E-MORB and OIB petrogenesis investigated with machine learning

Zachary Eriksen[1], Stein Jacobsen[1], Charles Langmuir[1], Junjie Dong[1], Matthew Brennan[1], and Jesse Gu[1]

[1]Harvard University

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Abstract

Oceanic basalts provide an invaluable window into evolutionary processes governing mantle spatial and temporal chemical heterogeneity. Ocean island basalts (OIBs) and enriched mid-ocean ridge basalts (E-MORBs) are powerful tracers of mantle melting and crust-mantle recycling processes. Whether the elemental and isotopic variations observed in both E-MORBs and OIBs are derived from similar mechanisms, however, remains under debate. Investigating compositional differences between E-MORBs and OIBs is a simple approach to constrain their origins, a technique for which machine learning classification algorithms are optimal. Here we implemented a novel machine learning approach complemented by mantle component mixing models to highlight compositional differences between E-MORBs and OIBs and further investigate their petrogenesis (data sourced from GEOROC database and Gale et al., 2013). Considering Random Forest-based Gini indexes, elements sensitive to pressure and degree of melting (FeO, TiO_2, Lu, and Sr) were identified as the best discriminators between E-MORBs and OIBs. Our Gaussian process classification algorithm successfully classified OIBs and E-MORBs better than 97% of the time when considering 1) Sr & FeO and 2) TiO_2 & Lu. The probabilistic nature of Gaussian process modeling permitted calculation of new quantitative discriminant diagrams rooted in probability (Sr vs. FeO and TiO_2 vs. Lu). Complementary trace element modeling yielded compositionally similar E-MORB and OIB sources with moderately incompatible element enrichments in the OIB source due to the influence of recycled oceanic crust (Prytulak & Elliott, 2007). Our source compositions are consistent with a simple, joint model for E-MORB and OIB petrogenesis after Donnelley et al. (2014): low-degree partial melts of subducted slabs metasomatize the depleted mantle producing a re-fertilized mantle (RM). RM is randomly sampled at mid-ocean ridges to produce E-MORB, while upwelling plumes sample both RM and recycled oceanic crust, yielding OIB. References: Donnelly et al. (2004). Earth and Planet. Sci. Lett., 226(3–4), 347–366. Gale et al. (2013). Geochem., Geophys., Geosyst., 14(3), 489–518. Prytulak & Elliott (2007). Earth and Planet. Sci. Lett., 263(3–4), 388–403.

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Z. T. Eriksen (eriksenz@g.harvard.edu), S. B. Jacobsen, C. H. Langmuir, J. Dong, M. C. Brennan, J. T. Gu

Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA

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1. Introduction:

- Oceanic basalts provide an invaluable window into evolutionary processes governing spatial and temporal chemical heterogeneity in the mantle.
- Ocean island basalts (OIB) and enriched mid-ocean ridge basalts (E-MORB) are powerful tracers of mantle melting and crust-mantle recycling processes.
- Whether the elemental and isotopic variations observed in both E-MORB and OIB are derived from similar mechanisms, however, remains under debate.
- We implemented a novel machine learning approach complemented by mantle mixing models to highlight compositional differences between E-MORB and OIB and further investigate the significance of the best elemental discriminators.

2. Methods:

- OIB and E-MORB data were compiled from GEOROC database and Gale et al. (1) (**Fig. 1**).
- Our compilation was filtered for data quality and to eliminate samples affected by fractional crystallization.

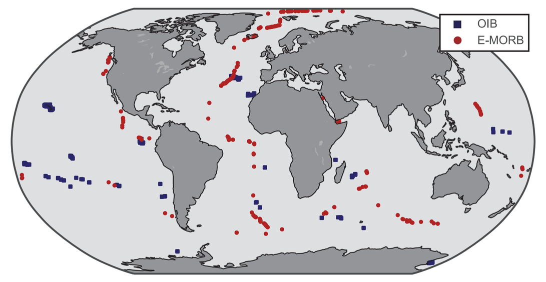


Figure 1. OIB and E-MORB sample locations.

Machine learning approach:

- Random Forest (RF) modeling was implemented to identify the best elemental predictors.
- Probabilistic OIB/E-MORB discriminant diagrams were constructed using the best RF elemental predictors as inputs into Gaussian process(GP) discrimination models.

