

Cover sheet for preprint submission to EarthArXiv

Title: A 400 Myr subduction memory in the mid-ocean ridge source

Authors: Jacqueline Dixon, University of South Florida, USA; jdixon@usf.edu
R. Dietmar Müller, EarthByte Group, School of Geosciences, The University of
Sydney, NSW, Australia; dietmar.muller@sydney.edu.au
Adriana Dutkiewicz, EarthByte Group, School of Geosciences, The University of
Sydney, NSW, Australia; adriana.dutkiewicz@sydney.edu.au
Ben R. Mather, University of Melbourne, Australia;
ben.mather@unimelb.edu.au

This manuscript is a non-peer-reviewed preprint submitted to EarthArXiv. It was submitted to *Geology* on 10/7/2026.

A 400 Myr subduction memory in the mid-ocean ridge source

Jacqueline Dixon^{1,*}, R. Dietmar Müller², Adriana Dutkiewicz², and Ben R. Mather³

¹ University of South Florida, USA

²EarthByte Group, School of Geosciences, The University of Sydney, NSW, Australia

³ University of Melbourne, Australia

* Correspondence to: jdixon@usf.edu; ORCID ID: 0000-0001-8021-759X

ABSTRACT

The upper mantle sampled by mid-ocean ridges carries the volatile imprint of past subduction, but the global distribution of hydration through time and how long that imprint survives mixing and melt extraction are poorly known. We investigate the history of mantle hydration by calculating where and when hydration occurred using a plate reconstruction model of subducted water over the past 410 Myr. We compare model results to present-day mantle hydration based on H₂O/Ce in ~1,340 mid-ocean ridge basalt (MORB) glasses from ~1,050 sites. Estimated hydration ages vary by region: ~120 Ma for the Arctic, ~320 Ma for the northern Mid-Atlantic Ridge (NMAR), ~220 Ma for the mid-latitude Mid-Atlantic, and ~380 Ma for the southern Mid-Atlantic (SMAR). Most Pacific ridges show no evidence of hydration. Globally, MORB derived from mantle with a modeled hydration age has a higher median H₂O/Ce than MORB from mantle with no modeled water delivery (249 versus 200). Neither hydration age nor duration affects H₂O/Ce in present-day MORB. Agreement between model and data is particularly strong in the North Atlantic and Arctic. Here, hydrated mantle remained largely undisturbed until the post-130 Ma westward migration of North America. Subduction signatures may remain detectable as long as 400 Myr after hydration, well beyond the lifetime of the plate configuration that produced them.

INTRODUCTION

Earth's mantle is compositionally heterogeneous at all sampled scales. Much of that heterogeneity is inherited from subducted oceanic lithosphere, redistributed by convection and plumes (Rampone and Hofmann, 2012; Bekaert et al., 2021; van Keken et al., 2025). Volatile-rich subduction components have been recognized in oceanic basalts and subcontinental lithospheric mantle (e.g., Urann et al., 2020; Yang et al., 2021; Liu et al., 2022; Doucet and Li, 2024; Gibson et al., 2025). Although hydration occurs above individual subduction zones, trench migration distributes its cumulative imprint over time (van Keken, 2003). The age and persistence of this inheritance at specific locations are unresolved.

Compositional anomalies in the NMAR and Arctic ridges illustrate the difficulty. MORB from the NMAR are enriched in H₂O and fluid-mobile elements relative to those from the SMAR and Pacific (Michael, 1995; Fig. 1). Michael (1995) linked this enrichment to subduction during closure of the Iapetus Ocean (485–393 Ma) or assembly of Pangea (359–299 Ma). For the Gakkel Ridge, others invoke younger South Anyui subduction (145–100 Ma; Richter et al., 2020; Yang et al., 2021). Geochemistry alone cannot distinguish the proposed sources. Because H₂O and Ce behave similarly during melting and crystallization (Aubaud et al., 2004), MORB H₂O/Ce can trace hydrous source components.

We investigate the timing and persistence of mantle hydration by combining a plate reconstruction with a thermodynamic model of water transport and release by subducting plates. In a reference frame fixed to the deep mantle, we track cumulative water delivery at each location through time. Changes between time steps yield delivery rates. At each site, we determine the time since water last arrived (hydration age) and how long delivery lasted (hydration duration). Neither measure is fitted to geochemistry, so comparing them with measured H₂O/Ce directly tests the model.

METHOD

We use the mantle-reference frame global plate reconstruction of Zahirovic et al. (2022), which begins at 410 Ma. We track subducting plate segments and water in sediments, altered crust and hydrated lithospheric mantle with Mather et al.'s (2026) pyGPlates workflow. Total subducted water is assigned to reconstructed trench positions without assigning a depth, smoothed with an isotropic Gaussian filter (300 km length scale), and accumulated on a 0.2° grid (Fig. 2, Videos S1–S2). Hydration ages are calculated where present-day ridge axes overlie hydrated mantle. The model omits mantle flow, dilution by mixing, and extraction by melting. We calculate delivery rates from changes in cumulative hydration over successive 20 Myr intervals (Fig. 3). A location is hydrated when the rate exceeds 0.5 t m⁻² Myr⁻¹, about one tenth of the typical rate beneath active subduction zones. For each site, we record hydration age from the most recent qualifying interval and hydration duration.

Plate positions relative to the deep mantle are the least certain part of plate reconstructions. We repeat the calculation in three different reference frames (Tetley et al., 2019), varying only the rotation of the plate system relative to the mantle. At 240 Ma, trench positions differ by up to 900 km. We use the optimized mean-net-rotation frame as our preferred model; no-net-rotation and maximum-net-rotation models provide bounds, not equally probable alternatives. The former imposes zero net rotation; the latter permits net rotation rates up to 0.30° Myr⁻¹, the upper limit from seismic anisotropy and mantle flow models (Conrad and Behn, 2010; Becker et al., 2015). We compare modeled hydration ages and durations with a curated global MORB H₂O/Ce dataset (Table S1, Fig. 1B). After removing duplicates, 1,344 samples

represent 1,048 distinct positions (sites). To match the 300 km smoothing of trench hydration, we group sites into 300 km along-ridge clusters and calculate median $\text{H}_2\text{O}/\text{Ce}$ for each (136 such clusters). Full methods and figures showing robustness and sensitivity tests for modeled hydration ages (Figs. S1-S6) are in the Supplemental Material.

PRESENT-DAY RIDGE MANTLE HYDRATION RECORDS THE TIMING AND LOCATION OF ANCIENT SUBDUCTION

Site-specific hydration ages reveal a pattern obscured by basin averages (Fig. 4A). Last water delivery dates to 120 Ma beneath Arctic ridges, 320 Ma beneath the NMAR, 220 Ma beneath the mid-latitude Mid-Atlantic Ridge (MAR), and 380 Ma beneath the SMAR at 0° – 28°S (Fig. 4). Of 1,344 samples, 801 have no hydration age: the model places no subducted water at their sources over 410 Myr, chiefly in the Pacific interior, the SMAR, and the Indian Ocean (Fig. 4A). Delivery typically lasts 40–80 Myr (half of cases; none >180 Myr; Fig. S7). At nearly all dated sites, time since delivery is several times its duration, suggesting that the water signature survives prolonged mantle stirring. Reference-frame choice changes the number of hydrated sites (554/1,048 with no net rotation; 329 with maximum net rotation, 413 in the preferred frame), but less often their ages: of 543 samples, 383 are hydrated in all frames and 342 retain identical ages. The Arctic (120 Ma) and mid-latitude MAR (220 Ma) ages are unchanged, and the hydrated–unhydrated contrast remains significant in each frame ($p \leq 0.003$ globally). The NMAR value of 320 Ma holds in the preferred and no-net-rotation frames, whereas the geodynamically unlikely maximum net rotation hydrates only 3 of 117 NMAR sites.

Across all sites, MORB from mantle hydrated within the past 400 Myr has a greater median $\text{H}_2\text{O}/\text{Ce}$ than MORB from sites without (249 ± 15 versus 200 ± 6 ; $p = 0.003$). The same holds in the Atlantic–Arctic corridor (275 ± 16 versus 229 ± 23 ; $p = 0.039$; Fig. S6). Hydration age shows no detectable relation to $\text{H}_2\text{O}/\text{Ce}$ (rank correlation $+0.08$, $p = 0.56$). Every age class has higher $\text{H}_2\text{O}/\text{Ce}$ than the Pacific, the least hydrated ridge region (Fig. 4C). Each time interval is dominated by a specific region, so differences between age intervals record where the ridges are rather than when they were supplied. The duration of supply also contributes no new information once the age is known (Fig. S1). Hydrous heterogeneities can persist for ~ 400 Myr despite convective stirring, implying slow erosion of compositional structure in parts of the upper mantle. Along-ridge chemical variation may therefore reflect ancient subduction, as well as present-day melting and plume influence.

