# Mantle plumes and their interactions

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## Abstract

Hotspots are regions of intraplate volcanism or especially strong volcanism along plate boundaries, and many of them are likely caused by underlying mantle plumes – localized hot upwellings from deep inside the Earth. It is still uncertain, whether all plumes or just some of them rise from the lowermost mantle, and to what extent and where they entrain chemically different materials. Also, large uncertainties exist regarding their size. Some plumes (such as Hawaii) create linear hotspot tracks, as the plate moves over them and can therefore serve as reference frames for plate motions, whereas others (such as Iceland) show a more complicated distribution of volcanic rocks due to variable lithosphere thickness and plume-ridge interaction. Plumes may also weaken plate boundaries and hence influence plate motions. They may influence surface features such as ice sheets, and therefore climate, but we are just beginning to study and understand processes jointly involving solid earth, hydrosphere and atmosphere.

## Keywords.

Plumes, hotspots, tomography, convection, thermochemical

## The larger context

Currently, Earth science is undergoing a phase where plate tectonics is being integrated into a theory that also includes lithosphere dynamics and processes in the whole mantle, such as plumes and convection. This phase has been likened to a "fourth revolution in the geosciences" by Trond Torsvik – after the first three revolutions: continental drift, sea floor spreading and plate tectonics. In an even wider historical context, Schellnhuber (1999) terms the current situation as "the second Copernican revolution" where our view of the Earth yet again fundamentally changes. Two of the contributing factors are global monitoring, in his words, "the bird's-eye principle", and modeling, "the digital-mimicry principle". "Earth system" analysis means that, for the first time, we can attempt to obtain a comprehensive view of the interaction of all the different "spheres" such as atmosphere, biosphere, cryosphere, geosphere. It includes, for example, also effects that the development of life may have on mantle dynamics, not just the other way round. Doubtlessly, our view on mantle plumes and their interaction with other "spheres" such as the atmosphere will also be affected by these profound transformations (Torsvik et al., 2021). It is therefore timely to take a view at our current understanding of mantle plumes, how this view has developed over time, what are the important open questions, and what new developments are to be expected.

Reviewing such a wide subject as mantle plumes will necessarily entail omissions. Since this review is supposed to have a personal flavor, I (B.S.) will focus on those papers that most influenced me, often by those people I interacted with along my path through the field, and I will discuss them while describing this personal path.

## Wilson, Morgan and how the concept of mantle plumes came about

By 1967, Wegener's (1915) continental drift theory had been developed into plate tectonics (McKenzie & Parker, 1967; Morgan, 1968) building onto the intermediate step of sea floor spreading (Dietz, 1961; Vine and Matthews, 1963; Pitman and Heirtzler, 1966). Unlike subduction zones, spreading ridges and transform faults, seamount chains such as the exemplary Hawaii-Emperor chain are not a feature that is required in plate tectonics. However, following an earlier suggestion by Wilson (1963) that those regions of intraplate volcanism arise from stationary areas within convection cells, Morgan (1971) showed that the geometry of Pacific island and seamount chains can in fact be created by moving a rigid plate over fixed hotspots. He proposed that they are caused by "convection plumes in the lower mantle" – rather narrow, focused upwellings, which form those chains like a flame cutter as the plate moves over them, as illustrated in Figure 1.

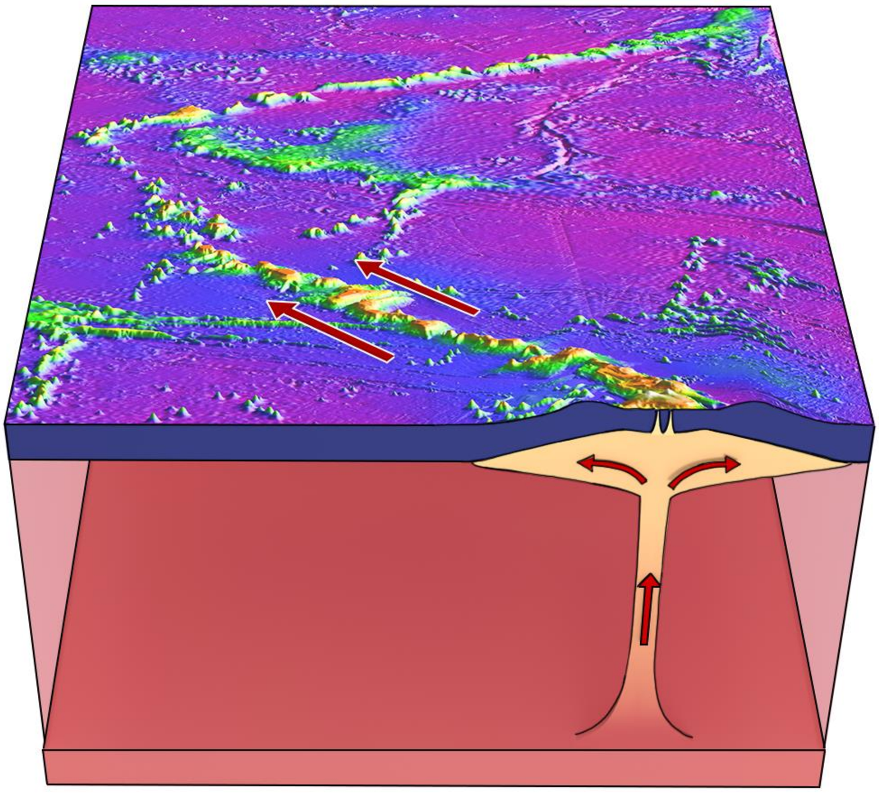


*Figure 1: Oblique view of Hawaiian-Emperor chain towards northwest. The Hawaii plume corresponding to the classical concept of Morgan (1971) is drawn beneath. Map colors indicate topography; darker areas (bluish in color version) surrounding the Hawaiian chain show the hotspot swell that is presumably caused as hot material flows out of the conduit and spreads beneath the lithosphere, forming a steady-state "plume head" that is being dragged along with, and re-heats and thins the moving plate.*

About 50 years later, this basic explanation – that hotspot tracks are caused by plumes from the deep mantle – is the consensus view. However, the proposal that they are stationary was soon questioned by Molnar and Atwater (1973): They showed that, when combining models of relative plate motion with the assumption of hotspot fixity, the computed hotspot tracks cannot be matched simultaneously on all plates with observed ones. Rather, relative hotspot motions at rates of 0.8 to 2 cm/yr are required. Another possible indication of hotspot motion are paleolatitudes of seamounts: If these do not correspond to present-day hotspot latitudes, this may be an indication of hotspot motion, but it may also be caused by true polar wander – a wholesale re-orientation of the entire crust and mantle relative to the Earth's axis. Kono (1980) derived from drill cores obtained at Suiko Seamount in the Emperor chain during DSDP leg 55 that this seamount formed at a paleolatitude of 26.9°+-2°, i.e. significantly further north than Hawaii. The debate which plumes are moving, and at what speed, still goes on after more than 50 years.

