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Key Points:
- Eight absolute plate motion models were studied for consistency with available observations of seamount trail geometry, ages, and paleolatitudes
- Age progressions for older sections of the Emperor and Louisville seamounts remain poorly defined
- Absolute plate motion from slab pull explains paleolatitudes but yields implicit plume motions at odds with recent geodynamic flow models

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Assessing Models for Pacific Absolute Plate and Plume Motions

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Abstract Absolute plate motion (APM) models derived from hot spot trails must satisfy trail geometries, ages, and paleolatitudes, which requires modeling explicit plume motions. Models lacking plume motions or derived independently from seamounts must also fit these data, provided the implicit plume motions are geodynamically reasonable. We evaluate eight Pacific APM models; three have explicitly modeled plume motions. Seven derive from seamount age progressions; one is a geodynamic model driven by slab pull and ridge push. Using the long-lived Hawaii-Emperor and Louisville chains, we derive implicit motions of Hawaii and Louisville plumes for models lacking explicit estimates and compare them with observed paleolatitudes. Inferred plume motions are plausible given rheological constraints on mantle flow, but rates vary considerably and not all models fit the data well. One potential endmember model predicts no APM direction change at 50 Ma, which best explains trails and paleolatitudes, minimizes predicted rotation of Pacific-Farallon ridge and assumes no true polar motion, yet its implicit plume drift is inconsistent with global circulation models. Alternatively, a global moving hot spot model yields acceptable fits to geometry and ages, implies a major APM change at 50 Ma, but requires significant true polar wander to explain observed paleolatitudes. The inherent inconsistency between age progressions and paleolatitudes may be reconciled by true polar wander, yet questions remain about the accuracy of age progressions for older sections of the Emperor and Louisville chains, the independent geologic evidence for an APM change at 50 Ma, and the uniqueness and relevance of true polar wander estimates.

Plain Language Summary Rising plumes leave surface expressions of volcanism, including the prominent Hawaiian and Louisville seamount trails. These trails reflect both tectonic plate motions and lateral drift of the plume within the mantle. Separating these components is challenging because plate motion models make different assumptions about plume drift. Examining implicit plume drift for eight published models and explicit plume drift for one of them, we explore how these drifts satisfy latitudinal histories (paleolatitude data) and geodynamic feasibility of the predicted drift within the convecting mantle. Models have made different compromises as to which constraints they seek to fit: Geodynamic models that minimize a directional change in Pacific motion at the time of the Hawaii-Emperor bend require significant drift and greater plate acceleration, but better fit the paleolatitude data. Models that allow for a change in Pacific plate motion direction predict plume drift and plate motion histories that may be more geodynamically reasonable, but require true polar wander (global shifts of the entire planet relative to the north pole) to explain paleolatitude anomalies. New observations of volcanic age and paleolatitude from the Hawaiian and Louisville trails, improvements to geodynamic models, and additional constraints on mantle flow patterns may resolve the remaining uncertainties.

1. Introduction

The plate tectonic revolution was quantified by determining the relative motions (RPM) between pairs of plates inferred from the pattern of magnetic lineations produced by seafloor spreading (Le Pichon, 1968; McKenzie & Parker, 1967; Morgan, 1968). However, it is also of interest to measure the absolute plate motion (APM) relative to the deep mantle, since such models are believed to more directly reflect the geodynamic forces acting on the plates. Seamount chains with approximately monotonic age progressions are believed to have formed over plumes in the mantle as the plate moved over them (Wilson, 1963). Changes in plate or plume motions would thus give rise to changes in the observed surface geometry of seamount trails. Traditionally, plumes were assumed to be fixed in the mantle or move very slowly relative to the motion

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of plates. With this assumption, a unique APM model can be determined. Thus, early in the plate tectonic revolution the ~60° Hawaii-Emperor Bend (HEB) was interpreted as primary evidence for an APM change (Morgan, 1971) estimated to have taken place ~42 Myr ago (Duncan & Clague, 1985); later age revisions have now placed the event closer to ~50 Myr (Sharp & Clague, 2006).

The Pacific plate is presently the largest of Earth's tectonic plates, representing seafloor from the present time back to the mid-Jurassic (e.g., Müller et al., 2016). Given its longevity, it has recorded numerous events such as the formation and evolution of large igneous plateaus and several hot spot island and seamount trails. Unlike most other large tectonic plates, the Pacific carries no continents and is separated from those who do by destructive plate boundaries. It has therefore been difficult to determine its APM by propagating motions determined for other plates into the Pacific (e.g., Acton & Gordon, 1994; Raymond et al., 2000). Most attempts to independently establish a Pacific APM have relied on the Indo-Atlantic to Pacific plate circuit, which involves Antarctica and Australia.

However, inferences of paleolatitude anomalies at several locations along such seamount trails have been attributed to either true polar wander (TPW; Acton & Gordon, 1994; Gordon & Cape, 1981; Gordon, 1983; Morgan, 1981; Petronotis et al., 1994) or motion of the hot spot (e.g., Tarduno et al., 2003; Tarduno & Cottrell, 1997), or a combination (e.g., Torsvik et al., 2017). These anomalies seem to require that at least some, or perhaps all, of the hot spots have moved significantly during the formation of the chains (Tarduno et al., 2009). Given the width of hot spot chains and the uncertainty in identifying current hot spot locations, any minor deviations from rigid plates (e.g., Mishra & Gordon, 2016) can be ignored. Thus, the problem of determining past APM reduces to finding the present and past locations of hot spots and the total reconstruction rotations for a rigid plate at various times. While it is possible to come up with models for such hot spot and plate motions, their uniqueness will depend on the data constraints available. If no hot spot drift has taken place, then a best fit solution can be derived from chain geometry and age progressions alone (e.g., Duncan & Clague, 1985). However, if one or more hot spots have moved over geologic time, then the problem requires additional constraints. To date, the only models that include hot spot motions have relied on mantle convection predictions of plume behavior (Steinberger & O'Connell, 1998) or some idealized representation of hot spot motion, based on such models (Steinberger & Gaina, 2007). Such flow models strongly depend on rheological parameters and the history of past plate motions, as well as assumptions about the mantle's heterogeneous density structure at past times. By selecting flow calculations whose predictions of plume motion generally satisfy the limited paleolatitude data, one can combine these hot spot location predictions with chain geometry and age data to solve for the complete APM model (e.g., Doubrovine et al., 2012; O'Neill et al., 2005; Steinberger, 2000; Steinberger et al., 2004). The scarcity of paleolatitude data and the nonuniqueness of flow model predictions have yielded a variety of APM models whose trail predictions approximately follow the observed trails. Given the large number of additional parameters involved in modeling moving hot spots, it is not clear that these models describe the motions of plates well or if they are geodynamically feasible, especially given their approximate fit to data. For instance, plume drift predictions (Doubrovine et al., 2012) for the last 5 Ma have been shown to be at odds with recent motions inferred from observations (Wang et al., 2019), suggesting that more data need to be included in order to constrain such models.

Torsvik et al. (2017) suggested that the implied plume and plate motions required to explain the HEB entirely in terms of southward plume motion, as Tarduno et al. (2009) has argued, are simply not compatible with the motions predicted by mantle circulation models and the relative plate motion history of the Pacific. Consequently, they argued that a prominent change in APM must be required to explain the observed geometry and age progression. Reigniting the debate over which geodynamic forces could have driven the Pacific plate northward before the HEB, Domeier et al. (2017) suggested that an east-west oriented intraoceanic subduction zone to the north may provide the missing piece. These interpretations have implications for how the paleolatitudes obtained from the Emperor seamounts should be interpreted, with perhaps a considerable amount needing to be attributed to TPW (Gordon & Cape, 1981; Koivisto et al., 2014; Morgan, 1981; Petronotis et al., 1994; Woodworth & Gordon, 2018). In strong contrast to these views are the arguments recently made by Bono et al. (2019) which reiterate that the HEB was caused by southward plume motion and that TPW can be excluded as a relevant factor. The range of published arguments would therefore seem to suggest that the motion of the Pacific plate and the plumes beneath it remains an unresolved problem in plate tectonics.