Along the Arctic ridges north of 70°N , the 120 Ma hydration age (Fig. 3C) is consistent with Early Cretaceous subduction independently inferred from the geochemistry of Gakkel Ridge basalts (Richter et al., 2020; Yang et al., 2021). Along the NMAR, hydration ages are older and more variable. Hydration

ages are 320 Ma between 50°N and 70°N and 220 Ma between 20°N and 35°N. Between 50°N and 70°N, the 320 Ma hydration age and modeled water delivery from east of Laurentia are consistent with Michael's (1995) proposed origin by closure of Iapetus or the Carboniferous assembly of Pangea. In contrast, between 20°N and 35°N, maximum water delivery at 220 Ma lies 404 km to the northwest. The two reconstructed margins of Farallon subduction beneath North America sit 160 km beyond it — the only region where the inferred direction of water delivery aligns with a reconstructed trench (Fig. 3A, 3B). Thus, the NMAR anomaly has two sources, on opposite sides of Laurentia and ~100 Myr apart. Both hydrated regions remained sequestered until North America began rapidly migrating at ~130 Ma; opening of the North Atlantic followed after 65 Ma. The young migrating NMAR ridge contrasts with the relatively stationary regions in the SMAR, where melting may have depleted ancient hydrous components

DEEP RECYCLING OF WATER SAMPLED BY PLUMES

Mantle plumes also contribute water to the MORB source. Deeply recycled volatiles rise within a plume, and a rising plume entrains the upper mantle it traverses, including subduction-hydrated mantle. It is well established that most hotspots are also 'wetspots' (e.g., Schilling et al., 1980; Nichols et al., 2002; Métrich et al., 2014; Fig. 1A), although each plume has its own unique volatile composition (e.g., Dixon et al., 2017). The North Atlantic hydration anomaly is also apparent in plume mixing end-member compositions (Fig. 1A). In the NMAR and Arctic, HIMU-like (high- μ , where $\mu = {}^{238}\text{U}/{}^{204}\text{Pb}$) plumes (e.g., Jan Mayen, Iceland, Azores Platform), characterized by ${}^{206}\text{Pb}/{}^{204}\text{Pb} > 19.0$, have $\text{H}_2\text{O}/\text{Ce}$ of 330 ± 50 . North Atlantic enriched mantle (EM-type) end-members, characterized by ${}^{206}\text{Pb}/{}^{204}\text{Pb} < 19.0$ combined with elevated ${}^{87}\text{Sr}/{}^{86}\text{Sr}$ and Ba/Nb , are even wetter, with $\text{H}_2\text{O}/\text{Ce} > 350$. In contrast, South Atlantic and Pacific HIMU-like plumes (e.g., Easter–Salas y Gómez, Galápagos) have $\text{H}_2\text{O}/\text{Ce}$ of 220 ± 10 . SMAR and Pacific EM-type end-member compositions are even drier with $\text{H}_2\text{O}/\text{Ce} < 150$ (e.g., Discovery plume).

To evaluate the contribution of plumes to the MORB $\text{H}_2\text{O}/\text{Ce}$ dataset, we used trace element and radiogenic-isotope compositions to identify and exclude 74 samples with enriched compositions indicative of plume influence. These include samples associated with Jan Mayen, Reykjanes Ridge north of 61°N, the Azores Platform, the 35°N and 14°N off-axis anomalies, and the Sierra Leone segment at ~1.7°N. Exclusion of these plume-influenced samples does not change the result (Table S2). Globally, median $\text{H}_2\text{O}/\text{Ce}$ for non-plume-influenced MORB samples with a modeled hydration age is 247 ± 15 compared to 198 ± 6 for those without one ($p = 0.002$). In the Atlantic–Arctic corridor the contrast is larger: median $\text{H}_2\text{O}/\text{Ce}$ is 273 ± 17 at sites with modeled hydration ages versus 203 ± 24 at sites without ($p = 0.029$). This is not a surprise, given regional variations in plume compositions. The similar $\text{H}_2\text{O}/\text{Ce}$

of plume-influenced and nearby non-plume MORB suggest that subduction-derived hydration may extend deeper than 125 km into the mantle.

MODEL-DATA DISCREPANCIES

Elevated H₂O/Ce with no modeled source

Two MAR regions, at 35°N–50°N and 0°N–10°N, have elevated H₂O/Ce despite having no modeled hydration age. More than 100 NMAR samples at 35°N–50°N have a median H₂O/Ce of 265. In the equatorial ridge region at 0°–10°N, H₂O/Ce reaches 320, but only one of 32 sites has a modeled hydration age. We consider two possible explanations: model uncertainty and enriched mantle heterogeneity. First, both regions fall within reference-frame uncertainty. The no-net-rotation predicts hydration at 320 Ma throughout 35°–50°N, while the maximum-net-rotation frame assigns a 380 Ma hydration age to half the equatorial samples. These results do not confirm hydration, but show that uncertainty in reconstructed trench positions is large enough to account for a mismatch. Second, MORB from both areas display mixing trends with an enriched, HIMU-type component. In the equatorial MAR, this has been linked to the Sierra Leone plume at 1.7°N (Schilling et al., 1994). In addition, the MAR between 5°N and 10°N comprises short segments separated by closely spaced fracture zones. Elevated water contents in MORB near fracture zones have also been attributed to interaction between melts and serpentinized mantle (Ligi et al., 2005; Gose et al., 2009; Schmädicke et al., 2018; Le Roux et al., 2021). Basalts between 35°N and 50°N are characterized by extremely low degrees of partial melting, including the presence of alkalic compositions, that preferentially extract more fusible distributed heterogeneities (Shibata et al., 1979).

Dated hydration age without elevated H₂O/Ce

The converse—modeled hydration but unremarkable MORB H₂O/Ce—is easier to explain: water can be removed or redistributed after hydration, whereas enrichment cannot be produced without a source. Although we did not explicitly model the effects of rifting, several local discrepancies between the model and data provide insight. At ~15°S in the SMAR, the model predicts hydration at ~380 Ma (Fig. 3D), yet the few available samples have low H₂O/Ce (173 ± 8). Rifting in that area started at ~132 Ma and has been stable since that time (Fig. 2D, E, & F). Similarly, at ~50°S on the SMAR, MORB with normal H₂O/Ce overlies a modeled hydrated zone formed at ~380 Ma (Fig. 3D). Rifting began there at ~130 Ma, and the ridge has remained nearly stationary relative to the mantle since then. We infer that prolonged melting beneath a nearly stationary ridge could deplete the mantle of water over tens of millions of years, while associated mantle flow displaces upper mantle material laterally.

CONCLUSIONS

Reconstructing the last delivery of subduction-derived water beneath MORB sites in a mantle reference frame gives ridges a hydration age of 120 Ma in the Arctic, 320 Ma along the NMAR, 220 Ma along the mid-latitude MAR, 380 Ma in the SMAR, and no delivery at all beneath most of the Pacific over the past 410 Myr. Mantle hydrated at any point in the last 410 Myr carries higher H₂O/Ce than mantle that was not, both within and between ocean basins. The age of that hydration makes no difference to how wet the mantle is now. Thus, the subduction signature in the upper mantle source of MORB is able to survive for ~400 Myr, although the signal may be reduced by melting in areas with prolonged stationary seafloor spreading. Elevated H₂O/Ce in both North Atlantic plumes and MORB supports the concept of deep recycling of subducted volatiles. The Arctic anomaly dates to Early Cretaceous subduction. The NMAR anomaly reflects two sources on opposite sides of Laurentia: Farallon subduction from the west between 20°N and 35°N, and an eastern source north of 50°N about 100 Myr earlier. Our approach offers a way to link subduction-like signatures in ocean-ridge and continental intraplate basalts to specific episodes of ancient slab dehydration, mantle metasomatism and long-term volatile storage.

ACKNOWLEDGMENTS

JED was supported by NSF OCE 2401489, BRM by ARC and BHP IE240100170, and RDM by NCRIS via AuScope.

SUPPLEMENTAL MATERIAL

Detailed methods, sensitivity tests and data sources; Figures S1–S7; Tables S1–S3, the full sample table with derived hydration ages and durations, as a spreadsheet; and Videos S1–S2. Please visit <https://doi.org/10.1130/XXXX> to access the supplemental material, and contact editing@geosociety.org with any questions.

REFERENCES CITED

- Aubaud, C., Hauri, E. H., and Hirschmann, M. M., 2004, Hydrogen partition coefficients between nominally anhydrous minerals and basaltic melts: *Geophysical Research Letters*, v. 31, <https://doi.org/10.1029/2004GL021341>.
- Becker, T. W., Schaeffer, A. J., Lebedev, S., and Conrad, C. P., 2015, Toward a generalized plate motion reference frame: *Geophysical Research Letters*, v. 42, p. 3188-3196, <https://doi.org/10.1002/2015GL063695>.
- Bekaert, D. V., Turner, S. J., Broadley, M. W., Barnes, J. D., Halldórsson, S. A., Labidi, J., Wade, J., Walowski, K. J., and Barry, P. H., 2021, Subduction-driven volatile recycling: A global mass balance: *Annual Review of Earth and Planetary Sciences*, v. 49, p. 37-70, <https://doi.org/10.1146/annurev-earth-071620-055024>.

