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Plume-ridge interaction induced migration of the Hawaiian-Emperor seamounts

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ABSTRACT

The history of the Hawaiian hotspot is of enduring interest in studies of plate motion and mantle flow, and has been investigated by many using the detailed history of the Hawaiian-Emperor Seamount chain. One of the unexplained aspects of this history is the apparent offset of several Emperor seamounts from the Hawaii plume track. Here we show that the volcanic migration rates of the Emperor seamounts based on existing data are inconsistent with the drifting rate of the Pacific plate, and indicate northward and then southward "absolute movements" of the seamounts. Numerical modeling suggests that attraction and capture of the upper part of the plume by a moving spreading ridge led to variation in the location of the plume's magmatic output at the surface. Flow of the plume material towards the ridge led to apparent southward movement of Meiji. Then, the upper part of the plume was carried northward until 65 Ma ago. After the ridge and the plume became sufficiently separated, magmatic output moved back to be centered over the plume stem. These changes are apparent in variations in the volume of seamounts along the plume track. Chemical and isotopic compositions of basalt from the Emperor Seamount chain changed from depleted (strong mid-ocean ridge affinity) in Meiji and Detroit to enriched (ocean island type), supporting declining influence from the ridge. Although its surface expression was modified by mantle flow and by plume-ridge interactions, the stem of the Hawaiian plume may have been essentially stationary during the Emperor period.

1. Introduction

The Emperor-Hawaiian volcanic seamount chain consists of ~130 volcanoes and stretches for more than 6000 km across the Pacific plate. It played a key role in supporting the theory of plate tectonics and the plume hypothesis which suggested that the Hawaiian-Emperor chain formed by the motion of the Pacific plate over a stationary mantle plume [1,2]. The famous bend between the Emperor and the Hawaiian chains has been attributed to a major change in the drifting direction of the Pacific plate [1–4], induced by the collision along the Neo-Tethys Ocean [5,6]. This has been challenged by paleomagnetic results, however, which suggest that Detroit seamount (82–76 Ma) erupted at a paleolatitude of ~36°N (Fig. 1a). The plume then moved southward towards the current latitude [7,8]. Consequently, it has been proposed that the Emperor Seamount trend formed by the rapid migration of the Hawaiian plume between 81 and 47.5 Ma ago, rather than by changes in the direction of the Pacific plate [7], although this conclusion is by no means universally accepted [3,9]. Any explanation for the tracking of the Emperor Seamounts prior to

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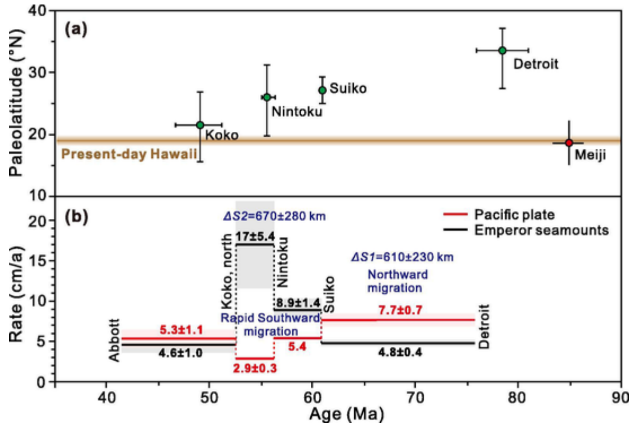

Fig. 1. Variation of the Paleolatitude of the Emperor seamounts and the movement rate of the Pacific plate and the Emperor seamounts with the age. (a) Paleomagnetic latitudes of Emperor seamounts. Note that the paleomagnetic latitudes of Meiji seamounts (19°N) are lower than the original position of the Hawaiian-Emperor plume (~21°N at Koko), which does not support the plume migration model by Refs. [7,8]. Paleomagnetic data from previous studies [7,13,36]. (b) The migration rates of Emperor seamounts and the Pacific plate. The northward migration rate of the Emperor seamounts is based on high precision ages [3] and the northward migration rate of the Pacific plate is calculated from plate reconstruction using GPlates [12] (averaged between seamounts). The different migration rates suggest that the Hawaiian plume moved northward relative to the mantle framework sometime between ~75 Ma (Detroit) to ~61 Ma (Suiko), and then changed to southward absolute motions. The total offsets resulted from these two relative motions are marked as ΔS_1 and ΔS_2, respectively.