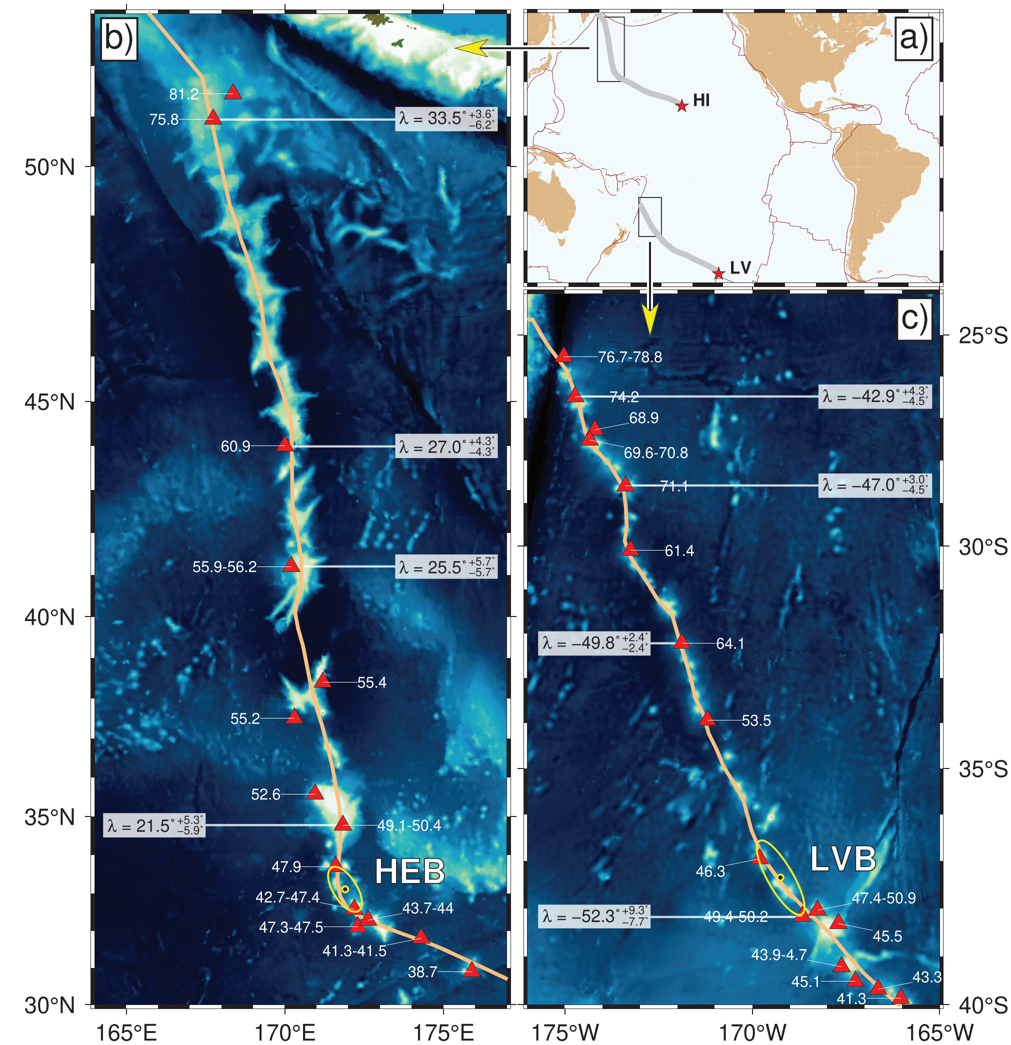

Figure 1. (a) Location map showing the Hawaii (HI) and Louisville (LV) chains, with subregions studied (rectangles). (b) Bathymetry of the Emperor chain, showing empirical central line (orange) with available samples (red triangles) and their ages in Myr. HEB indicates the ~Chron 21o bend with yellow uncertainty ellipse on the bend location. (c) Bathymetry of the older Louisville chain, similarly showing empirical central line (orange), available samples (red triangles) and their ages in Myr. LVB indicates the ~Chron 21o bend with yellow uncertainty ellipse. Gray labels indicate inferred paleolatitudes, λ, from paleomagnetics.

Here we investigate eight published APM models, representing a mix of fixed and moving hot spot assumptions. The purpose of this paper is to examine the amount of hot spot motion implied by each model, measure the extent to which the models fit the available data and are geodynamically reasonable, and examine if the hot spot motions are realistic given constraints on rheology of the upper mantle.

2. Data

We focus our attention on just the Hawaii-Emperor and Louisville hot spots and trails since their longevity means they dominate the information on Pacific plate motion for ages older than 30 Ma. While new data are now available to support a similar longevity for the Rurutu hot spot (Konrad et al., 2018), unlike for Hawaii and Louisville there are no paleolatitude constraints to consider. Figure 1 presents the geometric, chronologic, and paleomagnetic data available for the older sections of these two seamount chains (Bono et al., 2019; Clouard & Bonneville, 2005; Kono, 1980, Koppers et al., 2011; Koppers et al., 2012; Tarduno et al., 2003). Following Wessel and Kroenke (2009), we have determined an empirical median line for each seamount

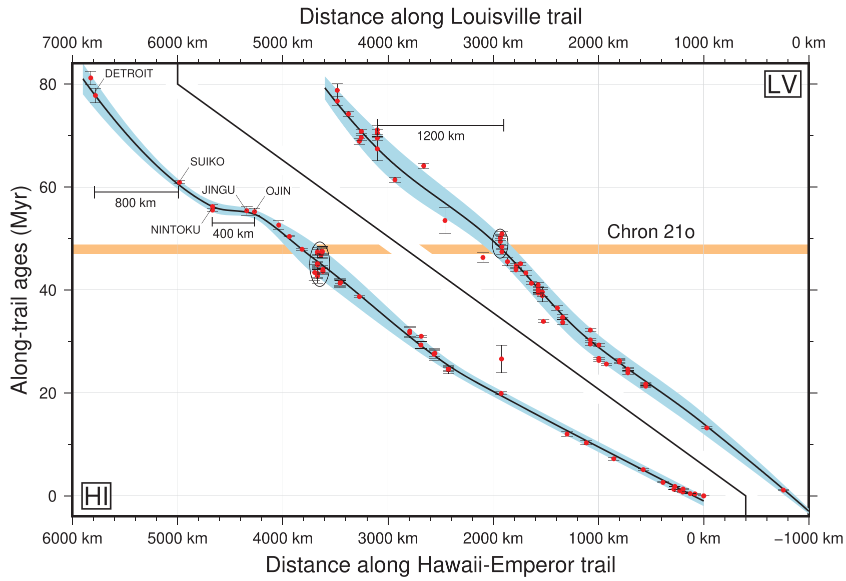

Figure 2. Observed sample ages (red circles) for the Hawaii-Emperor and Louisville chains, plotted versus the distance along each chain's empirical central line. Light blue envelope contains all observed ages (except one known outlier for HI and larger variability for LV in the 40–60 Ma range). See text for discussion and the acknowledgments for data sets.

trail and used these spatial curves to derive continuous and smooth age progression curves using splines (Figure 2). Similar analyses were also performed by O'Connor et al. (2013), Doubrovine et al. (2012), and Konrad et al. (2018). There are several points to note from these age progressions: (1) The data scatter about the mean trend (generally in the ±2–4 Myr range) greatly exceeds the individual age uncertainties, (2) considerable smoothing is necessary to avoid age reversals along track, (3) despite much recent sampling (e.g., Koppers et al., 2011; Koppers et al., 2012; O'Connor et al., 2013), the two chains feature several sections where age progressions are poorly expressed, and (4) the age of the respective bends in the trails are statistically indistinguishable from Chron 21o (47.9 Ma), yet the large number of age determinations at these bends exhibit a wide range of values. While our spatial curves are subjective, experiments with different median lines show that the above conclusions are robust. The methodology can nevertheless be improved further.

Much work has been done to understand the APM of the Pacific plate and the plumes over which it has moved (e.g., Doubrovine et al., 2012; Duncan & Clague, 1985; Koppers et al., 2001; Steinberger et al., 2004; Wessel & Kroenke, 2008; Wessel & Kroenke, 2009). The most critical region for such studies involves the Emperor and the coeval old section of the Louisville chain. Figure 2 shows that serious data gaps continue to hamper a detailed understanding of these chains. For instance, for a length of ~1,200 km north of the Louisville bend (LVB) we find sparse ages with variability far beyond the apparent smoothness of the age progression model. In fact, here our smooth model is poorly supported by the data, with individual misfits exceeding 4–6 Myr. The situation for the Emperor chain is not much better. We find an 800-km gap in dated samples between Suiko and Detroit seamounts, while further south we have a 400-km section with three samples that all suggest an approximate seamount age of ~55.5 Ma. When our two age progression curves are used to derive the inter–hot spot separations (Wessel & Kroenke, 2009), the 400 km section of near-constant age translates to a large 3.4° offset in separation distance that divides two periods of approximately stable plume distances. It seems unrealistic to invoke extremely rapid plume or plate motions to explain the apparent constant ages, suggesting instead that the age data are not representative of the actual age progression along the Emperors. Alternatively, we are likely seeing the back-and-forth surface manifestation of the nonlinear dynamics of a thermochemical plume (Ballmer et al., 2013). Clearly, more and denser data will be required to resolve this dilemma. For now, we will employ the two smooth, continuous and monotonic age progression curves (Figure 2) as representative of the variation in age along the two trails, despite any shortcomings in data quality.

