Chemical trends in ocean islands explained by plume–slab interaction

Juliane Dannberg\textsuperscript{a,b,1,2} and Rene Gassmölle\textsuperscript{a,b,1}

\textsuperscript{a}Department of Mathematics, Colorado State University, Fort Collins, CO 80523-1874; and \textsuperscript{b}Department of Mathematics, Texas A&M University, College Station, TX 77843-3368

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Earth's surface shows many features, of which the genesis can be understood only through their connection with processes in Earth's deep interior. Recent studies indicate that spatial geochemical patterns at oceanic islands correspond to structures in the lowermost mantle inferred from seismic tomographic models. This suggests that hot, buoyant upwellings can carry chemical heterogeneities from the deep lower mantle toward the surface, providing a window to the composition of the lowermost mantle. The exact nature of this link between surface and deep Earth remains debated and poorly understood. Using computational models, we show that subducted slabs interacting with dense thermochemical piles can trigger the ascent of hot plumes that inherit chemical gradients present in the lowermost mantle. We identify two key factors controlling this process: (i) if slabs induce strong lower-mantle flow toward the edges of these piles where plumes rise, the piling of the plume preferentially samples material originating from the pile, and bilaterally asymmetric chemical zoning develops. (ii) The composition of the melt produced reflects this bilateral zoning if the overlying plate moves roughly perpendicular to the chemical gradient in the plume conduit. Our results explain some of the observed geochemical trends of oceanic islands and provide insights into how these trends may originate.

When projected to the lowermost mantle, many eruption sites of oceanic islands overlie the margins of large zones of reduced seismic shear-wave velocities (1), the large low shear velocity provinces (LLSVPs). Some of these displays parallel volcanic chains with distinct geochemical trends, exposing a different composition in the part of the dual chain closer to the LLSVP compared with the chain farther away from it. The most prominent example, the Hawaii-Emperor chain, overlies the northern edge of the Pacific LLSVP. Its southern “Loa” trend has been associated with a greater prominence of recycled mafic material in the melt source compared with the northern “Kea” trend (2), and both trends show very little compositional overlap (3). Recent studies suggest that more ocean islands feature geochemical asymmetry, including Marquesas (4, 5), Samoa (6), Society (7), Galápagos (8), Easter (8), and Tristan da Cunha/Gough (9, 10).

Mantle plumes—buoyant, hot upwellings from the Earth’s lowermost mantle (11)—could explain this phenomenon. They are thought to ascend from the edges of thermochemical piles (1, 12) (corresponding to the LLSVPs) and might inherit deep mantle chemical heterogeneities. When approaching the surface, plumes melt due to decompression and generate Earth’s oceanic island chains (13). The islands’ distinct geochemical trends may arise from melting of a bilaterally zoned underlying mantle plume, one side sampling the LLSVP and the other sampling the ambient mantle composition (2, 4, 14).

Supporting this hypothesis, geodynamic modeling studies of thermally buoyant plumes show that if chemical gradients are present at the core–mantle boundary, they can be preserved during plume ascent (14–16) and would be reflected in magma compositions (14, 17). However, these models disregard material entrainment from thermochemical piles into plumes and consider compositional heterogeneity as a passive feature without effects on physical properties like density. As stable thermochemical piles are expected to be at least 2% denser than the background mantle (18–22) (SI Materials and Methods), the arising buoyancy difference crucially influences the entrainment and ascent of chemically heterogeneous material (23, 24). A recent study including this effect (25) has shown that—in the absence of ambient mantle flow driven by other phenomena than the plume itself—already small density differences focus entrainment into the hot plume center, creating concentric zoning instead of bilaterally asymmetric plumes. Consequently, plumes would not preserve the spatial distribution of geochemical domains in the lowermost mantle, suggesting that chemical anomalies at the surface are not directly related to lower-mantle structure. Another recent study suggested that even if plume tails were to be bilaterally zoned, melt generated from the side of the plume containing more mafic material might be dominated by melting of peridotite due to its higher temperatures, thus reversing the trend present in the plume tail (26). Thus, it remains unclear how bilateral chemical zoning develops in mantle plumes and how surface observations are linked to deep mantle structures.

We propose that the key to solving this problem is to consider the interaction of subducted slabs arriving at the core–mantle boundary, thermochemical piles, and starting mantle plumes. Ambient mantle flow associated with realistic plate motions

**Significance**

The composition of ocean island basalts is known to correlate with zones in the lowermost mantle almost 3,000 km below, thought to represent piles of hot, dense material. One important open question in the Earth sciences is the mechanism behind this link between the surface and Earth's deep interior. Here, we use high-resolution 3D geodynamic models with a realistic subduction history, plate geometries, and plate motions to identify a dynamically feasible mechanism for how rising hot material can inherit the lower-mantle geochemical structure despite variations in material density. Our findings provide a framework for mapping chemical anomalies at the surface to the deep mantle and illuminate the composition of one of the least well-understood regions of the Earth.