the bend must take into account the clear correlation between distance and age revealed by dating of the volcanoes of the Hawaiian chain. One of the features of this relationship, however, is that between about 80 and 55 Ma, the linear relationship breaks down (Fig. 2d) with offsets from the linear trend of as much as 300 km relative to the stationary Louisville seamount chain [10]. The offset has previously been explained by a combination of hotspot and plate motion changes driven by plate/mantle reorganization [10]. Others have proposed that the misfit between different reconstructions related to the Hawaiian and Emperor chains was due to intraplate deformation [11], whereas the paleomagnetic data were partly influenced by true polar wander [4].

Here we propose that the northward drifting of the ridge between the Izanagi/Kula and Pacific plate attracted the upper part of the plume, resulting in variation in the location of the plume's magmatic output at the surface while the stem of the plume remained stationary.

2. Migration rates of the Emperor seamounts

Paleomagnetic studies show that the Detroit seamount was located at ~36°N, suggesting that the Hawaiian-Emperor plume was located several hundred to two thousand kilometers north of the current position of the Hawaiian Island about 82–76 Ma ago (Fig. 1a). It then migrated southward to the Suiko seamount (~27°N) at 60.9 Ma, then to the Nintoku seamount (~26°N) at 56.2 Ma, and finally back to Koko (21°N) at ~52.6 Ma. This has been taken as key evidence that the Emperor chain was formed by the southward migration of the plume, rather than by the movement of the Pacific plate [7,8]. However, the Pacific plate indeed drifted northward during this period as indicated by plate tectonic reconstructions [12].

To solve this problem, we calculated the migration rates of both the Emperor seamounts and the Pacific plate. The northward migration rate of the Emperor seamounts was calculated from ages [3] and distances between corresponding seamounts, whereas the drifting rate of the Pacific plate was obtained via plate reconstruction based on magnetic anomalies using GPlates [12]. Interestingly, these two sets of drifting rates are dramatically different (Fig. 1b).

Based on isotopic dating results [3], the fast migration of the volcanos from Suiko to Nintoku (8.9 ± 1.4 cm/a and then to Koko (17 ± 5.4 cm/a) occurred between 60.9 ± 0.3 and 52.6 ± 0.8 Ma. In contrast, according to plate reconstruction, the Pacific plate drifted slowly (~2.9 to 5.4 cm/a) during this period. This misfit requires rapid southward migration of the surface expression of the hotspot by 670 ± 280 km. At older times the migration rate of the Hawaiian plume based on volcano ages is smaller than the drifting rate of the Pacific plate between ~76 and 60.9 Ma, obtained using the same methods, which requires northward migration of the plume by 610 ± 230 km, consistent with the distance of the southward migration within error (Fig. 1b). The southward migration of the seamounts should have commenced at Handel. However, no seamounts between Detroit and Suiko have been dated.

It is important to note the inconsistencies in some of the arguments with respect to paleolatitude. The Detroit volcano has ages ranging from 82 to 76 Ma, with large fluctuations in paleolatitude (~26–40°N) [7]. This is difficult to attribute to migration of the plume, because Meiji is located right next to Detroit, and Meiji was erupted at ~19°N 85–82 Ma ago, the same as the present Hawaii plume (Fig. 1a) [13], which is consistent with the stationary mantle plume model [2].

3. Plume-ridge interaction

When the movements of seamounts are viewed in the context of the changes in the volume of the Emperor Seamount chain with time and the variations in the geochemistry of the erupted volcanic rocks, they suggest that interaction of the plume with the spreading centers that were in the north Pacific at that time may contribute importantly to the age-distance disparities (Fig. 2a–d). During these time periods, the volume of the Emperor Seamount chain changed progressively. This is readily apparent from the map view of the seamount chain (Fig. 2a), and surface volumes are quantified in Fig. 2b (Supplementary materials). The volumes are largest for the oldest remaining parts of the seamount chain, Detroit and Meiji seamounts. The volumes decrease and then stabilize at about half the maximum volume, until they decrease to low values between Nintoku and Ojin (See the map in Fig. 2a).

These observations then suggest an explanation for the time-distance relationships of the Emperor seamounts that were influenced by plume-ridge interaction. Interactions between spreading ridges and mantle plumes are common in the Earth's history [14–20] and have previously been discussed to explain the Hawaii-Emperor bend [8].