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3. Methods

We examine a representative subset of published APM models that reflects a range of model behaviors, including the two fixed Pacific hot spot models KMM01 (Koppers et al., 2001) and WK08A (Wessel & Kroenke, 2008). These two models have a similar origin as they are only constrained by Pacific seamount track geometries and age progressions and do not consider paleolatitudes or hot spot motions. We include a partially fixed hot spot model (WK08D) in which the Hawaii hot spot implicitly migrates south during the Emperor stage at a rate selected to produce no change in plate motion direction (Chandler et al., 2012). It thus shares the assumptions of the three fixed APM models except during the Emperor stage. Next, we include two moving (OMS05, O'Neill et al., 2005, H2016, Hassan et al., 2016) and one fixed (M2015C, Maher et al., 2015) hot spot model satisfying data from the Indo-Atlantic realm and projected into the Pacific via the Africa-India-East Antarctica-Mary Byrd Land-Pacific plate circuit. Thus, these three models were derived from similar seamount trail data from the Indo-Atlantic but differ in that OMS05 used a moving hot spot reference frame tied to Africa while H2016 used the Torsvik et al. (2008) hybrid reference frame; the H2016 model also used a modified set of relative plate rotations to derive a Pacific APM model. We also include a global moving hot spot model (D2012) fitting five major hot spot chains from three of the world's major ocean basins (Doubrovine et al., 2012). This last model therefore is constrained by global seamount tracks as well as hot spot drifts largely consistent with observed paleolatitudes. Finally, we considered an APM model (B2014) predicted by geodynamic modeling of slab pull and ridge push (Butterworth et al., 2014). Unlike most other APM models (but see Gordon et al., 1978 for a similar approach), this model is independent of seamount geometry and age progressions and is only constrained by geodynamic boundary forces. The B2014 model only portrays Pacific APM during the 72–42 Ma time interval and thus was augmented with rotations from the most similar APM model (WK08D) for the more recent motion since 42 Ma; we also extended B2014's oldest stage rotation back to 80 Ma.

While there are additional moving hot spot APM models discussed in the literature (e.g., Koppers et al., 2004; Steinberger et al., 2004; Torsvik et al., 2008), they are not easily reproducible because the coordinates of plume paths were not published along with the plate rotation parameters. Based on these eight APM models, Figure 3 shows the past motion of the Pacific plate predicted for points that originated at the (present) Hawaii (HI) and Louisville (LV) hot spots. The colored tracks thus reflect APM and should only honor the two seamount trails if the APM model assumed no hot spot motion; this includes KMM01 and WK08 for the Pacific and M2015C from the Indo-Atlantic domain. This is so because in that scenario the trails are assumed to reflect the entire APM whereas for the moving hot spot models at least part of the geometry will be attributed to the motion of the plumes. Consequently, the past motions of a point beneath the present hot spots and the corresponding trail geometries depart, reflecting various amounts of hot spot motion.

Given a model for Pacific APM we can now take the continuous age-progression curves (Figure 2) and reconstruct each point along the curves back to zero age. This technique was independently developed by Torsvik et al. (2017) and Wessel and Conrad (2017). For models derived for fixed hot spots these reconstructions should all fall close to the present (fixed) hot spot, while for models designed relative to a set of moving hot spots the reconstructions should reflect the prescribed plume paths. Finally, for models determined for other ocean basins but propagated into the Pacific via a plate circuit the reconstructions will show the plume motion history that is required for the APM model to satisfy the age progression constraints from Pacific seamount trails alone. In other words, given observed age progressions and an APM we can extract the *implicit* plume drift histories for each trail. We have made these calculations for the eight published APM models listed above and present them separately for Hawaii (Figure 4a) and Louisville (Figure 5). In addition to reconstructing the inferred hot spot motion paths we also reconstructed individual age samples as colored triangles (and these will scatter about the reconstructed plume paths since the latter is a smooth continuous representation of the former) as well as the limited paleolatitude estimates (circles) from each trail (Bono et al., 2019; Kono, 1980; Koppers et al., 2012; Tarduno et al., 2009). The colors of these circles reflect the misfit between observed and predicted paleolatitudes; see color scale in Figures 4 and 5 for range.

4. Results

Examining the plots in Figures 4 and 5, we see similar responses for the two fixed hot spot models KMM01 and WK08A for HI (Figure 4). Since these two APMs were designed relative to fixed hot

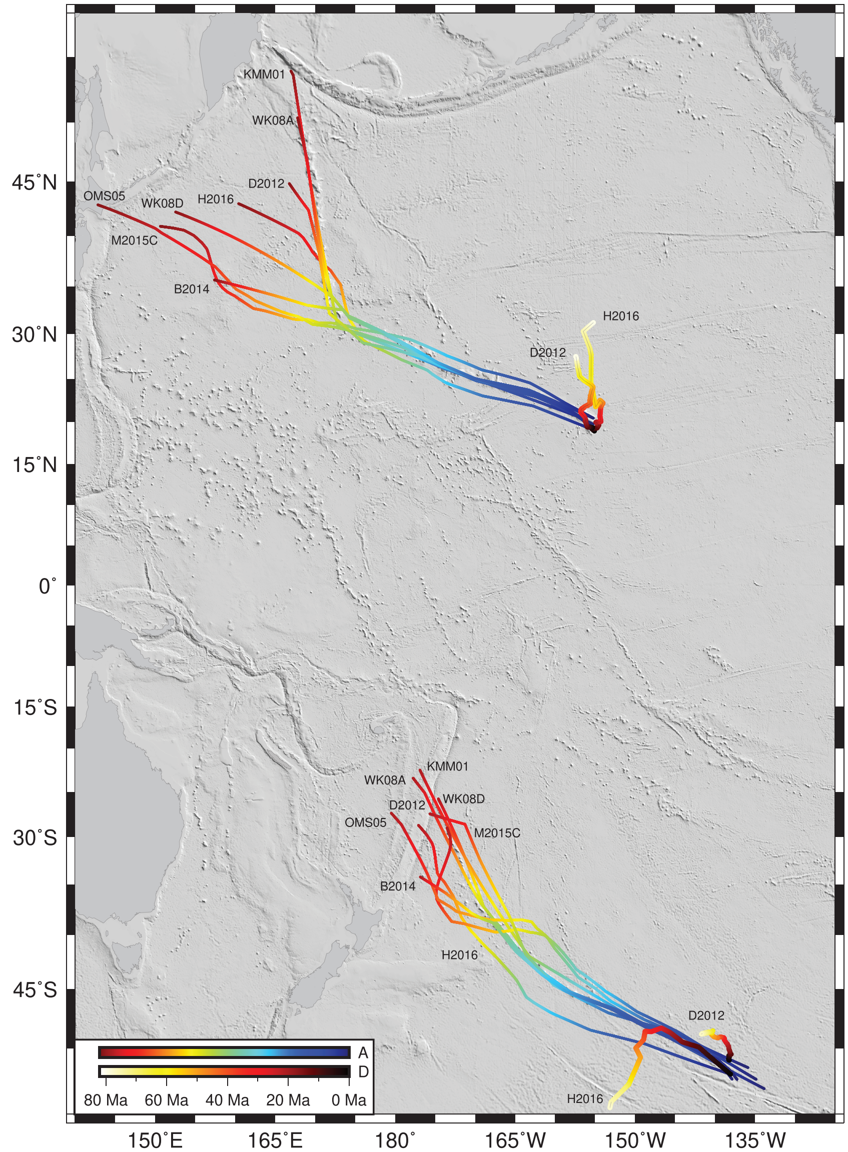

Figure 3. Eight proposed models for Pacific absolute motion (see text). Rainbow-colored paths reflect predictions of past motion of points presently at the two hot spots; these paths only coincide with the two hot spot trails for fixed hot spot models. Hot-cold paths reflect the published plume drift histories for D2012 and H2016; see text for discussion.

spots, the reconstruction of the hot spot paths should ideally converge on a single point, that is, the fixed hot spot. This is generally true, at least for the younger sections, and some of the discrepancies relate to revised age progressions since the models were published. For ages younger than 55 Ma the reconstructions are compatible with a single point (i.e., we observe modest scatter around the present hot spot consistent with the scatter in Figure 2). However, for older ages both models diverge. The KMM01 model requires a ~5° north to south motion for the pre-HEB time frame. The WK08A model fails to fit the oldest Hawaii and Louisville trail as well and requires a correction in the form of a north then south plume motion due to systematic misfits to the age progressions. In addition, both models fail (by design) to explain the paleolatitudes. Examining the predictions for LV for the same two models (Figure 5), we notice much larger discrepancies. KMM01 struggles to fit the age-progression, which has been revised by several new data sets collected after KMM01 was first developed. In contrast, WK08A benefitted from some of the newer LV age data and shows less scatter, yet several degrees of ESE to WNW plume motion is implied for the older Louisville section. As for

