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Key Points:

- The Hawaiian hot spot was fixed relative to the spin axis 48-12 Ma, but not in its present location, which contradicts some prior models
- The coherent shift of global hot spots since approximately 12 Ma is consistent with true polar wander that followed a mid-Cenozoic true polar stillstand
- Northern Hemisphere ice sheets formed coevally with late Cenozoic true polar wander, which moved Greenland nearer the North Pole

Supporting Information:

- Supporting Information S1

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Paleolatitude of the Hawaiian Hot Spot Since 48 Ma: Evidence for a Mid-Cenozoic True Polar Stillstand Followed by Late Cenozoic True Polar Wander Coincident With Northern Hemisphere Glaciation

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Abstract Paleospin axis locations since 48 Ma inferred from the distribution of equatorial sediment accumulation rates on the Pacific plate, together with paleomagnetic poles from magnetic anomaly skewness, indicate that the Hawaiian hot spot was nearly fixed in latitude from 48 to 12 Ma, but ≈3° north of its current latitude. From 48 to 12 Ma in the Pacific hot spot reference frame, which we take to be equivalent to the global hot spot reference frame, the spin axis was located near 87°N, 164°E, recording a stillstand in true polar wander. Global hot spots shifted coherently relative to the spin axis since ≈12 Ma, consistent with an episode of true polar wander, which may continue today. The motion of the spin axis away from the Hawaiian hot spot and toward Greenland since ≈12 Ma coincided with, and may have contributed to, the onset of northern hemisphere glaciation.

Plain Language Summary The Earth has shifted relative to its spin axis over the past 12 million years (Ma). This shift, which geoscientists call true polar wander, caused the Earth's mantle beneath the tropical Pacific to move southward while causing Greenland to move northward. The latter motion may have contributed to the onset of the current ice age, which began ≈3 Ma before present. These conclusions follow our analysis of the history of motion of the Pacific tectonic plate relative to the spin axis, which is preserved in sediments and rocks on the Pacific seafloor. We also infer the motion of the Pacific plate relative to the solid Earth from the plate's history of motion relative to hot spots, such as Hawaii. Hot spots are sites of voluminous volcanism, thought to lie over rising plumes of hot rock from deep in the Earth's mantle. As the Pacific plate moves over the Hawaiian plume, it creates a line of extinct volcanoes that record the motion of the plate relative to the plume. Combining this information, we find that Hawaii and other global hot spots were nearly fixed in latitude from 48 to 12 Ma before present, which marks a 36-Ma-long time interval preceding the shift.

1. Introduction

While it is well documented that the Hawaiian hot spot has shifted southward relative to the spin axis since the formation of some of the Emperor seamounts (Acton & Gordon, 1991; Beaman et al. 2007; Gordon, 1982; Gordon & Cape, 1981; Koivisto et al., 2011; Kono, 1980; Morgan, 1981; Petronotis & Gordon, 1999; Petronotis et al., 1994; Sager & Pringle, 1988; Tarduno & Cottrell, 1997; Tarduno et al., 2003), the paleolatitude of the hot spot during the formation of the Hawaiian chain is poorly understood. Recently, Zheng et al. (2018) estimated the location of the 44-Ma Pacific plate paleomagnetic pole by investigating the skewness (asymmetry) of 14 airplane and 19 shipboard magnetic crossings of anomaly 20r between the Murray and Marquesas fracture zones on the Pacific plate. Furthermore, Zheng et al. (2018) updated the pole for anomaly 12r (32 Ma) determined by Horner-Johnson and Gordon (2010). The updated 32-Ma paleomagnetic pole and the new 44-Ma paleomagnetic pole differ by 5 ± 3° (95% confidence limits here and throughout this paper) from the respective coeval poles expected if the Pacific hot spots have been fixed relative to the spin axis. The change in spin axis location is independently confirmed by paleomagnetic poles reconstructed from the continents, indicating that global hot spots have moved coherently relative to the spin axis, probably due to true polar wander (TPW, motion of the entire solid earth relative to the spin axis), which may continue today as recorded by optical astronomy and geodetic very long baseline interferometry (Argus & Gross, 2004; Gordon & Cape, 1981; Morgan, 1981; Zheng et al., 2018).