Plume material flows to the ridge at the base of the lithosphere, like an upside-down funnel, called by Schilling "plume source-ridge sink" [21]. In general, interactions between a stationary ridge and a plume cannot give rise to an age-distance relationship. The well-developed age-distance relationship was mainly due to the northward migrations of both the Pacific and Izanagi/Kula plates, and consequently the spreading ridge that separated them. The Pacific plate changed its drifting direction from southwestward to northwestward at ~125 Ma due to the eruption of the Ontong Java plateau [22,23], such that the

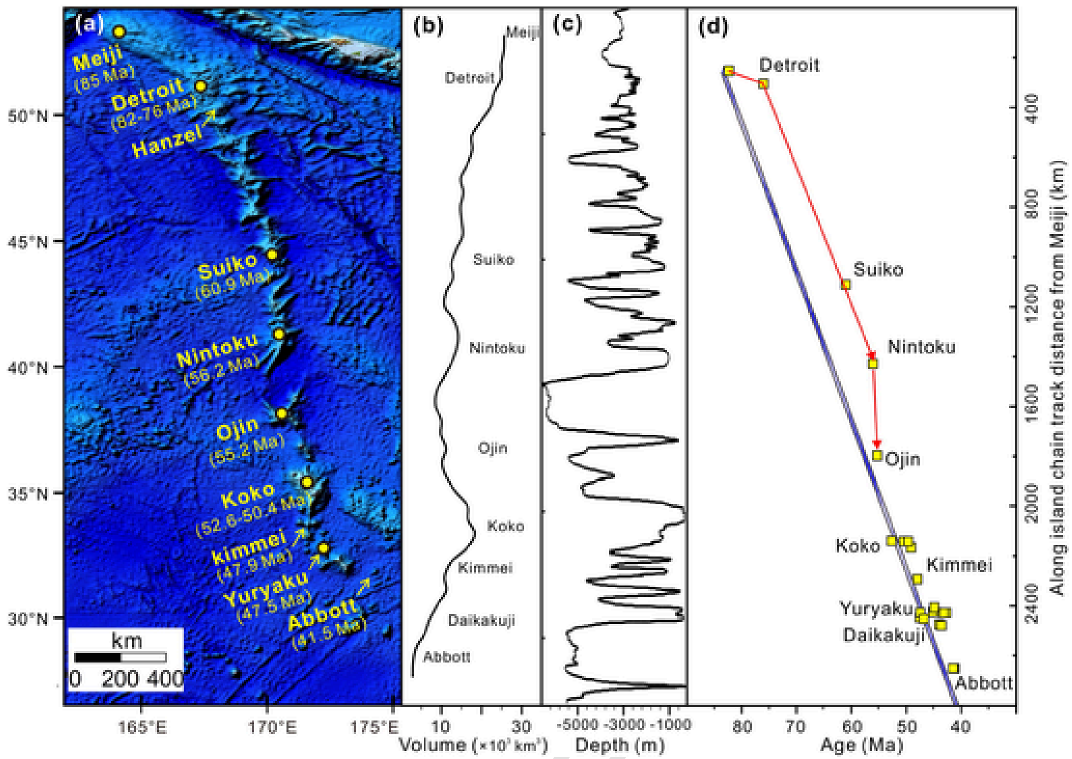

Fig. 2. Along track profiles of Emperor seamounts, volume, depth and migration of the Pacific plate. (a) Map showing the positions and ages of Emperor seamounts. Note that there is no seamount between Nintoku and Ojin. Base map is from NOAA (https://www.ngdc.noaa.gov/). (b) Along-track volume profile (five-point running average) of the Emperor Seamount chain, showing low volume between Nintoku and Ojin. (c) Along-track depth profile of the Emperor Seamount chain, which also shows the lowest depths between Nintoku and Ojin. (d) Age-distance diagram modified after Ref. [10], showing two major offsets of the Emperor chain relative to the Louisville chain, which correspond to a northward migration near Detroit seamount and a rapid southward migration between Nintoku and Ojin. Both the volume and the depth profiles were obtained using ArcGIS and bathymetry data (GEBCO, https://www.gebco.net/). Detailed volume calculation can be found in the Supplementary materials.

ridge between the Pacific and Izanagi/Kula plates was migrating northward [22,24]. Meanwhile, the spreading rate of the ridge decreased dramatically. At ~100 Ma, the Pacific plate started to drift roughly northward, i.e., both plates moved roughly in the same direction, such that the spreading rate of the ridge should have dropped dramatically. This retarded ridge has been moving northward ever since.