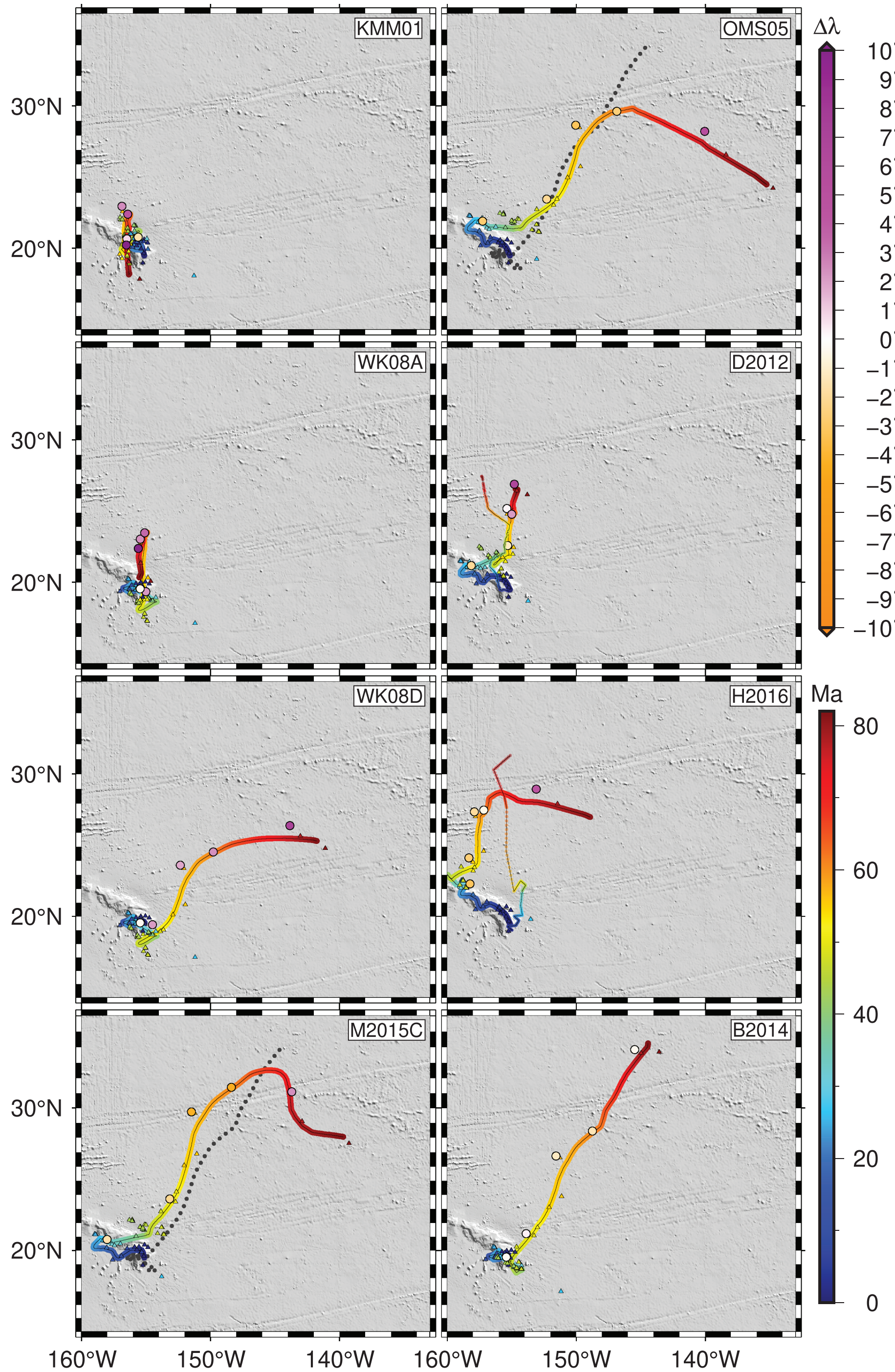

Figure 4. Inferred Hawaii plume paths for the eight APM models obtained by reconstructing the smooth, continuous age progressions back to zero age, with the explicit paths for D2012 and H2016 as thick colored lines. The color of these paths reflects the age (in Ma; bottom right). The colored triangles represent reconstructed individual samples, while colored circles represent misfits between observed and predicted paleolatitudes, $\Delta\lambda$, as coded by the colors shown on the top right (magenta colors mean underpredicted, orange colors mean overpredicted).

the Hawaii-Emperor chain, both models fail to satisfy the LV paleolatitude constraints by reconstructing the locations too far south.

The next APM candidate (WK08D) is a hybrid model that originated as a fixed hot spot model from the present back to the HEB (i.e., WK08A), but then the rotations for the Emperor age interval were adjusted to fit

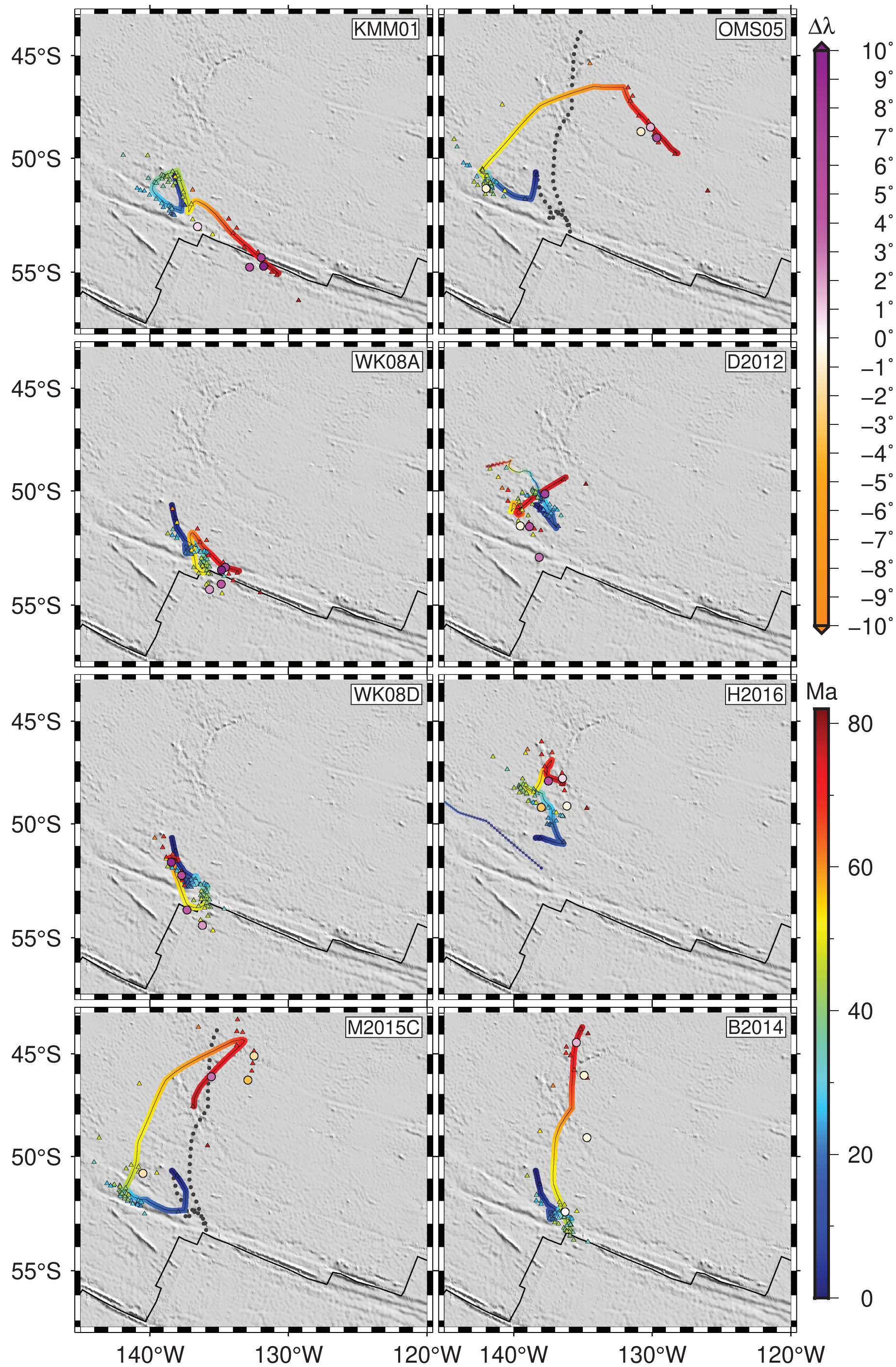

Figure 5. Same as Figure 4 but for Louisville plume paths. Black dotted line in panels for OMS05 and M2015C is the prediction for B2014, for first-order comparison.

only the Louisville trend while simultaneously ignoring the geometry of the Emperor track to yield no change in APM direction at HEB. While no moving hot spots were explicitly used to derive these rotations, the steady westward motion predicted by the model implicitly requires the HI plume to have moved south during the Emperor formation. Figure 4 reflects the implied nature of this required plume motion. For times before the HEB formation the plume is required to have moved westward then southwest to its present location. This plume history comes closer to fitting the paleolatitudes but underperforms for the oldest samples. Because the APM model still fits the Louisville chain, the plume predictions there (Figure 5) are similar to WK08A and hence fail to address the paleolatitude anomalies (which were obtained after WK08D was published).

