11:34, 17:49, and on December 21st at 03:03, with variable inclination angles and resolutions. However, identification of the lava flow fronts on the eastern side of the area was difficult due to the similarity in roughness between the new lava and pre-existing lava field.

January 14th-16th, 2024 eruption: Online web camera data provide information on the timing of the opening of the two fissures, and when the activity had shut down. Four aerial acquisitions providing orthomosaics, lava flow thickness maps, and lava outlines were used to identify the approximate timing of activity in the lava field at the lava sample locations. The aerial acquisitions were obtained on January 14 at ~13:50; ~14:00 and ~17:00 and Jan. 15 at ~14:00.

February 8-9 eruption: Online web camera data provide information on the timing of the opening of the fissures, the progression of the western lava flow that crossed the road Grindavíkurvegur and the hot water pipes, and the time when activity had ceased. Two flights providing orthomosaics, lava flow thickness maps and lava outlines were acquired on February 8 at ~13:00 and ~17:00 and another flight were acquired on February 14 after the eruption had stopped.

Where it was possible to constrain the timing of lava and tephra emplacement, this is given in Data S1. A qualitative assessment of the confidence in the time constraints is given, determined by the clarity of the remote sensing data and photo observations.

Software used for preparing figures and data analysis

Figures were prepared using pyGMT (59, 60) and Matplotlib (61). Data analysis was performed using pandas (62, 63) and numpy (64). Other software is cited in the appropriate methods section above.

Supplementary Text

Relative timing of lava emplacement and tephra deposition

Though the constraints on the relative timing of tephra deposition and lava emplacement during the December eruption remains largely uncertain (Fig. S7A), some qualitative constraints can be placed on the relative timing. The tephra deposited far from the vents (at the far east of the area shown in Fig. 1B and adjacent to the eastern lava front) is enriched. Where the tephra was collected adjacent to the lava flows, no tephra was seen on top of the lava, indicating it was deposited early and likely during the intense fountaining at the start of the eruption. The last major lobe to be emplaced at the edge of the flow field was at the

northwestern extent, which consisted of depleted lavas (Fig. 1A, fig. S6C). The tephra samples collected from close to the vents at the southern and northern extremities of the fissure show some variability in their ratios (Fig. 1B). These vents were active only near the start of the eruption yet display moderately low to high K_2O/TiO_2 ratios. As the eruption continued, lavas were largely emplaced on top of the flows emplaced within the first hours of the eruption. Samples could not be obtained from the middle of the lava field for safety reasons.

Mixing endmembers

To investigate the relationship between the depleted and enriched endmembers seen in the Sundhnúsgígur products and the Fagradalsfjall 2021 products (4), some illustrative mixing models were developed. We consider the $^{87}Sr/^{86}Sr$ - $^{143}Nd/^{144}Nd$ systematics first, and then separately K_2O/TiO_2 -La/Yb. We then show that while models can be developed in both spaces that match the data, they are inconsistent with each other, ruling out either endmember composition being the same in the Sundhnúsgígur magmas and the Fagradalsfjall magmas.

Since mixing arrays in $^{87}Sr/^{86}Sr$ - $^{143}Nd/^{144}Nd$ space are curved, when considering only this space (and no other chemical parameters) it would be possible to find two mixing lines from identical depleted and enriched endmembers that can match both Sundhnúsgígur and Fagradalsfjall. However, the curvature depends on the relative Sr and Nd concentrations. The solid black lines in Figs. S22 and S23A,B show the mixing model between possible endmembers identified for the Sundhnúsgígur products. The grey dashed line shows the mixing curve that is generated by mixing between the same endmembers but while simultaneously matching the Sr and Nd concentrations in the Fagradalsfjall 2021 lavas. The poor fit of the dashed line to the Fagradalsfjall 2021 data indicates that the mixing endmembers cannot have identical $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios for both Sundhnúsgígur and Fagradalsfjall. It is possible, however, to find a model that matches the observations but with the same depleted endmember and different enriched endmembers (the dotted line in Figs. S22 and S23A,B). The mixing model parameters are given in Table S6.

Likewise, a model can be developed that matches the K_2O - TiO_2 and La-Yb systematics for Fagradalsfjall and Sundhnúsgígur, with a single depleted endmember and different enriched endmembers (Figs. S4C, S22, S23C,D). The mixing model parameters are given in Table S7. However, the depleted endmember must be extended to a much more extreme composition than for the Sr-Nd isotope systematics. Consequently, the mixing models that match the K_2O - TiO_2 and La-Yb systematics with a single depleted endmember require different mixing proportions (indicated by the dots at 10% increments on each model line) for each sample relative to the mixing models that match the Sr-Nd systematics. The two models are mutually inconsistent, demonstrating that both the depleted and enriched endmember have distinct compositions to those seen at Fagradalsfjall.

The extent of fractional crystallization of the endmember melts

Though the preceding section has ruled out that endmembers of the same composition are parental to both the Fagradalsfjall and Sundhnúsgígur magmas, the compositional differences are subtle. The higher concentrations of incompatible elements (e.g., K_2O , TiO_2 , La, Yb) in the Sundhnúsgígur magmas (compared to Fagradalsfjall) is most likely generated largely by differing amounts of fractional crystallization, with the concentrations in the primary melts playing a subordinate role. Though the whole rock compositions are variably affected by crystal accumulation, which will act to dilute the incompatible elements, it likely has a similar magnitude effect in both the Fagradalsfjall and Sundhnúsgígur whole rocks. The relative K_2O concentrations of the endmember magmas can therefore be used to provide

an approximate estimate of the additional amount of crystallization experienced by the Sundhnúksgígar magmas.

Assuming perfect incompatibility, the relative amount of fractional crystallization between a more primitive melt C_0 and evolved melt C_1 is given by:

$$X = 1 - \frac{C_0}{C_1}$$

The maximum and minimum K_2O concentrations are used for the enriched and depleted melts, respectively, with C_0 derived from the Fagradalsfjall whole rock compositions (4), and C_1 from the Sundhnúksgígar whole rock compositions. This gives 46% crystallization for the depleted endmember and 35% crystallization for the enriched endmember.

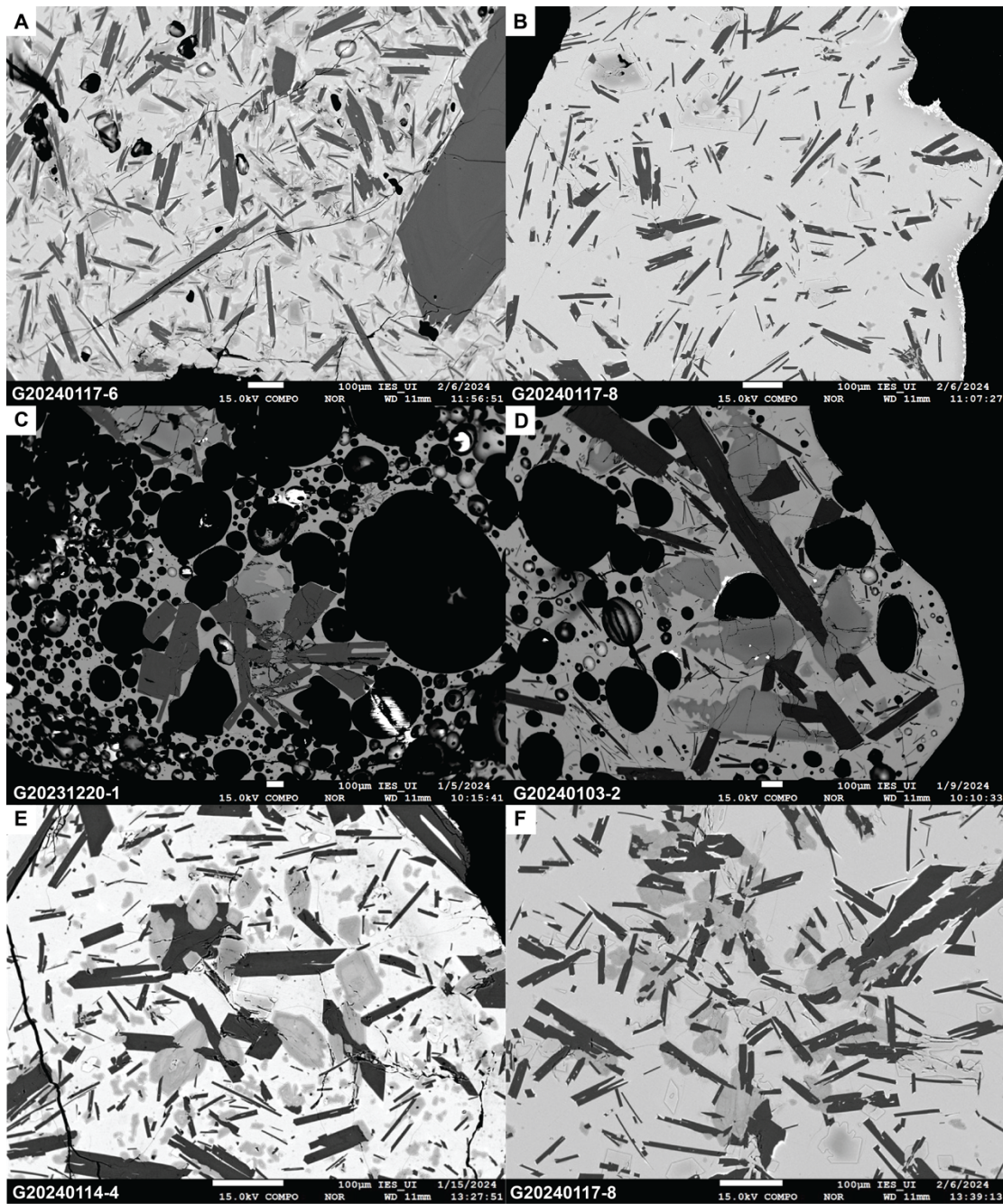


Fig. S1.

Backscatter electron images showing typical textures of the Sundhnúksígigar products. (A) shows the relatively microlite-rich glassy lava G20240117-6 from the January eruption. (B) shows glassy lava crust G20240117-8 from the January eruption. (C) shows vesicle-rich tephra G20231220-1 erupted in December. (D) shows tephra G20240103-2 also erupted in December. (E) and (F) show glomerocrysts of clinopyroxene, plagioclase, and olivine in lavas G20240114-4 and G20240117-8 erupted in January.