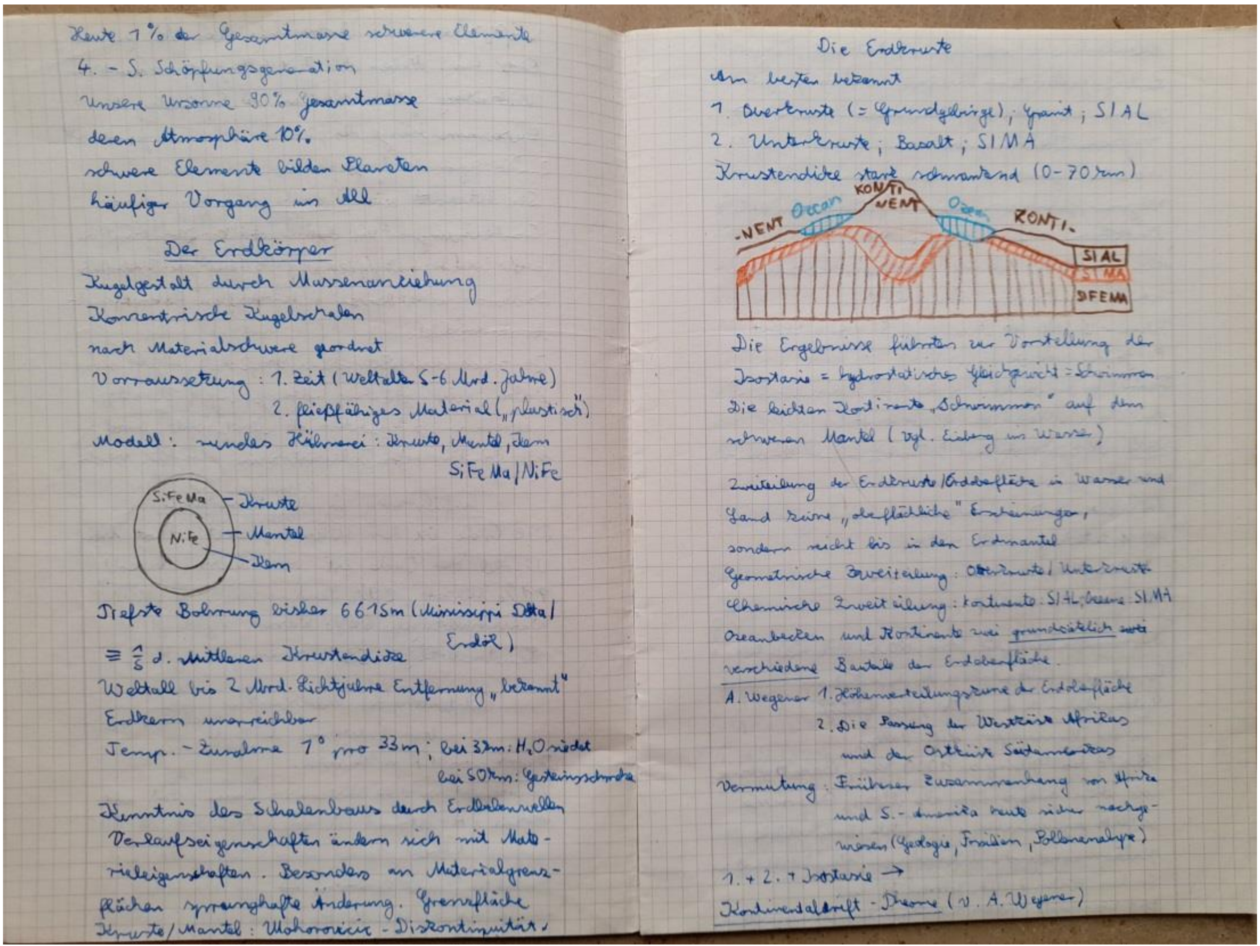
That narrow upwellings, corresponding to Morgan's plumes, may form when a less dense layer, such as a thermal boundary layer (TBL) starts rising through a denser, overlying mantle, was shown by laboratory experiments of Whitehead and Luther (1975). They described their shape as a `spherical pocket of fluid fed by a pipe', which was later usually described as plume head and plume tail. As mantle convection in general, the rise of plumes can be understood by a simple force balance: The driving force is buoyancy, i.e. density differences, especially due to temperature differences, the resisting force is due to viscous friction. In the simplest case of a sphere in an unbounded fluid of constant viscosity, the driving force is therefore proportional to the density difference of the sphere relative to its surroundings, and its radius cubed. The resisting force is proportional to the viscosity of the surrounding material, the radius of the sphere, and its rising speed. Force balance therefore yields Stokes' equation: The rising speed is proportional to density difference and radius squared, and inversely proportional to viscosity.

The density difference between core and mantle is so large that they essentially don't mix. Hence convective heat transfer is not possible, and heat has to be transferred by conduction. As heat conduction is proportional to the temperature gradient, a TBL, where these plumes may get generated, forms in the lowermost mantle (not in the core, because core viscosity is many orders of magnitude lower). Thermal radiation as a third heat transfer mechanism likely has not contributed significantly to cooling the Earth's core throughout geologic time, because ferropericlase, one of the major lower mantle minerals, is highly opaque (Lobanov et al., 2021). As instabilities grow in the TBL, they will eventually detach but remain connected to the TBL through a conduit (plume tail), so they keep growing. Flow speed through the conduit (described through Poiseuille's law) is inversely proportional to the viscosity inside the conduit, which is presumably lower than in the surrounding mantle, due to higher temperature, whereas the rise speed of the plume head depends on viscosity of the surrounding mantle. Hence the same amount of material may rise through a narrow conduit as in a large head causing the typical head-tail structure of plumes.

Crough (1978) showed that a hotspot swell, as observed (~1200 km wide and up to ~1 km shallower than expected for the age of the sea floor), may form. There are two effects that play a role: Firstly, due to its lower density, the plume exerts a buoyancy force on the lithosphere and pushes it upwards until it is high enough to push back with the same force. Secondly, it also re-heats and thins the lithosphere, causing additional buoyancy. The less dense mantle material by itself would cause a gravity and geoid low, but this is counteracted by the effect of the uplifted topography on gravity and geoid. Even for perfect isostatic compensation there would be non-zero total geoid, because the less dense mantle materials are at greater distance, hence their gravity effect is less. Accordingly, Crough (1978) showed that the geoid anomaly over the Hawaiian swell is consistent with compensation depths of 40 to 100 km. Combining the observations of hotspot tracks and swells and explanations through models and simple physics, one can say that this marks the beginning of "mantle plume theory", which subsequently could be used to make predictions to be tested against observations, and be further refined and modified.

## The role of mantle plumes in global geodynamics, and how I got into that game

My first exposure to plate tectonics was in fall 1979 during 11th grade in high school when our geography teacher Gerhard Weißörtel chose marine science as the focus topic for one semester. At that time, about 10 years after it was first proposed, plate tectonics became sufficiently widely accepted such that it made it into the high school curriculum. So I was probably among the first cohorts to already learn about plate tectonics in high school (Figure 2). My fascination with plate tectonics that developed during this class, along with my interest in math and physics that was nurtured by another high school teacher, Werner Konrad, combined to my decision to study geophysics, beginning in Munich in November 1983. As the topic of my diploma thesis, Prof. Nikolai Petersen initially suggested a study of true polar wander. I ended up working on a different topic (magnetotactic bacteria) but became hooked to true polar wander and wanted to work on it during my Ph.D. Since I felt that North America offered the most active research environment in geodynamics, I wanted to pursue my Ph.D. there.



Heute 1% der Gesamtmasse schwere Elemente
4. - 5. Schöpfungsgeneration
Unsere Ursonne 90% Gesamtmasse
deren Atmosphäre 10%.
schwere Elemente bilden Planeten
häufiger Vorgang im All

Der Erdkörper

Kugelgestalt durch Massenanziehung
Konzentrische Kugelschalen
nach Materialschwere geordnet
Voraussetzung: 1. Zeit (Weltalter 5-6 Mrd. Jahre)
2. fließfähiges Material („plastisch")
Modell: rundes Hühnerei: Kruste, Mantel, Kern
SiFeMa | NiFe

Tiefste Bohrung bisher 6615m (Mississippi Delta / Erdöl)
≡ 1/5 d. mittleren Krustendicke
Weltall bis 2 Mrd. Lichtjahre Entfernung „bekannt"
Erdkern unerreichbar
Temp.-Zunahme 1° pro 33m; bei 3km: $H_2O$ siedet
bei 50km: Gesteinsschmelze
Kenntnis des Schalenbaus durch Erdbebenwellen
Verlaufseigenschaften ändern sich mit Materialeigenschaften. Besonders an Materialgrenzflächen sprunghafte Änderung. Grenzfläche Kruste/Mantel: Mohorovičić-Diskontinuität,

Die Erdkruste

am besten bekannt
1. Oberkruste (= Grundgebirge); Granit; SIAL
2. Unterkruste; Basalt; SIMA
Krustendicke stark schwankend (0-70 km)

Die Ergebnisse führten zur Vorstellung der Isostasie = hydrostatisches Gleichgewicht = Schwimmen
Die leichten Kontinente „schwimmen" auf dem schweren Mantel (vgl. Eisberg im Wasser)