The Izanagi/Kula plate was moving northward, such that eruptions at the ridge should have formed seamount chains on the Izanagi/Kula plate as well. It is possible that the Shirshov plateau was formed during the eruption of Meiji, whereas the Bowers plateau formed together with Detroit [25]. These two plateaus should also have MORB affinities. These are readily testable by future ocean drillings. In contrast, the Pacific plate also drifted northward together with the ridge, such that there is no seamount chain formed until the ridge approaches the plume as it moves northwards. The distance between the plume and the ridge is the controlling factor. As the ridge continues northward moving away from the plume, flow towards the ridge diminishes, forming Hanzel, Suiko and Nintoku, etc., half way between the plume stem and the retreating spreading center. As the ridge moved still further northward, the ridge and plume melting became fully separated.

As shown by numerical modeling (Fig. 3 and Supplementary materials), as a spreading ridge moves, the interacting mantle plume may be deflected/carried along for millions of years through entrainment of plume flow by the ridge [26–30]. The interaction may also change the migration rate of the ridge [14], e.g., leading to a jump of the ridge towards the plume, giving rise to asymmetric sea-floor spreading [31,32]. Jellinek et al. [33] pointed out that a plume could be attracted towards an approaching ridge and eventually captured by it, leading to a surface manifestation of volcanism that is offset relative to the deep plume stem.

Our numerical modeling suggests that as the moving ridge approaches the plume, the plume is diverted towards the ridge, leading to an apparent offset in the surface volcanic manifestion of the plume relative to the deep plume stem (Fig. 3). Deeply rooted plume magmas can then be preferentially channeled to and erupted at the ridge axis with increased melt production. As the ridge subsequently moves away from the plume, the plume is no longer deflected and volcanism moves rapidly back to be positioned over the deeply rooted plume stem (Fig. 3).

4. Discussion

These various considerations of volume, geochemistry, observations of plume capture by spreading centers elsewhere and theoretical models raise the possibility that plume-ridge interaction influenced the ancient plume that formed the Emperor Seamounts.

Ridge-plume interaction at Detroit has long been identified by geochemists [34]. Schilling identified flow of plumes towards ridges to account for plume-like geochemical anomalies [21]. Jellinek et al. [33] pointed out that faster spreading ridges could be particularly effective in entraining plume flow. Previous numerical modeling consistently suggests that the plume may be offset by several hundred kilometers [29]. Wes-

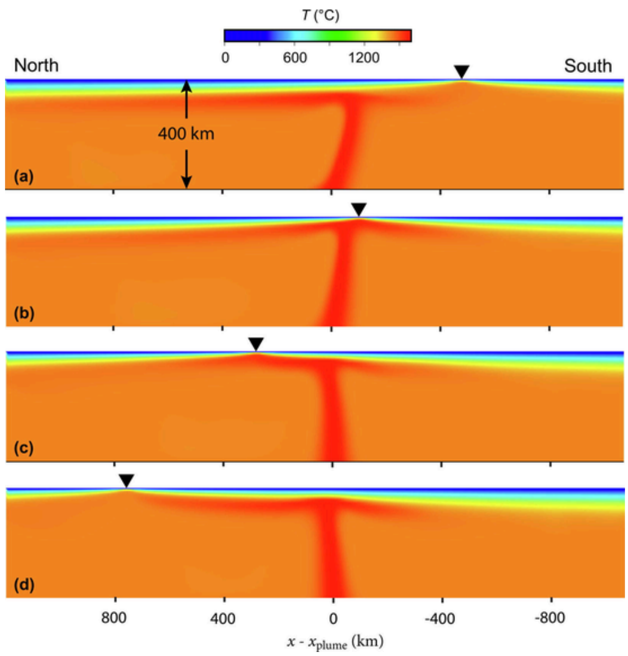

Fig. 3. Typical evolution of plume-ridge interaction predicted by the numerical model. The panels show temperature fields in the vertical symmetry plane normal to the ridge at four different stages of plume-ridge interaction. The plume has radius $a = 55$ km and excess temperature $\Delta T = 250$ K, and the half-spreading rate and migration rate of the ridge are $U = U_m = 3.2$ cm/a. Inverted triangles indicate the position of the ridge, which migrates to the left (North) relative to the plume. The ridge starts interacting with the plume at a distance $x–x_{plume}$ ~–580 km, and continues to do so until $x– x_{plume}$ ~ +750 km. Melting is intensified dramatically when the plume stem is close to the ridge (b). Please refer to the Supplementary materials for more detailed information.