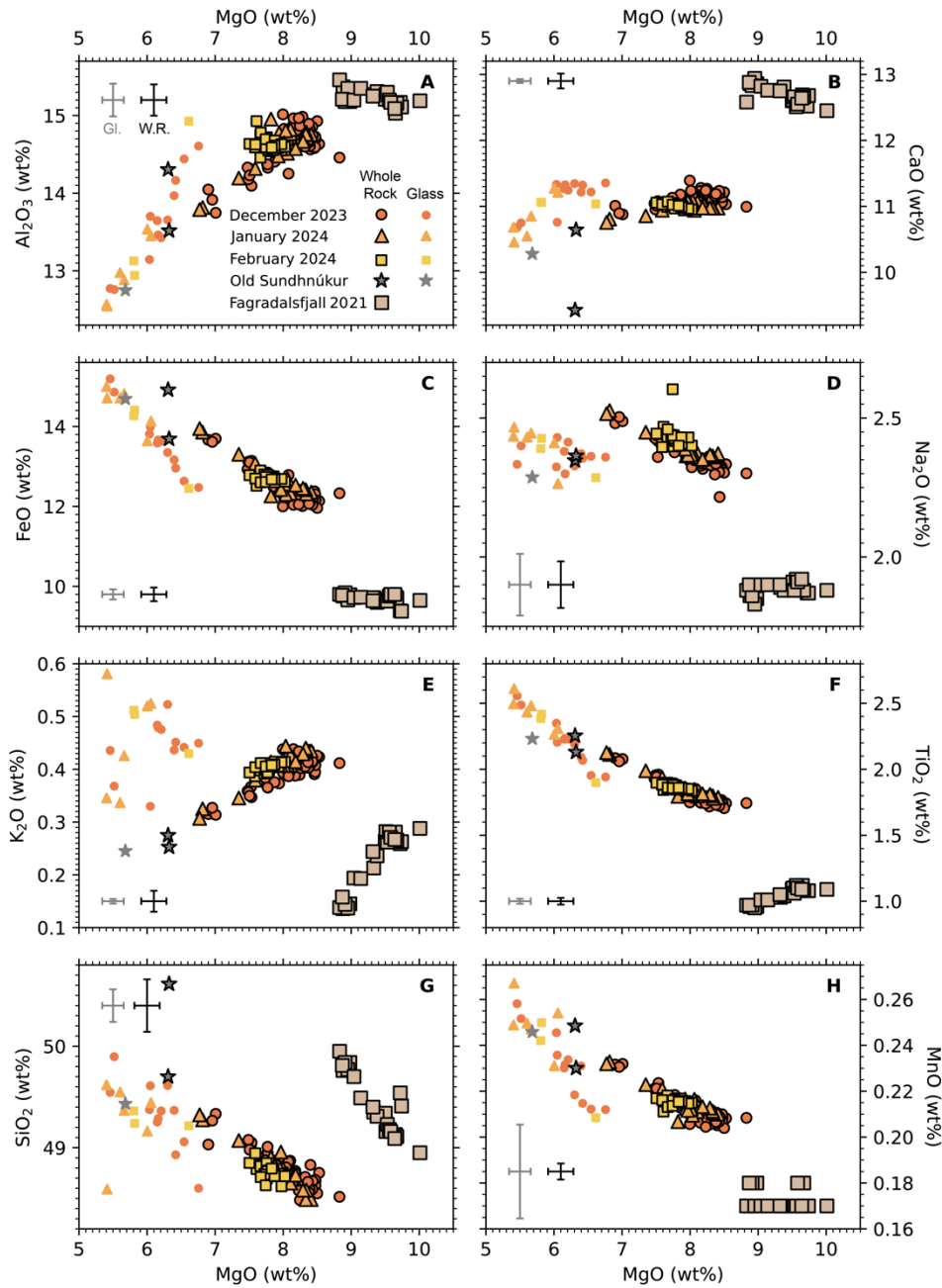


Fig. S2

The major element oxide concentrations for whole rocks and glasses from the Sundhnúkgígur eruptions compared with whole rock measurements from Fagradalsfjall 2021 (4) and old Sundhnúkgígur tephra. Each glass symbol shows the average of many EPMA analyses distributed across the sample. The error bars shown in black give the representative 2σ of repeat standard measurements across all ICP-OES sessions, and the accuracy is within this range. The grey error bars show 2σ variation between sessions of the mean of the analyses of secondary standard material A99.

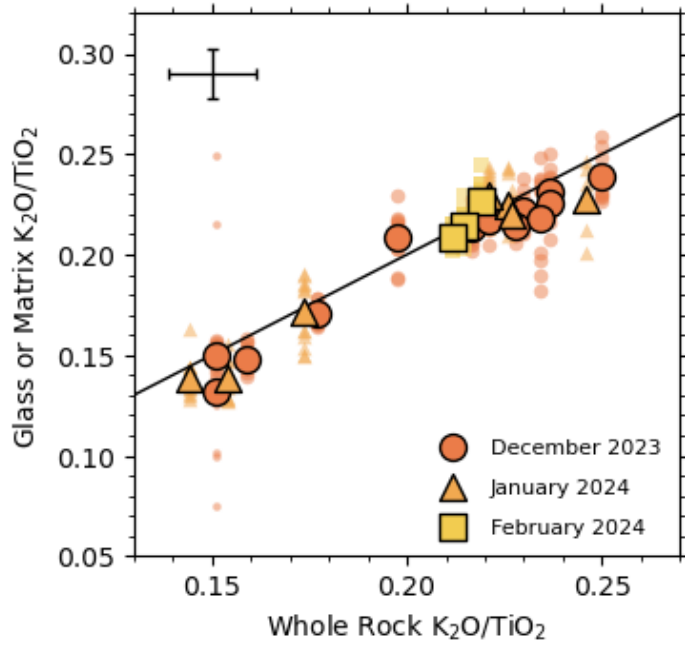


Fig. S3

Comparison of the K₂O/TiO₂ ratios measured on whole rock powders by ICP-OES and in-situ glass by EPMA. Small symbols show individual glass analyses, and large symbols show their mean. The small symbols at K₂O/TiO₂ ~0.15 are derived from measurements of a crystalline matrix with a defocused beam. The error bars are as described in the caption to Fig. S2. The solid line is a 1:1 line.

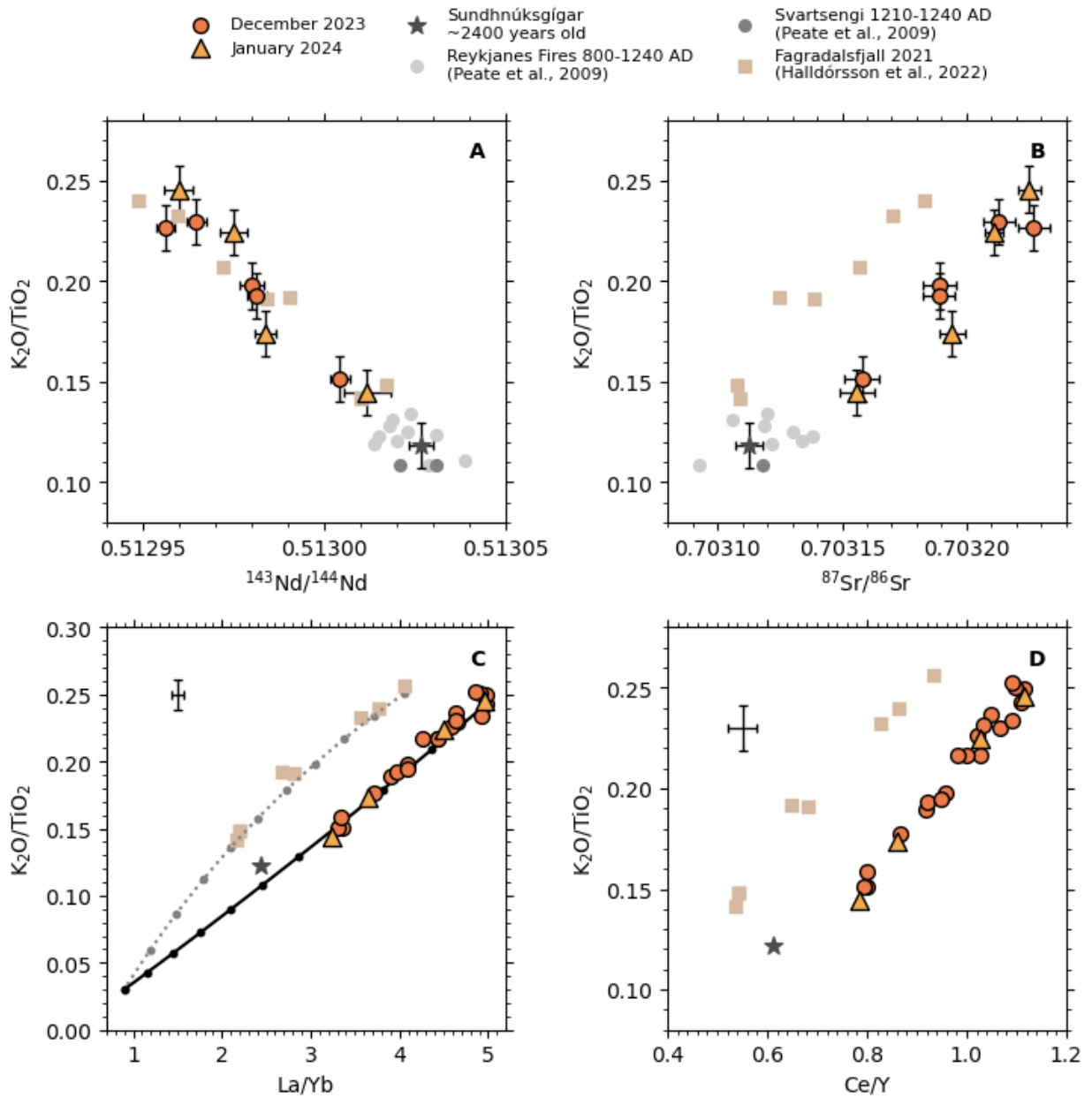


Fig. S4

Comparison of whole rock K_2O/TiO_2 with whole rock radiogenic isotope ratios and incompatible trace element ratios of picked glass. The error bars show the 2σ variability across measurement sessions, except for $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ where they are the 2 s.e. on each analysis. The lines in Panel (C) show the same mixing model as in Fig. S23B,C.

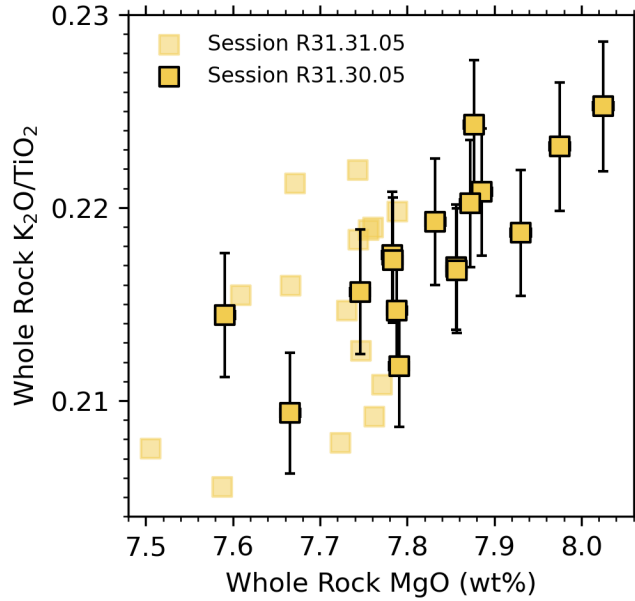


Fig. S5

The K₂O/TiO₂ ratios and MgO concentrations of the February lava and tephra. The analyses were performed over two sessions (R31.30.05 and R31.31.05). The internal precision of session R31.30.05 was sufficient to resolve variation in K₂O/TiO₂. The error bars show the estimated 2σ precision of the analyses on each sample analyzed in Session R31.30.05, using the precision on repeated BHVO-2 analyses (which was the least well reproduced standard in this session) and the formula $\sigma/\mu = \sigma_{BHVO2}/\mu_{BHVO2}/\sqrt{n}$, where n=2, the number of analyses of each sample, and μ is the mean. The precision of the MgO concentrations is smaller than the size of the symbol. The external accuracy is larger than the precision on the individual session and is better represented by the error bars on Fig. 2B of the main text.

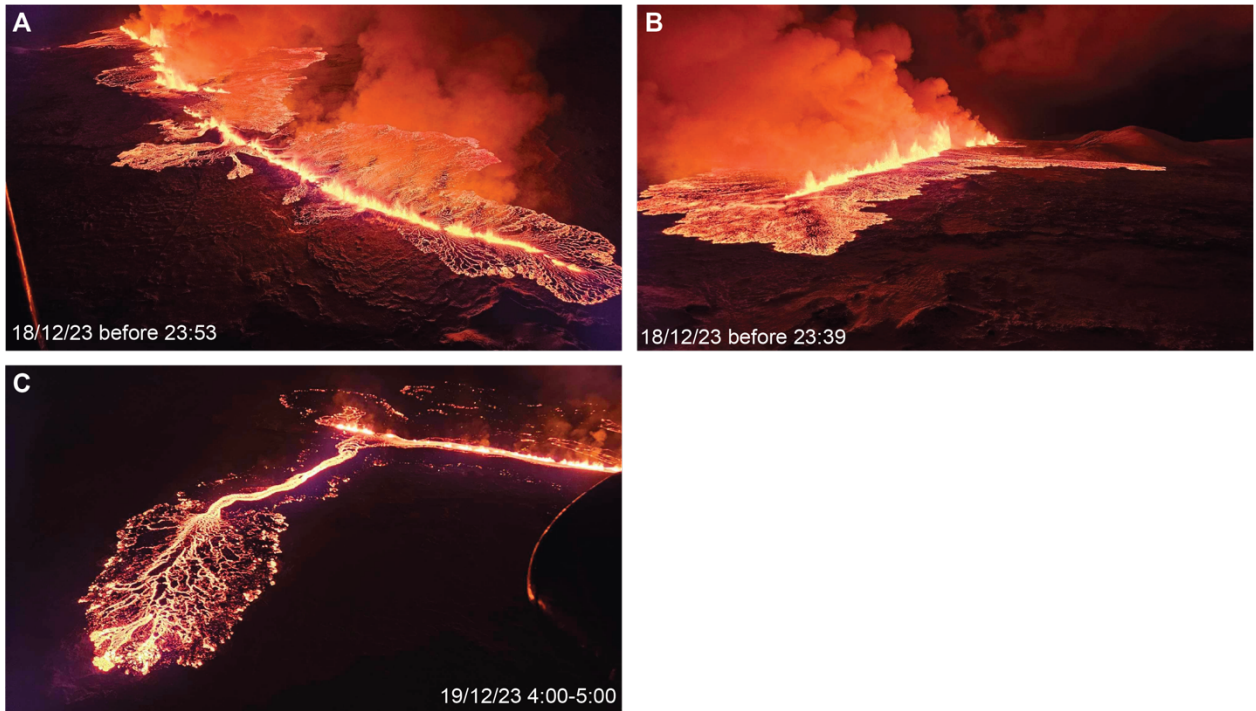


Fig. S6

Photos taken in the first hours of the December eruption during flights over the lava field. Photos courtesy of Almannavarnadeild Ríkislögreglustjóra (Department of Civil Protection and Emergency Management, Iceland). (A) is taken from the southwest corner of the flow looking northeastwards. (B) is taken from the northeast corner of the flow, looking southwestwards. (C) is taken in the northwestern corner of the flow looking northeastwards.