Zweiteilung der Erdkruste/Erdoberfläche in Wasser und Land keine „oberflächliche" Erscheinungen, sondern reicht bis in den Erdmantel
Geometrische Zweiteilung: Oberkruste/Unterkruste
Chemische Zweiteilung: Kontinente: SIAL; Ozeane: SIMA
Ozeanbecken und Kontinente zwei grundsätzlich verschiedene Bauteile der Erdoberfläche.
A. Wegener 1. Höhenverteilungskurve der Erdoberfläche
2. Die Passung der Westküste Afrikas und der Ostküste Südamerikas
Vermutung: Früherer Zusammenhang von Afrika und S.-Amerika heute sicher nachzuweisen (Geologie, Fossilien, Pollenanalyse)
1. + 2. + Isostasie →
Kontinentaldrift-Theorie (v. A. Wegener)

*Figure 2: My 11th grade class notes about continental drift, Alfred Wegener etc.*

At that time, both the monitoring and modeling aspects of geodynamics were further advancing, largely due to the availability of more powerful computers. For the monitoring, seismic tomography had crystallized as the most important tool (Dziewonski and Woodhouse, 1987) to image the Earth interior, although of course resolution was still much too low to "see" mantle plumes. In terms of modelling, Bercovici et al. (1989) had developed the first three-dimensional spherical models of mantle convection. These models already featured cylindrical mantle plumes as the only form of active upwelling, although these were still wider than what would be expected, for example, by scaling the experiments of Whitehead and Luther (1975). But the foundations for integrating plate tectonics into a framework of mantle dynamics and defining the role of plumes in this system had been laid.

In order to decide about the university, I attended in 1989 first the AGU Fall meeting in San Francisco and then visited different universities where I had been offered Ph.D. studentships. The first person I recall I ran into and briefly talked to at the meeting was James Heirtzler – an impressive beginning to by chance get to talk to someone I knew from the textbooks. At that time, the AGU meeting was still much smaller than the size it had reached before the Corona pandemic. Since already back then (as I am still now – see e.g. Hagedorn, 2019 for a letter I also signed) I was concerned about my $CO_2$ footprint I wanted to at least avoid intra-continental flights and hence went for a greyhound bus trip across the USA and Canada in December 1989. This was just 1 month after opening of the Berlin Wall, and as a German I was greeted everywhere with friendly curiosity. I also felt flattered that top-notch scientists spent time with me, when I hadn't even finished my undergraduate studies. All this made me feel very welcome to the geodynamics community and confirmed for me, that going across the Atlantic was the right move – and I still think so.

## Hotspots fixed or moving, tilted or vertical?

In the end I decided to work with Rick O'Connell. He suggested to me to research how plumes would get deflected, and hence hotspots moved due to large-scale mantle flow. There had been some conceptual approaches before, showing how shear flow causes plume deflection (Richards and Griffiths, 1988) and that in the case of whole-mantle convection a substantial increase in viscosity is required in the lower mantle to ensure that lower mantle flow is sufficiently slow such that relative motion between hotspots rising from the lower mantle is confined to approximately an order of magnitude less than fast plate motions (Richards, 1991) – ~1 cm/yr versus ~10 cm/yr. Building upon those insights, we developed a more actualistic models with mantle flow based on seismic tomography (Steinberger and O'Connell, 1998; Steinberger, 2000) in order to contribute to the debate on hotspot fixity vs. mobility. We found that, with viscosities in the lower part of the mantle approaching $10^{23}$ Pas, mantle flow and inferred hotspot motion is sufficiently slow to yield hotspot motions at a speed of a few mm/yr to somewhat more than 1 cm/yr compatible with observed hotspot tracks. Specifically, we typically found about 1-1.5 cm/yr south- to southeastward motion for the Hawaii hotspot. In contrast, building upon Griffiths and Richards' (1989) theory, we found that the sharp Hawaiian-Emperor bend requires viscosities of about $1.5 \cdot 10^{20}$ Pas or less in the uppermost mantle, in order to sufficiently decouple Pacific plate motion and mantle flow: for a larger viscosity, such as $10^{21}$ Pas below the plate throughout the upper mantle, plate motion induced shear flow would strongly tilt the conduit. Thus, even if plate motion changes abruptly, the shape of the conduit would only gradually adjust, leading to a much more rounded bend than observed. Our models predict tilted plume conduits due to large-scale flow, with sources shifted with lower mantle flow towards large-scale upwellings. These models are simplified in that conduits are treated as sets of tracer particles in large-scale flow, but have the advantage that actual hotspots can be matched exactly, by inserting those particles in the right places. More recently, fully dynamic models of plumes in large-scale flow have been developed (Hassan et al., 2016; Arnould et al., 2019). In this case, places where plumes develop don't exactly match hotspot locations, but often match sufficiently closely such that a comparison is possible.

Although at that time I didn't fully realize that, this was a very suitable scientific project because the model I was developing not only aimed at explaining observations (i.e. age progression along and geometry of hotspot tracks) but could also yield predictions (such as the shape of the underlying conduits) that could be tested against future observations, which is an essential part of scientific activity (Burke, 2016). So it was falsifiable in principle, as any scientific theory should be (Popper, 2002), although in practice, it is not so clear. For example, how different would the observation have to be in order to "falsify" the model? Or, there are always many unknown parameters one can adjust, and one can argue that one just hasn't yet found the right combination of parameters – something that is easily possible in a nonlinear system. In any case, I am very grateful to Rick to give me this project as an entry point to the world of geodynamics.

## Mantle plumes and their role in defining reference frames for plate motions

The project Rick set me up with also fitted quite well with the project idea on true polar wander which I brought with me from Munich and which I pursued as well, because both are related to the question what is an appropriate reference frame for plates moving over the mantle. In particular, changes in hotspot paleolatitude with time, such as found for the Emperor Seamount Chain (Kono, 1980; Tarduno and Cottrell, 1997) may be due to hotspot motion in a "mantle reference frame", but they may also be due to "true polar wander", that is re-orientation of the entire crust and mantle as a whole with respect to the spin axis, which corresponds to the paleomagnetic axis averaged over ~10,000-year periods, or a combination of both. In order to obtain better data constraints, I joined John Tarduno and Rory Cottrell to propose an IODP cruise to drill more of the Emperor Seamounts. I participated in the cruise in summer 2001. The results confirmed a gradual southward motion of the Hawaii hotspot with respect to the Earth's spin axis during formation of the Emperor Chain (Tarduno et al., 2003). The cruise began and ended in Yokohama, Japan. Little did I know at that time, that I would actually live in Yokohama from 2002 to 2004.

Besides paleomagnetic data, motions of hotspots, and the motion of plates relative to them can also be constrained from age data along hotspot tracks. Duncan and Clague (1985) showed that geometry and existing age data on Pacific hotspot tracks can be fit with a plate moving over fixed hotspots. More recent, refined age dates showed that an even better fit can be obtained if the Hawaii hotspot has been moving several 100 km southward, mainly between 62 and 47 Ma, relative to other hotspots (Konrad et al., 2018).

However, when computing Pacific absolute plate motion based on an Indo-Atlantic fixed hotspot reference frame (e.g., Müller et al., 1993) and a relative plate motion chain connecting the Pacific plate to the African hemisphere through Antarctica, this would result in a track for a fixed Hawaii hotspot that is south of the actual track and continues, without much of a bend and with similar age progression, towards the northwest (Molnar and Stock, 1987; Raymond et al., 2000). Hence for times prior to the age of the bend ~47 Ma (Sharp and Clague, 2006) the predicted track is southwest of actual seamounts of same age.

When computing the motion of the Hawaii hotspot due to large-scale mantle flow, the plume source is advected southward with large-scale flow towards a large-scale upwelling above the south central Pacific. Subsequently the tilted conduit rises to the surface and straightens up again due to its own buoyancy, resulting in a southward hotspot motion (Steinberger et al. 2004). A rather similar result was obtained in the fully dynamic model of Hassan et al. (2016). The predicted track remains also similar if the computed motion of hotspots in the African hemisphere – typically modelled to occur at slower speed (O'Neill et al., 2005) – is considered. Hence, if models of hotspot motion are considered, an East-West misfit typically remains. This misfit can be removed if, in addition to the motion between plates, an intra-plate deformation between East and West Antarctica is assumed, corresponding to lithosphere extension in the West Antarctic Rift System and compression in the region of the Antarctic Peninsula (Figure 3). For geometric reason, the required deformation is much less than the hotspot track misfit. If relative motions in

Zealandia are used as additional constraints a similar internal deformation of Antarctica and hotspot track prediction results (Matthews et al., 2016).