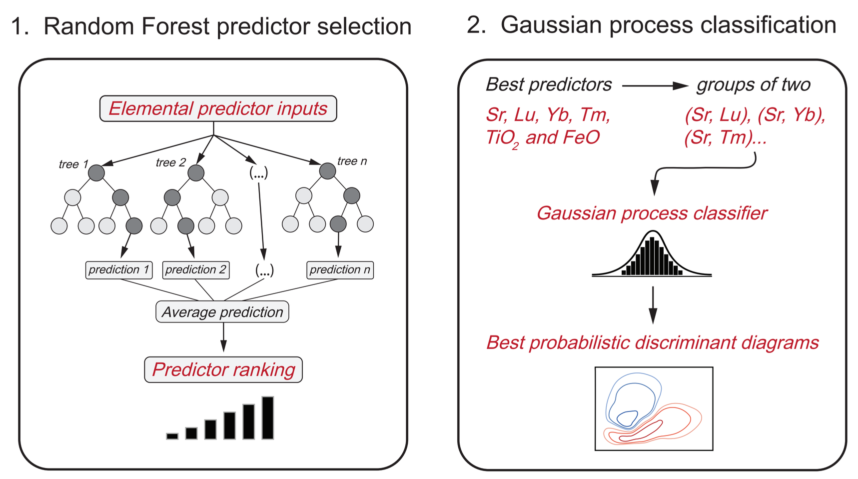


Figure 2. Machine learning recipe implemented here.

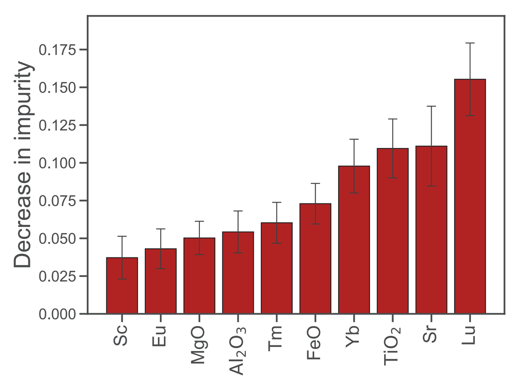
Trace element modeling approach:

- OIB and E-MORB sources were inversely modeled considering median OIB and E-MORB.
- We varied the proportions of depleted mantle (*DM*), low-degree slab melt (*melt*), and recycled oceanic crust (*ROC*) to identify possible source compositions and successful parameter combinations (**Table 1**).

	OIB source	E-MORB source
X_{DM}	0.85 - 1.00	0.98 - 1.00
X_{melt}	0 - 0.15	0 - 0.02
X_{ROC}	0 - 0.15	-
F_{slab}	0 - 0.03	0 - 0.03
F_{source}	0.01 - 0.10	0.08 - 0.2

Table 1. Parameter ranges considered in OIB and E-MORB mixing models.

3. Results:



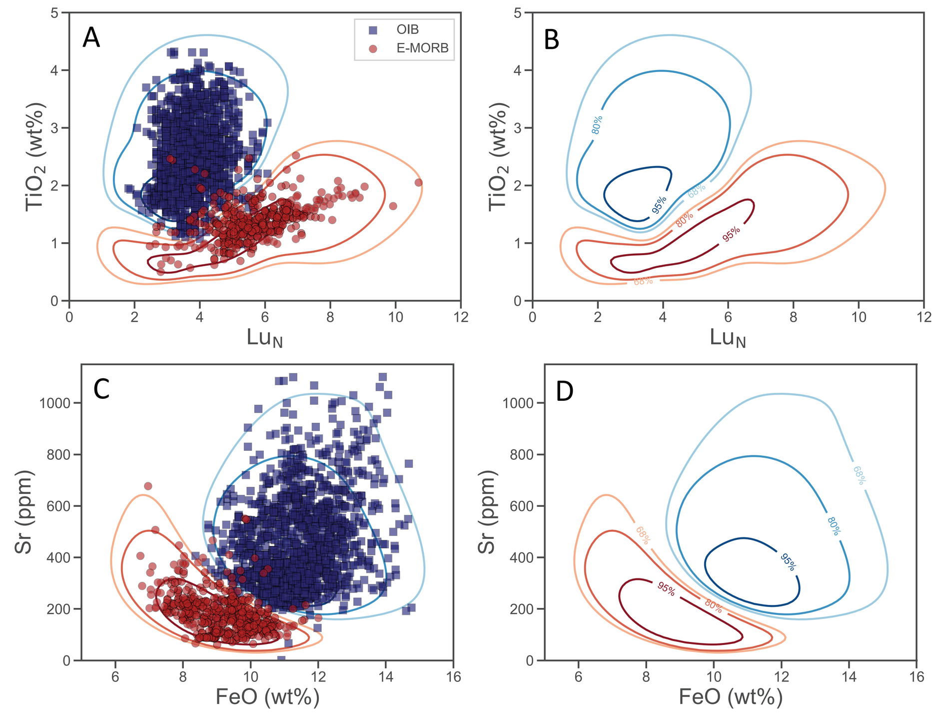


Figure 3. (above) Ten best predictors from RF modeling.