It is desirable, however, to have more estimates of the location of the paleospin axis during the formation of the Hawaiian chain, both to independently test the locations found from the skewness poles (Horner-Johnson & Gordon, 2010; Zheng et al., 2018) and to have further constraints on the timing of the latitudinal shift of the Hawaiian hot spot and the associated coherent global shift of the hot spots relative to the spin axis. Insofar as motion between Pacific hot spots and the spin axis is recording TPW, it is important to have a record of hot spot-spin axis motion independent of the continental data, for which the apparent polar wander (APW) paths are highly smoothed and thus have low age resolution. The importance of knowing the amount, timing, and rate of true polar has implications far beyond the Pacific.

Thus, herein we examine and analyze additional sources of information on the paleolatitude of the Pacific plate and thus of the Hawaiian hot spot. There are few useful and reliable paleomagnetic poles for the Pacific plate for the past ≈48 Ma, the time interval when the Hawaiian chain was formed. For example, the pioneering study of Grommé and Vine (1972) of paleomagnetic results from vertical cores of basaltic lava flows from two deep drill holes through the reef limestone of Midway Atoll (28 Ma) was later recognized to have large uncertainties because secular variation is little sampled by the lavas they investigated (Cox & Gordon, 1984). Cox and Gordon (1984) estimate a paleolatitude of 17.5°N ± 8.5°, the uncertainties of which are too large to usefully distinguish between competing hypotheses. Another example comes from the work of Acton and Gordon (1994), who estimated poles for 26 and 39 Ma that they determined from a combination of paleocolatitudes from paleomagnetic inclinations of basalt and sediment piston cores, equatorial sediments, and seamount paleomagnetic poles. Because of the dependence on paleomagnetism from sediment cores, which tend to give shallowly biased inclinations (cf. Gordon, 1990), and on seamount poles, the accuracy of which are questionable especially for seamounts formed during intervals of rapid reversals (Gee et al., 1993), we no longer consider these two poles to be reliable. Beaman et al. (2007) provide a more recent set of poles for 30 and 39 Ma using declinations from seamount poles and paleomagnetic inclinations from basalt and sediment cores. The paleolatitudes indicated by these data are dominated by the results from paleomagnetic inclinations from sediments and indicate slightly more northward motion of the Pacific plate than do the data we use herein. The differences may be due to some combination of inclination error in the paleomagnetism of sediments and the effects of a persistent nondipole component of the paleomagnetic field (Text S2 and Figures S2 and S3 in the supporting information; Acton et al., 1996; Gordon, 1990; McElhinny et al., 1996; Wilson, 1970).

A better approach for estimating the paleomagnetic pole position may be through the analysis of the skewness of marine magnetic anomalies due to seafloor spreading. Skewness (asymmetry) is usually quantified as the phase shift between the observed magnetic anomaly and a synthetic magnetic anomaly calculated for the vertical component of the magnetic field produced by a vertically magnetized crust and uppermost mantle (Cande, 1976; Dyment & Arkani-Hamed, 1995; Gordon & Cox, 1980; Schouten & Cande, 1976). From the skewness, the effective inclination of the remanent magnetization of the crust can be calculated, where effective inclination is the inclination of the magnetization vector projected onto the vertical plane perpendicular to magnetic striping. For anomalies recording Pacific-Farallon spreading on the Pacific plate, because the strike of the anomalies is subparallel to the magnetic declination, effective inclination varies much more rapidly with paleolatitude than does ordinary inclination with paleolatitude (Acton & Gordon, 1991). For this reason, effective inclinations estimated from observations of anomaly skewness are highly sensitive to the location of the paleomagnetic pole.