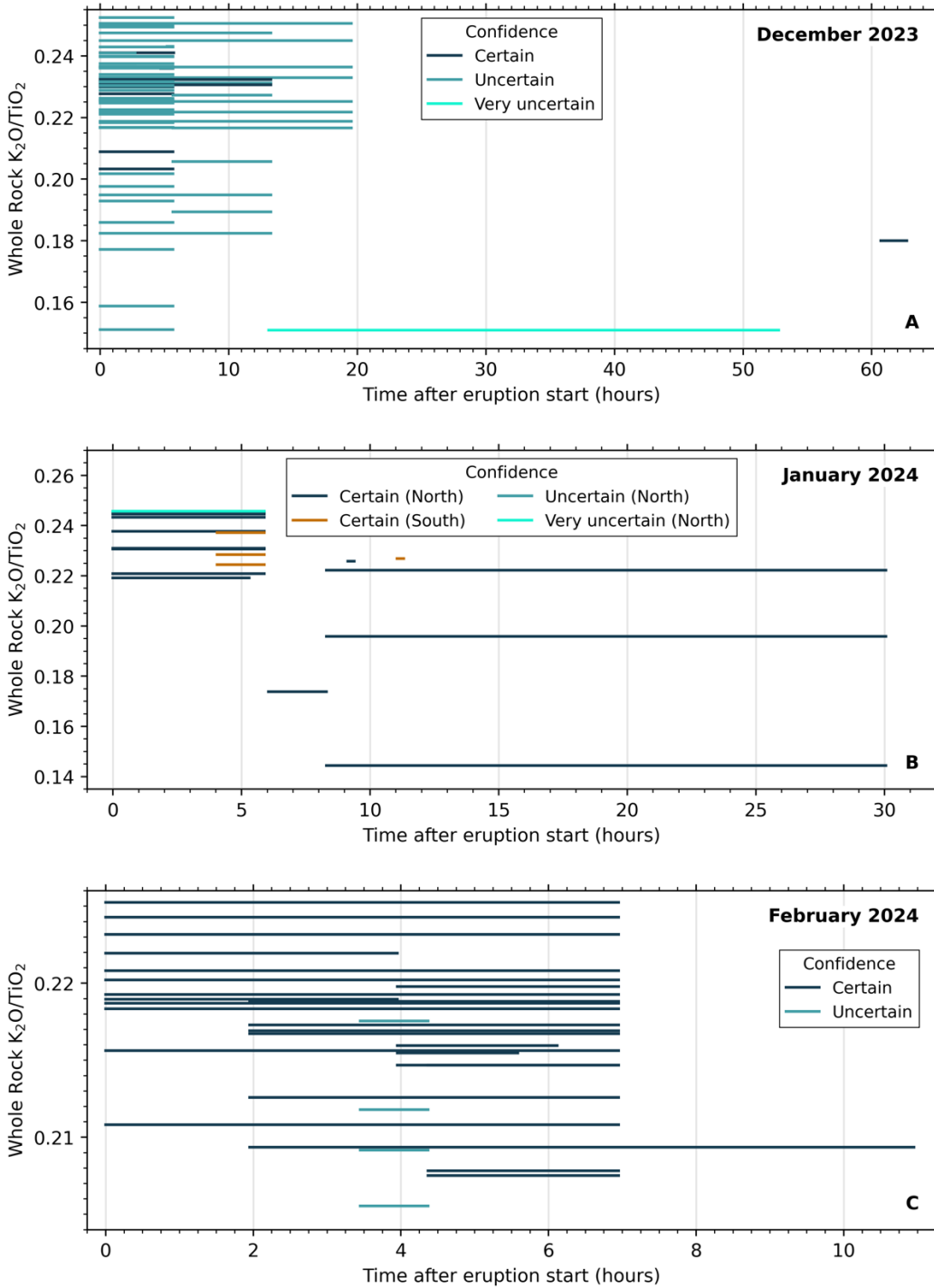


Fig. S7

Each line shows an individual lava or tephra sample and indicates the time window in which it could have been emplaced, alongside the whole rock K_2O/TiO_2 ratio. Qualitative indications of the certainty of these constraints are indicated by the color/shading of each line. Since eruption occurred from two distinct fissures in January, these samples are separated in panel (B).

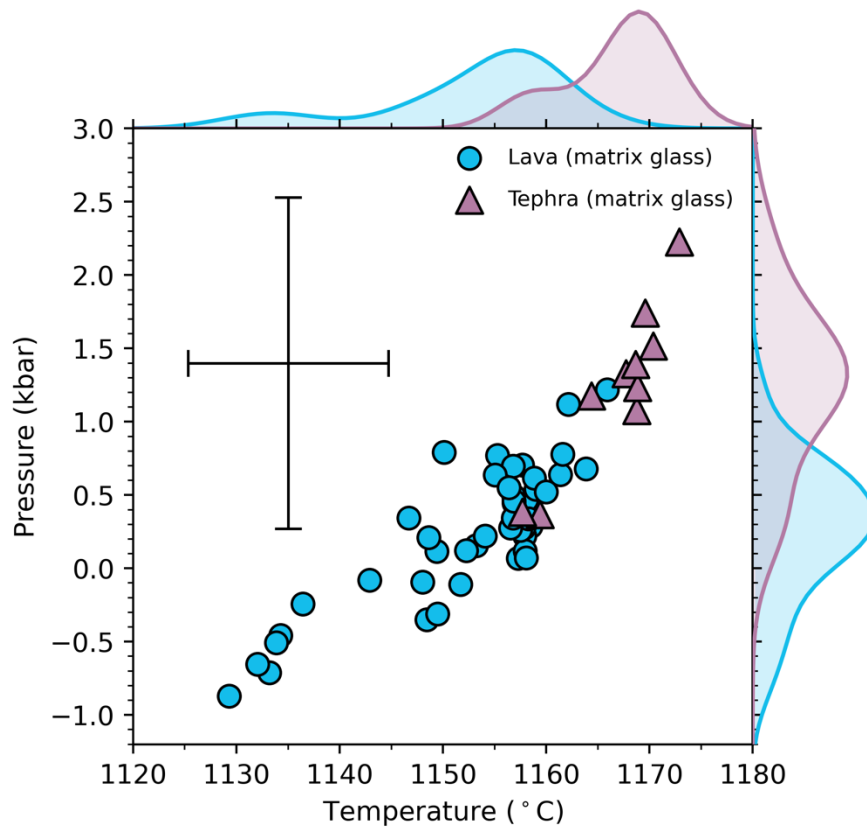


Fig. S8

Equilibration temperatures and pressures of lava and tephra glass calculated using the OPAM geothermobarometer (54). Only results where the estimated probability of three-phase saturation was > 0.8 are shown. The error bars show the mean absolute error of the parameterization (23, 53).

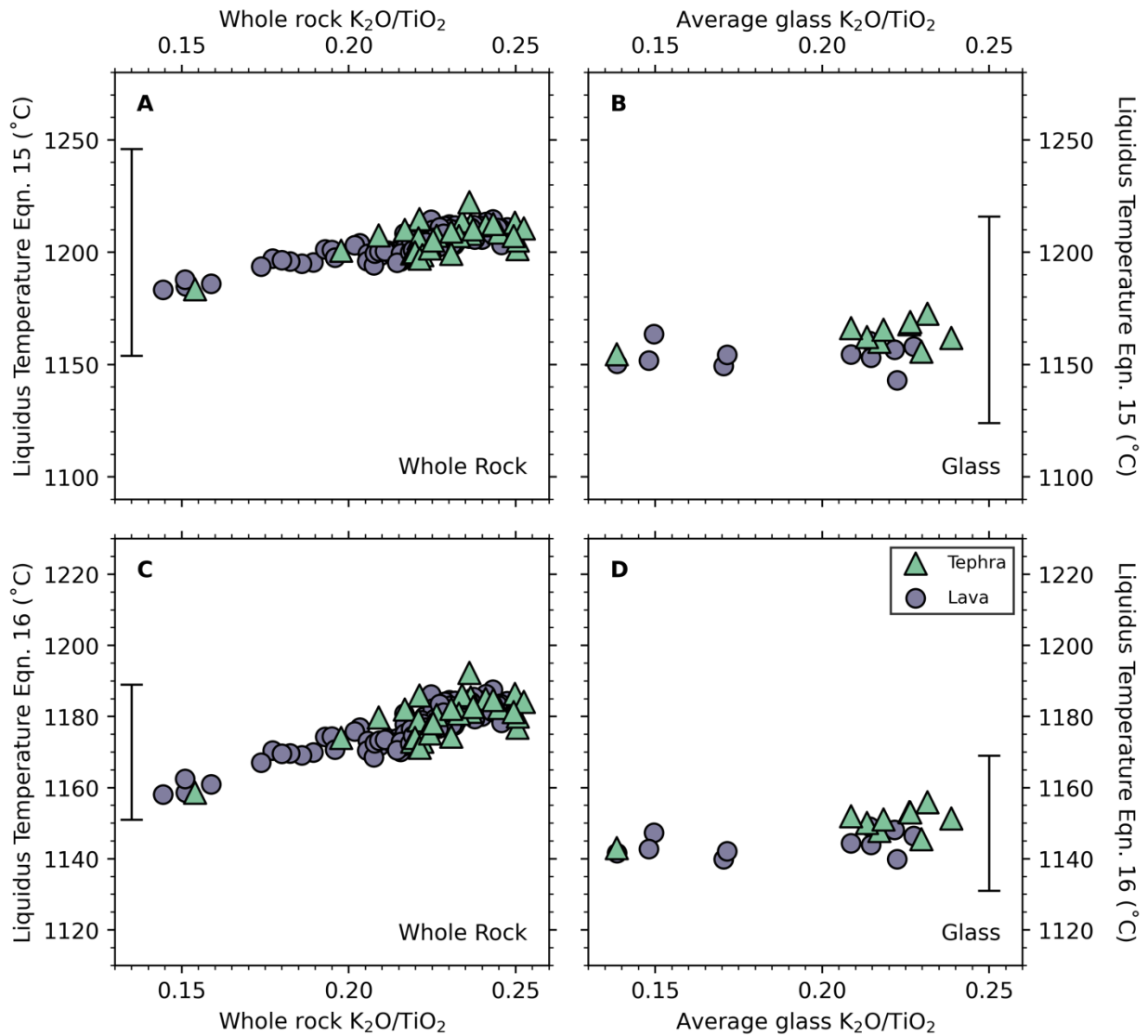


Fig. S9

Liquidus temperatures calculated using parameterizations of olivine-saturated (Eqn. 15) and olivine-clinopyroxene-plagioclase-saturated (Eqn. 16) experiments (57), using the major element oxide concentrations in whole rocks (A & C) and in glass (B & D). The error bars show the reported uncertainty on the thermometer (57). Error bars for K_2O/TiO_2 are omitted.