The OMS05 model is an Africa plate-based model defined relative to a set of moving Indo-Atlantic plumes (O'Neill et al., 2005), and we have projected the finite rotations into the Pacific via the Africa-India-East Antarctica-Mary Bird Land-Pacific plate circuit; other plate circuits are of course also possible, but for consistency we use this one when projecting Indo-Atlantic models into Pacific. As such, there is no model drift for Pacific plumes to which we can compare our results. When reconstructing the age progressions using this model we obtain the implicit HI and LV plume motions required to match the age and geometry observations. For HI, the OMS05 implies a near-sinusoidal plume drift with its most distal latitude reached around 60 Ma and then returning south for older ages. Thus, some paleolatitudes are adequately explained but the oldest observations are not. The situation for LV is similar, that is, a large excursion of implied plume drift with modest predictive powers to explain observed paleolatitudes. The H2016 model was developed to support the claim that a rapid burst of hot spot motion is needed to explain the formation of the HEB (Hassan et al., 2016). However, while the combination of their modeled plume motion and Pacific APM approximately predicts the Hawaii-Emperor trail, the age progressions are not well matched, resulting in an implicit plume drift quite different from their explicit path (Figure 4). For Louisville the model does not match the geometry and age progression very well (Figure 3), and the implicit drift curve is very different from that modeled (Figure 5). Part of the explanation of the misfit is likely related to the fact that the model Louisville plume emanated very far from the actual Louisville location, and while the predictions were translated the mantle flow regimes at the two sites are unlikely to be similar (Hassan, Pers. Comm., 2018).

When examining predictions from the fixed Africa hot spot model M2015C (Maher et al., 2015) we surprisingly find a very similar situation in that the inferred hot spot motions in the Pacific to first order equal those of other Indo-Atlantic models. This similarity suggests that the main cause of the implied plume motions may have its origin in the plate circuit, which possibly may be inaccurate for older ages (e.g., Acton & Gordon, 1994; Koivisto et al., 2014), but relative plume drift between Atlantic and Pacific hot spots may also play a role.

The next APM candidate (D2012) is the only model that describes global APM relative to five long-lived plumes distributed across three ocean basins (Doubrovine et al., 2012). Both the HI and LV plumes were among the plumes modeled and their expected motions were included when fitting the APM (and displayed in Figure 3). In the case of HI, we find that the plume is relatively stationary back to ~55 Ma, but earlier there is an almost north to south drift. While this motion helps to reduce the paleolatitude anomalies, it is still failing to explain their full range, especially for the oldest Emperor section. For LV, there is more east-west motion implied, and as for HI the paleolatitudes are underpredicted. The overall shapes of the implicit plume motions (from smoothed age progressions) to first order match the prescribed (explicit) plume motions for this model (Figure 3; also shown for this panel in Figure 4), yet the explicit and implicit D2012 plume motions have significant differences, particularly in longitude.

Our final model (B2014) differs from all other APM models as it is a geodynamic model driven by forces acting on the Pacific plate (Butterworth et al., 2014). Hence, no seamount trail geometry and age progressions were used, and it may therefore serve as an independent test of expected Pacific motion driven by boundary forces. For HI, this APM model implies a strong monotonic plume drift from NNE to SSW over the timeframe ~80 Ma to ~50 Ma, and consequently the plume history largely matches the paleolatitude constraints. The situation is very similar for LV, where an almost north-to-south plume motion during the same timeframe is implied. As for HI, the LV paleolatitudes are well modeled. However, B2014 is not representative of all geodynamic models being driven by boundary forces. Earlier efforts (e.g., Conrad & Lithgow-Bertelloni, 2004; Faccenna et al., 2012; Gordon et al., 1978) also considered different combinations of forces acting on the base and/or edges of the Pacific plate, but their results diverge from B2014, especially for the Emperor era due to different plate geometries and different forcing combinations. Further evaluations of such models may address the uniqueness of geodynamic APM models and their dependence on past plate tectonic histories.

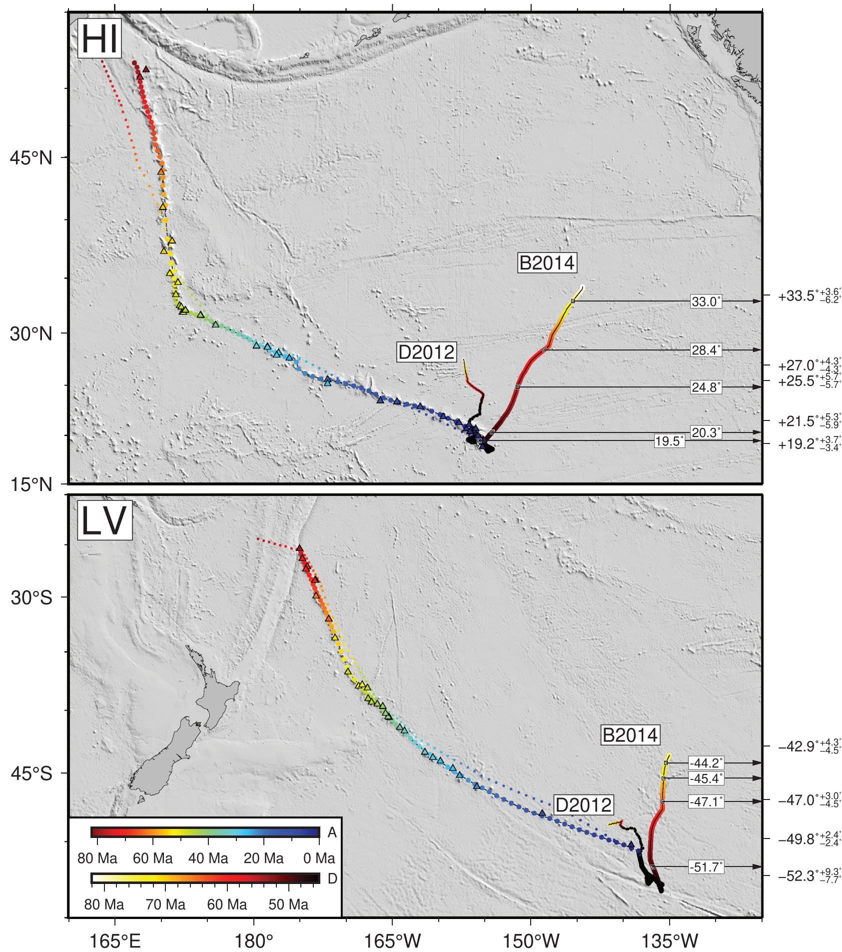

Figure 6. Predicted Hawaii (a) and Louisville (b) trails (color-coded circles, color table A) and plume paths (colored path, color table B) for B2014 (larger circles) and D2012 (smaller circles). The colored triangles represent observed seamount samples. Squares on plume paths are predicted paleolatitudes, with rightside map annotations indicating observed paleolatitude ranges.

5. Discussion

Clearly, the APM models examined differ in the amount and direction of predicted or implied plume drift. The fixed hot spot models highlight the long-known fact that most of the observed Pacific age progressions can be fit with a fixed hot spot model, but this condition breaks down around 55–60 Ma (O'Connor et al., 2013; Wessel & Kroenke, 2009). Furthermore, they ignore the observed paleolatitudes, instead (implicitly) attributing the paleolatitude anomalies to TPW (e.g., Wessel & Kroenke, 2008), which would seem to be in the 5–10° range (Torsvik et al., 2017). That some of the mismatch between observed and predicted paleolatitudes may be due to TPW is not a new idea (e.g., Gordon & Cape, 1981; Morgan, 1981; Petronotis et al., 1994), and some authors consider TPW to have played a much larger role during the formation of the HEB (e.g., Wilson, 2016; Woodworth et al., 2017). It is also possible that uncertainties in the global plate circuit prevent accurate predictions of Indo-Atlantic models projected into the Pacific (e.g., Acton & Gordon, 1994; Koivisto et al., 2014).