With skewness data there are no concerns about the limitations hindering some alternative approaches. For example, inadequate averaging of secular variation is a major impediment to investigations of the paleomagnetism of lava flows (Cox & Gordon, 1984). In contrast, each point along a magnetic profile used in skewness analysis averages over a lateral distance of seafloor comparable to the distance above the seafloor of the measurement. For profiles obtained on a ship this is ≈5 km and for profiles obtained on an airplane ≈12 km. For half spreading rates of 50 mm/a, this indicates that each point along the profile averages over ≈100 ka for shipboard profiles and ≈240 ka for airplane profiles. Thus, the effects of secular variation, the longest periods of which are generally thought to be ≈10 ka (e.g., Cox & Gordon, 1984), have negligible effect on the estimated effective remanent magnetic inclination.

With skewness data there is also no concern about a shallow bias in inclinations as there is with the results from paleomagnetic investigations of sediment cores. Finally, unlike seamount poles, there is little reason

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to be concerned about biases due to induced or secondary magnetizations because a uniformly magnetized infinite sheet produces no magnetic anomaly; thus, a uniform overprint over a larger distance than that included in the portion of the magnetic profile including the anomaly of interest and immediately adjacent anomalies causes no bias in the skewness. Differential overprints over a smaller distance may contribute to the dispersion in the skewness estimates, but that is already implicitly included in the error estimates for the resulting paleomagnetic pole positions. Although skewness analysis at slow spreading centers must account for so-called anomalous skewness (Cande, 1976; Koivisto et al., 2011), it is negligible for spreading centers with a spreading half-rate above ≈50 mm/a (Dyment & Arkani-Hamed, 1995; Dyment et al., 1994; Roest et al., 1992), as is the case with all the anomalies that were used to determine the poles that we use in this paper.

The main source of information that we use herein, however, is the paleolatitude information from Pacific plate crossings of the paleo-equator inferred from high accumulation rates in equatorial sediments (Gordon & Cape, 1981; Moore et al., 2004; Parés & Moore, 2005; Suárez & Molnar, 1980; van Andel et al., 1975; Winterer, 1973). To constrain the northward motion of the Pacific plate since 70 Ma, Suárez and Molnar (1980) and Gordon and Cape (1981) analyzed paleo-equatorial crossings, recognized mainly by the high accumulation rates in equatorial sediments identified in deep sea drilling boreholes (van Andel et al., 1975). The results from analysis of equatorial sediments indicated modestly less northward motion of the Pacific plate (from about 100 to a few hundred kilometers) indicated by equatorial sediments than did analysis of dated volcanic edifices along the Hawaiian chain (Figure 3 of Gordon & Cape, 1981).

Moore et al. (2004) and Parés and Moore (2005) analyzed a much more comprehensive set of variations in accumulation rates in Pacific plate paleo-equatorial sediments to show that the Hawaiian hot spot shifted relative to the spin axis during the formation of the Hawaiian chain. They were not only able to determine the position of the paleo-equator at single points but also to estimate a great circle fit through the data for 10 time windows since 56 Ma. Herein we build on their results, which can be used to estimate the position of the paleospin axis for nine time intervals during formation of the Hawaiian chain with a precision and age resolution superior to most paleomagnetic poles (Moore et al., 2004). Results from later drilling in Pacific plate paleo-equatorial sediments (Pälike et al., 2010) are consistent with the analysis and interpretation of Moore et al. (2004; cf., Moore et al., 2014). Moreover, the resulting estimates of the spin axis location are unaffected by persistent nondipole components of the paleomagnetic field that may bias paleomagnetic estimates of the spin axis location.

2. Spin Axis Locations and Confidence Limits From Analysis of Equatorial Sediment Accumulation Rates

The APW path shown with green filled circles in Figure 1a consists of the spin axis locations that we determined from the locations of paleo-equator segment end points of Table 1 of Parés and Moore (2005; Text S1 and Tables S1 and S2). Also shown in blue in Figure 1a are the Pacific plate paleomagnetic poles for anomaly 12r (32 Ma) and anomaly 20r (44 Ma) determined from skewness analysis (Table S3; Horner-Johnson & Gordon, 2010; Zheng et al., 2018). The 32-Ma paleomagnetic pole lies inside the 95% confidence limits of the 32-Ma equatorial sediment pole and the 44-Ma paleomagnetic pole lies inside the 95% confidence limits of the 43-Ma equatorial sediment pole, indicating their mutual consistency. The good agreement between poles estimated from sediment paleo-equators and the skewness poles is encouraging given their disparate methodologies and underlying assumptions.