- Conrad, C. P., and Behn, M. D., 2010, Constraints on lithosphere net rotation and asthenospheric viscosity from global mantle flow models and seismic anisotropy: *Geochemistry, Geophysics, Geosystems*, v. 11, <https://doi.org/10.1029/2009GC002970>.
- Dixon, J. E., Bindeman, I., Kingsley, R. H., Simons, K., Le Roux, P., Hajewski, T., Swart, P., Langmuir, C., Ryan, J., and Walowski, K., 2017, Light stable isotopic compositions of enriched mantle sources: Resolving the dehydration paradox: *Geochemistry, Geophysics, Geosystems*, v. 18, p. 3801-3839, <https://doi.org/10.1002/2016GC006743>.
- Doucet, L. S., and Li, Z.-X., 2024, Large-scale mantle heterogeneity as a legacy of plate tectonic supercycles: *Nature Geoscience*, v. 17, p. 1175-1181, <https://doi.org/10.1038/s41561-024-01558-3>.
- Gibson, S. A., Jackson, C. J., Crosby, J. C., and Day, J. A. F., 2025, The role of C-O-H-F-Cl fluids in the making of Earth's continental roots: *Nature Communications*, v. 16, p. 7842, <https://doi.org/10.1038/s41467-025-62888-3>.
- Gose, J., Schmädicke, E., and Beran, A., 2009, Water in enstatite from Mid-Atlantic Ridge peridotite: Evidence for the water content of suboceanic mantle?: *Geology*, v. 37, p. 543-546, <https://doi.org/10.1130/g25558a.1>.
- Le Roux, V., Urann, B. M., Brunelli, D., Bonatti, E., Cipriani, A., Demouchy, S., and Monteleone, B. D., 2021, Postmelting hydrogen enrichment in the oceanic lithosphere: *Science Advances*, v. 7, p. eabf6071, <https://doi.org/10.1126/sciadv.abf6071>.
- Ligi, M., Bonatti, E., Cipriani, A., and Ottolini, L., 2005, Water-rich basalts at mid-ocean-ridge cold spots: *Nature*, v. 434, p. 66-69, <https://doi.org/10.1038/nature03264>.
- Liu, J., Tao, C., Zhou, J., Shimizu, K., Li, W., Liang, J., Liao, S., Kuritani, T., Deloule, E., Ushikubo, T., Nakagawa, M., Yang, W., Zhang, G., Liu, Y., Zhu, C., Sun, H., and Zhou, J., 2022, Water enrichment in the mid-ocean ridge by recycling of mantle wedge residue: *Earth and Planetary Science Letters*, v. 584, p. 117455, <https://doi.org/10.1016/j.epsl.2022.117455>.
- Mather, B. R., Müller, R. D., Dutkiewicz, A., and Zahirovic, S., 2026, Carbon emissions along divergent plate boundaries modulate icehouse-greenhouse climates: *Communications Earth & Environment*, v. 7, p. 48, <https://doi.org/10.1038/s43247-025-03097-0>.
- Métrich, N., Zanon, V., Créon, L., Hildenbrand, A., Moreira, M., and Marques, F. O., 2014, Is the 'Azores hotspot' a wetspot? Insights from the geochemistry of fluid and melt inclusions in olivine of Pico basalts: *Journal of Petrology*, v. 55, p. 377-393, <https://doi.org/10.1093/petrology/egt071>.
- Michael, P., 1995, Regionally distinctive sources of depleted MORB: Evidence from trace elements and H₂O: *Earth and Planetary Science Letters*, v. 131, p. 301-320, [https://doi.org/10.1016/0012-821X\(95\)00023-6](https://doi.org/10.1016/0012-821X(95)00023-6).
- Nichols, A. R. L., Carroll, M. R., and Höskuldsson, Á., 2002, Is the Iceland hot spot also wet? Evidence from the water contents of undegassed submarine and subglacial pillow basalts: *Earth and Planetary Science Letters*, v. 202, p. 77-87, [https://doi.org/10.1016/S0012-821X\(02\)00758-6](https://doi.org/10.1016/S0012-821X(02)00758-6).
- Rampone, E., and Hofmann, A. W., 2012, A global overview of isotopic heterogeneities in the oceanic mantle: *Lithos*, v. 148, p. 247-261, <https://doi.org/10.1016/j.lithos.2012.06.018>.
- Richter, M., Nebel, O., Maas, R., Mather, B., Nebel-Jacobsen, Y., Capitanio, F. A., Dick, H. J. B., and Cawood, P. A., 2020, An Early Cretaceous subduction-modified mantle underneath the ultraslow spreading Gakkel Ridge, Arctic Ocean: *Science Advances*, v. 6, p. eabb4340, <https://doi.org/doi:10.1126/sciadv.abb4340>.
- Schilling, J.-g., Bergeron, M. B., and Evans, R., 1980, Halogens in the mantle beneath the North Atlantic: *Philosophical Transactions of the Royal Society of London, Series A: Mathematical and Physical Sciences*, v. 297, p. 147-178, <https://doi.org/10.1098/rsta.1980.0208>.
- Schilling, J. G., Hanan, B. B., McCully, B., Kingsley, R. H., and Fontignie, D., 1994, Influence of the Sierra Leone mantle plume on the equatorial Mid-Atlantic Ridge: A Nd-Sr-Pb isotopic study: *Journal of Geophysical Research: Solid Earth*, v. 99, p. 12005-12028, <https://doi.org/10.1029/94JB00337>.

- Schmädicke, E., Gose, J., and Stalder, R., 2018, Water in abyssal peridotite: why are melt-depleted rocks so water rich?: *Geochemistry, Geophysics, Geosystems*, v. 19, p. 1824-1843, <https://doi.org/10.1029/2017GC007390>.
- Shibata, T., Thompson, G., and Frey, F. A., 1979, Tholeiitic and alkali basalts from the Mid-Atlantic Ridge at 43°N: *Contributions to Mineralogy and Petrology*, v. 70, p. 127-141, <https://doi.org/10.1007/BF00374441>.
- Tetley, M. G., Williams, S. E., Gurnis, M., Flament, N., and Müller, R. D., 2019, Constraining absolute plate motions since the triassic: *Journal of Geophysical Research: Solid Earth*, v. 124, p. 7231-7258, <https://doi.org/10.1029/2019JB017442>.
- Urann, B. M., Dick, H. J. B., Parnell-Turner, R., and Casey, J. F., 2020, Recycled arc mantle recovered from the Mid-Atlantic Ridge: *Nature Communications*, v. 11, p. 3887, <https://doi.org/10.1038/s41467-020-17604-8>.
- van Keken, P., E, Chauvel, C., and Ballentine, C., J, 2025, Dynamical Geochemistry: Ocean crust recycling through plate tectonics and its role in the formation of mantle heterogeneity, *Treatise on Geochemistry*, Elsevier, p. 647-670, <https://doi.org/10.1016/b978-0-323-99762-1.00103-0>.
- van Keken, P. E., 2003, The structure and dynamics of the mantle wedge: *Earth and Planetary Science Letters*, v. 215, p. 323-338, [https://doi.org/10.1016/S0012-821X\(03\)00460-6](https://doi.org/10.1016/S0012-821X(03)00460-6).
- Yang, A. Y., Langmuir, C. H., Cai, Y., Michael, P., Goldstein, S. L., and Chen, Z., 2021, A subduction influence on ocean ridge basalts outside the Pacific subduction shield: *Nature Communications*, v. 12, p. 4757, <https://doi.org/10.1038/s41467-021-25027-2>.
- Zahirovic, S., Eleish, A., Doss, S., Pall, J., Cannon, J., Pistone, M., Tetley, M. G., Young, A., and Fox, P., 2022, Subduction and carbonate platform interactions: *Geoscience Data Journal*, v. 9, p. 371-383, <https://doi.org/10.1002/gdj3.146>.

FIGURE CAPTIONS

Figure 1. The global H₂O/Ce anomaly. (A) MORB and enriched mixing end-members in H₂O/Ce–Ba/Nb space, showing higher H₂O/Ce in the NMAR and equatorial MAR relative to the SMAR and Pacific. BABB reach ~4000 H₂O/Ce (off scale). Data sources in Table S1 caption. G—Gakkel; RR—Reykjanes Ridge; AP—Azores Platform; SyG—Salas y Gómez; NAEM—North Atlantic EM1; SAEM—South Atlantic EM1. (B) Global along-ridge H₂O/Ce in MORB glasses, projected onto the plate-boundary network by distance-weighted interpolation of samples within 150 km of each ridge segment. Gray lines are plate boundaries. Winkel Tripel projection.

Figure 2. Cumulative subducted water in a mantle reference frame from 400 to 0 Ma. Selected ages mark highlighted hydration events: (A) 400 Ma (model initiation), (B) 320 Ma (NMAR), (C) 220 Ma (mid-latitude MAR) and (D) 120 Ma (Arctic). Colors show cumulative water on a logarithmic scale. Water is added at each reconstructed trench and remains at those locations. Continents are light gray; plate boundaries gray; subduction zones red with teeth on the overriding side.

Figure 3. Subduction geography at each ridge region's last hydration under three mantle reference frames. (A–D) Water delivered during each 20 Myr hydration window in the preferred frame for key times, with coeval continents, plate boundaries and subduction zones. Red and blue show reconstructed plate

boundaries in the no-net-rotation and maximum-net-rotation frames; their separation shows absolute-frame uncertainty. Site symbols are filled if hydrated in the shown window, gray if hydrated at another time, and open if no water reached them. Sites are fixed in the mantle frame, so present-day coordinates are also reconstructed positions (Fig. S2). (E) Regional hydration ages by frame with interquartile ranges; hydrated fractions shown where below 90%.