sel and Kroenke [4] discussed the potential effects of plume-ridge interaction in the Emperor chain to explain the relative motion of the Hawaii and Louisville plumes. They, however, thought that "it remains a speculative scenario that is difficult to test".

Our numerical modeling clearly indicates that plume-ridge interaction may plausibly explain the offsets obtained by comparing the migration of the Emperor seamounts and the drifting of the Pacific plate. At the time of formation of Meiji, the oldest remaining part of the chain, the Hawaiian plume first encountered the approaching ridge, leading to a slight southward movement of the shallow part of the plume to feed the ridge. This led to increases in volume and a depleted chemical signature of basalts as the ridge approached the plume, which explains the large volume of Meiji and Detroit. As the ridge moved northwards away from the plume, plume flow was still entrained by the ridge, distorting the age-distance relationships. Once the ridge was far enough away, plume-related volcanism would move rapidly to be directly over the plume stem, causing a southward migration of surface volcanism. This migration would lead to low eruptive volumes at the surface until the volcanism was once again stably aligned over the deep plume center. This would account for the low volumes of the Emperor chain, apparent in the map and volume data, between Nintoku and Ojin seamounts (Fig. 2a–c).

The geochemical signatures of basalts from the Emperor Seamount chain also change systematically with time from depleted (similar to mid-ocean ridge basalt, MORB like) to enriched (ocean island basalt, OIB, affinities) [34,35], with significant correlations between ages (or distance), and isotope and element ratios (Fig. 4, Dataset online). For example, the average $^{87}Sr/^{86}Sr$ increases from a MORB value in Detroit volcanic rocks up to an OIB value in Mauna Kea basalts (Fig. 4a). The change in average Nd isotope composition is less striking. It drops from MORB values towards Mauna Kea values (Fig. 4b). The average $^{3}He/^{4}He$ ratio increases with decreasing ages, from 10.6 ± 1.95 (close to MORB values) in Detroit volcano to typical OIB values of 21.35 ± 1.90 in Koko samples (Fig. 4c) [35]. Trace element ratios sensitive to MORB and OIB components also correlate with age. These geochemical characteristics can be plausibly explained by mixing of enriched and depleted components (Figure S6 and Dataset online). The average La/Yb ratios increase from MORB values in Detroit volcano to typical OIB values in Koko samples (Fig. 4d). The average Zr/Y ratios increase from 2.49 ± 0.03 in Detroit to 9.66 ± 2.61 in Koko (Fig. 4e). Given that La and Zr are more incompatible than Yb and Y, respectively, the La/Yb and Zr/Y ratios decrease with increasing degrees of partial melting, as shallower meltng also decreases the influence of garnet. Meanwhile, depleted sources have lower La/Yb and Zr/Y values. Therefore, these trends are due to larger degrees of partial melting and consequently more depleted components at the ridge.

The MORB affinities of the Emperor volcanos increased from Meiji at ~85 Ma and peaked at Detroit at 82–76 Ma and then declined continuously (Fig. 4). In addition, the Meiji and Detroit seamounts are similar to oceanic plateaus in size, much larger than other Emperor Seamounts. There is also a relationship between the estimated volumes of the individual Emperor Seamounts and the proportions of depleted components in the sampled basalts (Supplementary materials). The large volumes of these two seamounts are consistent with a plume-ridge interaction model.

Plume magmas form through decompression partial melting of hot mantle materials. The thickness of oceanic lithosphere decreases towards the spreading ridge. A ridge-centered plume has the longest melting column, enabling larger degrees of melting and, in addition, experiences dilution of plume magma by the depleted asthenospheric melts. Consequently, in addition to enriched components (OIB affinities), depleted (MORB-like) components that are refractory under normal oceanic lithosphere are also melted [34].