Figure 4. (right) Best discriminant diagrams from GP modeling (A, C) and their associated probability contours (B, D).

- TiO_2 versus Lu and Sr versus FeO are the two best discriminant diagrams to differentiate OIB and E-MORB, with F1 scores better than 97% (**Fig. 4**).

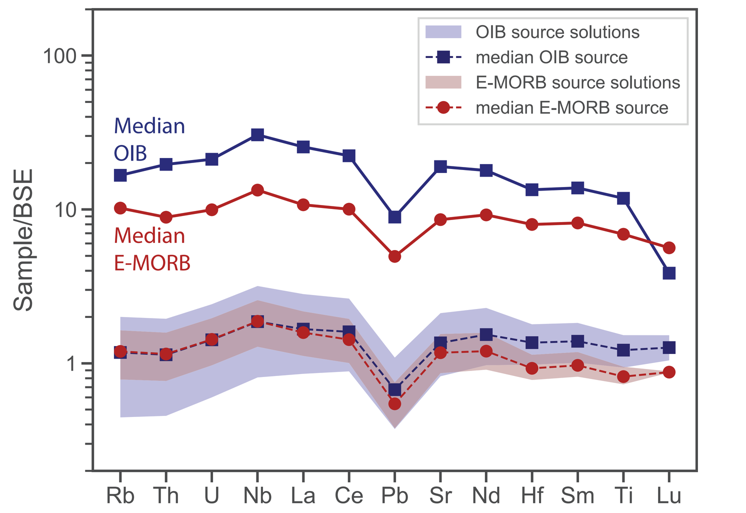


Figure 5. Compositional ranges of calculated OIB and E-MORB sources.

- OIB sources range from depleted to slightly enriched, while E-MORB sources are exclusively enriched (**Fig. 5**).
- Median OIB and E-MORB sources have indistinguishable highly incompatible element concentrations (**Fig. 5**), but OIB sources are more enriched in moderately incompatible elements (e.g., Sr, Nd, Hf, Sm, Ti, Lu) (2).

- OIB sources require both ROC and low-degree eclogite melt.
- Progressively more enriched sources (made by Increasing [$X_{ROC} + X_{melt}$] or X_{melt}, or by decreasing F_{slab}) require higher F_{source} values to successfully model median OIB and E-MORB (**Figs. 6A and 6C**).
- The median values of F_{slab} and X_{melt} for E-MORB and OIB sources are similar (**Figs. 6b and 6d**), indicating that E-MORB and OIB sources do not require metasomatic fluids of different compositions.

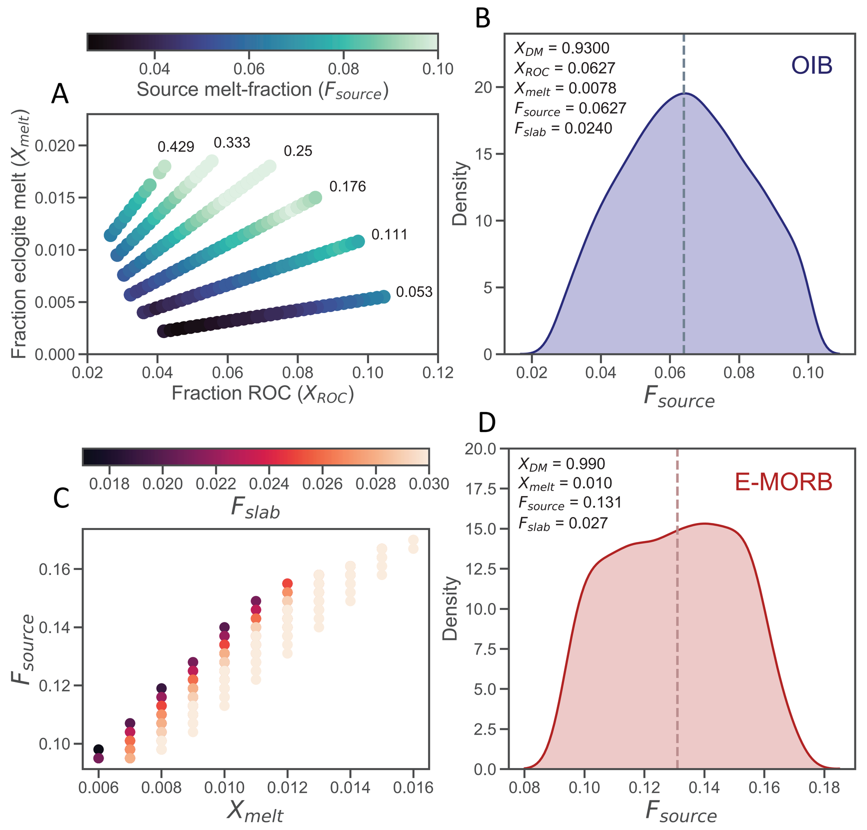


Figure 6. Successful parameter combinations for calculated OIB and E-MORB sources; median values for each modeling parameter are listed in panels B and D.