Figure 4. Hydration age and MORB H₂O/Ce. (A) Site hydration ages; open symbols mark 801 samples unreached by modeled subduction water over 410 Myr. (B) The Atlantic–Arctic corridor (50°W–5°E) by latitude: 5° bin median and interquartile range of H₂O/Ce above, underlying mantle hydration age below (colors as in A; hatching marks where no delivery). Dashed H₂O/Ce = 250 separates normal from enriched MORB. (C) H₂O/Ce by hydration-age class (one value per 300 km cluster), compared with Pacific cluster median and interquartile range; counts denote clusters.

SUPPLEMENTAL MATERIAL

A 400-million-year memory of subduction in the mid-ocean ridge source

Jacqueline Dixon, R. Dietmar Müller, Adriana Dutkiewicz, and Ben R. Mather

* Correspondence to: jdixon@usf.edu

Contents: detailed methods, sensitivity tests, and discussion of mantle-wedge transport and water budgets; Figures S1–S7; Table S1 (spreadsheet), Tables S2 and S3; Videos S1 and S2.

S1. METHODS

S1.1 Plate reconstruction and reference frame

All reconstructions use the global plate model of Zahirovic et al. (2022) in a mantle reference frame, which joins the Paleozoic model of Young et al. (2019) to the post-250 Ma model of Müller et al. (2019) and begins at 410 Ma. A mantle reference frame is essential here: the quantity of interest is where slab water entered the mantle relative to the deep mantle rather than relative to any moving plate, and only a mantle-frame reconstruction makes delivery at different times directly comparable.

S1.2 Mantle reference-frame uncertainty

Where the plates sat relative to the deep mantle is the least certain part of any reconstruction, and it bears directly on a calculation that places water at reconstructed trench positions. Relative plate motions are tightly constrained by seafloor and geological data; the absolute frame is not. We therefore repeat the whole calculation in three alternative frames from the EarthByte optAPM optimisation (Tetley et al., 2019): no-net-rotation (NNR), and optimised mean and maximum net rotation.

The mean-net-rotation frame best balances net rotation, trench migration, plate velocities and hotspot tracks against the other candidates, and is the frame the published Zahirovic et al. (2022) rotations correspond to; we treat it as the preferred estimate, with NNR and maximum net rotation bracketing its uncertainty (net rotation medians of 0, 0.080° and 0.165° Myr⁻¹, respectively, all within the range permitted by seismic anisotropy and mantle flow models; Becker et al., 2015; Conrad and Behn, 2010).

The three alternative frames differ from the published rotations in only one relative plate rotation, so each alternative water field is obtained by rigidly rotating the published cumulative grids rather than re-running the subduction workflow — a procedure we verified conserves mass to better than 0.01%. Displacements between frames reach ~900–2,200 km by 400 Ma, large next to the 300 km smoothing length, yet the regional hydration ages are largely insensitive to this choice: of 543 samples hydrated in the published frame, 383 are hydrated in all four frames and 342 carry an identical age, and the hydrated-versus-

unhydrated H₂O/Ce contrast is significant in every frame ($p \leq 0.003$). The Arctic (120 Ma) and mid-latitude Mid-Atlantic (220 Ma) ages are unchanged across all four frames; the northern Mid-Atlantic age of 320 Ma holds in three of the four. Two of the main text's model–data discrepancies fall within this uncertainty, and are discussed there rather than repeated here.

S1.3 Slab volatile reservoirs

Each subducting plate carries three volatile reservoirs — deep-sea sediment, hydrothermally altered oceanic crust, and serpentinized lithospheric mantle — with thicknesses and water contents from the workflow of Mather et al. (2026), consistent with standard subduction-factory treatments (Hacker, 2008; Hacker et al., 2003; Kelley et al., 2003; Rüpke et al., 2004). We report the sum of the three (the grid archive's “mantle” variant).

S1.4 Slab water flux and the devolatilization question

The quantity used throughout this paper is the total water carried into the mantle by each subducting segment — the sum of the three reservoirs above, counted as it crosses the trench — fixed upstream of any devolatilization and independent of what the slab later does with that water. The grid archive also carries a thermodynamic split of that total into water released above versus retained below 125 km slab depth, estimated with a Perple_X-based approach (Connolly, 2009) following Mather et al. (2026). We use that split only once, as a sensitivity check (Section S1.8; Fig. S5), where it makes no material difference to the results; none of the paper's conclusions depends on the devolatilization calculation or its depth cut-off.

S1.5 From subduction to cumulative grids

At each time step the subducted water is assigned to the reconstructed mantle-reference-frame position of the trench, smoothed with an isotropic 300 km Gaussian filter, and summed through time onto a 0.2° global grid. The kernel is symmetric about the trench and so places water on the subducting side as well as the overriding side, which is not where slab water goes; Section S1.8 measures how much that matters. Nothing is advected afterwards. The calculation contains no velocity field, no particle paths, no phase segregation, no mixing, no lithospheric capture and no melt extraction. The resulting field is a cumulative record of where water entered the mantle at subduction zones, evaluated under an explicit zero-post-emplacement-displacement end-member; it is not a prediction of the present-day distribution of hydrated mantle, and no statement in the main text depends on treating it as one.

S1.6 The start of the reconstruction, and sites without an age

The reconstruction begins at 410 Ma, so the cumulative fields begin there too and no rebaselining is needed: the totals are zero at the model start by construction. This bounds what can be measured. A site

has a hydration age only if subduction water came within reach of it at some time in the 410 Myr covered. Where none did, the site has no age, and 801 of the 1,344 samples (Table S1) are in that position. Two distinct situations produce that outcome and the reconstruction cannot separate them: mantle that has never received subduction water, and mantle that received it before 410 Ma. Every comparison in this paper is therefore between mantle supplied within the last 400 Myr and mantle not supplied within it, which is also why no upper limit on the lifetime of the signature can be given.

SI.7 Hydration age and episode duration

Let $W(T)$ be the cumulative water at a fixed mantle-frame point at reconstruction age T , sampled every 20 Myr. The delivery rate over the window between T_{k+1} and T_k is

$$\text{rate}(T_k) = [W(T_k) - W(T_{k+1})] / (T_{k+1} - T_k) \quad \text{in } \text{t m}^{-2} \text{ Myr}^{-1}$$

and the point is *in reach* of subduction water in that window when the rate exceeds a threshold, $0.5 \text{ t m}^{-2} \text{ Myr}^{-1}$ throughout the main text. Two quantities follow:

- Hydration age — the youngest in-reach window. This is how far back one must go to find the most recent delivery of slab water to that point.
- Episode duration — the length of the contiguous run of in-reach windows ending at the hydration age, with runs separated by gaps shorter than 20 Myr treated as continuous.

Where no window meets the test, the site has no hydration age and no duration; that is a statement about the reconstruction, not a missing measurement. Thresholds are expressed as rates rather than as per-window increments so that the numbers do not change if the time step changes. Both quantities can only fall on the reconstruction time steps, and are reported as whole numbers of Myr. Sites are sampled from the grids by the same nearest-neighbor lookup used by the figure scripts; about 3% of sites lie close enough to a grid-cell boundary that indexing convention alone can shift the sampled value by more than 1000 t m^{-2} .

SI.8 Sensitivity

Three choices in the procedure could in principle drive the result: the delivery-rate threshold, the isotropic smoothing of water about the trench, and the decision to count total subducted water rather than only the part released at shallow depth. None of them does.

Delivery-rate threshold. Across a fifty-fold range (0.05 – $2.5 \text{ t m}^{-2} \text{ Myr}^{-1}$) every regional median hydration age is unchanged (Fig. S4); only the number of qualifying samples shifts, from 582 to 499 against 543 at the working value.

Kernel placement. The smoothing kernel is symmetric about the trench, so half of it lies over the subducting plate rather than the overriding plate, where slab water actually goes; displacing every site 300 km along each of eight bearings tests the effect. The northern and mid-latitude Mid-Atlantic ages are unchanged in every case and the Arctic within one 20 Myr step; at most 6.9% of individual sites change age class, with zero median change. Only the southern Mid-Atlantic — resting on seven dated sites — shifts under two of the eight displacements, and nothing in the paper depends on it.

Shallow versus deep water. This is the one place the thermodynamic split is used. Hydration ages from the shallow release component alone match those from the total water at 98% of sites (99.8% within one 20 Myr step); the deep component agrees at 87%. Every regional median is identical across all three (Fig. S5), so the split cannot discriminate a shallow from a deep origin for the signal, and the main text reports total subducted water only.

SI.9 MORB H₂O/Ce compilation

The compilation merges five sources: the Le Voyer et al. (2019) global compilation of SIMS H₂O measurements made under a single protocol; the eastern Gakkel Ridge dataset of Cai et al. (2021); the Mid-Atlantic Ridge dataset of Silantyev et al. (2008), with H₂O by FTIR and trace elements by LA-ICP-MS on the same glass chips; a curated compilation assembled for this study; and the original Michael (1995) dataset. Duplicates across sources are identified by matched sample identifiers and position, or by close position combined with matching H₂O/Ce, resolved in that priority order, with every collapse recorded in an audit file distributed with the code. Of 1,667 raw candidates, 323 are removed as duplicates, leaving 1,344 unique samples at 1,048 sites: 945 from Le Voyer et al., 254 curated, 56 from Cai et al., 48 from Michael (1995) and 41 from Silantyev et al.