Viewed from this perspective, both the volume and geochemical data suggest that the ancient Hawaiian plume was interacting with the fossil spreading center between the Pacific and Izanagi/Kula plates. The Hawaiian plume is currently located at 19°N. It was located at ~22°N, however, before it was bent southward at ~5 Ma. At ~85 Ma, the plume was attracted southward to a spreading center (to 19°N, Fig. 1a), leading to large eruptive volumes and more depleted compositions. This is consistent with plate reconstructions using GPlates and previous results [4,14,25] which suggest that the Hawaiian plume was near the northern Pacific spreading centers at ~85 Ma.

Similar to our model, previous authors proposed that the southward movement of the plume may have started at the Bowers Ridges in the Bering Sea [25]. Plate reconstruction shows that the Hawaiian plume may have started to interact with the Pacific-Izanagi/Kula spreading ridge at ~90 Ma ago [14]. As the spreading ridge moved to the north, plume volcanism was shifted towards it, forming Detroit, Suiko etc. As the ridge moved further, it lost contact with the Hawaiian plume, leading to the exceptionally rapid southern migration

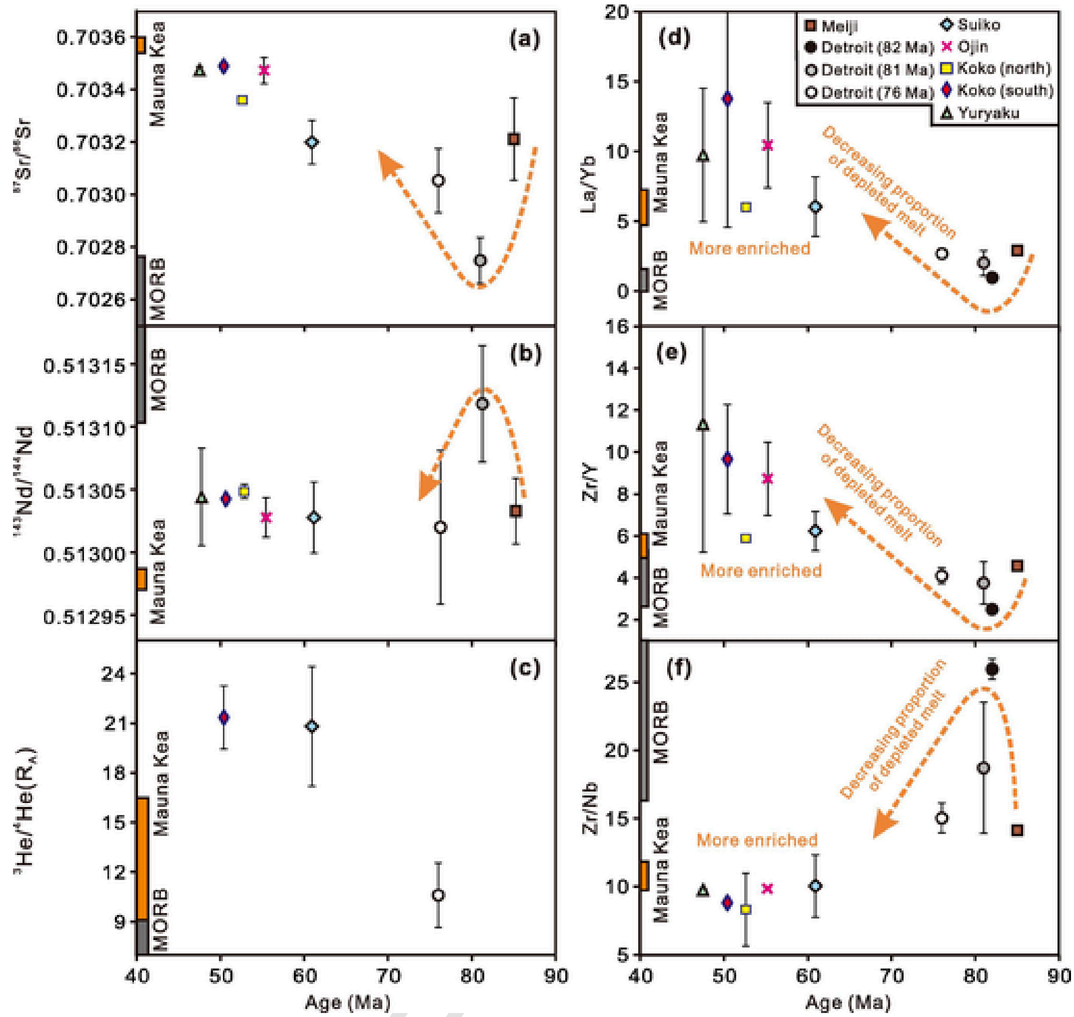

Fig. 4. Changes of the geochemical characteristics of basalts from the Hawaiian-Emperor chain with age. (a) $^{87}Sr/^{86}Sr$; (b) $^{143}Nd/^{144}Nd$; (c) $^{3}He/^{4}He$; (d) La/Yb; (e) Zr/Y; (f) Zr/Nb. All these indices show that Detoit has the highest proportion of depleted melt, which decreases with decreasing ages. The volumes of the Emperor Seamounts are positively correlated with proportions of MORB components. The volumes of Meiji and Detroit are very large, comparable to oceanic plateaus with large proportions of MORB components, supporting plume-ridge interactions. The declining MORB components southward may best be explained by the southward migration of the Hawaiian plume and increasing age (and thus thickness) of the oceanic lithosphere. Data are listed in the Dataset (online).