3. Pacific Hot Spot Reference Frame

By reconstructing each spin axis location shown in Figure 1a relative to Pacific hot spots along with the Pacific plate (by interpolating from the rotations of Koivisto et al., 2014), we construct an APW path of Pacific hot spots (Figure 1b). The 11 reconstructed poles cluster tightly around the mean pole, 86.6°N, 163.7°E ($A95_1$ = 1.0°, $A95_2$ = 0.5°, $\theta95_1$ = 33°, where $A95_1$ is the length of the major semiaxis of the 95% confidence ellipse, $A95_2$ is the length of the minor semiaxis, and $\theta95_1$ is the azimuth of the major semiaxis measured clockwise from north), indicating a 3.4° offset between the present spin axis and the mean spin axis location from 48 to 12 Ma (Figure 1b and Tables S4 and S5).

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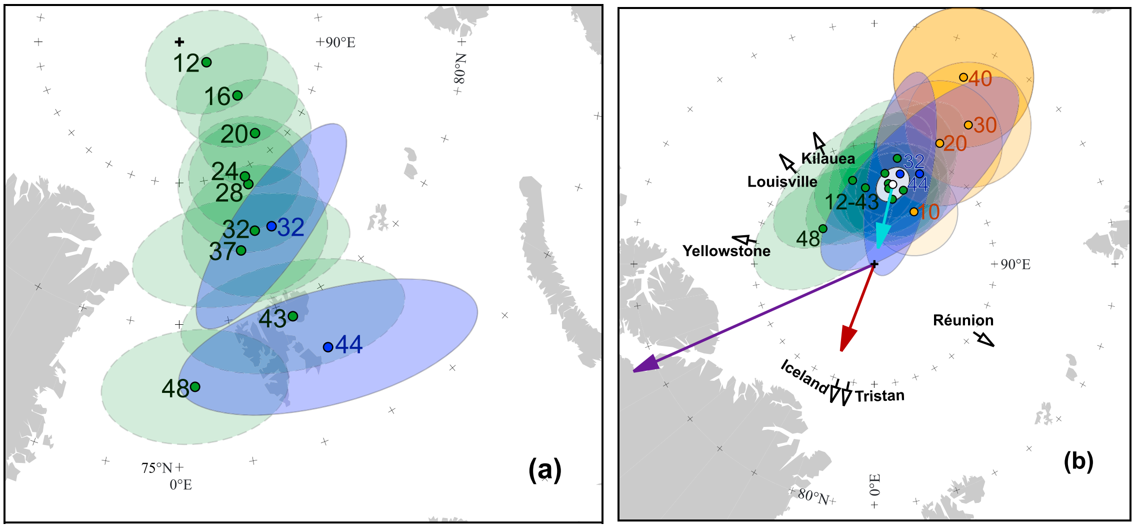

Figure 1. (a) Apparent polar wander path of the Pacific plate for the past 48 Ma. Green filled circles and ellipses: spin axis locations and 95% confidence limits from analysis of equatorial sediments; blue filled circles and ellipses: paleomagnetic poles and 95% confidence limits determined from skewness. Numerals give ages in million years ago. (b) Apparent polar wander of Pacific (and global) hot spots for the past 48 Ma. White: Mean pole and 95% confidence ellipses for Pacific hot spots from Pacific plate data; orange: Mean continental poles and 95% confidence circles from Torsvik et al. (2012). Purple arrow: Motion of the spin axis relative to the global hot spot reference frame over the past century (Argus & Gross, 2004); red arrow: True polar wander over the past 1 million years calculated from a mantle advection model (Steinberger & O'Connell, 1997); blue arrow: Motion of the spin axis relative to Pacific and global hot spots since ≈12 ma. Arrow lengths are proportional to the indicated rate of true polar wander. Short arrows with open arrowheads indicate direction toward various hot spots on Earth's surface.