One key distinguishing feature of the predictions in Figure 4 is the difference between the Pacific models and the Indo-Atlantic models projected into the Pacific. Despite the differences between the OMS05 (moving Indo-Atlantic plumes) and M2015C (fixed hot spots) models, both yield to first order very similar plume predictions for both HI and LV (again, specifics depend on the plate circuits). Part of this is expected, since the modeled plume motions in OMS05 for the post-80 Ma period are statistically insignificant (O'Neill et al.,

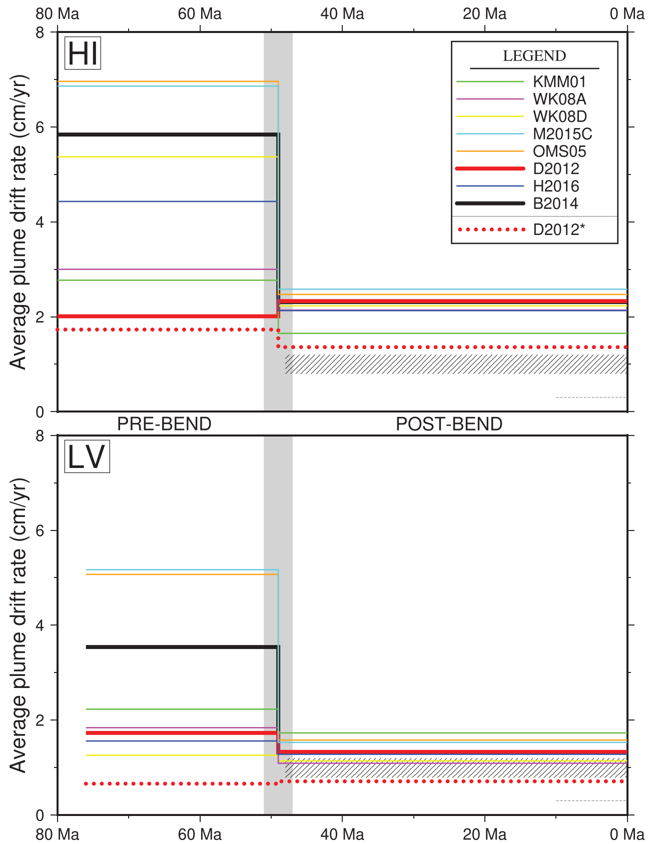

Figure 7. Implicit mean hot spot drift rates before and after HEB, as implied by published APM models (see legend for models). Gray band reflects the 51–47 Ma time window of HEB formation. (top) Hawaii plume drift rates. (bottom) Louisville plume drift rates. D2012* refers to the explicit model. Note that WK08A is identical to, and plotted behind, WK08D after the HEB. Gray hachured area shows a limit on inter–hot spot motion (Koivisto et al., 2014) since 48 Ma and gray dashed line gives an upper limit on recent hot spot motion (last 10 Ma; Wang et al., 2019).

2005). We interpret the first-order NE-to-SW drift pattern to reflect either artifacts in the plate circuit or systematic differences between Pacific and Indo-Atlantic plume drifts.

A recently proposed technique called "ridge-spotting" has been used to test the validity of APM models (Wessel & Müller, 2016). Ridge-spotting combines both APM and RPM and explores model predictions for the long-term behavior of spreading ridges. While all tested APM models predicted large amounts of northward migration and monotonic clockwise rotation of the Pacific-Farallon ridge, it was not immediately clear if the technique ruled any APM model out. However, it seemed intuitive that models predicting large-scale ridge rotation were geodynamically the least likely. Furthermore, the Africa-based models resulted in extensive east-to-west ridge migration that more likely reflects inaccuracies in the plate circuit than actual ridge dynamics. The B2014 model was considered to be the most stable model in that it predicted the smallest amount of ridge rotation (Wessel & Müller, 2016). Yet, we caution that minimal implied ridge rotation may not necessarily be a defining characteristic of an optimal APM model, but also note that Becker et al. (2015) in fact suggested a "ridge-no-rotation" reference frame as a possible candidate for APM. The B2014 model predictions are further highlighted in Figure 6 where we take the implied plume motions for HI and LV and use them with the B2014 rotations to predict the HI and LV seamount trails. While the generally good fit to the observed seamount ages is partly a consequence of the way we reconstruct the implicit plume paths, the straightness of the plume paths and the good fit to observed paleolatitudes is what distinguishes B2014 from all other APM model predictions in Figure 4. Unlike D2012, the B2014 model predictions for Louisville shows straight and extensive north-to-south drift, thus matching the Louisville paleolatitudes better than other models. We do note the D2012 rotations appear to contain components that yield a systematic offset along the oldest section of the Emperor trail (Figure 6). Hence, there may be important discrepancies between D2012's geodynamic predictions and actual Pacific plate motions for the pre-60 Ma period, notwithstanding the broader scope of D2012 (global) versus B2014 (Pacific only).

If we examine the plume drift rates that are implied by the APM models and the observed age progressions, we find that plume drift predictions vary considerably and, in some cases, have large differences before and after HEB time. Figure 7 shows the mean pre-HEB/post-HEB predictions for both the (a) Hawaii and (b) Louisville plumes. The drift rates were obtained by taking the predicted plume paths histories and estimating a time derivative via finite differences. Because discrete APM models may yield jumps in speeds and since the noise in the empirical age progressions will be amplified by the finite differencing, we have averaged the results for either side of the HEB. There are several observations we can make from these results: (1) There is broad agreement that plume drift rates following the HEB event are in the 1.5–2.5 cm/yr for Hawaii and 0.5–1.5 cm/yr for Louisville. All models, whether explicitly modeling drift or not, have explicit or implicit rates in these ranges. (2) The pre-HEB domain presents a dramatically different picture, with a wide range of average drift rates from 2–7 cm/yr. Implicit plume motions for the two Africa-derived models are both very high, regardless of being a fixed or moving Africa hot spot model. The geodynamic B2014 model shows a 6 cm/yr average rate required to fit the seamount geometry. The Pacific fixed hot spot models show little change, as discussed earlier – their main failing lies in ignoring paelolatitudes. The H2016 model explicit drift rate for Hawaii is considerably higher than that of the D2012 explicit rates, by a factor of 2. (3) All implicit mean plume drifts exceed observational speed limits for the post-HEB era (Koivisto et al., 2014) as well as inferred hot spot drift rates for the last ~5 Myr (Wang et al., 2019).