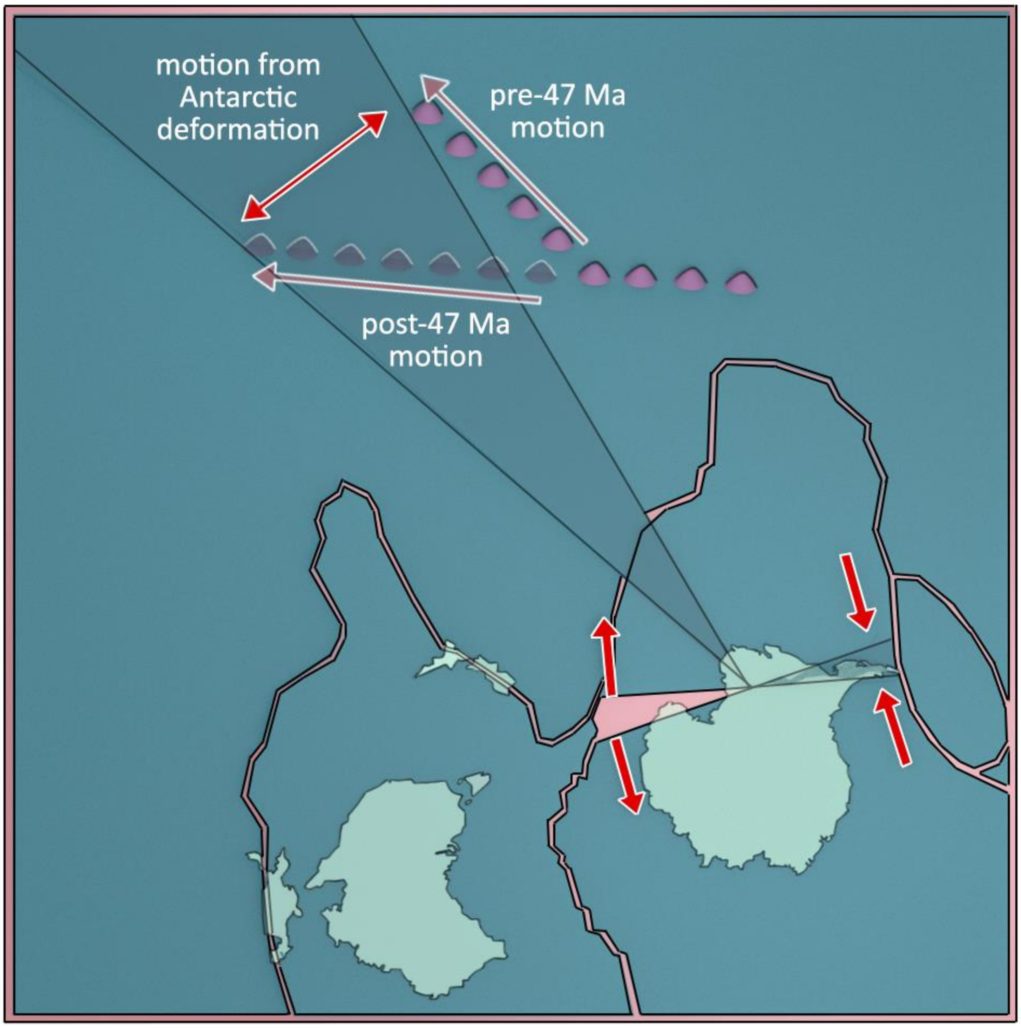


*Figure 3: Antarctic deformation and Pacific plate motion change. Diagrammatic representation of the main result obtained in Steinberger et al. (2004): A change in Pacific plate motion that – in combination with moderate (~1000 km) southward hotspot motion during formation of the Emperor chain – can explain the geometry and age progression of the Hawaii-Emperor chain, is compatible with plate reconstructions and hotspot tracks globally, if an additional (few 100 km) deformation within the Antarctic plate (extension in Ross Sea, compression in Antarctic peninsula) is assumed.*

### Where and how do plumes form?

There is pronounced thermal boundary layer (TBL) at the base of the mantle, with an estimated temperature drop of between 500 and 1800 K, corresponding to a heat flow of 5-15 TW across (Lay et al., 2008). Both numerical and laboratory experiments show that this heat will rise to the surface through thermal plumes. That core cooling works via convective flow in a thin D'' layer and narrow plumes is remarkably independent of mantle rheology (Loper, 1984). Hence the existence of plumes from the lowermost mantle is largely agreed upon. Although shallower depths of origin have also been proposed for some hotspots (e.g., Courtillot et al., 2003), we focus this review on lowermost mantle plumes, and hence this section on where in the lowermost mantle plumes form. If the TBL was largely undisturbed, plumes would just form at random locations, however that is not the case because the TBL is disturbed by the sinking of cold slabs. Accordingly, it has been noted that hotspots are not randomly distributed (Jurdy and Stefanick, 1990).

Where slabs sink to the lowermost mantle, they are expected to displace and thin the TBL, hence suppress the formation of plumes. Once seismic tomography had resolved large-scale mantle structure, it became clear that fast seismic velocities in the lowermost mantle are correlated with regions of past subduction (Engebretsen et al., 1992). The slow regions, above which subduction was mostly absent, were later named Large Low Velocity Provinces (LLVPs; Lay, 2005) or LLSVPs (with S for "shear"). So, are then hotspots correlated with slow regions? This was in fact found by Kuo and Wu (1997) after inverting for global shear velocity heterogeneities in the D″ layer. However, when tomographic images of the lowermost mantle became somewhat better resolved, a slightly different and somewhat more surprising pattern became apparent: That plumes not so much cluster above regions with the slowest shear velocities, but rather where horizontal gradients are strongest in the lowermost mantle (Thorne et al., 2004). These regions with strong gradients often fall along the margins of LLSVPs. Kuo et al. (2000) compare the advected bases of plumes (Steinberger, 2000) with D″ shear velocities and find again a correlation with low velocities. This is not surprising, given that bases get advected towards the LLSVP centers. In order to address the question where plumes initially start rising, it is perhaps better to compare the reconstructed eruption locations of Large Igneous Provinces (LIPs), which have been proposed to be the surface manifestation of plume heads (Richards et al., 1989), to lowermost mantle structure. If they rise approximately vertically, then this should correspond to the locations where they lifted off the CMB. Also, LIPs are perhaps more likely to correspond to deep mantle plumes, whereas not all hotspots may be of deep origin (Courtillot et al., 2003) but it is hard to know which ones are. This line of evidence was pursued in a series of papers (e.g. Torsvik et al., 2006) that were the result of a number of visits by Kevin Burke at the Geological Survey of Norway (NGU) where I also was working at that time. The result confirmed Thorne et al. (2004) in that LIPs eruption locations were reconstructed close to the LLSVP margins, near the strongest lateral velocity gradients. Subsequently, there has been a debate (Austermann et al., 2014; Doubrovine et al., 2016) whether the proposed pattern is statistically robust, or whether one can merely associate LIPs with seismically slow velocities, and the relation to the margins results because the LLSVPs are rather narrow and the margin is rather not straight, such that being close to a suitably chosen margin is a criterion that is relatively easy to be satisfied. It is also a question how far back in time this relation holds, since a relation of past LIP eruption location and present-day LLSVP margins also implies that the LIPs have remained stable in place from that past time until now. If LLSVP locations are long-term stable, this relation of LIPs to LLSVP margins could help to constrain plate motions for the more distant past, where hotspot tracks are no longer available (Torsvik et al., 2014).

What then could be the reason for plumes primarily initiating along LLSVP margins? One mechanism could be that they form at the edge of slabs (Tan et al., 2002). If LLSVPs simply correspond to the regions where the thermal boundary layer at the base of the mantle has been pushed by the slabs and thickened, then plume formation at slab edges also corresponds to plumes at LLSVP margins.