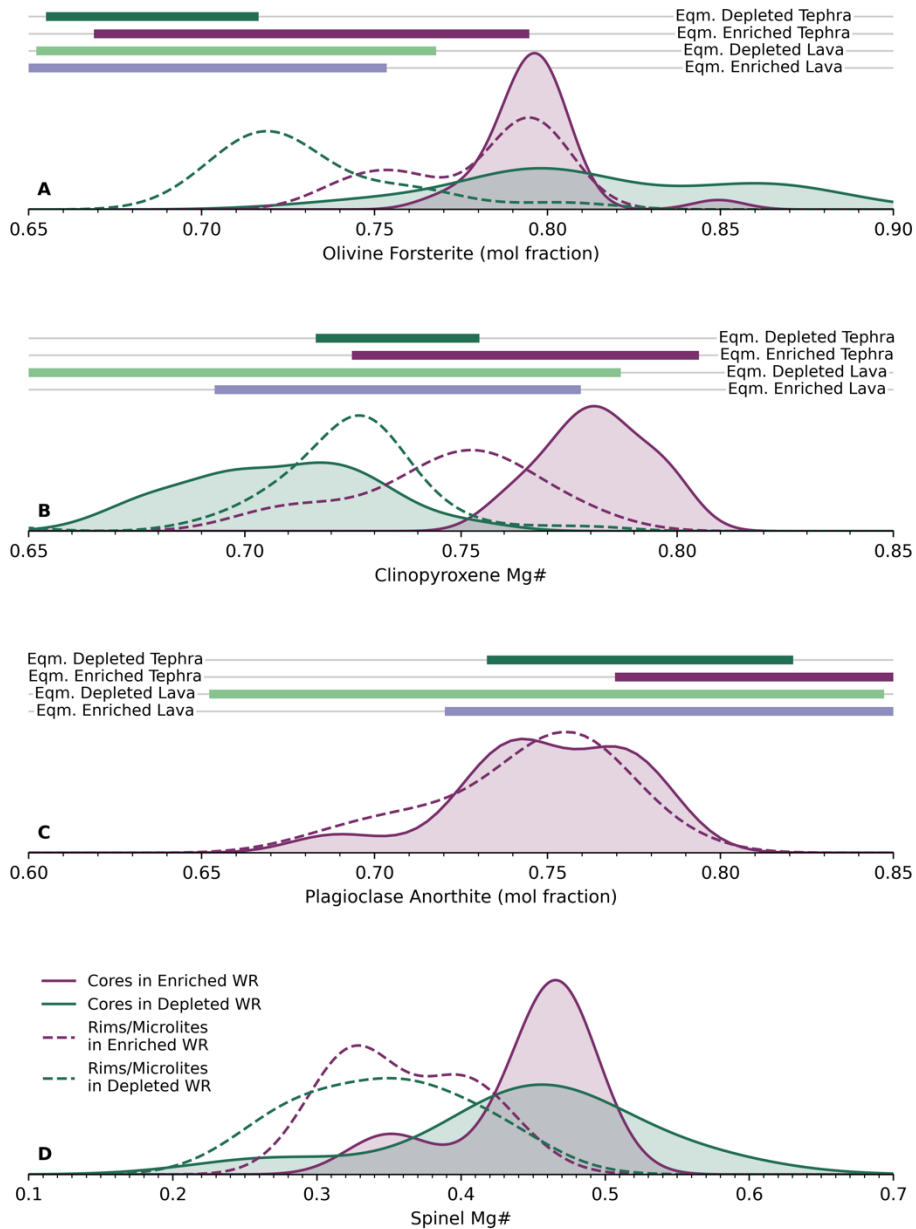


Fig. S10

Summary of olivine (A), clinopyroxene (B), plagioclase (C), and spinel (D) compositions, grouped into categories based on whole rock $K_2O/TiO_2 < 0.19$ (depleted) and $K_2O/TiO_2 > 0.19$ (enriched). The range in composition of olivine, clinopyroxene, and plagioclase predicted to be in equilibrium (marked Eqm. on the figure) with glass from the depleted and enriched tephra and lava are shown. The equilibrium olivine compositions were calculated assuming a K_d of 0.3. The equilibrium clinopyroxene compositions were calculated using the method by Wood & Blundy (65). The equilibrium plagioclase compositions were calculated using the method of Namur et al. (66). The individual analyses are shown vs whole rock K_2O/TiO_2 in Fig. S24.

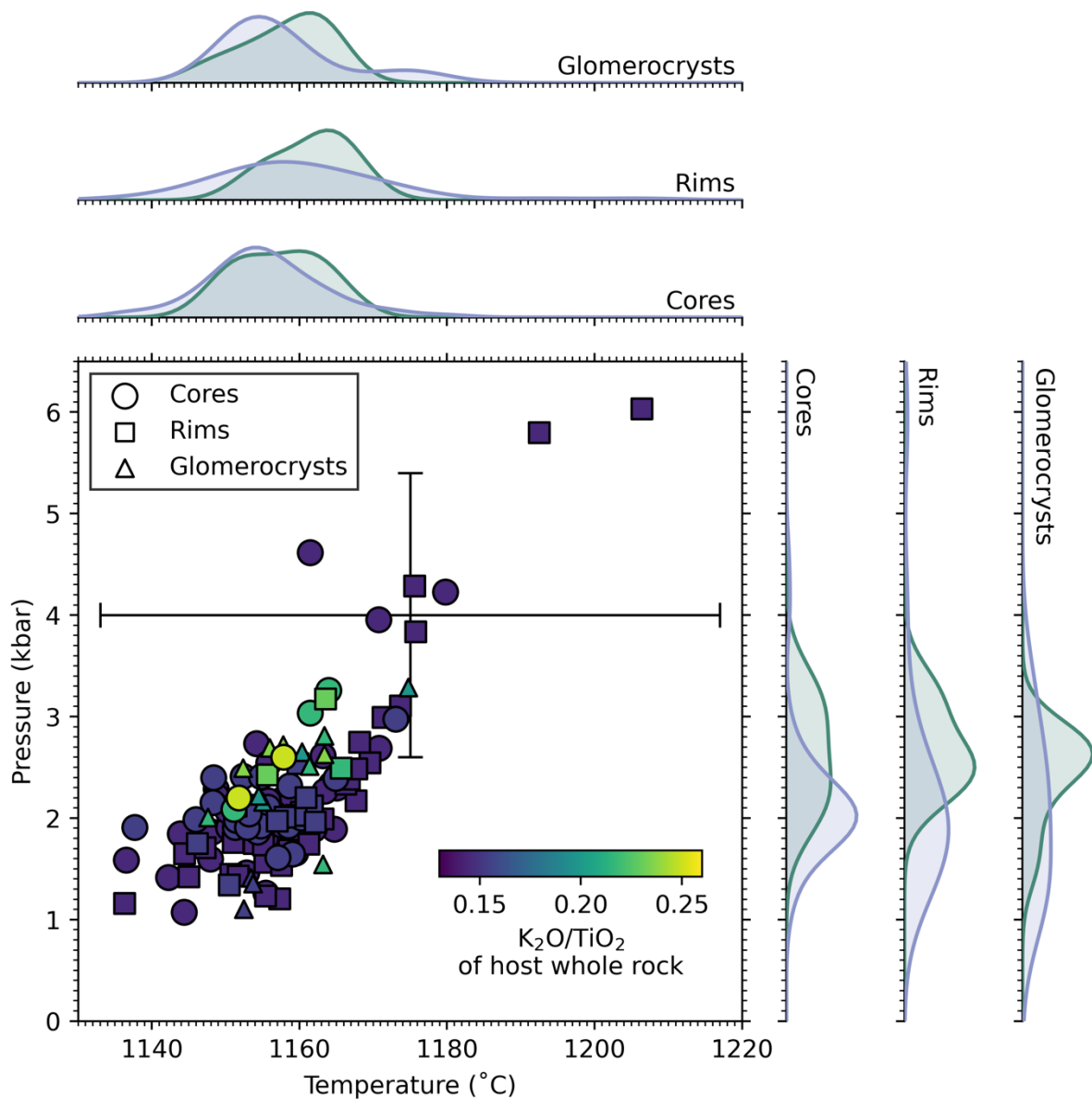


Fig. S11

Results of applying the clinopyroxene-liquid geothermobarometer (20, 56). Each symbol indicates the mean temperature and pressure calculated from a single clinopyroxene analysis and all matched liquids. The shading of the symbols shows the $\text{K}_2\text{O}/\text{TiO}_2$ ratio of the whole rock whence the crystals derived. The kernel density estimates show pressures and temperatures grouped according to whether the whole rock has $\text{K}_2\text{O}/\text{TiO}_2 < 0.19$ (depleted, blue) or $\text{K}_2\text{O}/\text{TiO}_2 > 0.19$ (enriched, green). The error bars show the reported uncertainty of the geothermobarometer.

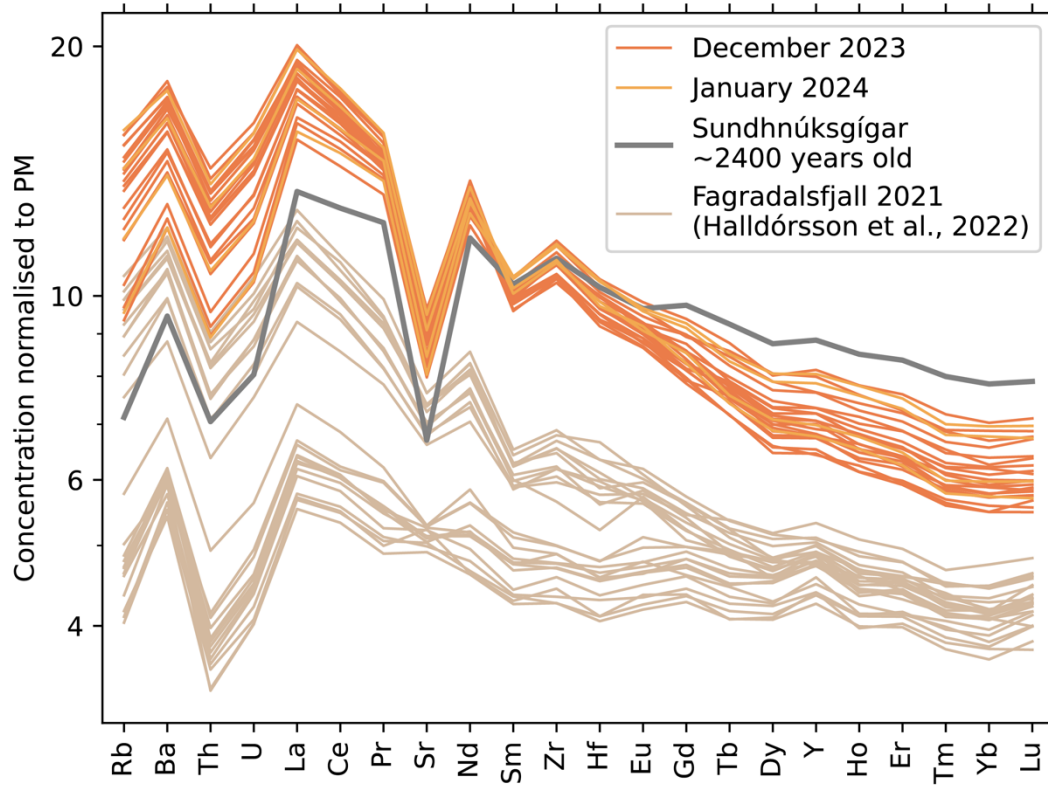


Fig. S12

Comparison of the trace element concentrations in the December and January eruptions with Fagradalsfjall 2021 (4) and old Sundhnúksígígar. Each line represents a single sample. The concentrations are normalized to the composition of the primitive mantle (67).