Author contributions: J.D. and R.G. designed research, performed research, analyzed data, and wrote the paper. The authors declare no conflict of interest.

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1 Present address: Department of Earth and Planetary Sciences, University of California, Davis, CA 95616.

2 To whom correspondence should be addressed. Email: juddannberg@gmail.com.

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controls the location of subduction zones and the evolution of the associated slabs in the lower mantle—a process that is thought to be intimately connected to LLSVP formation and the origin of plumes (20, 27). This highlights a probable close link between slabs and LLSVP processes, suggesting that slab–LLSVP–plume interaction has a significant effect on the thermochemical structure of plumes and that considering slabs is crucial to understanding LLSVP processes. Investigating this inherently 3D interaction and the material entrainment in mantle plumes requires high-resolution models with a realistic spatial distribution of slabs and their appropriate ages and is the novelty of this study. Our findings advance the current understanding of how geochemical anomalies at the surface are related to the deep mantle and hence provide a framework for mapping the composition of one of the least well-understood regions of the Earth.

Development of Chemical Zoning in Plumes

To model this process, we use the mantle convection code ASPECT (Advanced Solver for Problems in Earth’s ConvectIon) (28, 29) to combine high-resolution 3D regional plume models and global mantle convection simulations. We assume an average mantle composition of 82% harzburgite and 18% recycled oceanic crust (30) and compute the material properties using the software package Perple_X (31, 32). The global model (29) uses plate reconstructions for the last 250 Myr (33) to create a realistic subduction history. As found in earlier studies, sinking slabs push chemically dense material (in our models assumed to be recycled crust) at the core–mantle boundary into piles near the location of today’s LLSVPs and subsequently initiate the ascent of plumes at positions comparable to present-day hotspots (27, 33, 34). Using these simulations as velocity, temperature, and composition boundary conditions for

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Fig. 1. Time snapshot of a simulation of a bilaterally asymmetric zoned plume in the geographical setting of the South Pacific. (Top Left) The main plot shows isosurfaces of excess temperature and composition, together with arrows indicating the direction of flow in the deep mantle (black) and the direction of plate motion (red). Subducted slabs (blue) arriving from the south push material against the thermochemical pile in the lowermost mantle (green) and trigger the ascent of a bilaterally zoned plume (orange and green). (Bottom) This process is illustrated in the drawing. Top Right Inset displays a top view with isosurfaces representing the fraction of melt: melt generated from average mantle (peridotite melt) shown in orange and melt generated from recycled crust (pyroxenite melt) shown in green. The black sphere has a radius of 500 km and indicates the volume we use to compute the bilateral asymmetry number in the melting zone \( Z_m \). (SI Materials and Methods), which compares the melt composition in the two hemispheres, divided by a vertical plane parallel to the direction of plate motion (marked by the black dashed line). Red and blue areas inside the light orange and blue dashed lines illustrate plume temperature and composition at 500 km depth, using the same color scale as in Fig. 2A. The full model development is presented in Movie S1.
Conditions for Bilaterally Asymmetric Zoning in the Plume Tail

A series of models with different plume temperatures and different geographical settings reveals the controlling factors for the development of zoning in rising plumes (Fig. 2). While some plumes feature a bilaterally asymmetric structure, illustrated by the fact that regions of highest plume temperature (white areas) and highest content of recycled crust (blue contours) do not match (Fig. 2 A and J), other plumes are concentrically zoned, even though they rise from the edges of thermochemical piles (Fig. 2 E and H). As indicated in previous studies (25), a higher plume temperature (entailing a lower buoyancy ratio $B$, defined as the ratio between the chemical and the thermal density contrast driving the flow; SI Materials and Methods) generally promotes bilateral chemical zoning (Fig. 3A). However, we find appreciably bilaterally zoned plumes up to much higher buoyancy ratios ($B = 2.3$), corresponding to a chemical density contrast of $\Delta \rho_C = 2.8\%$ and a thermal density contrast of $\Delta \rho_{th} \approx 1.2\%$ between pile material and background mantle; Fig. S4) compared with the results of previous 2D models (25) ($B \approx 0.5$, $\Delta \rho_C = 0.75\%$, $\Delta \rho_{th} = 1.5\%$). In contrast to this previous study, we include the effect of ambient mantle flow controlled by past plate motion, and we discuss the effect of this below.

