Divergence Between Paleomagnetic and Hotspot Model Predicted Polar Wander for the Pacific Plate with Implications for Hotspot Fixity

William W. Sager
Department of Oceanography
Texas A&M University
College Station, TX 77845
wsager@ocean.tamu.edu

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ABSTRACT

If mantle plumes (hotspots) are fixed in the mantle and the mantle reference frame does not move relative to the spin axis (i.e., true polar wander), a model of plate motion relative to the hotspots should predict the positions of past paleomagnetic poles. Discrepancies between modeled and observed poles thus may indicate problems with these assumptions, for example that the hotspots or spin axis have shifted. In this study, I compare paleomagnetic and hotspot model predicted apparent polar wander paths (APWP) for the Pacific plate. Overall, the two types of APWP have similar shapes, indicating general agreement. Both suggest ~40° total northward drift of the Pacific plate since ~123 Ma. Offset between paleomagnetic and hotspot predicted poles is small for the past ~49 Ma, consistent with fixed hotspots during that time, but the offsets are large (6°-15°) for earlier times. These differences appear significant for the Late Cretaceous and early Cenozoic. During the period 94-49 Ma, the hotspot model implies the paleomagnetic pole should have drifted ~20° north without great changes in rate. Measured paleomagnetic poles, however, indicate rapid polar motion between 94-80 Ma and a stillstand from 80-49 Ma. Comparison with global synthetic APWP suggests that the 94-80 Ma polar motion may be related to true polar wander. The stillstand indicates negligible northward motion of the Pacific plate during the formation of the Emperor Seamounts. This observation is drastically different from most accepted Pacific plate motion models and requires rethinking of western Pacific tectonics. If the Emperor Seamounts show relative motion of the plate relative to the Hawaiian hotspot, the implied southward hotspot motion is ~19°. Lack of a diagnostic coeval phase of polar wandering in global APWP and consideration of the significance of the Hawaiian-Emperor Bend imply that true polar wander is probably not the cause. Likewise, mantle flow models do not readily explain the large southward drift of the hotspot or its inferred

large westward velocity component. Thus, current models for the formation of the Emperor Seamounts appear inadequate and new ideas and further study are needed. Comparison of the Pacific APWP with a global APWP, both rotated into the Antarctic reference frame, shows an offset of ~10°, implying problems with plate circuits connecting Antarctica with surrounding plates. This result suggests that caution is required when predicting trends of hotspot seamount chains using plate circuits through Antarctica.

INTRODUCTION

How did Hawaiian-Emperor seamount chain (Fig. 1) come into being and what is the significance of the bend where the two chains meet? For many years, the answer seemed obvious. Wilson (1963) explained the Hawaiian chain and its linear age progression as volcanism that occurred on the Pacific plate as it drifted over a mantle plume (often given the generic name "hotspot") that was either fixed or moving slowly relative to the mantle. Morgan (1971; 1972) noted similarities in trend between the Hawaiian-Emperor and three other Pacific seamount chains (Cobb-Bowie, Austral-Cook-Gilbert-Ellice, and Tuamotu-Line; Fig. 1) and suggested that these and other linear seamount chains were all formed by plumes that were nearly fixed in a stable lower mantle. Studies of linear seamount chains in other oceans gave similar results, supporting the fixed hotspot hypothesis (e.g., Duncan, 1981; Morgan, 1983; Müller et al., 1993). Owing to its simplicity and the fact that it made tectonic predictions that seemed consistent with observed geology, the fixed hotspot hypothesis became widely accepted. Indeed, most introductory textbooks in geology and oceanography written within the last several decades contain a figure showing the Hawaiian-Emperor chain, explaining its formation to be the result of plate motion over a nearly fixed plume with the bend having resulted from a change in plate motion.