However, there are a number of indications that LLSVPs are not only hotter, but also chemically different and denser than the overlying mantle. These indications include their increased density inferred from seismology (Lau et al. 2017) although this may be limited to their lowermost ~100 km (Koelemeijer et al, 2017), their sharp edges (Ni et al., 2002; Wang and Wen, 2004) and the anticorrelation of s-wave and bulk sound velocities (Masters et al., 2000). This chemical density contrast could promote their long-term stability at the base of the mantle. Tan et al. (2011) investigate the location of plumes relative to chemical structures, which are composed of dense, high bulk modulus material and find that more plumes occur near the edges, rather than on top, of the chemical domes. Motivated by discussions with Kevin Burke during his visits to Trondheim, I also conducted numerical models that could yield insights why plumes primarily form at margins of thermochemical piles. We used subduction history of the past 300 Myr and found that a chemical layer at the base of the mantle is indeed shaped into piles resembling the two LLSVPs. Furthermore, slabs push the thermal boundary layer towards the edge of these piles, where it is forced upward and starts rising in the form of plumes (Steinberger and Torsvik, 2012; Figure 4). In this model, chemical piles are pushed around by subducted slabs, somewhat different from the immobile piles envisioned by Kevin. However, in order to partly reconcile our model with Kevin’s viewpoint, we also conducted a re-run where we started with the present-day configuration and imposed the past 300 Myr of subduction history for a second time. In this second round, the piles in fact more or less remain in place, because also the overall locations of subduction zones have not shifted dramatically. Hence we showed plausibly that keeping piles spatially stable for ~300 Myr is not too difficult to achieve. It gets more difficult, though, when the model is extended further back in time to also include the subduction between continents during assembly of the supercontinent Pangaea. Our model was also simplified in that lateral viscosity variations were not considered. This has been included by Dannberg and Gassmöller (2018). Since their model is sufficiently high resolution they were also able to study the entrainment of chemically distinct material in plumes. They find bilaterally asymmetric chemical zoning, whereby the pile-facing side of the plume preferentially samples material originating from the pile, if slabs induce strong lower-mantle flow toward the edges of these piles where plumes rise. Using 2-D models, Mulyukova et al. (2015) were able to study a wider variety of cases at even higher resolution. They also find that bilateral zoning may occur, but their focus was on the age distribution (i.e. time since subduction) of entrained subducted slab materials. They find that typically, but not always, the youngest materials, that have not yet resided at the bottom of the mantle for very long are preferentially entrained i.e. overturn times of a few hundred Myr.

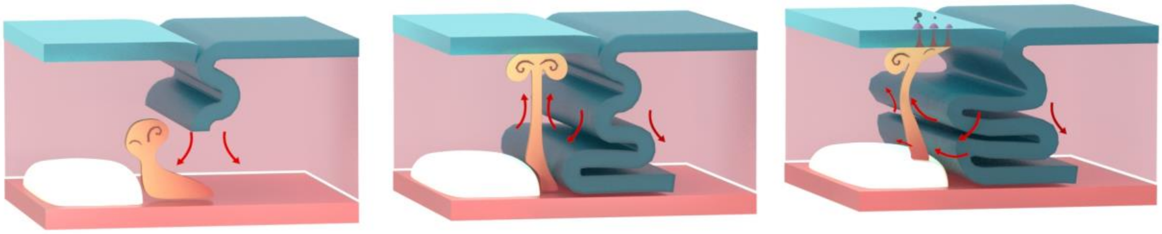


*Figure 4: Schematic representation of modelling results (e.g., Steinberger and Torsvik, 2012; Dannberg and Gassmöller, 2018) of plumes forming at the margins of thermochemical piles. Left: Plume head detaches; Middle: plume head arrives beneath the lithosphere; Right: plume gets tilted and produces a hotspot track*

## Plumes, plates and their interactions

### *Distribution of plume-derived volcanism*

Not all hotspot tracks are a simple age-progressive chain as Hawaii. Complications essentially arise, if plume material flows laterally beneath the lithosphere and causes melting and volcanism elsewhere. This may especially happen, if plume material is drawn towards a spreading ridge, both because it flows upwards towards thinner lithosphere due to its buoyancy, and because it is sucked into the spreading ridges, where plates are forced apart. Morgan (1978) proposed a second kind of hotspot island that is caused in this case by channeling from a hotspot to a nearby rise crest. Also, if the lithosphere has variable thickness for other reasons, plume material may flow towards thinner lithosphere, a process which was suitably termed “upside down drainage” (Sleep, 1996) and for example applied to explain the distribution of volcanism in Africa as caused by a single plume (Ebinger and Sleep, 1998). I was drawn to this topic through my participation in SPP SAMPLE (South Atlantic Margin Processes and Links with onshore Evolution) for the Ph.D. project of René Gassmöller. We were able to explain separation of volcanism into the Tristan and Gough chain by the position of the plume relative to the ridge and the influence of the global flow field. We found that  plume material below the off-ridge track can flow toward the ridge and regions of thinner lithosphere, where decompression melting leads to the development of a second volcanic chain resembling the Tristan and Gough hotspot tracks (Figure 5; Gassmöller et al., 2016).

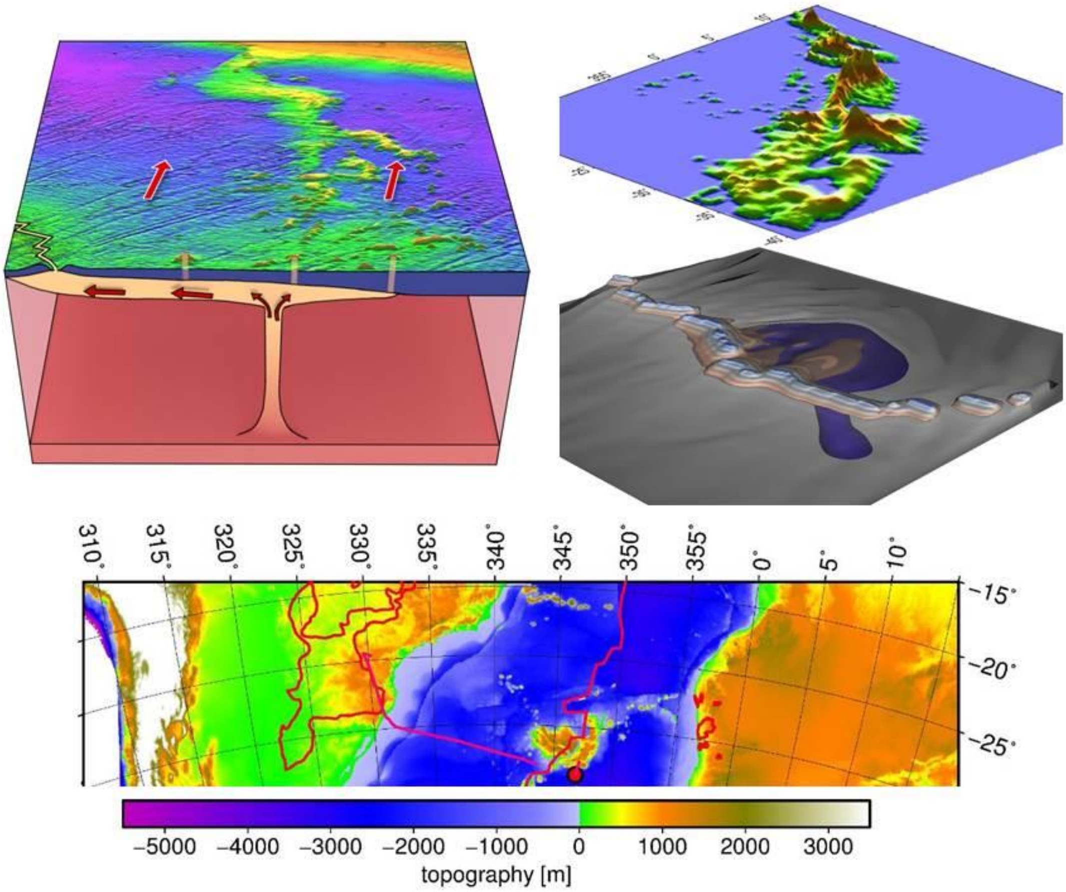


*Figure 5: Tristan plume and interaction with mid-Atlantic ridge: Left: Oblique view of topography of the Walvis Ridge, the track of the Tristan hotspot, towards N45E. Beneath, a drawing of the plume feeding into the ridge, also causing volcanism between plume and ridge. Right: Oblique view of integrated melt production, corresponding to expected topography. Beneath, numerical model result for present-day: melt_fraction 2% isosurface, with colors showing temperature deviation from adiabat (-400 K blue to +150 K red). Also shown is the 50 K temperature anomaly isosurface (in blue) for the plume stem. Grayscale isosurface T=1613 K for base of lithosphere with colors for depth (0 km white to 150 km black) and shading. Same perspective as above, but slightly different areal extent. Plume reaches surface at 38.7°S, 11.3°W. Figure by René Gassmöller. Bottom: 85 Ma reconstruction. Sea floor topography is corrected for age. Walvis ridge next to Rio Grande Rise constitute an "Iceland in the South Atlantic", soon after the ridge has crossed the plume around 90 Ma. Red dot is plume position and red line the hotspot track according to the model of Doubrovine et al. (2012). Also shown are outlines of Parana (in South America) and Etendeka (in Africa) flood basalts corresponding to the plume head, and the mid-Atlantic ridge at 85 Ma.*