SI.10 Statistical methods

Ridge samples tens of kilometres apart are not independent observations of a field smoothed over 300 km, so every comparison first collapses each 300 km cluster (complete-linkage, matching the smoothing length of the grids) to a single median; the compilation holds 136 such clusters. Confidence intervals come from resampling whole clusters and proportions carry Wilson binomial intervals. Change points along the Mid-Atlantic Ridge are located by scanning candidate split latitudes and maximising the Mann–Whitney z-statistic for north-over-south (Fig. S3): with the previously unsampled 15°–20°N interval now filled, the strongest step moves from the equator to 28°N ($z = 12.9$), though the statistic is broad — flat at $z = 11.0$ from 17.5°N to 22°N — so the ~22°N boundary proposed by Michael (1995) sits on that plateau rather than being distinct from it. The new data establish a southern limit to the anomaly in the low tropics, without locating it to better than about ten degrees of latitude.

The central comparison, between clusters with and without a modeled hydration age, is reported in the main text for all basins and for the Atlantic–Arctic corridor. Four of the 136 clusters contain both dated and undated sites and so contribute a median to each group; restricting the test to the 132 unambiguous clusters gives an essentially identical result (250 against 200, $p = 0.002$).

Within the dated interval there is no dependence on age (rank correlation $+0.07$, $p = 0.60$): only the 100–200 Ma bracket lies clearly above the undated level (289 against 200, $p = 0.004$), and the other three brackets do not differ significantly from it. These differences do not form a trend — each bracket is dominated by one stretch of ridge (100–200 Ma is almost entirely Arctic; 200–300 Ma the Mid-Atlantic between 11°N and 34°N) — so the aggregate dated-versus-undated comparison, not the age breakdown, is the statistic the paper rests on. Every age class lies above the Pacific, the least hydrated part of the ridge system (Fig. 4C).

SI.11 Plume influence

Ridge-centered plumes redistribute enriched material and could in principle generate a pattern that mimics a hydration-age effect. We test this in two ways. The first is a distance criterion: the great-circle distance from every sample to the nearest of 22 ridge-centered or near-ridge hotspots, with plume-proximal samples excluded. Samples within 500 km of a hotspot have a *lower* median $\text{H}_2\text{O}/\text{Ce}$ than the rest, 207 against 231, so they are not inflating the signal. Excluding them leaves the global contrast intact and weakens the corridor contrast; extending the exclusion to 1000 km removes half the compilation.

A radius is a blunt instrument, because the length of ridge a plume actually affects varies by an order of magnitude between plumes. The second test therefore uses six geochemically defined segments instead — Jan Mayen, the Reykjanes Ridge north of 61°N , the Azores Platform, the 35°N and 14°N off-axis anomalies, and the Sierra Leone segment — removing 74 samples rather than the several hundred a 500 km radius would take. Both contrasts survive this stricter test (Table S2; reported in the main text), and the corridor contrast is if anything stronger, because the radius approach also removes plume-enriched clusters that have no hydration age and so inflates the unhydrated median. Adding the 5° – 10°N stretch, where closely spaced fracture zones offset very short ridge segments, changes the result only marginally.

Table S2. Robustness of the hydrated-versus-unhydrated $\text{H}_2\text{O}/\text{Ce}$ contrast to plume exclusion, with and without the six geochemically defined plume-affected ridge segments described above (74 of 1344 samples). Medians are per-cluster (300 km complete-linkage); p is Mann-Whitney U on cluster medians.

Scope	Plume segments	Hydrated median $\text{H}_2\text{O}/\text{Ce}$	Hydrated n (clusters)	Unhydrated median $\text{H}_2\text{O}/\text{Ce}$	Unhydrated n (clusters)	Difference	Mann-Whitney p
Global	Included	249	55	200	85	49	0.003
Global	Excluded	247	54	198	81	49	0.002
Atlantic-Arctic corridor	Included	275	24	229	29	46	0.039

Atlantic-Arctic corridor	Excluded	273	23	203	25	69	0.029
--------------------------	----------	-----	----	-----	----	----	-------

The samples a distance criterion removes are worth looking at directly. Between 55°N and 61°N on the Reykjanes Ridge there are 70 samples, every one with a hydration age of 320 Ma, and their median H₂O/Ce of 353 is the highest of any segment in the compilation; a radius drawn around Iceland removes them along with genuinely plume-proximal samples. Plumes are also a second route for water into the ridge source rather than only a confounder (main text); where a plume meets a ridge the two sources are not independent, and no test here separates them.

S1.12 Scope and limitations

The workflow reconstructs where water was carried into the mantle at subduction zones and how that accumulated at fixed points in a mantle reference frame. It does not simulate mantle stirring, small-scale convective mixing, fluid or melt segregation, lithospheric capture and later release, or the efficiency with which repeated ridge upwelling and melt extraction erase a hydrated anomaly. It cannot determine a unique storage depth, transport path, retained fraction or residence time for any individual parcel. What it does supply is a per-site age for the most recent delivery of slab water, and the empirical observation — independent of any transport model — that mantle supplied within the last 400 Myr carries higher H₂O/Ce than mantle that was not, with no dependence on when within that interval the water arrived. That contrast is what constrains chemical survival; the reconstruction itself constrains only geography and timing.

S1.13 Mantle-wedge dynamics and the transport this model omits

The zero-displacement end-member of Section S1.5 is a deliberate simplification. Below about 70–80 km depth the mantle wedge is an open, advecting system — hot asthenosphere is drawn in to feed sub-arc melting and processed mantle recirculates along the slab (Hall et al., 2012; van Keken, 2003; Wada and Wang, 2009), made still more three-dimensional by rollback, slab tears and edge flow (Kincaid and Griffiths, 2004). Only the cold, weakly coupled forearc nose is close to stagnant, and even that moves with the overriding plate once incorporated into the lithosphere. Fluids and melts likewise migrate relative to the solid mantle (Wilson et al., 2014), so the true emplacement geometry is not the symmetric, trench-centered one our smoothing kernel imposes, and migrating continental keels deflect the asthenosphere beneath them further still. None of this is addressed by a kinematic reconstruction, which would require a full time-dependent geodynamic model tracking particle paths through the flow field.

A mean net displacement below 1 mm yr^{-1} would be needed to hold material within 300 km of its emplacement site for 320 Myr — an order of magnitude slower than typical mantle flow (1 cm yr^{-1} traces 3,200 km over the same interval) — so geographic persistence of a hydrated parcel is not a defensible reading of these maps, and no result in the paper depends on one. Downward export does not, however, preclude later sampling at a ridge: hydrated material can be carried into the transition zone and returned by larger-scale circulation (Hébert and Montési, 2013; Barry et al., 2017), and recycled subduction-processed mantle has been recovered directly at the Mid-Atlantic Ridge, the Gakkel Ridge and the Southwest Indian Ridge (Urann et al., 2020; Richter et al., 2020; Liu et al., 2022). This is why the hydration age is used throughout as a date rather than a location, and the evidence for chemical survival is the measured contrast between supplied and unsupplied mantle rather than the geometry of the maps.

SI.14 Water budget and comparison with a modern arc

Because the analysis uses total water carried into the mantle, the partition between arc crust, mantle wedge and deeper slab does not enter any result. For context only, the shallow component of the grid archive (released above 125 km) is a median 75% of the total at MORB sample sites (interquartile range 64–99%) — quoted for comparison with modern arcs, where the depth-dependent water flux has been estimated independently (Kimura and Nakajima, 2014; van Keken et al., 2011).

We do not report a fraction delivered to arc crust, because nothing in this workflow computes melt generation or crustal storage. We also withdraw an inference made in an earlier version of this manuscript, that a 29% wedge-stored fraction combined with an 11% fraction retained in the slab beyond 180 km constrains long-term local retention of water. The arithmetic was correct but the inference was not: those are steady-state regional estimates for one modern subduction factory, the 11% is explicitly slab-bound, and neither bears on whether hydrated material remains at a fixed upper-mantle location for hundreds of millions of years.

SI.15 Does the length of supply matter?

Each site carries a second quantity besides the hydration age: the length of the most recent spell of supply. It turns out to add almost nothing. Working within the Atlantic–Arctic corridor and taking one value per 300 km cluster, as everywhere else, a rank regression of $\text{H}_2\text{O}/\text{Ce}$ on hydration age explains 1.2% of the variation across the 33 dated clusters, and adding the length of supply raises this only to 1.5%. On its own the length of supply is unrelated to $\text{H}_2\text{O}/\text{Ce}$ ($\rho = +0.06$, $p = 0.72$), and it remains unrelated once the hydration-age effect is removed ($\rho = +0.04$, $p = 0.83$; Fig. S1). Neither quantity explains much: among sites that were supplied at all, neither when the water arrived nor how long it kept arriving predicts how wet the source is. What distinguishes wet from dry mantle is whether it was supplied, not the details of

the supply. The one place where the length of supply is the only quantity available is the Arctic, where every site has essentially the same hydration age. We do not read anything into it there either, given how little it explains elsewhere.

S1.16 How well the source of the water can be localized

The hydration age says when water last arrived beneath a site, not which subduction zone sent it. Water is summed at reconstructed trench positions and smoothed over 300 km, so the identity of the contributing trench is not retained in the fields. A source can still be identified where two independent tests agree. The first is proximity: at a region's hydration age, how far is the nearest resolved subduction zone from the region's sites. The second is direction: within 1200 km of the region, where does the delivered water actually peak, and how far is that maximum from the candidate trench. Proximity alone is not sufficient, because a boundary can lie near a region without having supplied it; we accept an attribution only where the delivery maximum falls within one smoothing length of the candidate.