4. Discussion:

- The best elemental discriminators (TiO_2, Lu, Sr, and FeO) are all sensitive to degree of melting (*F*) and depth/pressure of melting.
- OIB have higher FeO and TiO_2 and lower Lu than E-MORB because OIB melts form at higher *P*.
  - The TiO_2 effect may be exacerbated by relative enrichment in the OIB source (**Fig. 5**) (2).
- Sr may also be sensitive to *P*, because it behaves more incompatibly with increasing garnet in the source (**Fig. 7**).

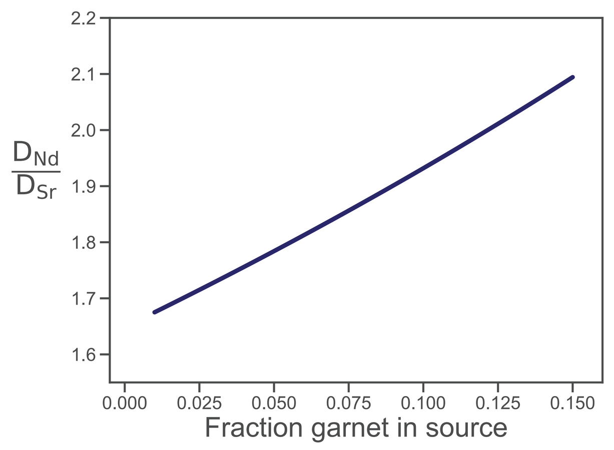


Figure 7. Ratio of bulk Nd and Sr partition coefficients (*D*) with increasing garnet in the mantle source.

Joint petrogenetic model:

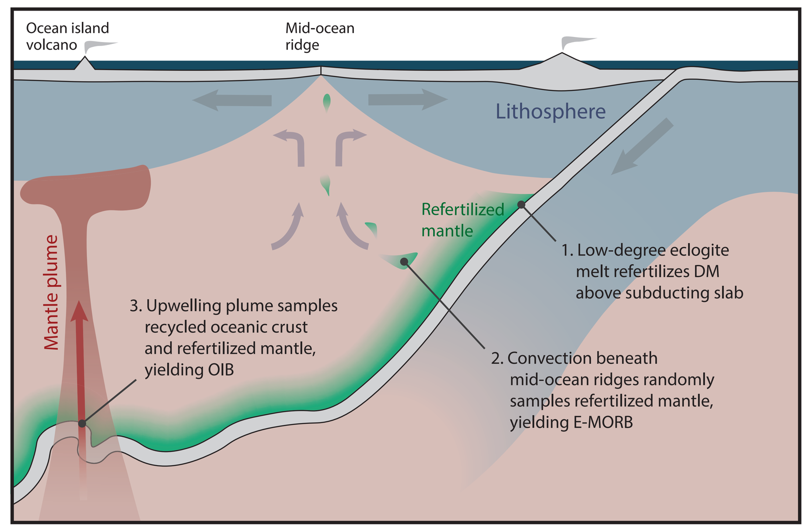


Figure 8. Joint petrogenetic model for OIB and E-MORB.

- A simple, joint model for E-MORB and OIB petrogenesis is proposed after Donnelly et al. (3): Low-degree partial melts of subducted slabs metasomatize the depleted mantle producing a re-fertilized mantle (RM). RM is randomly sampled at mid-ocean ridges to produce E-MORB; upwelling plumes sample both RM and ROC, yielding OIB (**Fig. 8**).

5. Conclusions:

- ❖ GP classification is a powerful ML algorithm to produce probabilistic geochemical discriminant diagrams
- ❖ The best discriminators between OIB and E-MORB are elements sensitive to pressure and degree of melting (TiO_2, Lu, Sr, and FeO).
- ❖ E-MORB and OIB sources are compositionally similar, but OIB sources are more enriched in moderately incompatible elements due to the influence of ROC.
- ❖ OIB and E-MORB sources can be modeled through the same mechanism, involving low-degree melting of a subducting slab and subsequent metasomatism.

References:

[1] Gale, A. et al. (2013). *Geochem. Geophys. Geosyst.* 14, 489–518. **[2]** Prytulak, J. and Elliott, T. (2007). *Earth and Planetary Science Letters* 263, 388–403. **[3]** Donnelly, K.E. et al. (2004). *Earth and Planetary Science Letters* 226, 347–366.