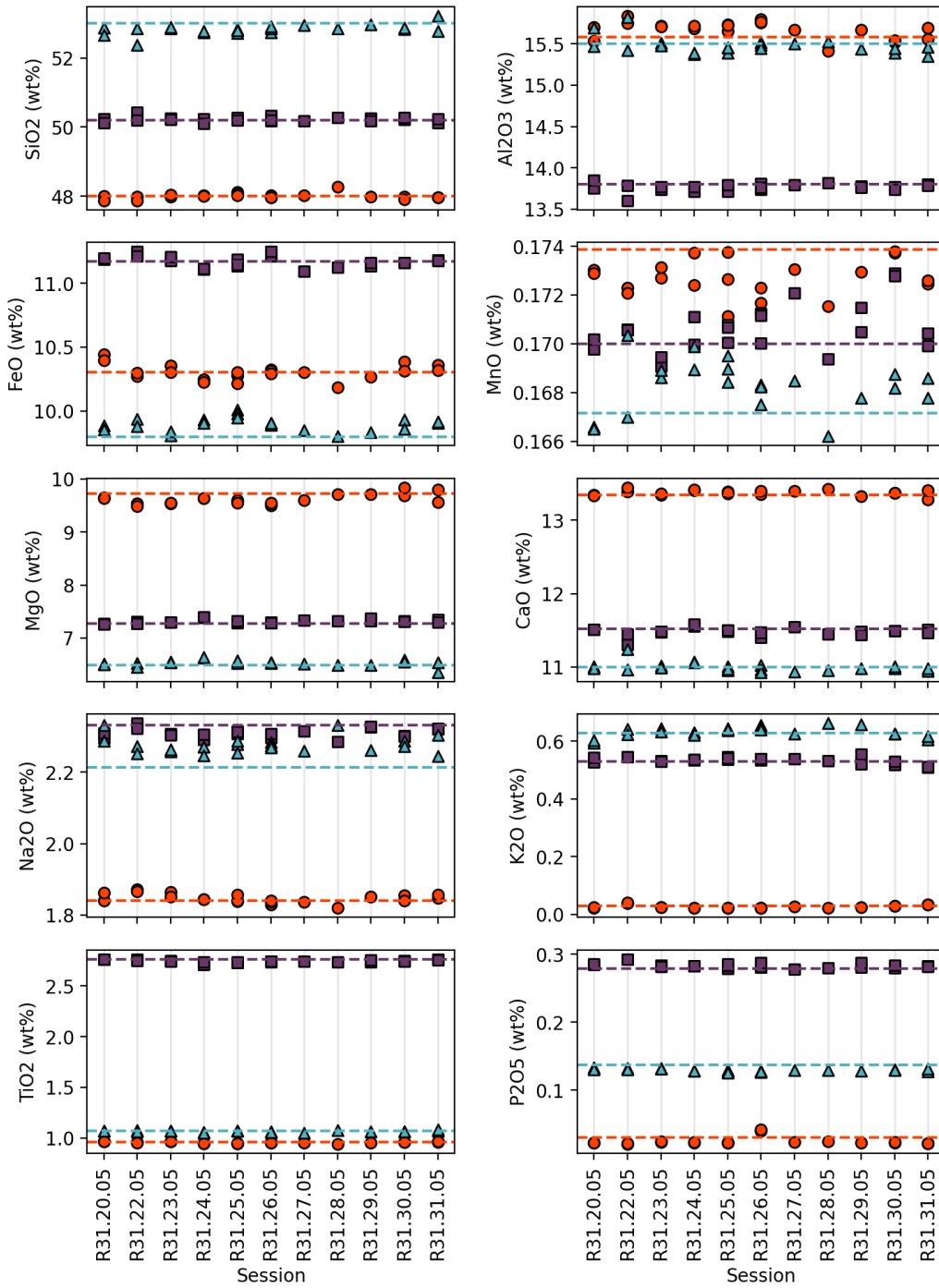


Fig. S13

Summary of the standard analyses during each ICP-OES session. The horizontal dashed lines show the GEOREM preferred values. The red circles are BIR-1, the light blue triangles are W2, and the dark blue squares are BHVO-1.

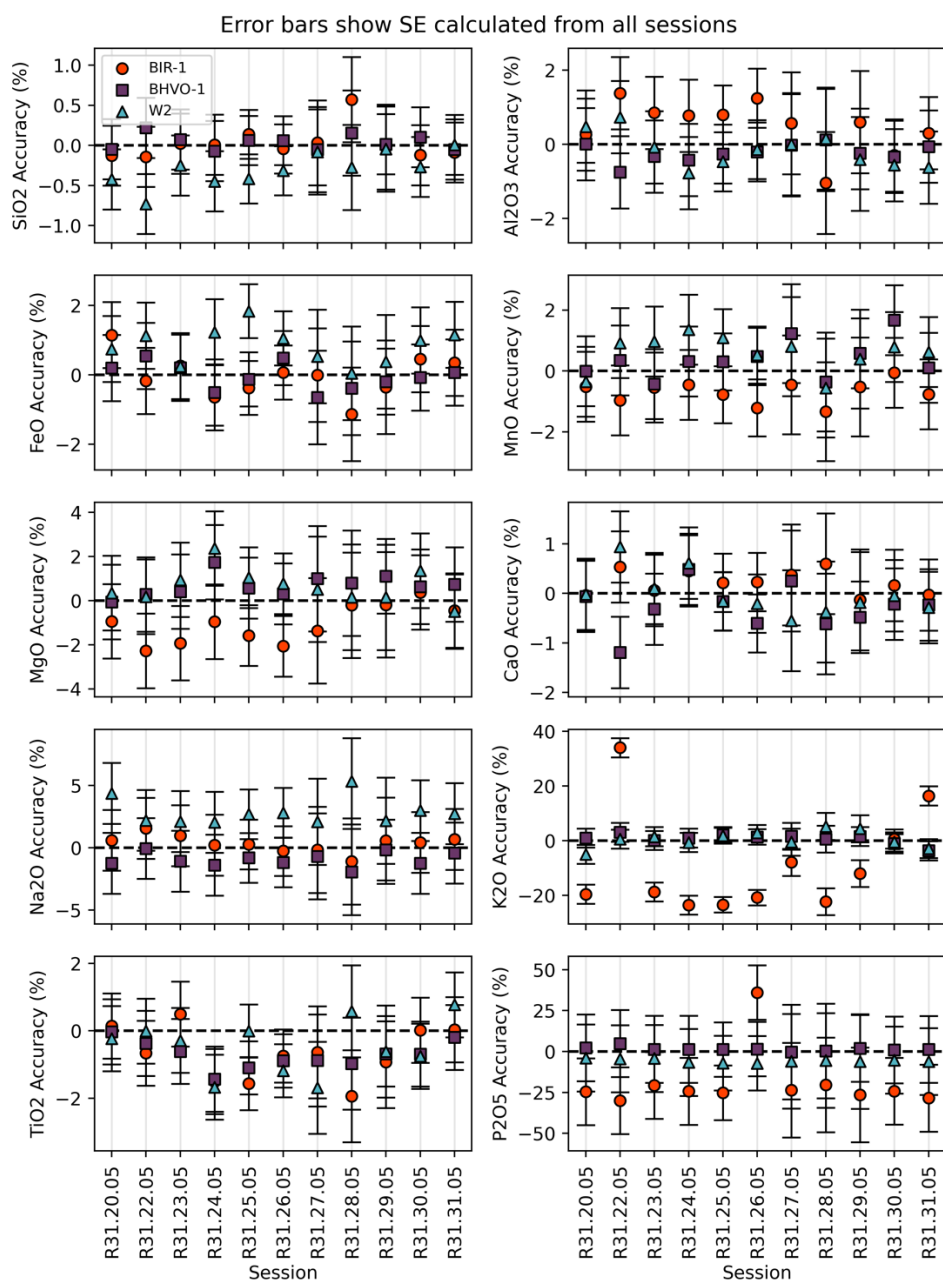


Fig. S14

Summary of the relative accuracy of the standard measurements during each session. The error bars show the relative standard error in the mean across all standards and sessions. For K₂O, the standard error does not include BIR-1 as the K₂O concentration is much lower than the other standards and all sample measurements reported here.

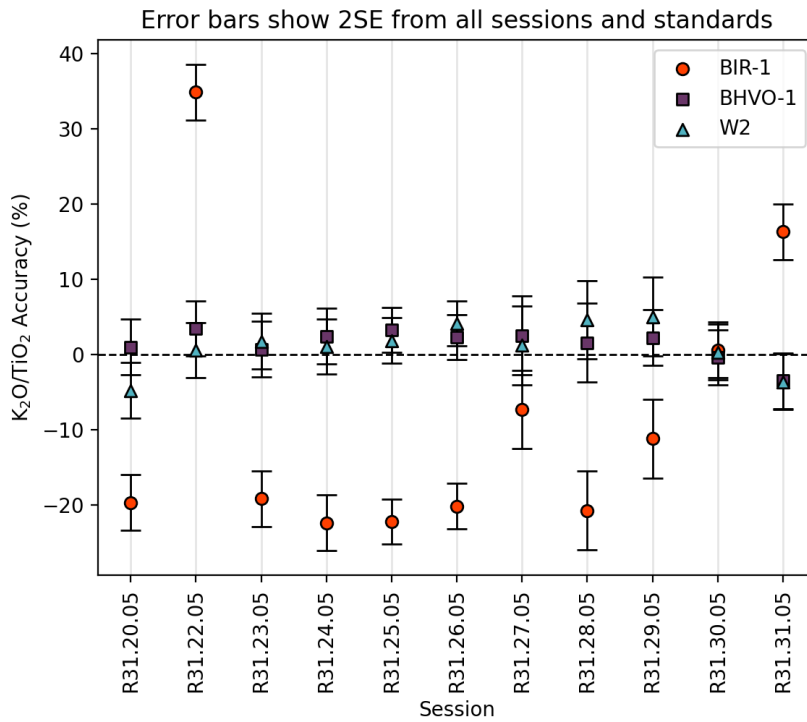


Fig. S15

Summary of the relative accuracy of the K_2O/TiO_2 ratio during each session. The error bars show the relative standard error in the mean for BHVO and W2 across all sessions. The standard error was calculated without BIR-1 as the K_2O concentration is much lower than the other standards and all sample measurements reported here.

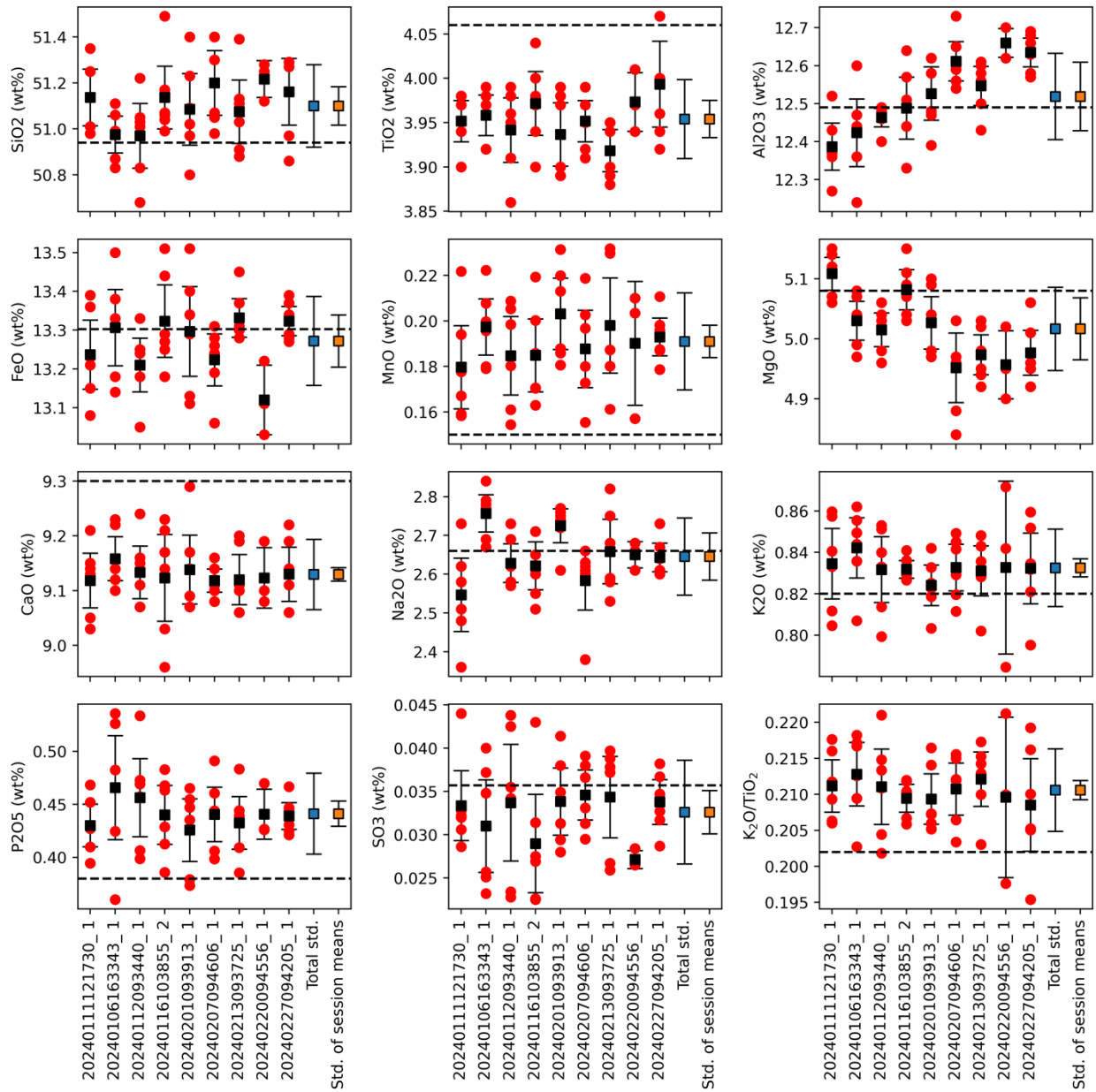


Fig. S16

Summary of repeated analyses of secondary standard material A99. The red circles show individual analyses, the black squares show the session mean, and their error bars show 2s.e. in the mean. The horizontal dashed lines show the accepted values.