Table S3. Source-attribution test for candidate hydration regions (Section S1.16). For each region, the delivery maximum is the direction and distance from the region within which the modelled delivered water actually peaks, searched within 1200 km; the nearest subduction zone is the closest reconstructed trench at the region's own hydration age; separation is the distance between the two. An attribution is accepted only where the separation falls within one smoothing length (300 km) of the candidate trench, met here only by the Farallon band and the wider Mid-latitude Mid-Atlantic Ridge band (160 km each).

region	age	delivery maximum	nearest subduction zone	separation
Farallon band, 20°–35°N	220 Ma	404 km NW	western North American margins, 457 km W	160 km
Mid-latitude MAR, 11°–34°N	220 Ma	761 km N	western North American margin, 711 km NW	160 km
Northern MAR, 50°–70°N	320 Ma	1195 km E	Siberian margin consuming Arctic seafloor, 434 km SE	982 km
Arctic ridges	120 Ma	733 km NW	Uda-Murgal, 1746 km NW	1017 km
South Atlantic	380 Ma	438 km S	Western Gondwana, 3634 km SW	3229 km

Two regions pass, and they are the same source seen at two widths — the Farallon attribution the main text names (Table S3). For the ridge north of 50°N the two tests disagree, so the paper claims only the age and direction of arrival there, not a source; the Arctic and South Atlantic fail the same test by a wide margin (Table S3). Identifying sources directly, rather than by this indirect test, would require the subduction workflow to retain the water contributed by each trench segment at each time step rather than only the summed field.

S2. SUPPLEMENTARY FIGURES AND TABLE

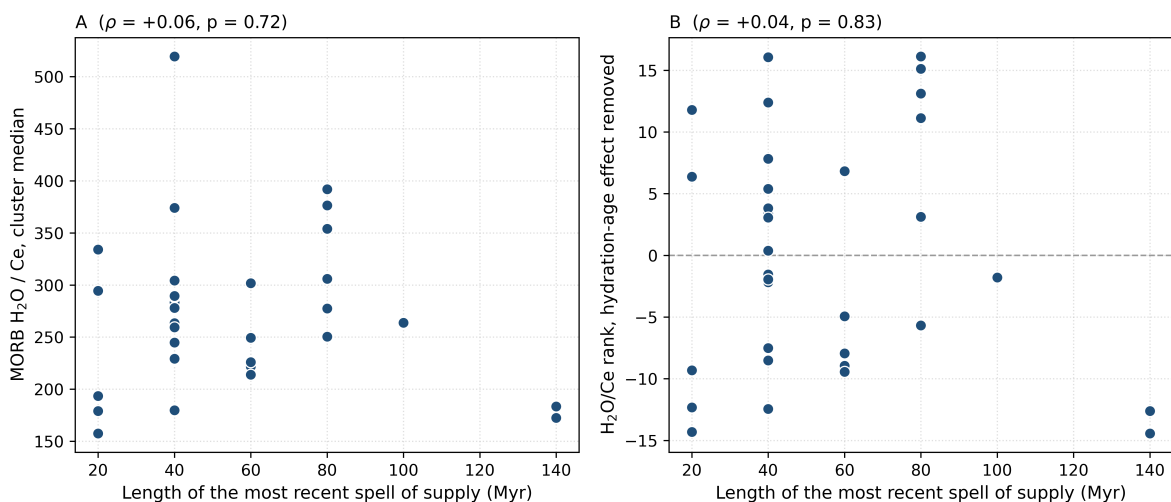


Figure S1. Does the length of a spell of supply matter? (A) Cluster-median H₂O/Ce against cluster-median length of the most recent spell of supply, for the Atlantic–Arctic corridor, one point per 300 km cluster. (B) The same after the hydration-age effect has been removed, plotted as the residual of H₂O/Ce about a rank regression on hydration age; if the length of supply carried information beyond the age, structure would appear here. Neither panel shows a relationship.

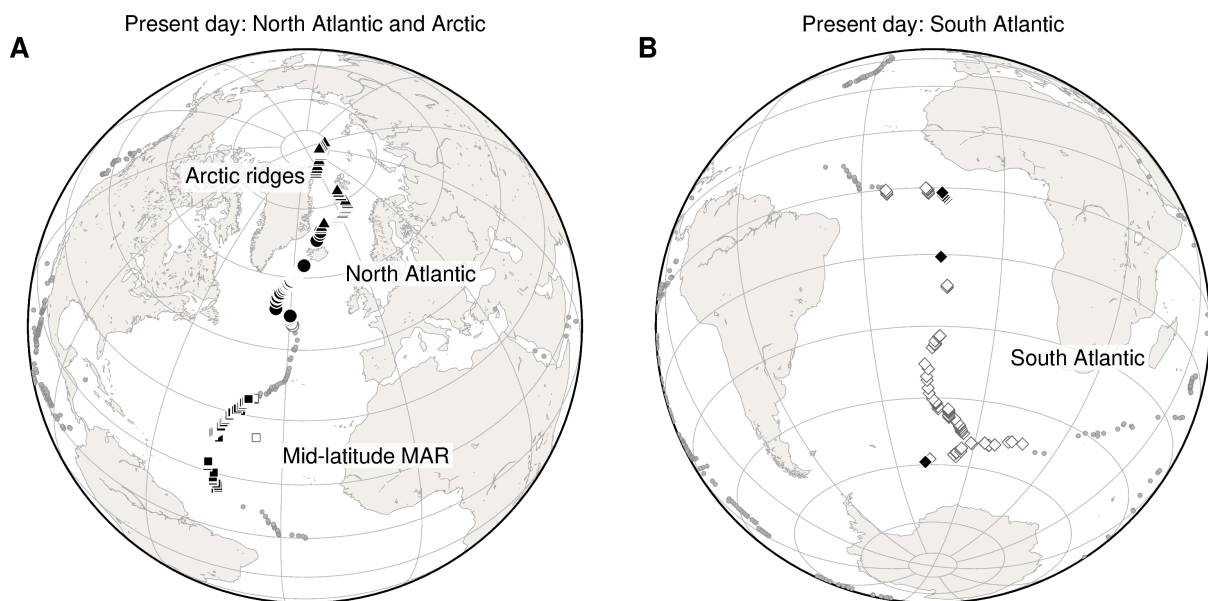


Figure S2. Which samples belong to which region. Two present-day orthographic maps, centered on the North Atlantic and Arctic (A) and on the South Atlantic (B). Small grey circles are the sites outside the four regions, most of them Pacific. The four regions carry their own symbol — circles for the North Atlantic (50°–70°N), squares for the mid-latitude Mid-Atlantic Ridge (11°–34°N), triangles for the Arctic

ridges (north of 70°N) and diamonds for the South Atlantic — filled where the site has a hydration age and open where it has none. Figure 3 shows the same four regions on reconstructions at their own hydration ages. The regions hold similar numbers of sites (85, 89, 89 and 86) but not similar numbers of dated ones: 83, 79 and 89 in the three northern regions against 7 in the South Atlantic, where almost every site lies beyond the reach of any subduction the reconstruction resolves.

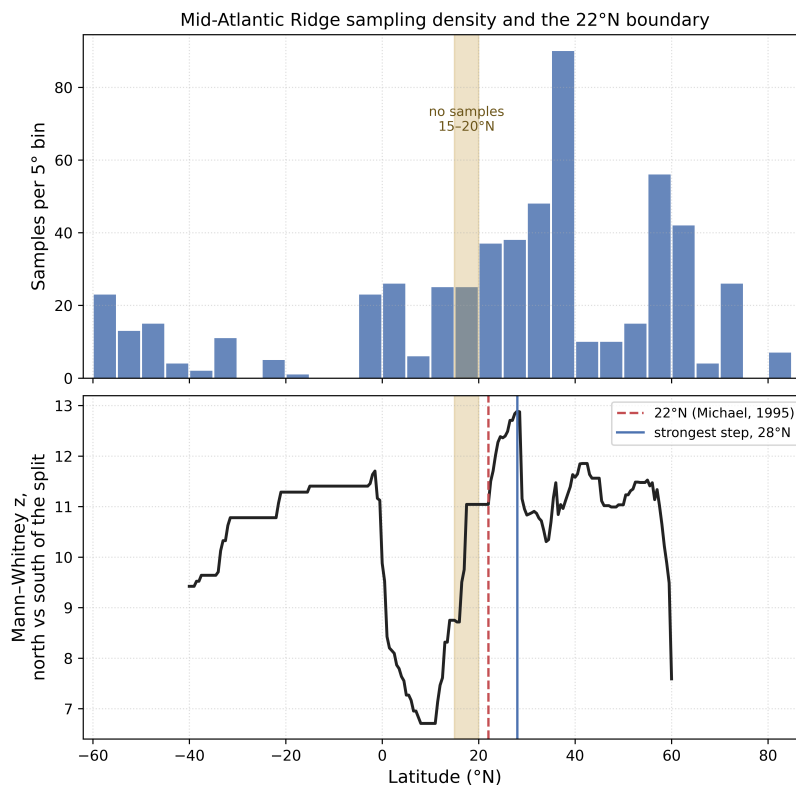


Figure S3. Sampling density and the southern boundary of the North Atlantic anomaly. (Top) MORB samples per 5° latitude bin along the Mid-Atlantic Ridge corridor (50°W–5°E). The 15°–20°N interval, unsampled in earlier compilations, holds 25 samples at 21 sites from Silantyev et al. (2008). (Bottom) Mann–Whitney z-statistic for a north-over-south difference in H₂O/Ce as a function of split latitude. With the gap filled the maximum moves from the equator, where the missing samples had placed it, to 28°N ($z = 12.9$); the statistic is flat at $z = 11.0$ between 17.5°N and 22°N, so the ~22°N boundary proposed by Michael (1995) is consistent with the data without being singled out by them.