Figure 1b also shows the 10- to 40-Ma poles from the continents (Torsvik et al., 2012) reconstructed into the Pacific hot spot reference frame using the same plate reconstruction parameters as those used by Koivisto et al. (2014), except that herein we incorporate the motion between East and West Antarctica estimated by Granot et al. (2013). The poles reconstructed from the continents are compared with the 12- to 48-Ma mean location of the spin axis relative to Pacific hot spots. The reconstructed continental poles for 10 and 20 Ma show a similar offset from the spin axis, confirming the shift relative to the spin axis indicated by the Pacific plate data.

The 30- and 40-Ma poles from the continents indicate a larger offset from the present spin axis than indicated by the Pacific plate data. As the continental poles have been rotated relative to Pacific plate poles by a relative plate motion circuit through Antarctica, the difference cannot be attributed to motion between hot spots. Instead, it might be explained by (1) errors in the relative plate motion circuit, (2) errors in one or more of the paleomagnetic poles, (3) nonrigidity of the plates, (4) significant persistent nondipole components of the paleomagnetic field, or (5) in the case of the 40-Ma pole, poles with ages greater than 48 Ma influencing the location of the pole.

Regarding explanation (2) above, the continental poles incorporate many data lacking tilt control or the full range of internal consistency tests. Moreover, they can be affected by various biases such as incomplete removal of secondary magnetizations (cf. Vandamme et al., 1991). The construction of continental APW paths tends to rely on the hope that including many data will average out these additional sources of error. The continental pole paths are typically averaged over 20-Ma-long intervals and thus may not be representative of their nominal ages and are not well suited to capture pole shifts that occur over short intervals of geologic time.

Whatever the explanation, it is likely that the Pacific plate APW path has greater accuracy and age resolution than does the highly smoothed APW path formed from the continental poles. Below we focus on the agreement between the two sets of poles, especially for the most recent 20 Ma. Figure 1b shows that the global hot spots have shifted coherently relative to the spin axis since 12 Ma, as expected if the cause is TPW.