We applied the workflow we developed also to a couple of other hotspots, including Iceland (Steinberger et al., 2019a), where there is even no classical hotspot track at all; instead there is simultaneous widespread volcanism around 60 Ma, over an area of ~2000 km lateral extent. The scenario favoured here is that the Iceland plume reached the base of the lithosphere long before 60 Ma (several tens of Myr) and hot plume material accumulated beneath thick lithosphere, but could only reach shallower depths and initiate melting after the lithosphere had thinned due to rifting and sea floor spreading. This happened around 60 Ma at widespread locations both east and west of Greenland. Figure 6 visualizes this situation: The stretch drawn across Greenland hereby is based on the 100 K isosurface at 68 Ma in the model computation of Steinberger et al. (2019a).

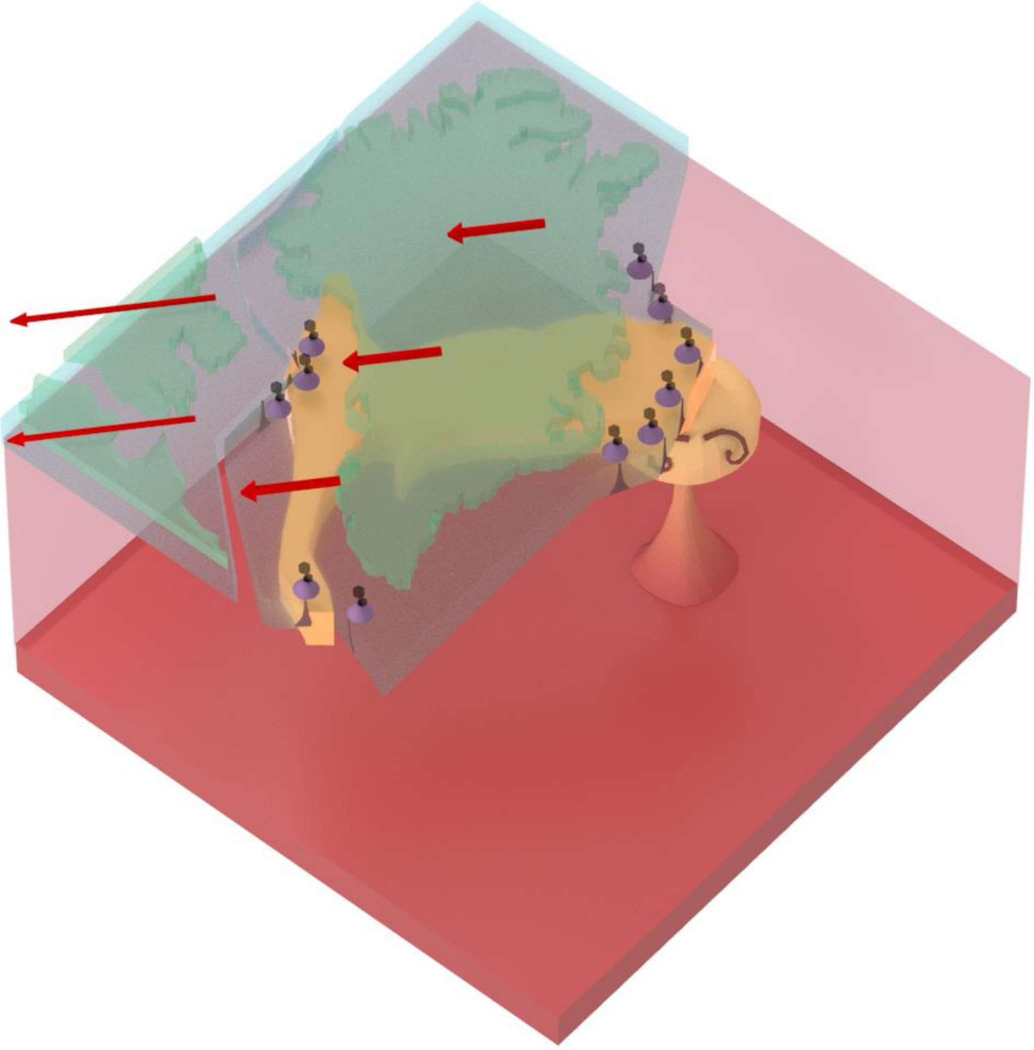


*Figure 6: Iceland plume at 60 Ma. At this point, the Iceland plume is located near the East coast of Greenland. However, in this scenario, Greenland had previously migrated across the plume, and hence hot plume material exists all across Greenland, as well as along its west coast, and can lead to volcanism there once the lithosphere is being thinned through rifting, around that time.*

*Plumes and continental break-up*

One considerable simplification in our workflow was that surface plate motions were simply prescribed. In reality, there may be a feedback mechanism: While rifting is initiated by tectonic forces and plume material flows to the thinned rifted lithosphere, it may in turn help to trigger the final continental break-up (Buiter and Torsvik, 2014). Brune et al. (2013) find that plume-related lithosphere erosion leads to a moderate lithospheric strength reduction. In a force-limited environment, this may have strong influence on the timing of continental break-up, or whether continental break-up takes place at all.

*Plumes and the initiation of subduction*

Plumes may not only be instrumental in the breaking apart of plates, but also in the initiation of subduction. Baes et al. (2016) show that self-sustaining subduction is induced by plume–lithosphere interaction when the plume is sufficiently buoyant, the oceanic lithosphere is sufficiently old and the plate is weak enough to allow the buoyant plume to pass through it. In this case, partially molten plume material may spread across the top of broken lithospheric segments (proto-slabs) and pushes them downward into the asthenosphere (Ueda et al., 2008). Plume-induced subduction initiation could have started the first subduction zone without the help of plate tectonics (Gerya et al., 2015). With this mechanism, subduction is initiated in the vicinity of the plume, whereas van Hinsbergen et al. (2021) propose a scenario where a plume rising below a plate boundary induces a relative rotation between two plates, causing compression far away from the plume head along the same plate boundary (Figure 7). They provide simple estimates showing that, if this plate boundary is pre-weakened, stresses may be sufficient to cause convergence, and the amount of convergence caused may be sufficient to initiate self-sustaining subduction.