Today the picture is not so clear. Questions have arisen about the number and even existence of deep mantle plumes (e.g., Courtillot et al., 2003; Anderson, 2000; 2005; Foulger and Natland, 2003) and several lines of evidence suggest that hotspots are anything but fixed. Because it is the archetype of hotspot seamount chains, the Hawaiian-Emperor chain is the nexus of many such observations and arguments. Drilling of the Emperor chain by the Deep Sea Drilling Project (DSDP) produced paleomagnetic data showing that Suiko Seamount formed ~7°

north of the current latitude of the hotspot (Kono, 1980). Subsequent paleomagnetic measurements from other Emperor seamounts cored by the Ocean Drilling Program (ODP) confirmed and augmented this observation, showing a progressive offset of paleolatitude along the chain from nearly zero near the bend to ~13° at the north end (Tarduno et al., 2003). These findings dovetail with mantle modeling studies that imply the hotspots should move with mantle flow (e.g., Steinberger, 2000; Steinberger et al., 2004) and reconstructions of Pacific plate motion derived from hotspot tracks in other oceans that fail to reproduce the Hawaiian-Emperor bend (HEB) and show significantly less northward motion during the Emperor Seamounts period (e.g., Cande et al., 1995; DiVenere and Kent, 1999; Raymond et al., 2000). As a result there is an ongoing re-examination of the fixed hotspot hypothesis in general and the meaning of the HEB in particular (e.g., Norton, 1995; this volume; Sharp and Clague, 2006). The outcome of this debate is of wide interest because of its implications for mantle properties, behavior, and the flux of deep volcanism to the Earth's surface.

Paleomagnetism is often used to examine plate motion because it gives an axially-symmetric, absolute reference frame tied to the Earth's spin axis. If fixed or slowly moving, mantle plumes can also be used as an absolute reference frame, so a comparison of predictions from the two is a useful way to examine hotspot motion and related phenomena (e.g., Gordon, 1987; Besse and Courtillot, 2002). The Pacific plate is ideal for such comparisons because plate motion has been rapid and it contains well-defined linear seamount chains, including the Hawaiian-Emperor chain, which has been used as the basis for numerous hotspot plate motion models. Moreover, updates of both reference frames are available. For paleomagnetic data, I call upon recent compilations of the Pacific paleomagnetic apparent polar wander path (APWP) (Sager, 2006; Beaman, M., Sager, W., Acton, G., Lanci, L., and Pares, J., Improved Late

Cretaceous and early Cenozoic Paleomagnetic Apparent Polar Wander Path for the Pacific Plate, Earth and Planetary Science Letters, submitted). For models of Pacific plate motion relative to the hotspots, I examine several, but focus on a recent, well-documented update (Wessel et al., 2006). In this article, I explore the similarities and differences between paleomagnetic observations and hotspot model predictions. The results suggest a general agreement overall and close agreement for the past ~49 Myr, but imply significant relative motion between the two reference frames for earlier times.

BACKGROUND

Apparent and True Polar Wander

An APWP is a time series of paleomagnetic poles showing pole movement relative to a particular plate or collection of plates. It is usually calculated by averaging many paleomagnetic poles from individual geologic formations grouped by age (e.g., Irving and Irving, 1982; Besse and Courtillot, 2002; Schettino and Scotese, 2005). APWP construction makes two fundamental assumptions: the time averaged geomagnetic field is dipolar and all sites for which data are averaged are on the same rigid plate. The first assumption allows the paleomagnetic inclination and declination at a given site to be translated simply into paleolatitude and the azimuth of the spin axis (e.g., Butler, 1982). Various studies have found this so-called geocentric axial dipole assumption to be a good first-order approximation through time with non-dipole fields having simple zonal form (i.e., axially symmetric) and usually averaging less than 5% (e.g., McElhinny et al., 1996; Merrill and McFadden, 2003; Courtillot and Besse, 2004) to 10% (e.g., Torsvik and Van der Voo, 2002) during the last 200 Myr. A 5% contribution from a low-order zonal non-dipole field (for example g^0_2 or g^0_3) would cause a perturbation of only ~4° in paleomagnetic inclination or ~2° in paleolatitude compared to that calculated using the dipole field assumption

(Merrill et al., 1996). The second assumption is important because plates with different drift histories give divergent APWP, with possibly confusing results if poles from more than one independent plate are combined without proper reconstruction of relative motions.

Polar wandering, the apparent movement of paleomagnetic poles with time, happens for several reasons. Most polar wander occurs as a result of plate motion. If a plate's motion is described by a pole of rotation, the same rotation will affect the paleomagnetic pole and the resulting polar path follows a small circle concentric with the rotation axis (Fig. 2A). Naturally, if a plate's history is described by more than one rotation pole, the APWP will assume more complex shape. In general, an APWP consists of a series of small-circle segments congruent with rotation poles that describe the motion of the plate relative to the spin axis (Gordon et al., 1984).