as plume magmatism returned to a position centered on the plume stem (Fig. 5). The main differences are that our data suggest that Meiji and Detroit were erupted on the ridge and left on the Pacific plate, whereas Shirshov and Bowers seamounts were left on the Izanagi/Kula plate.

5. Conclusions

The ridge-plume interactions that we propose here are supported by plate reconstructions. The spreading ridge between the Izanagi/Kula and the Pacific plates moved northward at least since 125 Ma and passed over the Hawaiian plume. Our results suggest that the stem of the Hawaiian plume likely had a stable location at least since ~85 Ma. The discrepancies with the linear age-distance trends were caused by the interaction of the upper part of the upwelling plume conduit with the spreading ridge during this period. This would resolve the problem of very fast migration rates as well as the discrepancies between the Hawaiian and Louisville hot spot tracks, and account for the marked changes in eruption volumes and chemical compositions during this period of time.

Author contributions

Weidong Sun initiated the study, and conceived and drafted the manuscript. Lipeng Zhang carried out plate reconstruction using GPlates and plotted related figures. Charles H. Langmuir provided key points and suggestions on the chemical characteristics and volume of the seamounts. Neil M. Ribe did the numerical modeling. Saijun Sun plotted the geochemical figures. Paul J. Tackleyg and Patrick Sanan wrote and maintained the code StagYY. Weidong Sun, Charles H. Langmuir and Neil M. Ribe finalized the manuscript with input from all authors.

Conflict of interest

The authors declare that they have no conflict of interest.

