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Basalts as selective tracers of mantle source and process

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Ocean island basalts (OIB) constrain crust-mantle mass cycling, yet a quantitative framework to disentangle melting versus source controls on their compositions remains underdeveloped. Here, we extract a dominant multivariate melt-degree signal (57% explained variance) from global tholeiitic OIB major and trace element compositions using bootstrapped principal factor analysis. Across hotspots, tholeiitic melt-degree factor scores correlate with buoyancy flux and upper mantle shear-wave velocity anomalies (ΔVs), indicating that tholeiitic OIB compositions track differences in melt productivity. In contrast, the analogous melt-degree factor in alkaline OIB shows markedly more scattered relationships with buoyancy flux and ΔVs. We explain this discrepancy with a mass balance model for melting a lithologically heterogeneous mantle (peridotite + recycled pyroxenite). At low melt fractions (F) typical of alkaline OIB ($0.01 < F < 0.06$), rapid, compatibility-driven changes in the proportional contribution of each lithology to the aggregate melt dominate the multivariate melting signal, weakening systematic links with geodynamic controls on melting. In the tholeiitic regime ($0.07 < F < 0.18$), the proportional contribution of each lithology to the aggregate melt is effectively constant, so the melt-degree factor more directly traces absolute melt extent and thus covaries with metrics of melt productivity like buoyancy flux and ΔVs.

We extend this perspective to isotope systematics with an isotope "coherency" metric that, for a fixed source composition, quantifies the extent to which two isotope systems sample the same lithologic mixture across alkaline (low-F) and tholeiitic (high-F) regimes. We find that radiogenic–radiogenic isotope pairs are largely coherent (e.g., $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$), while stable–radiogenic isotope pairs (e.g., $\delta^{44}Ca$ vs. $^{87}Sr/^{86}Sr$) are typically non-coherent. In stable–radiogenic isotope cross plots, variable F can generate apparent arrays in alkaline OIB. Tholeiitic OIB, by contrast, are largely insensitive to F, but mixing-line interpretations are invalid because stable and radiogenic isotope systems sample different effective lithologic mixtures. Ultimately, resolving how stable and radiogenic isotope ratios vary with melt fraction enables targeted selection of samples and tracers and more robust inferences of mantle source heterogeneity from basalt compositions.