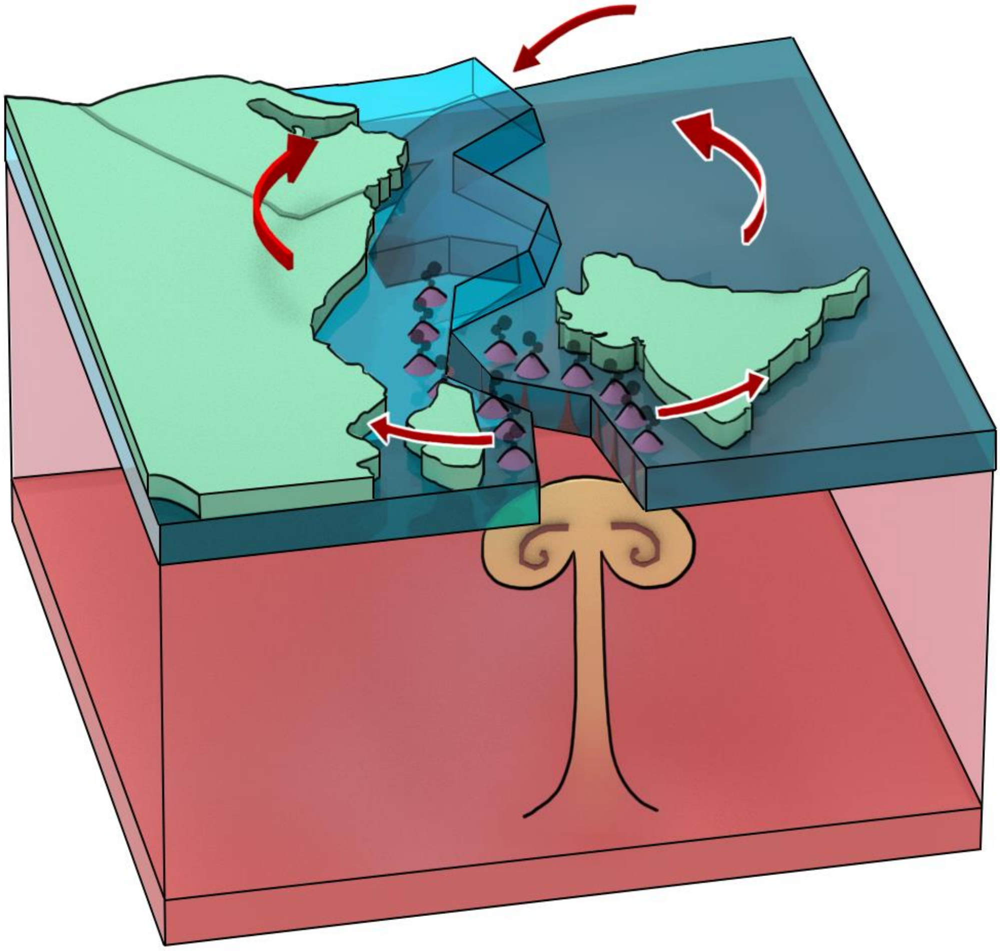


*Figure 7: Conceptual model of plume-induced plate rotations triggering seafloor spreading and subduction initation along the same plate boundary (van Hinsbergen et al., 2021).*

*Plumes and lithospheric uplift*

Plumes not only cause horizontal displacement of plates, by inducing Poiseuille-type flow in the asthenosphere underlying the plates, but through their buoyancy also vertical displacement, so-called dynamic topography. This gives rise to their hotspot swells, which can be used to estimate their anomalous mass flux or buoyancy flux (Davies, 1988; Sleep, 1990), a measure for the size of plumes. This swell is most clearly visible for Hawaii as a topography anomaly ~1200 km wide and 3000 km long, with associated geoid anomaly, leading to a buoyancy flux estimate of 2200 to 3500 kg/s (Ribe and Christensen, 1999). Hawaii has long been regarded as the largest plume on Earth with the highest buoyancy flux, whereby estimates for Iceland have been around 1400 kg/s (Sleep, 1990). However, Parnell-Turner et al. (2014) estimate 18,000 kg/s based on the geometry of the youngest V-shaped ridges south of Iceland, assuming these record pulses of upwelling within the plume (Vogt, 1971). Assuming the upper mantle seismic anomaly north of Iceland shown in Figure 8 (top) is due to outflow of hot plume material, we estimated between 7000 and 9000 kg/s buoyancy flux (Steinberger et al. 2015). With both estimates, Iceland would be the largest plume on Earth. Importantly, the Iceland plume is not only big, but its size also appears to be fluctuating. Besides the short-term fluctuations indicated by the V-shaped ridges, the transition from smooth to rough seafloor south of Iceland (i.e. the variable extent of smooth seafloor as a function of its age) points towards longer-term variations over ~35 Myr. Jones (2003) suggests that the apparent increase in the size of the Iceland Plume head since ~35 Ma can be explained by westward migration of the Reykjanes Ridge relative to the centre of a plume of constant flux on timescales over 8 Myr, the periodicity of the plume inferred from V-shaped ridges since ~35 Ma (Parnell-Turner et al., 2014). A pulse of plume material moving northward within the asthenosphere, could have caused a recent uplift of East Greenland lithosphere, possibly playing a key role in the onset of large-scale glaciations in the northern hemisphere since 2.6 Ma (Steinberger et al., 2015). Such a pulse could be inferred from the distribution of seismic anomalies in the upper mantle (Figure 8, top).

Another example where a plumes might interact with glaciation is West Antarctica, where the lithosphere is extending (Figure 3) and a plume has been proposed (Seroussi et al., 2017) but with clear evidence missing. If it really exists, it may lead to a thinner lithosphere in West Antarctica, and a relatively low viscosity in the asthenosphere beneath, allowing faster lithosphere uplift upon melting and thus somewhat counteracting the marine ice-sheet instability, which is predicted to cause long-term partial collapse of the West Antarctic Ice Sheet at global warming levels around 2 degrees above pre-industrial levels (Garbe et al., 2020). However, if the ice sheet does collapse, the relatively rapid postglacial rebound would presumably contribute additional sea level rise (Pan et al., 2021).

In other cases, it is puzzling that uplift is absent, although it would be expected due to thermal buoyancy. For example the case for the Siberian LIP, a kilometer-scale surface uplift would be expected for a thermal plume, but is absent (Czamanske et al., 1998). Dannberg and Sobolev (2015) show that, if plumes contain up to 15–20% of recycled oceanic crust in a form of dense eclogite, their buoyancy is drastically reduced, and they cause only negligible surface uplift. Nevertheless, they can rise through the whole mantle despite their low buoyancy, because their tails are rather bulky with radius >200 km. According to Poiseuille's law, flow through the conduit is proportional to the 4th power of conduit radius, hence doubling the radius allows the same volume flux even if the pressure gradient driving flow through the conduit, which is caused by density differences between plume and surrounding mantle, is reduced by a factor 16.