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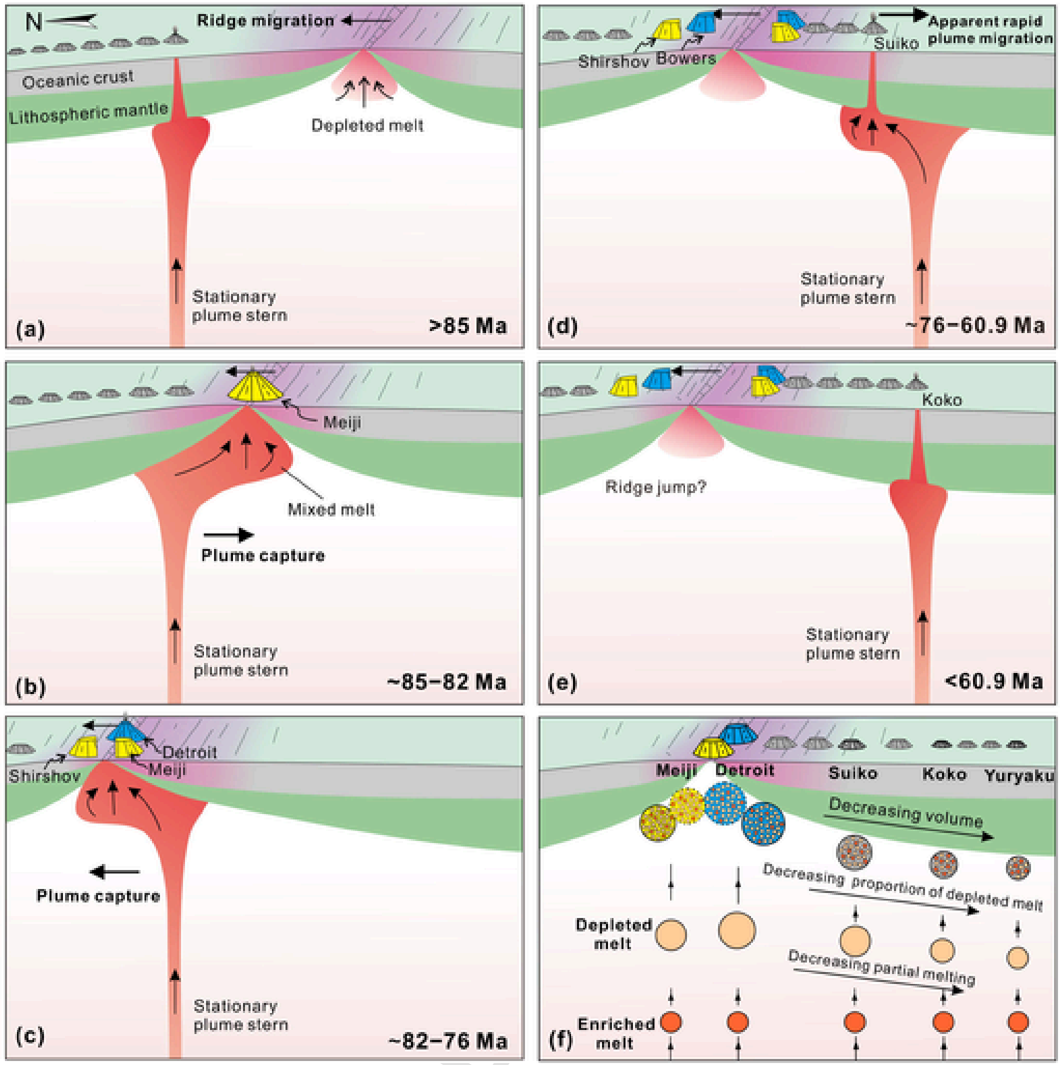

Fig. 5. Cartoon showing ridge-plume interactions when the northward migrating spreading ridge passed the originally stationary Hawaiian mantle plume. (a) The Hawaiian plume was originally located to the north of the spreading ridge between the Pacific and Izanagi/Kula plates. (b) Plume is attracted southward, with intensified eruptions and an increasing proportion of MORB component as the spreading ridge approaches (Meiji), because of decreasing thickness of the overriding plate. (c) The plume is channeled to the ridge, and is further intensified, with more MORB component as the ridge moves further north, carrying the plume with it. Meanwhile migration of the ridge may slow due to plume-ridge interaction. (d) As the ridge moves further to the north, the plume-ridge interaction becomes weaker, such that seamounts migrates southward. (e) The ridge loses contact with the plume, such that the magmatism from the plume migrates rapidly southwards, leading to very low volumes at the surface during the transit. (f) Cartoon illustrating the volume and proportions of depleted melt and plume components of the Emperor seamounts. The degrees of partial melting (orange dots) decrease from the ridge outwards. Meanwhile, the amount of enriched melt (red dots) is relative constant. Therefore, the proportion of depleted melt (colored dots) decreases with increasing distance from the ridge. The mixing simulation process and data are listed in the Supplementary materials and Dataset online.

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Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2021.04.028.

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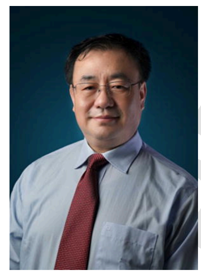
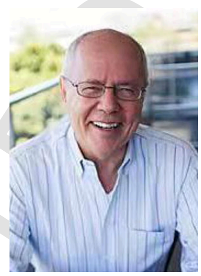
Biography



Weidong Sun is a marine geologist from the Institute of Oceanology, Chinese Academy of Sciences. He works on plate subduction, plate reconstruction, and the subduction factory, etc. He is currently Board of Directors of the Society of Oceanology and Limnology of China (2017–). He served in the Goldschmidt Award Committee (2013–2015) and Science Evaluation Panel of the International Ocean Discovery Project (IODP, 2013–2016).



Charles H. Langmuir is a solid Earth geochemist from Harvard University. He carries out research on diveres aspects of the plate tectonic geochemical cycle, including ocean ridges, convergent margins and intraplate volcanism.