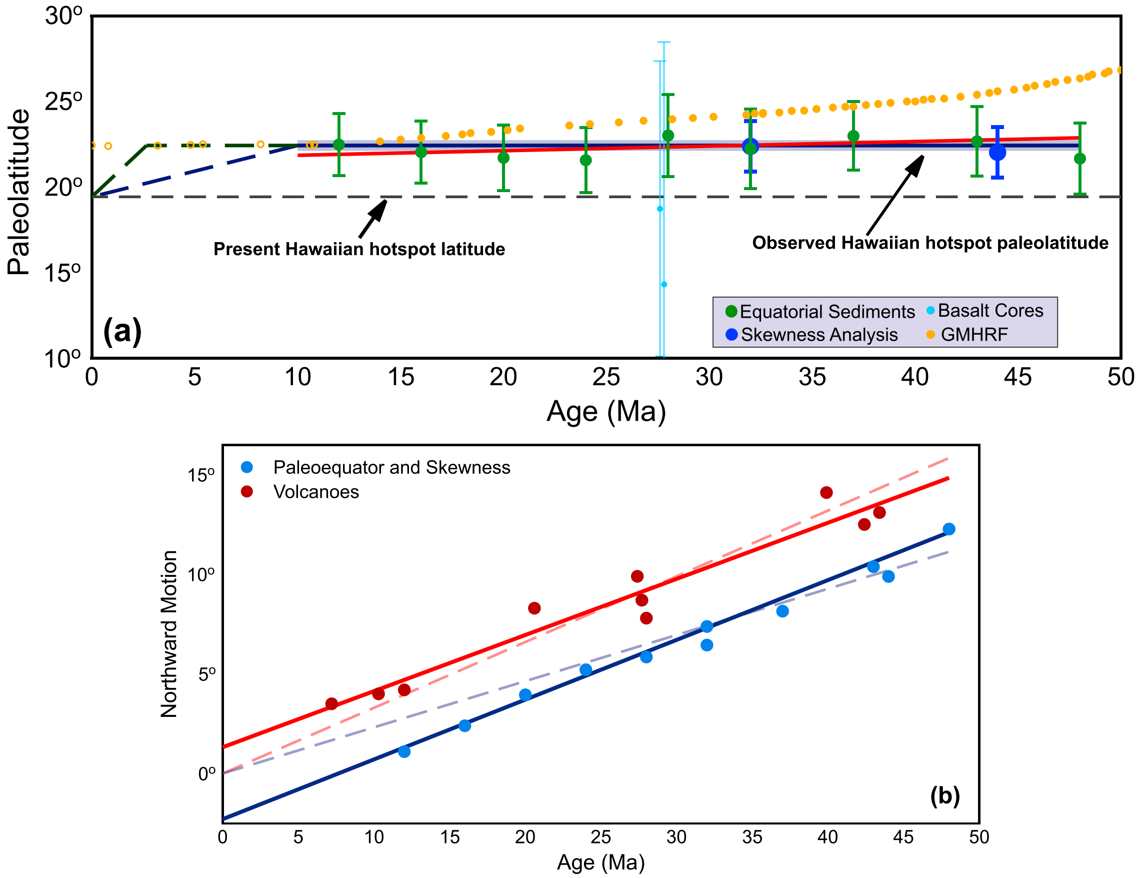

Figure 2. (a) Paleolatitude of the Hawaiian hot spot for the past 48 Ma. The best fit straight line for 48 to 12 Ma has a slope of 3 ± 5 mm/a (95% confidence limits here and below) and is more efficiently described by its mean paleolatitude: 22.4°N ± 0.5°, which is 3.0 ± 0.5° north of the present latitude of Kilauea. The predicted latitudinal shift of the Hawaiian hot spot relative to a deep mantle reference frame (global moving hot spot reference frame, GMHRF; Doubrovine et al., 2012) offset for our estimate of true polar wander since 12 Ma is shown by orange filled circles for 12 to 48 Ma and by unfilled orange circles for ages <12 Ma. (b) Pacific plate northward motion relative to the spin axis is compared with Pacific plate northward motion relative to the Hawaiian hot spot. The northward motion of the Pacific plate relative to the Hawaiian hot spot is determined by finding the difference between the current latitude of each ancient volcano and that of the Hawaiian hot spot (19.4°N). The northward motion from the equatorial sediments is determined for the age-appropriate point along the Hawaiian chain. A best fit straight line constrained through the origin results in a slope of 0.39 ± 0.06°/Ma for plate motion relative to the Hawaiian hot spot (red dashed line) and 0.25 ± 0.8°/Ma relative to the spin axis (blue dashed line). Unconstrained best fit straight lines have slopes of 0.28 ± 0.05°/Ma relative to the hot spot (red solid line) and 0.22 ± 0.05°/Ma relative to the spin axis (blue solid line) with intercepts that differ by 3.62°. The paleomagnetic and equatorial sediment data are consistent with the spin axis being stationary relative to Pacific hot spots from 48 to 12 Ma, but in a different location from the present spin axis.

4. Paleolatitude of the Hawaiian Hot Spot Since ≈48 Ma

By determining the angular distance between Kilauea and each pole shown in Figure 1b, the paleolatitude of the Hawaiian hot spot can be determined as a function of time (Figure 2a). Also shown in Figure 2a are additional paleolatitudes from igneous rocks recovered from boreholes on Midway Island (Grommé & Vine, 1972), but these do not add much information because the uncertainties are so large.

The best fitting line for the data from 48 to 12 Ma has a slope of 0.027 ± 0.046°/Ma and an intercept of 21.6°N ± 1.5° (red line in Figure 2a). (If, instead of the rotations of Koivisto et al., 2014, we used the rotations of Wessel and Kroenke, 2008, we obtain the same slope, 0.027°/Ma, but with an intercept of 21.8°N.) The indicated motion of the Hawaiian hot spot relative to the spin axis is 3 ± 5 mm/a southward, but the intercept is significantly north of the present 19.4°N latitude of Kilauea. As the slope does not differ significantly from 0, it is statistically more efficient to describe the line only by its mean value, which is 22.4°N ± 0.5°. Thus, from ≈48 to ≈12 Ma ago, the Hawaiian hot spot was fixed in latitude, but 3.0 ± 0.5° (95% confidence limits) north of its current location.