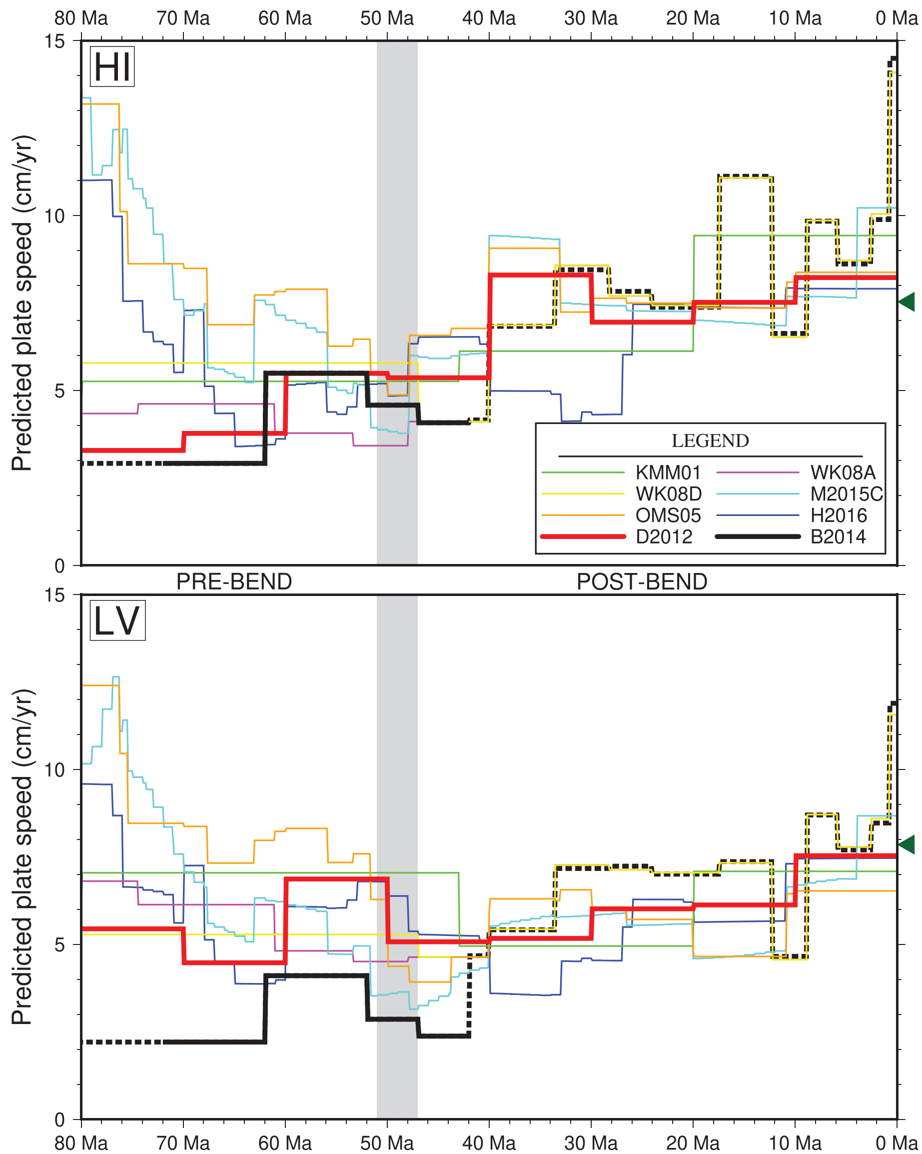

Figure 8. Inferred Pacific absolute plate speed as implied by published APM models (see legend for models). Gray band reflects the 51–47 Ma time window of HEB formation. (top) Plate speeds at Hawaii hot spot. (bottom) Plate speeds at Louisville hot spot. The dashed part of B2014 indicates where we extended the model (extension of oldest stage back to 80 Ma and following WK08D after 42 Ma). Green triangles indicate current plate speed from HS4-UW-MORVEL56 (Wang et al., 2017).

Despite the conclusions of Tarduno et al. (2009) and Bono et al. (2019) suggesting the HEB predominantly reflects a change in north-to-south plume motion, there has been evidence presented in the literature that appears to require a significant component of plate motion change (Wessel & Kroenke, 2009; Woodworth et al., 2017). Recently, Torsvik et al. (2017) demonstrated that a Pacific APM change at HEB time is in fact required by showing predictions of three simple plume/plate motion scenarios (their Figure 3). In all three cases the Pacific plate motion undergoes no change in direction. The first two cases maintain a constant Pacific angular velocity throughout and highlight the directions and rates of plume motions required to satisfy the Emperor geometry. In Case 1, to satisfy Emperor age progression a plume drift of 0.6°/Ma (6.7 cm/yr) from the NW is required, but there is no geodynamic basis for the plume to drift in this direction (Torsvik et al., 2017). In contrast (Case 2), a more north-to-south drifting plume (which is much closer to actual predictions from mantle circulation models) would need an excessive drift rate of 3.8°/Ma (42

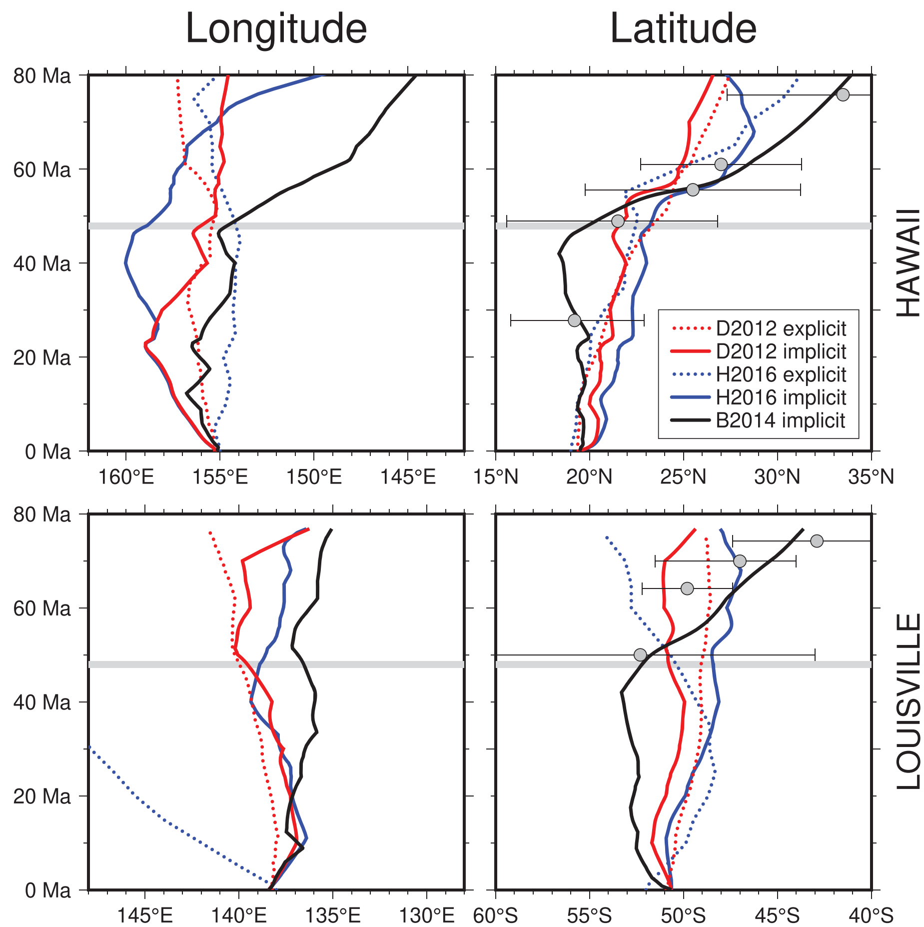

Figure 9. Longitude and latitude of plume drift versus time; see legend for APM models. Gray horizontal band indicates the 51–47 Ma time window of HEB formation. Gray symbols with error bars represent observed paleolatitudes with $\pm 2\sigma$ uncertainties.

cm/yr) to match the geometry, yet at this rate it grossly fails to match the observed Emperor age progression. Finally, they show (Case 3) that a north-to-south drifting plume at 0.58°/Ma (6.4 cm/yr) rate can fit both geometry and age progression, provided the Pacific APM motion was vastly slower prior to the HEB. Seen in this context, B2014 may represent a blend of their first and third cases: A drift direction (from N33°E) closer to SSW than S, but with a drift rate closer to 0.5°/Ma (5.6 cm/yr). Interestingly, the APM models unaffected by Pacific hot spot trails (OMS05 and M2015C) have implicit plume motions that, to first order, have key similarities with those of B2014: a plume trail trending from an azimuth of ~30° (Figure 4). While this could be a coincidence related to systematic uncertainties in the plate circuit, it could also be taken as supporting evidence for a component of SW drift prior to the HEB, consistent with the above-described Case 1. Furthermore, the B2014 model shows that slow motion of the Pacific plate prior to the HEB, as required by the above-described Case 3, is consistent with the time evolution of forces on that plate. On the other hand, the need for Hawaiian plume drift to the SW or SSW is not consistent with models of mantle flow, which indicate drift to the S or SSE without a westward component (e.g., Torsvik et al., 2017).

As for the plate speed change required in Case 3, Figure 8 shows the predicted plate motion speeds at Hawaii and Louisville for the models discussed. We note the predictions of B2014 are in the same sense as suggested by Torsvik et al. (2017; the plate was moving slower prior to the HEB), yet the change is closer to a factor of 2 than their factor of 6 because B2014 also includes a compensating component of westerly plume drift (as in Torsvik et al.'s, 2017; Case 1). Isochrons from the seafloor between the Clarion-Clipperton fracture zones covering the HEB transition indeed show a corresponding sharp increase in RPM after the HEB