![Diagram](image-url)
High plume temperatures (and low buoyancy ratios $B$) alone do not guarantee bilateral zoning near the surface (Figs. 2F and 3A). The relative position of chemical pile, plume, and subducted slab additionally controls the plume tail structure. In particular, the angle of lower-mantle flow with respect to the edge of the pile is crucial (Figs. 2C, G, and K and 3B): An arriving slab moving roughly normal to the edge of the LLSPV (Fig. 2C and K) facilitates bilateral zoning in the plume, while for flow parallel to the edge of the pile (Fig. 2G) or away from it concentric zoning develops. The important difference is that strong lower-mantle flow toward the pile creates starting plumes directly at the edge of the thermochemical pile and makes this feeder zone much more asymmetric (Figs. S5A and S6G–I), creating a bilaterally asymmetric distribution of pile material in the plume tail for a wider parameter range, including values expected in the Earth. If the lower mantle does not (or only very slowly) flow toward the pile (Fig. 2G), vertically integrating the amount of generated melt reveals a clear spatial variability in composition on a profile across the hotspot track (Fig. 4C). Conversely, a small angle between chemical gradient in the plume and plate motion (Fig. 4E) causes filaments of distinct chemical composition that approach the base of the plate upstream of the plume center to flow on top of the downstream filaments, leading to mostly vertical chemical variations in the melting region. Lateral variations in chemical composition present in the plume tail would be sampled equally by different volcansoes and would not be visible in melt compositions (Fig. 4B). Finally, concentric zoning of the plume conduit (Fig. 4D) leads to a roughly symmetric distribution of melt composition across the hotspot track (Fig. 4D), regardless of the direction of plate motion.

The presented results show that slab-induced lower-mantle flow enables plumes to entrain even chemically dense material asymmetrically, facilitating bilateral zoning up to much higher chemical density contrasts than previously thought (25), including the values expected in the Earth’s mantle. Our models explain a possible cause for bilateral asymmetry of hotspots, in general, and in particular in the South Pacific (Fig. S1), where they reproduce, for example, the observed north-side prominence of mafic material in the source of the Easter hotspot (8). Furthermore, our models show the observed north–south zoning of Samoa, but contrary to geochemical data (4, 6), our models predict prominence of mafic material in the northern part—toward the LLSPV—and it remains unclear why Samoa features the opposite trend. A potential explanation is provided by a recent study (26), showing that due to lateral temperature differences, bilateral chemical trends in the plume tail might be reversed in the generated melts. An additional complexity in this setting is posed by the subduction zone nearby. Finally, the proposed mechanism could explain why asymmetry has not been found at North Atlantic hotspots: Past lower-mantle flow mostly parallel to the edge of the African LLSPV prevented bilateral chemical zoning in starting mantle plumes.

We note that our models do not take into account melt migration or magma plumbing and its interaction with lithospheric flexure. Our results can explain the chemical trends in ocean islands only if melts do not mix completely on their pathway from the melting region if the plume is sheared by a moving plate (14, 15, 23). Whether bilateral zoning of the plume tail is reflected in a chemical gradient of melt compositions across the hotspot track depends on the speed (15) and direction of plate motion (14). Experiments have shown that only if the overriding plate moves slowly (15) or if the angle between plate motion and the chemical gradient in the plume is large (>45°) (14), chemical trends in the plume conduit remain horizontally separated and parallel volcanic chains develop distinct chemical compositions. Our models reveal the same trend: For a plate moving roughly perpendicular to the chemical gradient in the plume (Fig. 4F), vertically integrating the amount of generated melt reveals a clear spatial variability in composition on a profile across the hotspot track (Fig. 4C). Conversely, a small angle between chemical gradient in the plume and plate motion (Fig. 4E) causes filaments of distinct chemical composition that approach the base of the plate upstream of the plume center to flow on top of the downstream filaments, leading to mostly vertical chemical variations in the melting region. Lateral variations in chemical composition present in the plume tail would be sampled equally by different volcanoes and would not be visible in melt compositions (Fig. 4B). Finally, concentric zoning of the plume conduit (Fig. 4D) leads to a roughly symmetric distribution of melt composition across the hotspot track (Fig. 4D), regardless of the direction of plate motion.