5. When and How Fast Did the Hawaiian Hot Spot Move?

Our analysis indicates that during formation of most of the Hawaiian chain (i.e., from 48 to 12 Ma), the motion of the Hawaiian hot spot relative to the spin axis was insignificant, merely 3 ± 5 mm/a (95% confidence limits). Over this interval other Pacific hot spots have evidently moved little relative to one another (Wessel & Kroenke, 2008, 2009) and have been approximately fixed relative to global hot spots with little or no significant motion (Koivisto et al., 2014; Wang et al., 2017). Therefore, global hot spots were nearly stationary relative to the spin axis from 48 to 12 Ma, indicating a stillstand in TPW that lasted ≈36 Ma.

In contrast, the Hawaiian hot spot and other Pacific plate hot spots drifted southward by ≈330 km in the past 12 Ma for a mean rate of ≈28 mm/a, due not to motion of the Hawaiian hot spot or plume through the mantle or relative to other hot spots, but due to TPW during which the entire solid Earth moved relative to the spin axis. As the most recent constraint on TPW is the ≈12-Ma sediment paleo-equator pole, ≈28 mm/a is a minimum rate as the entire shift could have occurred in a shorter amount of time, for example, between 12 and 6 Ma, or since 3 Ma, for which the rate would respectively be 2 or 4 times 28 mm/a.

Figure 2a also compares the observed latitudinal motion of the Hawaiian hot spot with that predicted (relative to their global moving hot spot reference frame, GMHRF) by Doubrovine et al. (2012) and Torsvik et al. (2017). Like the interpretation of Parés and Moore (2005), the predicted values of the latitude of the Hawaiian hot spot show a progressive southward motion of the plume through the mantle over the past 50 Ma, but at a rate slightly lower than the 13 mm/a of Parés and Moore (2005). In Figure 2a, we shift the GMHRF predictions by 3.0° to account for the TPW that we find to have occurred since 12 Ma. As can be seen, the GMHRF predictions indicate more southward motion of the Hawaiian hot spot than allowed by the 32 and 44-Ma paleomagnetic poles and by the 32, 43, and 48-Ma spin axis locations from sediment accumulation rates. Therefore the GMHRF predictions can be rejected as being inconsistent with the observed paleolatitude.

Thus, relative to the spin axis, the Hawaiian hot spot moved insignificantly during the formation of most of the Hawaiian chain (from 48 to 12 Ma) and moved ≈28 mm/a since 12 Ma, consistent with a coherent rotation of global hot spots. The southward motion was not progressive over ≈50 Ma, as interpreted by Parés and Moore (2005) and predicted by Doubrovine et al. (2012) and Torsvik et al. (2017), but dominantly occurred in an episode of TPW since ≈12 Ma (Figure 1b).

6. TPW and Northern Hemisphere Glaciation

Because of the global nature of the post-12-Ma shift of the hot spots relative to the spin axis (Horner-Johnson & Gordon, 2010; Zheng et al., 2018), no motion of the Hawaiian plume through the mantle is required by our data, but up to a few millimeters per year (Wang et al., 2017) or up to ≈10 mm/a (Koivisto et al., 2014) of motion is allowed by the paleomagnetic and plate reconstruction data. The dominant signal, however, is of global hot spots moving coherently relative to the spin axis as a result of TPW.

The direction of TPW over the past 12 Ma is similar to that observed over the past century, but the rate is lower (28 mm/a for the former versus ≈130 mm/a for the latter; Figure 1b; Argus & Gross, 2004; Gordon, 1987; Morgan, 1981; Zheng et al., 2018). TPW over the past century is likely a combination of TPW driven by deglaciation (e.g., Chan et al., 2015) plus a longer-term component similar to that we infer herein (Gordon, 1995; Steinberger & O'Connell, 1997).