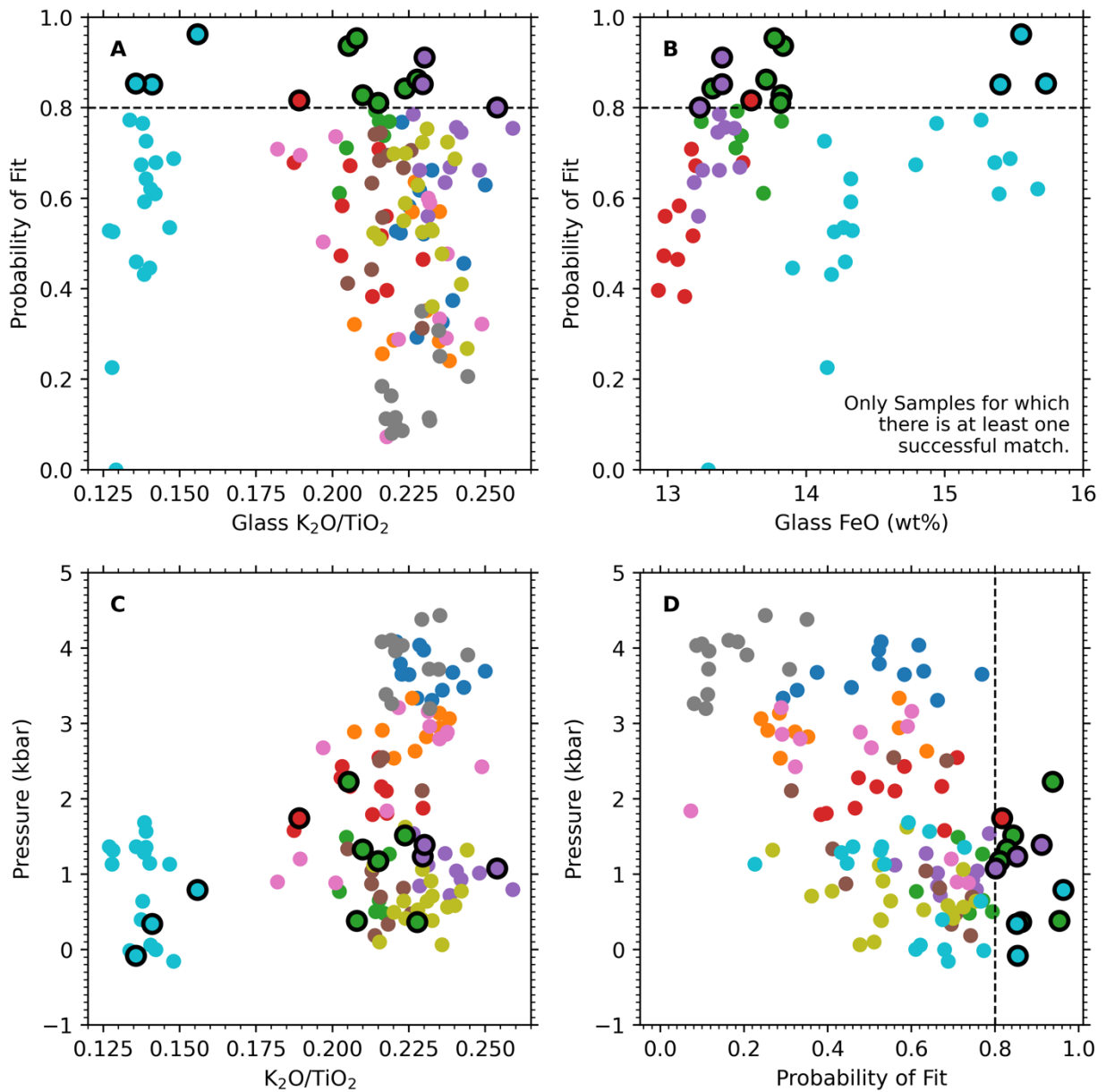


Fig. S17

Results of the tephra OPAM calculations, including glass analyses that had a low probability of fit. The symbols outlined in bold show the analyses with a probability of fit > 0.8, which are the pressures shown in Fig. 3. Glass analyses from the same sample are shown with the same color.

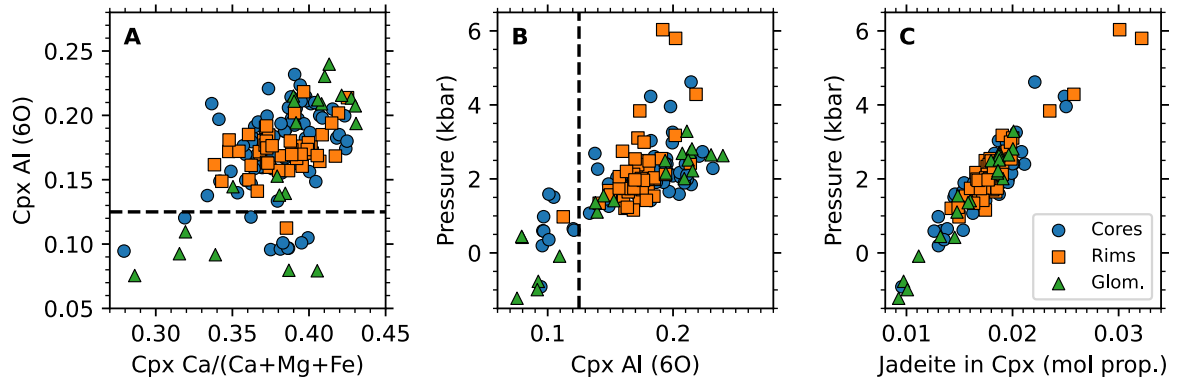


Fig. S18

Results of the clinopyroxene-liquid calculations, including results that are filtered out on the basis of low Al contents. The threshold for filtering is shown by the dashed line in panels (A) and (B).

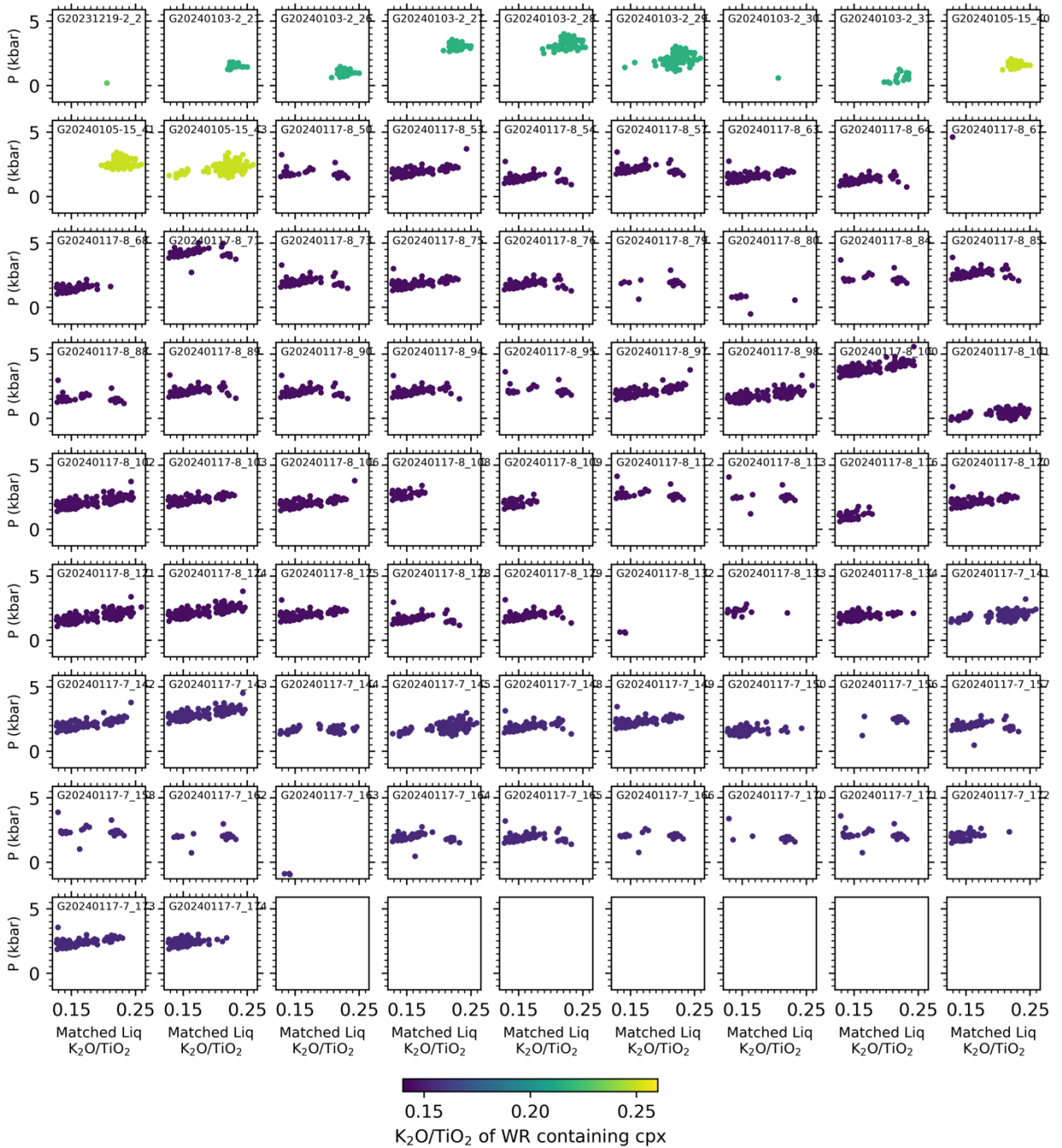


Fig. S19

Results of clinopyroxene-liquid geobarometry calculations for clinopyroxene cores. Each panel shows an individual clinopyroxene core analysis, and the symbols show the K_2O/TiO_2 of the glass compositions identified as potential equilibrium matches and the pressure for each liquid-pyroxene pair.