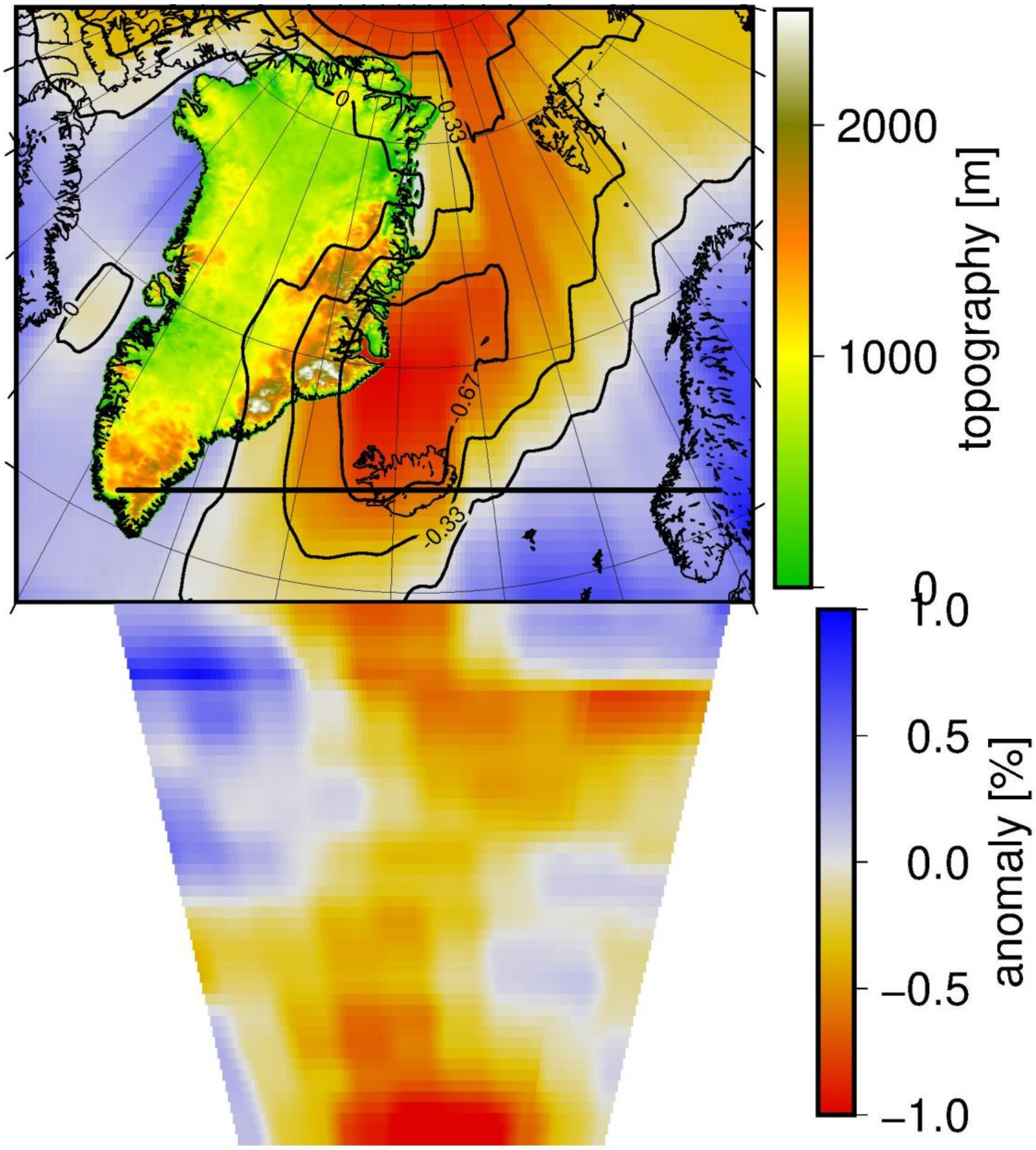


*Figure 8: Top: Unglaciated topography of Greenland, assuming isostatic uplift (i.e. the ice sheet has been replaced by a mantle layer of the same mass per area). Elsewhere the top panel shows tomography model TX2019slab-S (Lu et al., 2019) at depth 385 km. Bottom: Cross section for depths below 385 km through the same model, along the line indicated in top panel. Data extracted by SubMachine (Hosseini et al., 2018). A "votemap" constructed with SubMachine looks very similar, so the streak of fast anomaly northward from Iceland appears to be a robust feature.*

## Do plumes exist? The hunt for evidence.

The existence of plumes has long been widely agreed upon, as they form in models (both numerical and laboratory) of a bottom-heated mantle, and there is evidence for them on the surface. Yet undisputed detection by seismic tomography or any other means has long been elusive (Ritsema and Allen, 2003). Various authors have interpreted slow anomalies underlying hotspots such as Iceland (Bijwaard and Spakman, 1999; see also Figure 8 for a cross section through a more recent model of the mantle below Iceland), but also many others (Montelli et al., 2004; Zhao, 2004) as whole-mantle plumes. Yet it has been questioned whether models have sufficient resolution to show plumes, and also the shape of these anomalies was often different from the simple narrow conduits connecting the lowermost and uppermost mantle. In Boschi et al. (2007) we therefore took a different approach and rather than looking for individual conduits, we found that plume conduits predicted from numerical models preferentially appear in seismically slow regions. Correlation between plumes and tomography significantly improves compared to vertical conduits if advection of the plume source is taken into account, and correlation of modelled conduits for actual hotspots is also significantly better than for tilted conduits at random locations (Boschi et al. 2008). A deep mantle origin is therefore likely for a limited number of hotspots. Because of the limited resolution of global tomography, dedicated ocean bottom seismometer arrays have been deployed around known plume candidates, especially Hawaii and La Réunion, with station spacing and aperture suitable such that it should be possible to image a plume conduit in the lower mantle. Wolfe et al. (2009) revealed a several-hundred-kilometer-wide region of low velocities beneath and southeast of Hawaii down to 1500 km, the maximum extent of their resolution, suggesting a lower-mantle origin of Hawaii. The model of Thsekhmistrenko (2018) reveals a massive upwelling rooted in the African LLVP, with branches tilting up- and outward from a central cusp at around 2000 km depth, connecting to the hotspot locations of La Réunion, Afar, Kerguelen, and possibly Crozet. Hence the observed depth-averaged tilts for Hawaii and these hotspots are similar to the modelled ones in Steinberger (2000). French and Romanowicz (2015) found that plumes are actually broader than expected if they were purely thermal, and with a whole-mantle seismic imaging technique combining accurate wavefield computations with information contained in whole seismic waveforms they were able to reveal conduits beneath many hotspots globally. They report plumes that are nearly vertical below depth ~1000 km, where some are deflected horizontally. This differs from my numerical model results (Steinberger, 2000) with similar tilts throughout the mantle. The Yellowstone plume is not detected by French and Romanowicz (2015), but using the close station spacing of USArray, Nelson & Grand (2018) were able to detect a tilted whole-mantle conduit beneath Yellowstone, which is sufficiently narrow (diameter ~350 km) such that it could be interpreted as a thermal plume. Here the tilted plume direction and magnitude can be matched with numerical model results (Steinberger et al., 2019b).

## Challenges for the future: What we still don’t understand about plumes (actually, a lot …) and what new tools we might harness.

We have now a far-reaching (although not universal) agreement on the existence of whole-mantle plumes, and that they are at least partly thermal. But there is also ample evidence, especially from geochemistry, that at least some of them are chemically different from ambient mantle, presumably due to entrainment of recycled and primordial reservoirs in the deep mantle (Jackson et al., 2021). However, many questions are unresolved: are the plumes imaged by tomography so broad because their buoyancy is substantially reduced due to chemical entrainment? Or do they reflect a complex visco-plastic rheology with yield stress in the lower mantle (Davaille et al., 2018)? Are there also more narrow plumes, like the one beneath Yellowstone, that are currently not (yet) imaged by tomography? Why are many broad plumes almost vertical below ~1000 km depth and appear not to be deflected by the “mantle wind”? Could that mean that the rheology of the lower mantle is such that mass movements below ~1000 km are essentially limited to vertically sinking slabs, horizontal flow in the bottom TBL and plumes coming up vertically, as proposed by Kevin Burke (2014)? If so, could rheological contrasts in the lower mantle be due to bridgmanite-enriched ancient mantle structures (BEAMS) with a 20-fold increased viscosity (Ballmer et al., 2017)? Or could the fact that bridgmanite is substantially stronger than magnesiowüstite lead to strain weakening and resultant shear localization in the lower mantle (Girard et al., 2016)? This may occur if large enough strains produce interlinking of the weak magnesiowüstite phase instead of a load-bearing framework of bridgmanite. "Are" plumes the upward flow, or are they embedded in large scale ambient flow, with upward flow primarily above the LLSVPs? How large is the heat flow from the deep mantle through plumes? Various estimates cover a wide range, for example for Iceland (Parnell-Turner et al., 2014), and this is relevant for the total core-mantle boundary heat flow (Lay et al., 2008).

Besides these questions that concern the Earth interior, plumes also influence surface processes and climate. To date, this influence has been far less studied and hence connections beyond the well-known temporal link between mass extinctions and large igneous provinces (Wignall, 2001), but also theories about the cause of this link, have often remained speculative and controversial. Mantle plume research will benefit from the ever-increasing speed and power of computers. In particular, the field of pattern recognition through neural networks now increasingly yields interesting results. With respect to mantle plumes, such techniques might for example be applied to the interpretation of tomography, geochemistry and topography, yielding new insights about plumes.

Findings in mantle plume research (as in research, in general) often come serendipitously and unexpectedly, though. For example, that plumes primarily rise from the margins of LLSVPs was completely unanticipated. Hence, discussing future challenges is also a bit pointless. One thing I particularly like about my work as a researcher of mantle plumes (among other topics) is that, when I go to my office (home-office during these Corona days) in the morning, I never know what surprises the day might have in store for me, and which certainties of the morning have crumbled by the evening.

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**Online Supplementary Materials:**

*Figure 6 different style*

***Supplementary videos:***

Iceland Plume 120 Ma to present, seen from the North (supporting Figure 6). Plume is shown as +80 K non-adiabatic temperature contour, base of the lithosphere by the -300 K contour, making plate motions visible. Colour represents pressure, approximately corresponding to depth. https://www.youtube.com/watch?v=g1uvi0f2stE

A film about the creation of Iceland (supporting Figure 6):
https://www.youtube.com/watch?v=hLGp6lRaSs0

Paper cut demonstration of the mechanism of plume-induced subduction initiation shown in Figure 7: https://www.youtube.com/watch?v=1VzCzg2KRgg

India ocean plate motions: https://www.youtube.com/watch?v=wlekz4y7PEM