Fig. 3. Plume tail bilateral asymmetry vs. (Top) excess temperature and (Bottom) the angle between the flow in the lower mantle and the edge of the thermochemical pile. Bilateral zoning is quantified using the bilateral asymmetry number $Z_h$, where $Z_h = 0$ indicates no bilateral zoning, and $Z_h = 1$ indicates maximum bilateral zoning. For the detailed definition of $Z_h$ see SI Materials and Methods. Data point colors mark different geographical settings (Fig. S1), for each setting we performed a series of models, varying the plume excess temperature. Both high temperatures and steep angles (strong flow toward the pile) are required for the development of bilateral zoning. The excess temperature was computed as the maximum temperature difference between the plume and the mantle adiabat in a depth of 500 km (in the slices shown in Fig. 2). From spatial resolution tests, we estimate the relative error in $Z_h$ to be ~10%. A contour plot is shown in Fig. 5B, and all values of $Z_h$ are listed in Table S2.

Although spatially separated chemical trends are generally preserved during plume ascent, they might end up overlying each other in the melting region if the plume is sheared by a moving plate (14, 15, 23). Whether bilateral zoning of the plume tail is reflected in a chemical gradient of melt compositions across the hotspot track depends on the speed (15) and direction of plate motion (14). Experiments have shown that only if the overriding plate moves slowly (15) or if the angle between plate motion and the chemical gradient in the plume is large (>45°) (14), chemical trends in the plume conduit remain horizontally separated and parallel volcanic chains develop distinct chemical compositions. Our models reveal the same trend: For a plate moving roughly perpendicular to the chemical gradient in the plume (Fig. 4F), vertically integrating the amount of generated melt reveals a clear spatial variability in composition on a profile across the hotspot track (Fig. 4C). Conversely, a small angle between chemical gradient in the plume and plate motion (Fig. 4E) causes filaments of distinct chemical composition that approach the base of the plate upstream of the plume center to flow on top of the downstream filaments, leading to mostly vertical chemical variations in the melting region. Lateral variations in chemical composition present in the plume tail would be sampled equally by different volcanoes and would not be visible in melt compositions (Fig. 4B). Finally, concentric zoning of the plume conduit (Fig. 4D) leads to a roughly symmetric distribution of melt composition across the hotspot track (Fig. 4D), regardless of the direction of plate motion.

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We note that our models do not take into account melt migration or magma plumbing and its interaction with lithospheric flexure. Our results can explain the chemical trends in ocean islands only if melts do not mix completely on their pathway from the source region to the hotspot volcanoes.

Another shortcoming of the current model is that it fails to predict a plume near Hawaii and a number of other observed present-day hotspots. This implicates that we cannot test our hypothesis for all oceanic islands. We mainly attribute this to uncertainties in the used plate reconstruction (35) and the material properties of the mantle: Our modeled thermochemical pile extends farther north than the observed LLSPV (Fig. S1), a feature also observed in other global convection models (27, 34).
This means that a plume rising from the edge of this pile would not reach the surface at the present location of Hawaii. The pile shape and position are controlled by the subduction history, and recently it has been shown that updating the plate reconstruction of ref. 35 allows it to achieve a more realistic location of the Hawaiian plume (36). Hence, accurate models of past plate motion are invaluable for relating surface observations to the deep mantle.

Although our models did not include plumes close to Hawaii or Tristan da Cunha, they provide a general mechanism that explains their observed bilateral asymmetry. Hawaii’s high excess temperature and the presumed steep angle between lower-mantle flow and LLSPV (see, e.g., the models of ref. 36, which predict southward lower-mantle flow toward the northern edge of the Pacific LLSPV for the last 100 My) give reason to expect the development of bilateral chemical zoning by the mechanism proposed in this study. Previously, it was not obvious why Tristan da Cunha and Gough show the observed dual chains with distinct chemical trends (9, 10), as they are thought to have only a moderate excess temperature (37, 38). However, our proposed mechanism for asymmetric entrainment suggests that the supposedly strong lower-mantle flow from the South American subduction zone (36) could provide sufficient support to develop bilateral asymmetry in the plume.

We conclude that only certain conditions allow mapping geochemical anomalies from the surface to the core–mantle boundary. Considering the directions of current plate motion and past lower-mantle flow is crucial for inferring lower-mantle compositional heterogeneities from surface observations. Hence, accurate plate reconstructions and global flow models inferred from seismic tomography and advected backward in time might prove to be valuable tools for deciphering the present and past lower-mantle chemical structure.

## Code Availability

The geodynamic models were computed with the open-source software ASPECT (aspect.dealii.org) (28, 29) and visualized with the open-source programs VisIt (https://wci.llnl.gov/simulation/computer-codes/visit) and GMT (39). The version of ASPECT we used to run our models is available online (https://github.com/gassmoeller/aspect/releases/tag/plume-zonation).

## Data Availability

All of the input files that are required to reproduce this study are provided in Datasets S1–S19.

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