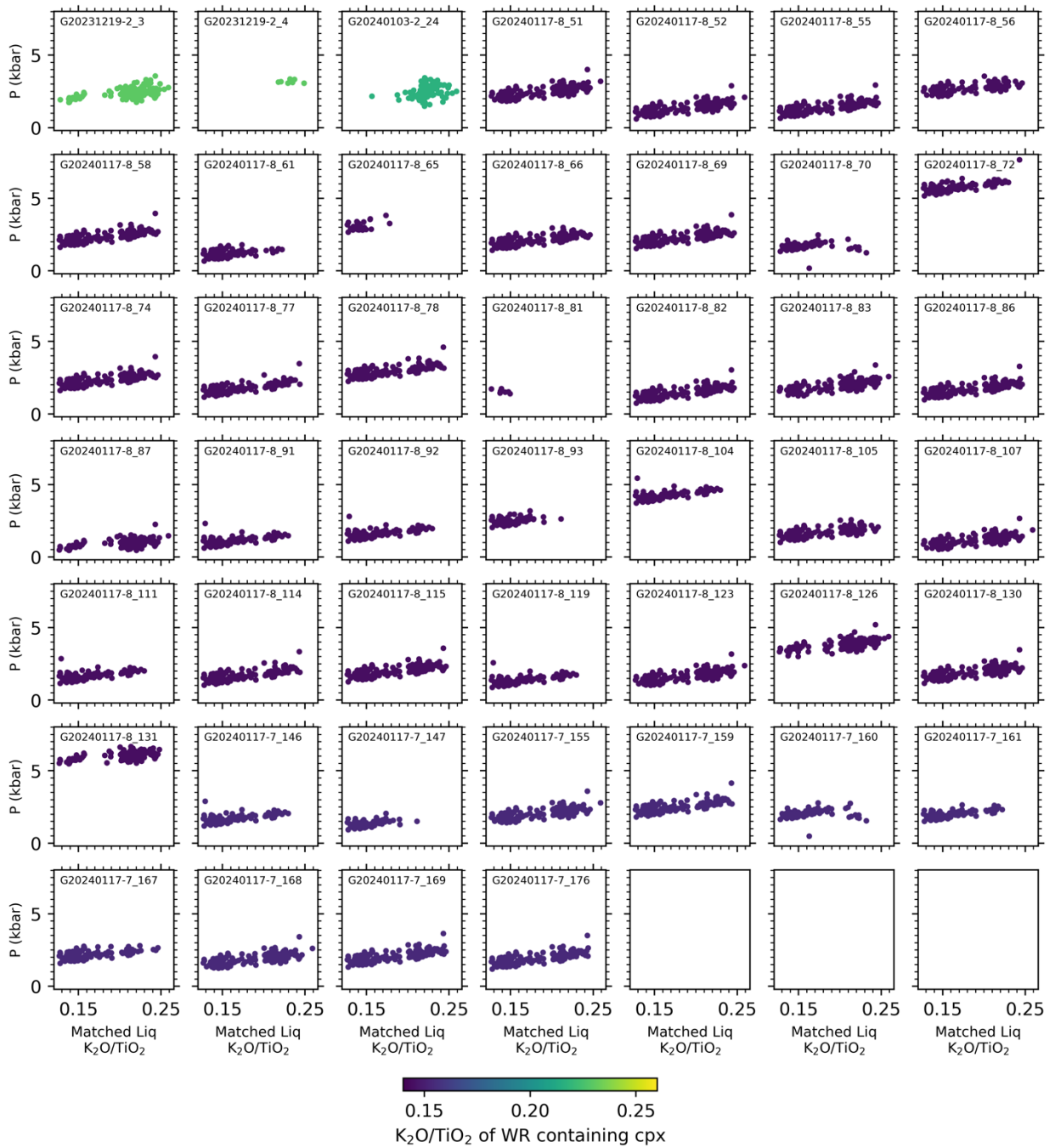


Fig. S20

Results of clinopyroxene-liquid geobarometry calculations for clinopyroxene rims. Each panel shows an individual clinopyroxene rim analysis, and the symbols show the K_2O/TiO_2 of the glass compositions identified as potential equilibrium matches and the pressure for each liquid-pyroxene pair.

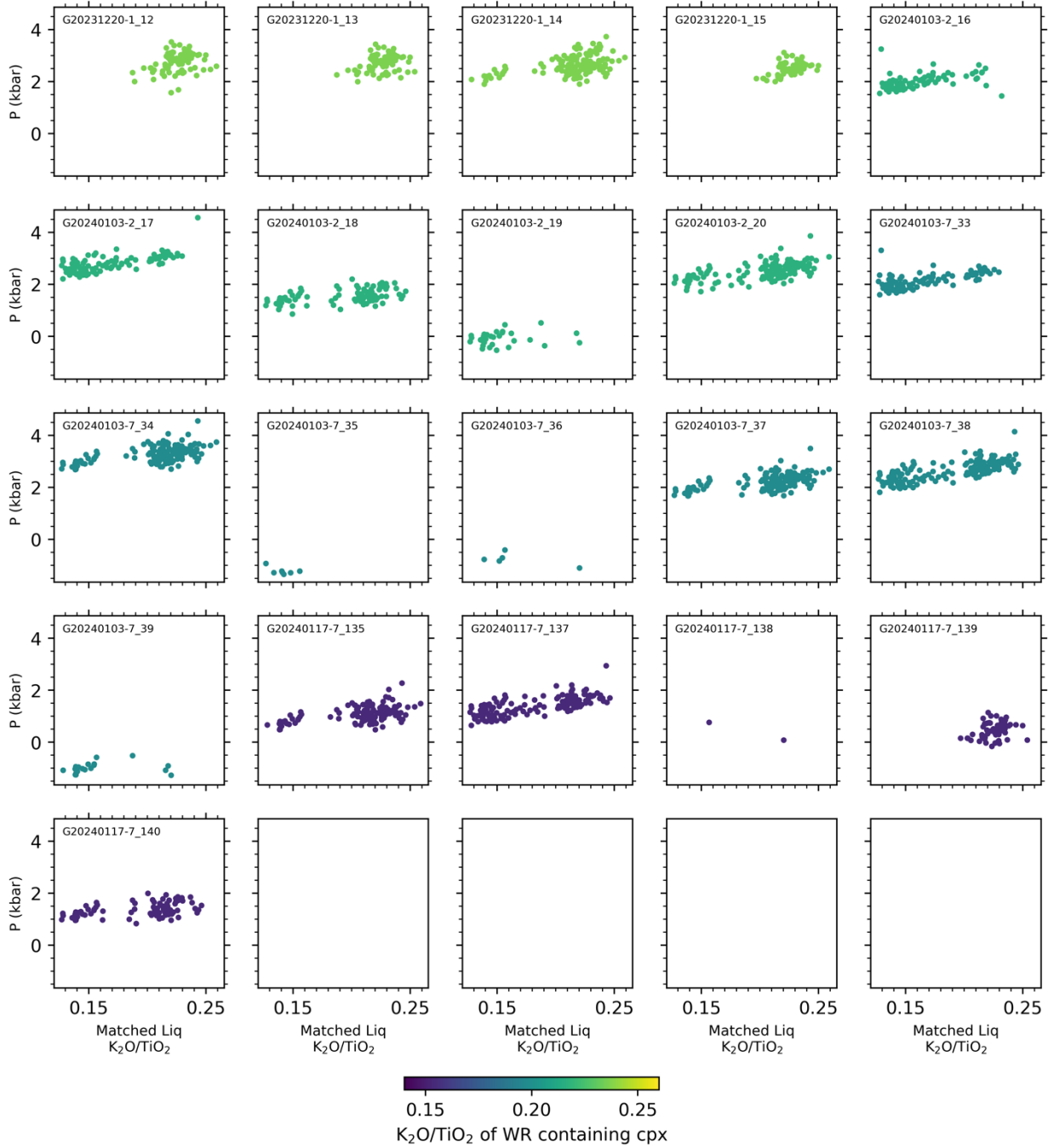


Fig. S21

Results of clinopyroxene-liquid geobarometry calculations for clinopyroxene glomerocrysts. Each panel shows an individual clinopyroxene glomerocryst analysis, and the symbols show the K_2O/TiO_2 of the glass compositions identified as potential equilibrium matches and the pressure for each liquid-pyroxene pair.

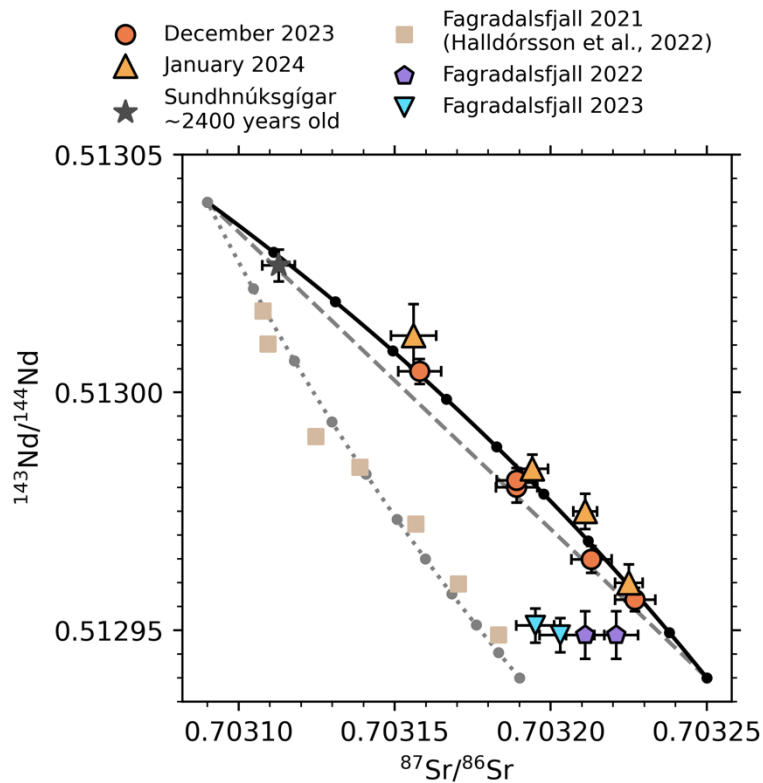


Fig. S22

Illustrative mixing models for Sr-Nd between the depleted and enriched endmembers. The solid line shows the model for the Sundhnúksgígar eruptions. The dashed line is the mixing line for endmembers with the same $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios but Sr and Nd concentrations required to match the Fagradalsfjall 2021 Sr and Nd concentrations (Fig. S23). The dotted line shows the model for the Fagradalsfjall 2021 lavas. Increments of 10% mixing are shown by the circles. The mixing lines are chosen to illustrate where a single depleted endmember would sit (see supplementary text). See the caption to Fig. 2 for information about the symbols and error bars. The mixing model parameters are given in Table S6.

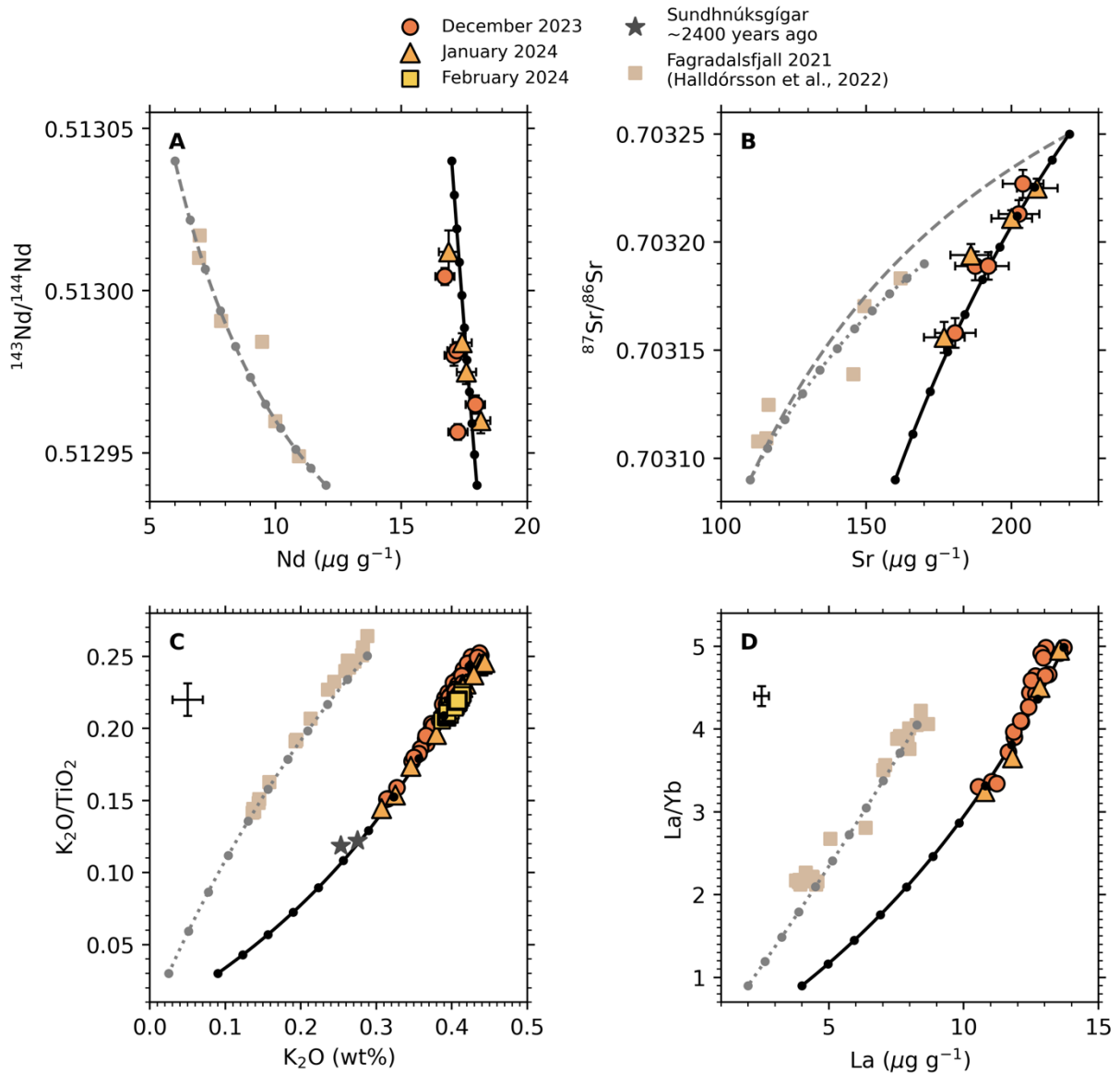


Fig. S23

Illustrative mixing models between the depleted and enriched endmembers. Panels (A) and (B) show mixing models that match the Sr-Nd systematics, and panels (C) and (D) show different models that match the K_2O - TiO_2 -La-Yb systematics. The solid lines show the mixing models for the Sundhnúksgígar eruptions. The dashed lines in panels (A) and (B) are mixing lines for endmembers with the same $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios but Sr and Nd concentrations required to match the Fagradalsfjall 2021 Sr and Nd concentrations. This is the same model as shown by the dashed line in Fig. S22. The dotted line shows the model for the Fagradalsfjall 2021 lavas. Increments of 10% mixing are shown by the circles. The mixing lines are chosen to illustrate where a single depleted endmember would sit (see supplementary text). Notice the models in (A) and (B) have inconsistent mixing proportions with the models in (C) and (D). The mixing model parameters are given in Tables S6 and S7.