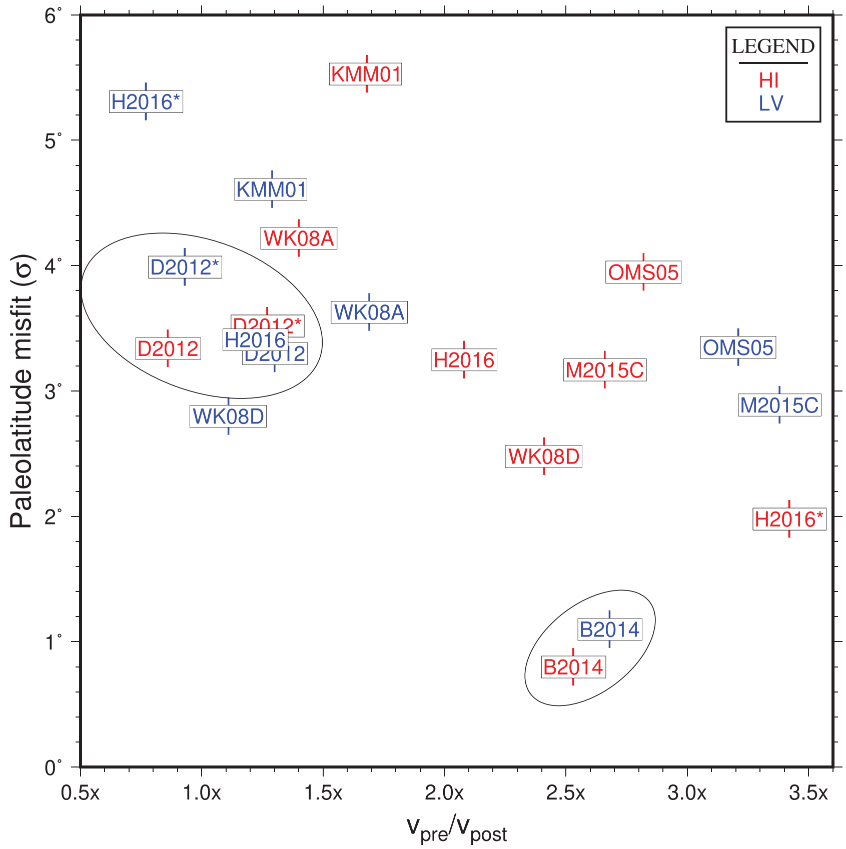

Figure 10. Grouping of APM model results for Hawaii (red) and Louisville (blue) in terms of the misfit to paleolatitude observations versus the prebend/postbend drift rate ratios. Ellipses highlight the D2012 implicit and explicit (marked by asterisk) results versus the B2014 implicit results.

(Barckhausen et al., 2013), which likely reflects an increase in APM. This behavior strengthens the idea that some aspects of B2014 may be valid but further refinements may be needed. Interestingly, while the B2014 is obviously a geodynamical model driven by boundary forces, its prediction of Hawaii plume motion has too much east-to-west motion (i.e., Case 1) compared with other predictions from mantle circulation models (e.g., Doubrovine et al., 2012; Steinberger, 2000; Steinberger et al., 2004). For the recent geological past, these models predict plate speeds that are largely compatible with estimates obtained by inverting current hot spot trail trends and the MORVEL model (Wang et al., 2019). Yet there are some large excursions predicted by the WK08 models that are likely the result of overemphasizing the age progression changes seen in the Hawaiian Islands (e.g., Clague, 1996).

The two models with explicit plume drift predictions (D2012 and H2016) are further compared with B2014 by examining longitude and latitude separately versus time (Figure 9). This analysis makes it clearer that the implicit plume drift for D2012 largely matches its explicit drift as far as latitude is concerned, but has larger and systematic discrepancies in longitude, especially for Hawaii. In contrast, the H2016 implicit and explicit curves show more variability and larger discrepancies, especially in longitude. These discrepancies are largest for Louisville, which we attribute to their plume being modeled too far from the actual Louisville location. Figure 9 makes it clear that B2014 best satisfies the paleolatitude data, in particular for the oldest and largest anomalies, provided that TPW is insignificant.

A final way to compare and contrast the APM predictions is to examine the paleolatitude misfits (seen in Figures 4 and 5) with respect to the change in plume drift across the HEB. Figure 10 shows this data set for all models, and it makes it clear that models trade off what they wish to minimize (whether implicitly or explicitly). Models that we know provide very good fits to the paleolatitude anomalies require a large change in drift rate before/after the HEB (e.g., B2014), while models with a steady drift rate have significantly poorer fits to the paleolatitudes (e.g., most models, including D2012). However, as Torsvik et al. (2017) point out, this relationship can change completely if TPW is used to adjust the paleolatitudes. Establishing robust estimates for TPW with broad community acceptance would be an important contribution that has the potential to settle the debate over the origin of the Hawaii-Emperor Bend.

6. Conclusions

D2012 and B2014 represent two different compromises of moving hot spot APM models for the Pacific: On one hand, the B2014 model fully attributes both the HEB and LVB to plume drift, predicts no APM change in direction, and maximizes the fit to observed paleolatitudes by assuming no TPW. At the same time, it yields a very good fit to the geometry and age progressions and is based on geodynamic estimates of plate-driving forces. However, B2014 also requires a factor of 2.5 speedup of Pacific plate motions (Figure 10) and a factor of 3 slowdown of plume drift (Figure 7) at HEB time. Also, like all geodynamic models, B2014 is dependent on assumptions about plate forces and mantle rheology, and is therefore nonunique. On the other hand, D2012 allows for a significant change in the direction of Pacific plate motion (Figure 3), and therefore does not require large changes in plume drift rate (Figure 7) or plate speed (Figure 8). However, D2012 fits the geometry and age progressions less well (trail predictions deviate systematically for older ages Figure 6) and requires considerable TPW adjustment to explain the large paleolatitude anomalies (Figure 10).

While D2012 attributes the HEB/LVB to a change in the direction of Pacific plate motion, B2014 requires plume drift rates to slow by a factor of ~3 during the HEB/LVB (Figure 7). Such rapid changes to the motions of both plates and plumes are challenging to explain geodynamically (e.g., Richards & Lithgow-Bertelloni, 1996) because both are driven by mantle buoyancy forces that change only gradually with time. However, plate motions are sensitive to rheological processes such as plate fracture or strain localization that can change plate-driving forces rapidly with time (e.g., Bercovici et al., 2000), for example, via slab cessation or breakoff, or plate boundary formation. By contrast, plume motions are sensitive to a vertically integrated column of slowly-moving mantle (Steinberger et al., 2004), which should make rapid changes in drift rate difficult. However, Tarduno et al. (2009) proposed that capture of the Hawaiian plume by the Kula-Pacific ridge may have relaxed at about 80 Ma, resulting in southward plume drift toward the current position of Hawaii by about 50 Ma (although we note this runs counter to the conclusions of Petronotis et al., 1994). This might make the B2014 plume drift scenario feasible for Hawaii (Figure 4), but cannot explain the similar slowdown of Louisville plume drift (Figure 5) because there is no ridge north of Louisville to capture that plume. These arguments seem to favor models such as D2012 that explain both the HEB and LVB via a change in direction of the Pacific plate, which is common to both plumes. Otherwise, a broad change in mantle flow patterns beneath the entire Pacific (e.g., induced by a major change in plate motions or descent of a new slab into the lower mantle) is required to simultaneously change the drift rates of both plumes.

One possible explanation for the conflict between the B2014 predictions and the requirements of plume behavior as proposed by Torsvik et al. (2017) may lie in an incomplete description of the boundary forces acting on the Pacific plate. The realization that the Emperor chain may after all reflect a more northerly motion of the large Pacific plate before HEB time has resurrected the suggestion (Gordon et al., 1978) of a missing east-west oriented subduction zone to the north (Domeier et al., 2017). While this suggestion remains speculative, if substantiated it would indeed provide a geodynamic scenario where northward Pacific plate motion would be predicted, reducing the magnitude of plume drift required to match seamount trail geometry and age progressions. A corollary of this interpretation would be that D2012 may represent the best model to date, despite implying a much higher Pacific-Farallon Ridge rotation than B2014 and being more dependent on TPW to satisfy observed paleolatitudes. It unequivocally requires a change in APM motion to explain the HEB and Emperor alignment (which is extended due to plume drift). The largest caveat in our analysis of plume motions comes from the level of uncertainty expressed in Figure 2. It is possible that further age determinations along the poorly dated sections could alter the final age progressions and hence drift rates. Hence, the balance between plate and plume motions in the Pacific remain poorly quantified but could be further clarified with improved age dating along the older sections of both the Emperor and Louisville seamount chains.

Finally, we note that while geodynamic models such as B2014 have yielded compelling predictions of plate motions, mantle flow, and plume drift that match many of the observations, we caution that more work will be required to confirm a robust result. In many regards, the geodynamic models so far have been simplistic; for example, B2014 models a constant viscosity slab sinking in an isoviscous mantle, uses a limited subduction history as starting condition, and must be extrapolated beyond its 72–42 Ma validity. Nevertheless, we believe that further consideration of geodynamic APM models is warranted, particularly those that address the influence of mantle density heterogeneities and viscosity structures on plume drift and plate motions. Such models need to be validated by all available data from geodesy, paleomagnetics, and geochronology, and could further utilize additional constraints on mantle flow, such as seismic anisotropy observations or seismic tomography models that reveal the tilts of plume conduits or slabs in the deeper mantle. Likewise, more rigorous statistical treatment of trail geometry, ages, and hot spot locations is needed to better quantify the uncertainties in the resulting absolute plate and plume models.

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