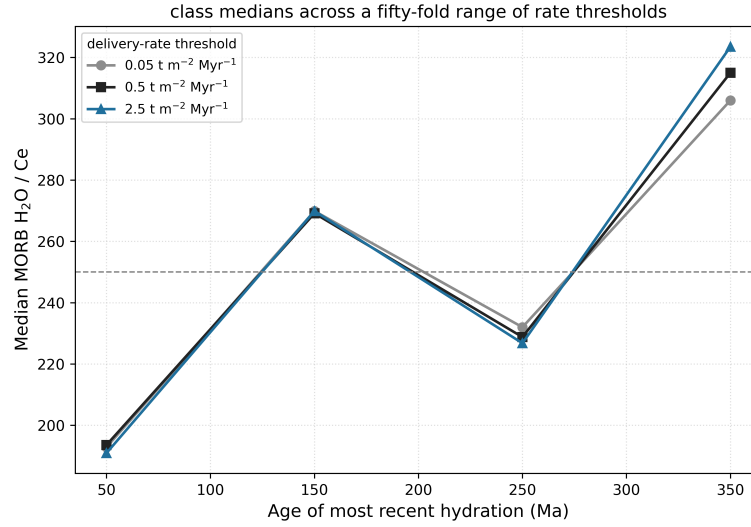


Figure S4. Median $\text{H}_2\text{O}/\text{Ce}$ in 100 Myr hydration-age classes, computed with delivery-rate thresholds of 0.05, 0.5 and $2.5 \text{ t m}^{-2} \text{ Myr}^{-1}$. The threshold is the only free choice in the procedure, and every regional media hydration age is identical at all three values.

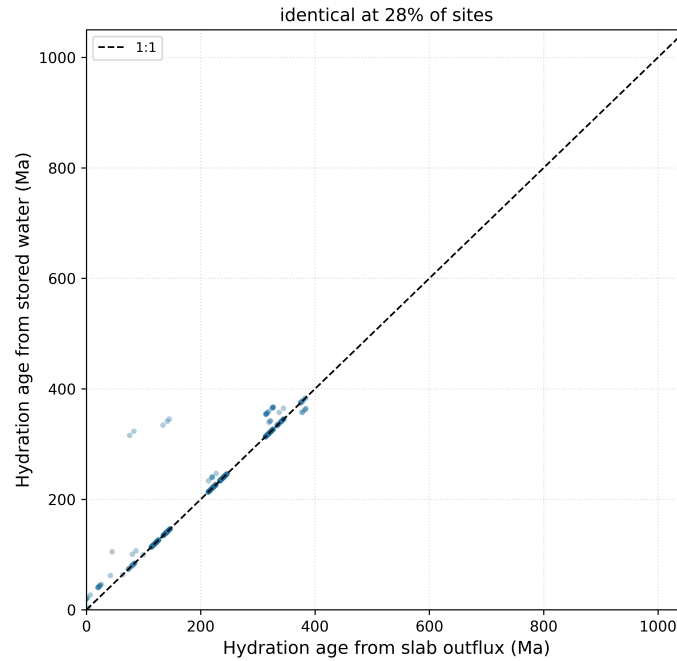


Figure S5. Hydration age computed from the shallow slab-outflux component against the same quantity computed from the deep stored component, for every sample site. Points are jittered by up to ± 7 Myr so that coincident values remain visible. Ages from the shallow component are identical to those from the total at 98% of sites and within one 20 Myr step at every site; the deep component agrees at 87%. No regional median differs at all, so the split does not discriminate between a shallow and a deep origin for the signal.

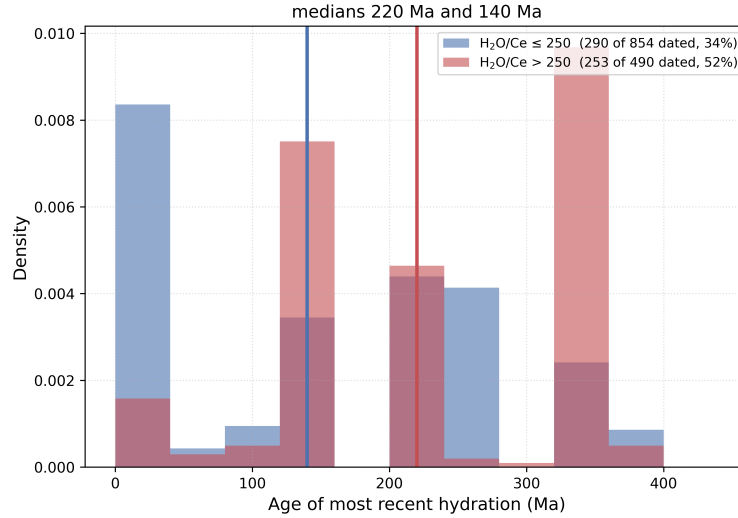


Figure S6. Distributions of hydration age for MORB with elevated H_2O/Ce (> 250) and for the remainder, with medians marked. Samples with no hydration age are counted separately rather than plotted at an age, since the reconstruction places them outside its reach.

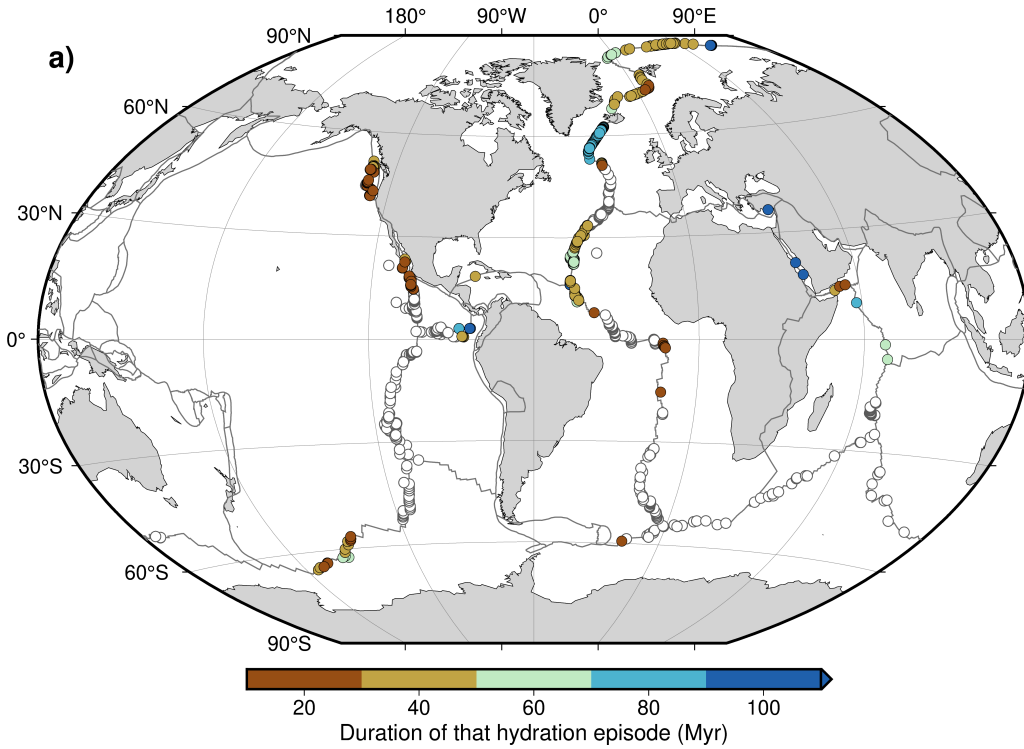


Figure S7. Duration of the most recent hydration episode at every sample site, the companion of the hydration-age map in Figure 4A. Durations are short: typically 40 Myr, half of them between 40 and 80 Myr, none longer than 180 Myr. Open white symbols mark sites with no hydration age. Section S1.15 shows that duration carries no information the age does not.

Table S1. The full sample table, as a spreadsheet. One row per MORB analysis: sample identifier, position, depth, ocean basin and source compilation; H₂O, Ce, H₂O/Ce, Ba, Nb, Ba/Nb and ⁸⁷Sr/⁸⁶Sr where available; and the derived hydration age, episode end age, episode duration, water delivered during the episode, number of in-reach windows and total accumulated water, for each rate threshold. A second sheet documents every column and its units; a third gives summary medians by ocean basin and by H₂O/Ce class.

Video S1. Cumulative subducted water in the mantle reference frame, 410–0 Ma, Zahirovic et al. (2022) reconstruction, with reconstructed continents, plate boundaries and subduction zones. Winkel Tripel projection, central meridian 60°W; logarithmic colour scale, 10–10,000 t m⁻², as in Figure 2. The reconstruction begins at 410 Ma, so the first frame is empty.