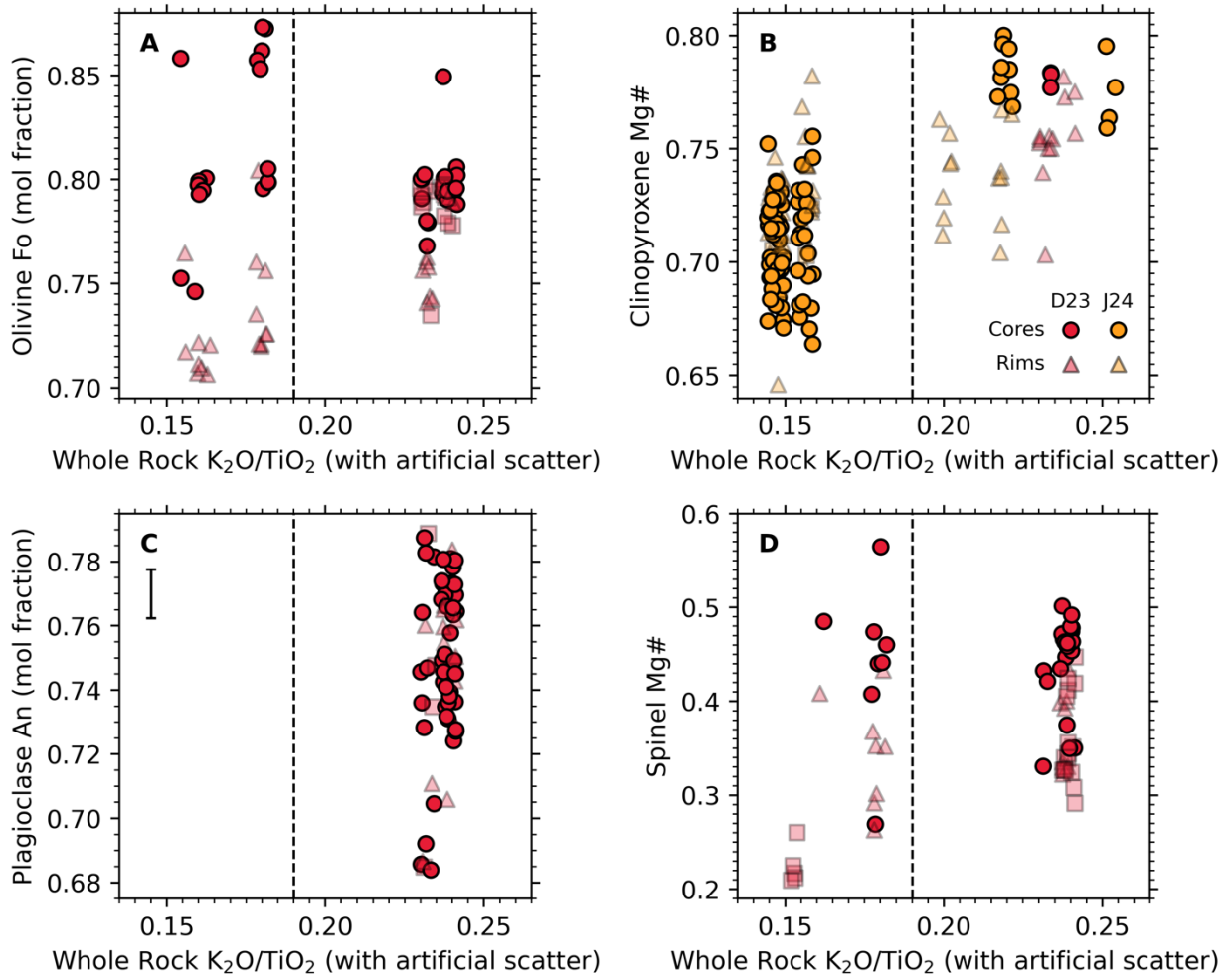


Fig. S24

Individual electron probe analyses of olivine (A), clinopyroxene (B), plagioclase (C), and spinel (D). The compositions are plotted at the K_2O/TiO_2 of the whole rock from which the crystal was derived. The dashed line shows the cut-off between depleted and enriched populations shown in Fig. S10. The 2σ uncertainty on the analyses are on the order of the symbol size, except for plagioclase An, the uncertainty for which is indicated by the error bar on panel (C).

Element	Spec	Crystal	Standard	Peak (sec)	Backgr. (sec)
Si	1	TAP	Tectite Glass (NMNH 2231) / Rhyolite Glass VG-568 (NMNH 72854)	30	10
Ti	2	PETJ	Hornblende (Kakanui) (NMNH 143965)	40	20
Al	1	TAP	Anorthite (NMNH 137041)	30	15
Fe	4	LIFL	G1401 (basaltic glass from P. Roeder)	40	20
Mn	4	LIFL	Bustamite (Astimex Standards Ltd.)	40	20
Mg	5	TAP	Diopside Glass (NASA)	30	15
Ca	2	PETJ	Diopside Glass (NASA)	30	15
Na	5	TAP	Omphacite (NMNH 110607)	20	10
K	2	PETJ	Corning Glass D (NMNH 117218-3)	40	20
P	2	PETJ	Apatite (Astimex Standards Ltd.)	40	20
S	3	PETH	Pyrite (Astimex Standards Ltd.)	120	60
Cl	3	PETH	Scapolite (Meionite) (NMNH R6600)	90	90

Table S1.

Standards, spectrometers and analytical crystals used, and counting times on peak and background on each side of peak for S- and Cl-bearing basalt glass analyses.

Element	Spec	Crystal	Standard	Peak (sec)	Backgr. (sec)
Si	1	TAP	Olivine (San Carlos) (NMNH 111312-44)	30	15
Ti	2	PETJ	Hornblende (Kakanui) (NMNH 143965)	30	30
Al	1	TAP	Pyrope (NMNH 143968)	30	30
Fe	3	LIFH	Fayalite (NMNH 85276)	30	15
Mn	4	LIFL	Bustamite (Astimex Standards Ltd.)	30	30
Mg	5	TAP	Olivine (Astimex Standards Ltd.)	30	15
Ca	2	PETJ	Diopside (NMNH 117733)	30	15
Cr	4	LIFL	Chromite (NMNH 117075)	30	30
Ni	3	LIFH	Pentlandite (Astimex Standards Ltd.)	30	30

Table S2.

Standards, spectrometers and analytical crystals used, and counting times on peak and background on each side of peak for olivine analyses.

Element	Spec.	Crystal	Standard	Peak (sec)	Backgr. (sec)
Si	1	TAP	Pyrope (NMNH 143968)	30	30
Ti	2	PETJ	Rutile (Astimex Standards Ltd.)	40	20
Al	1	TAP	Pyrope (NMNH 143968)	30	15
Fe	3	LIFH	Hematite (Astimex Standards Ltd.)	30	15
Mn	4	LIFL	Bustamite (Astimex Standards Ltd.)	30	30
Mg	5	TAP	Chromite (NMNH 117075)	30	30
V	4	LIFL	Vanadium (metal) (Astimex Standards Ltd.)	30	30
Cr	4	LIFL	Chromite (NMNH 117075)	30	15
Ni	3	LIFH	Pentlandite (Astimex Standards Ltd.)	40	20

Table S3.

Standards, spectrometers and analytical crystals used, and counting times on peak and background on each side of peak for spinel analyses.

Element	Spec.	Crystal	Standard	Peak (sec)	Backgr. (sec)
Si	1	TAP	Plagioclase (NMNH 115900)	40	20
Ti	2	PETJ	Hornblende (Kakanui) (NMNH 143965)	40	40
Al	1	TAP	Anorthite (NMNH 137041)	40	20
Fe	3	LIFH	Hornblende (Kakanui) (NMNH 143965)	40	20
Mn	3	LIFH	Bustamite (Astimex Standards Ltd.)	40	40
Mg	5	TAP	Hornblende (Kakanui) (NMNH 143965)	40	40
Ca	2	PETJ	Anorthite (NMNH 137041)	40	20
Na	5	TAP	Anorthoclase (NMNH 133868)	30	15
K	4	PETL	Microcline (NMNH 143966)	40	20
Ba	4	PETL	Corning Glass C (NMNH 117218-2)	40	40

Table S4.

Standards, spectrometers and analytical crystals used, and counting times on peak and background on each side of peak for plagioclase analyses.

Element	Spec.	Crystal	Standard	Peak (sec)	Backgr. (sec)
Si	1	TAP	Augite (NMNH 122142)	30	15
Ti	2	PETJ	Hornblende (Kakanui) (NMNH 143965)	30	30
Al	1	TAP	Pyrope (NMNH 143968)	30	15
Fe	3	LIFH	Hornblende (Kakanui) (NMNH 143965)	30	15
Mn	4	LIFL	Bustamite (Astimex Standards Ltd.)	30	30
Mg	5	TAP	Hypersthene (USNM 746)	30	15
Ca	2	PETJ	Diopside (NMNH 117733)	30	15
Na	5	TAP	Omphacite (NMNH 110607)	30	15
Cr	4	LIFL	Chromite (NMNH 117075)	30	15
Ni	3	LIFH	Pentlandite (Astimex Standards Ltd.)	30	30

Table S5.

Standards, spectrometers and analytical crystals used, and counting times on peak and background on each side of peak for clinopyroxene analyses.

Parameter	S1-D	S1-E	F1-D	F1-E	F2-D	F2-E
$^{87}\text{Sr}/^{86}\text{Sr}$	0.70309	0.70325	0.70309	0.70325	0.70309	0.70319
$^{143}\text{Nd}/^{144}\text{Nd}$	0.51304	0.51294	0.51304	0.51294	0.51304	0.51294
Sr ($\mu\text{g g}^{-1}$)	160	220	110	220	110	170
Nd ($\mu\text{g g}^{-1}$)	17	18	6	12	6	12

Table S6.

The parameters used in the mixing models shown in Figs. S22, S23A,B. The enriched endmembers are denoted with an “E” suffix, and the depleted endmembers are denoted with a “D” suffix. The S1 model is shown by the solid line in the figures. The F1 model is the dashed line in the figures. The F2 model is the dotted line in the figures.

Parameter	S-D	S-E	F-D	F-E
La ($\mu\text{g g}^{-1}$)	4.0	13.71	2.0	8.26
Yb ($\mu\text{g g}^{-1}$)	4.44	2.75	2.22	2.04
K ₂ O (wt%)	0.09	0.423	0.025	0.288
TiO ₂ (wt%)	3.0	1.74	0.83	1.15

Table S7.

The parameters used in the mixing models shown in Figs. S4C, S23B,C. The enriched endmembers are denoted with an “E” suffix, and the depleted endmembers are denoted with a “D” suffix. The S model is shown by the solid line in the figures. The F model is the dotted line in the figures.

Data S1. (separate file)

Sample information.

Data S2. (separate file)

Major oxide concentrations for the sample whole rocks and standard powders determined by ICP-OES.

Data S3. (separate file)

The data collected from glasses and minerals by electron microprobe analysis, including samples and standards.

Data S4. (separate file)

The trace element data collected by ICP-MS for both picked glasses from the samples and standard powders.

Data S5. (separate file)

The Sr and Nd radiogenic isotope analyses.