Figure 2b shows that since 12 Ma, following a 36-Ma-long TPW stillstand, when the spin axis was stationary relative to the hot spots, the spin axis has moved toward the east coast of Greenland, coincident with the onset of the permanent ice sheet on Greenland and the onset of glaciation in North America and Eurasia (Raymo, 1994; Zachos et al. 2001). We hypothesize that the motion of the solid Earth relative to the spin axis was an important contributor to this onset of glaciation. Daradich et al. (2017) have shown that poleward motion of Arctic North America would strongly promote glacial inception in Baffin Island. In particular, they developed a model to estimate the TPW-driven changes in positive-degree days at Cape Dyer, Baffin Island, over the past 20 Ma using the TPW path of Doubrovine et al. (2012). Daradich et al. (2017) found that TPW moves the North America climate system closer to a threshold for glacial inception. While they do not explicitly give that threshold in degrees of latitude, it appears to us from their analysis that this threshold is reached when the latitude is within merely ≈1−2° of the present latitude.

Although their assumptions about the amount and timing of late Cenozoic TPW are different from ours, their analysis implies that the spin axis could have been merely 3.4° from its present location, as we infer was true for 12–48 Ma, and not reach that threshold. The 3.4° shift in spin axis location would have moved the mantle now beneath Cape Dyer to higher latitudes, from 64.2°N at 12 Ma to its present latitude of 66.6°N, a change of merely 2.4°, but evidently enough to cross the threshold for the onset of glaciation in North America.

Our tectonic interpretation also differs from that of Daradich et al. (2017) in the role of plate motions. Daradich et al. (2017) assert that plate motion relative to the deep mantle contributed to the poleward motion of Cape Dyer and the rest of North America. We assert the opposite—plate motion relative to the deep mantle inferred either from hot spot tracks (Wang et al., 2017) or from the orientation of seismic anisotropy (Zheng et al., 2014) indicate that most of North America, including Cape Dyer, has been moving to the southwest to west-southwest relative to the deep mantle over the past several million years. The rate of this southward motion is low: Cape Dyer moves 18 mm/a toward 247° relative to the hot spots (HS4-EW-MORVEL angular velocities of Wang et al., 2017) and 21 mm/a toward 259° in a reference frame inferred from seismic anisotropy (SKS-MORVEL angular velocities of Zheng et al., 2014). The former velocity has a southward component of 7 mm/a and the latter velocity has a southward component of 4 mm/a, in both cases substantially less than the ≈28 mm/a northward motion due to TPW.

The important point is that TPW since 12 Ma was evidently the cause of the increase in latitude of North America (and Greenland and Eurasia) that in turn contributed to reaching a threshold latitude at which northern hemisphere glaciation was initiated. If so, it is impressive that such a small change in the location of the spin axis could have such a large effect after tens of millions of years at a fixed location.

7. Conclusions

Spin axis locations from analysis of equatorial sediment accumulation rates together with paleomagnetic poles from skewness analysis demonstrate that the Hawaiian hot spot (along with other Pacific hot spots) was fixed relative to the spin axis from ≈48 to ≈12 Ma, but at a different location than at present, indicating a mid-Cenozoic stillstand in TPW. Since 12 Ma the Hawaiian hot spot (along with other Pacific hot spots) shifted ≈3° southward relative to the spin axis.

Paleomagnetic poles from continents, when transferred into the Pacific hot spot reference frame, which Koivisto et al. (2014) showed to be consistent with the Indo-Atlantic hot spot reference frame and thus represents a global hot spot reference frame, independently confirm this shift. The coherent shifts of global hot spots since ≈12 Ma, including southward shifts of Hawaii and other Pacific hot spots, are consistent with TPW. The direction of TPW is similar to that observed over the past century (Argus & Gross, 2004), but at a lower average rate. Thus, the Earth experienced a late Cenozoic episode of TPW, which may have played an important role in triggering Northern Hemisphere glaciation.

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