Video S2. The same sequence for the region of mantle underlying the present-day North Atlantic and Arctic ridges, in orthographic projection centered on 30°W, 55°N. The view is fixed in the mantle reference frame, so the plates crossing it change through time.

S3. METHODS REFERENCES

Connolly, J.A.D., 2009, The geodynamic equation of state: what and how: *Geochemistry, Geophysics, Geosystems*, v. 10, Q10014, <https://doi.org/10.1029/2009GC002540>.

Hacker, B.R., 2008, H₂O subduction beyond arcs: *Geochemistry, Geophysics, Geosystems*, v. 9, Q03001, <https://doi.org/10.1029/2007GC001707>.

Hacker, B.R., Peacock, S.M., Abers, G.A., and Holloway, S.D., 2003, Subduction factory 2: Are intermediate-depth earthquakes in subducting slabs linked to metamorphic dehydration reactions?: *Journal of Geophysical Research: Solid Earth*, v. 108, 2030, <https://doi.org/10.1029/2001JB001129>.

Kelley, K.A., Plank, T., Ludden, J., and Staudigel, H., 2003, Composition of altered oceanic crust at ODP Sites 801 and 1149: *Geochemistry, Geophysics, Geosystems*, v. 4, 8910, <https://doi.org/10.1029/2002GC000435>.

Mather, B.R., Müller, R.D., Dutkiewicz, A., and Zahirovic, S., 2026, Carbon emissions along divergent plate boundaries modulate icehouse-greenhouse climates: *Communications Earth & Environment*, v. 7, p. 48, <https://doi.org/10.1038/s43247-025-03097-0>.

Müller, R.D., Zahirovic, S., Williams, S.E., Cannon, J., Seton, M., Bower, D.J., Tetley, M.G., Heine, C., Le Breton, E., Liu, S., Russell, S.H.J., Yang, T., Leonard, J., and Gurnis, M., 2019, A global plate model

including lithospheric deformation along major rifts and orogens since the Triassic: *Tectonics*, v. 38, p. 1884–1907, <https://doi.org/10.1029/2018TC005462>.

Rüpke, L.H., Morgan, J.P., Hort, M., and Connolly, J.A.D., 2004, Serpentine and the subduction zone water cycle: *Earth and Planetary Science Letters*, v. 223, p. 17–34, <https://doi.org/10.1016/j.epsl.2004.04.018>.

van Keken, P.E., Hacker, B.R., Syracuse, E.M., and Abers, G.A., 2011, Subduction factory 4: Depth-dependent flux of H₂O from subducting slabs worldwide: *Journal of Geophysical Research: Solid Earth*, v. 116, B01401, <https://doi.org/10.1029/2010JB007922>.

Young, A., Flament, N., Maloney, K., Williams, S., Matthews, K., Zahirovic, S., and Müller, R.D., 2019, Global kinematics of tectonic plates and subduction zones since the late Paleozoic Era: *Geoscience Frontiers*, v. 10, p. 989–1013, <https://doi.org/10.1016/j.gsf.2018.05.011>.

Zahirovic, S., Eleish, A., Doss, S., Pall, J., Cannon, J., Pistone, M., Tetley, M.G., Young, A., and Fox, P., 2022, Subduction and carbonate platform interactions: *Geoscience Data Journal*, v. 9, p. 371–383, <https://doi.org/10.1002/gdj3.146>.

S4. DATA SOURCES FOR FIGURE 1A

Clog, M., Aubaud, C., Cartigny, P., and Dosso, L., 2013, The hydrogen isotopic composition and water content of southern Pacific MORB: *Earth and Planetary Science Letters*, v. 381, p. 156–165, <https://doi.org/10.1016/j.epsl.2013.08.043>.

Cushman, B., Sinton, J., Ito, G., and Dixon, J.E., 2004, Glass compositions, plume-ridge interaction, and hydrous melting along the Galápagos Spreading Center, 90.5°W to 98°W: *Geochemistry, Geophysics, Geosystems*, v. 5, Q08E17, <https://doi.org/10.1029/2004GC000709>.

Davis, A.S., Clague, D.A., Cousens, B.L., Keaten, R., and Paduan, J.B., 2008, Geochemistry of basalt from the North Gorda segment of the Gorda Ridge: *Geochemistry, Geophysics, Geosystems*, v. 9, Q04004, <https://doi.org/10.1029/2007GC001775>.

Dixon, J.E., Stolper, E., and Delaney, J.R., 1988, Infrared spectroscopic measurements of H₂O and CO₂ contents in Juan de Fuca Ridge basaltic glasses: *Earth and Planetary Science Letters*, v. 90, p. 87–104, [https://doi.org/10.1016/0012-821X\(88\)90114-8](https://doi.org/10.1016/0012-821X(88)90114-8).

Dixon, J.E., Leist, L., Langmuir, C., and Schilling, J.-G., 2002, Recycled dehydrated lithosphere observed in plume-influenced mid-ocean ridge basalt: *Nature*, v. 420, p. 385–389, <https://doi.org/10.1038/nature01215>.

- Dixon, J.E., Bindeman, I.N., Kingsley, R.H., Simons, K.K., le Roux, P.J., Hajewski, T.R., Swart, P., Langmuir, C.H., Ryan, J.G., Walowski, K.J., Wada, I., and Wallace, P.J., 2017, Light stable isotopic compositions of enriched mantle sources: Resolving the dehydration paradox: *Geochemistry, Geophysics, Geosystems*, v. 18, p. 3801–3839, <https://doi.org/10.1002/2016GC006743>.
- Graham, D.W., and Michael, P.J., 2021, Predominantly recycled carbon in Earth's upper mantle revealed by He-CO₂-Ba systematics in ultradepleted ocean ridge basalts: *Earth and Planetary Science Letters*, v. 554, 116646, <https://doi.org/10.1016/j.epsl.2020.116646>.
- Hamelin, C., Dosso, L., Hanan, B., Barrat, J.-A., and Ondréas, H., 2010, Sr-Nd-Hf isotopes along the Pacific–Antarctic Ridge from 41 to 53°S: *Geophysical Research Letters*, v. 37, L10303, <https://doi.org/10.1029/2010GL042979>.
- Kingsley, R.H., Schilling, J.G., Dixon, J.E., Swart, P., Poreda, R., and Simons, K., 2002, D/H ratios in basalt glasses from the Salas y Gomez mantle plume interacting with the East Pacific Rise: *Geochemistry, Geophysics, Geosystems*, v. 3, 1025, <https://doi.org/10.1029/2001GC000199>.
- Le Voyer, M., Cottrell, E., Kelley, K.A., Brounce, M., and Hauri, E.H., 2015, The effect of primary versus secondary processes on the volatile content of MORB glasses: *Journal of Geophysical Research: Solid Earth*, v. 120, p. 125–144, <https://doi.org/10.1002/2014JB011160>.
- Lytle, M.L., Hauri, E.H., and Kelley, K.A., 2023, Volatile and trace elements in submarine glasses from global back-arc spreading centers, Version 1.0: Interdisciplinary Earth Data Alliance, <https://doi.org/10.26022/IEDA/112829>.
- Murton, B.J., Taylor, R.N., and Thirlwall, M.F., 2002, Plume–ridge interaction: a geochemical perspective from the Reykjanes Ridge: *Journal of Petrology*, v. 43, p. 1987–2012, <https://doi.org/10.1093/petrology/43.11.1987>.
- Nichols, A.R.L., Carroll, M.R., and Höskuldsson, Á., 2002, Is the Iceland hot spot also wet? Evidence from the water contents of undegassed submarine and subglacial pillow basalts: *Earth and Planetary Science Letters*, v. 202, p. 77–87, [https://doi.org/10.1016/S0012-821X\(02\)00758-6](https://doi.org/10.1016/S0012-821X(02)00758-6).
- Pineau, F., and Javoy, M., 1994, Strong degassing at ridge crests: The behaviour of dissolved carbon and water in basalt glasses at 14°N, Mid-Atlantic Ridge: *Earth and Planetary Science Letters*, v. 123, p. 179–198, [https://doi.org/10.1016/0012-821X\(94\)90266-6](https://doi.org/10.1016/0012-821X(94)90266-6).

Saal, A.E., Hauri, E.H., Langmuir, C.H., and Perfit, M.R., 2002, Vapour undersaturation in primitive mid-ocean-ridge basalt and the volatile content of Earth's upper mantle: *Nature*, v. 419, p. 451–455, <https://doi.org/10.1038/nature01073>.

Simons, K., Dixon, J.E., Schilling, J.-G., Kingsley, R., and Poreda, R., 2002, Volatiles in basaltic glasses from the Easter–Salas y Gomez Seamount Chain and Easter Microplate: *Geochemistry, Geophysics, Geosystems*, v. 3, 1039, <https://doi.org/10.1029/2001GC000173>.

Vlastélic, I., Dosso, L., Bougault, H., Aslanian, D., Géli, L., Etoubleau, J., Bohn, M., Joron, J.-L., and Bollinger, C., 2000, Chemical systematics of an intermediate spreading ridge: The Pacific–Antarctic Ridge between 56°S and 66°S: *Journal of Geophysical Research*, v. 105, p. 2915–2936, <https://doi.org/10.1029/1999JB900234>.