Another cause of polar wandering is actual motion of the spin axis relative to the Earth, a phenomenon termed true polar wander (TPW). TPW can occur owing to changes in the density structure of the mantle, which cause the maximum principle axis of inertia to shift and the spin axis to follow (i.e., Goldreich and Toomre, 1969). Whereas APWP for different plates are usually disparate owing to different plate drift histories, TPW is a globally coherent phenomenon. If TPW occurred in the absence of plate motion, all plates would have matching APWP.

A third cause of apparent polar wander is large changes to the average non-dipole components of the geomagnetic field, which would change paleomagnetic directions without concomitant changes in site location. As stated previously, there is little evidence that this phenomenon has caused significant polar wander because most studies have concluded that long-term non-dipole fields have been small for the late Mesozoic and Cenozoic (McElhinny et al., 1996; Courtillot and Besse, 2004).

If a hotspot is fixed relative to the spin axis and there is no TPW, the APWP and the hotspot track volcanoes both follow small circles concentric with the pole (Fig. 2A). Under these conditions, a model of plate motion based on hotspot tracks can be used to predict the APWP. If either assumption is invalid, this will not be true, so differences between hotspot track models and APWP can be interpreted as TPW or departures from hotspot fixity. For example, on an Earth with fixed hotspots but no TPW (Fig. 2B), hotspot paleolatitudes will not change. If hotspots are fixed but TPW occurs, hotspot track seamount paleolatitudes (and paleopoles) will change in a globally consistent manner (Fig. 2C). If there is no TPW, but the hotspots move relative to one another, the paleolatitudes (and paleopoles) will not show a globally consistent pattern (Fig. 2D).

Pacific Apparent Polar Wander Path

Most major continental plates have relatively dense areal and time coverage with paleomagnetic data (e.g., Irving and Irving, 1982; Besse and Cortillot, 2002; Schettino and Scotese, 2005), but development of the Pacific APWP has lagged owing to the inaccessibility of the plate. Furthermore, whereas APWP from continental plates bordering the Atlantic Ocean can be augmented by assimilating rotated paleomagnetic data from adjacent plates (e.g., Besse and Courtillot, 2002; Schettino and Scotese, 2005), such improvement is not possible for the Pacific plate because continental plates cannot be linked to the Pacific by direct seafloor spreading, except for Antarctica, which has few data and is characterized by uncertainty about its long-term rigidity (e.g., Acton and Gordon, 1994).

Pacific plate inaccessibility has also affected the type of data used for APWP calculations. Because most of the plate is covered by water, Pacific paleomagnetic data are mostly from modeling of magnetic anomalies and paleomagnetic studies of azimuthally-unoriented ocean drilling cores. Both types of data are only rarely used for continental plate APWP because fully-oriented data from rock outcrops are considered more reliable. As a result, the Pacific APWP still has significant uncertainties.

Magnetic anomaly studies include models of seamount magnetic anomalies (e.g., Francheteau et al., 1970), which give both inclination and declination data. They also include determinations of the skewness (asymmetry) of marine magnetic lineations, a quantity that is related to paleomagnetic inclination (Schouten and Cande, 1976). Core data, which are rarely oriented in azimuth and therefore give only paleomagnetic inclination (and paleolatitude), are derived mainly from sedimentary or basalt core samples (Cox and Gordon, 1984; Gordon, 1990). Almost all such data have issues with systematic errors, complicating interpretation of the APWP. A detailed discussion of these errors is beyond the scope of this article, but can be found elsewhere (Sager and Pringle, 1988; Sager, 2006; Beaman et al., submitted). In defining the Pacific APWP (Fig. 3), we have looked for consistency among data, combining different types when possible (Sager, 2006; Beaman et al., submitted).

Early studies of the Pacific APWP relied mainly on data derived from the modeling of seamount magnetic anomalies (Francheteau et al., 1970; Harrison et al., 1975; Gordon, 1983; Sager and Pringle, 1988). These data are suitable for showing the gross features of the APWP and were used extensively when few other data were available, but today they are considered the most problematic data type owing to potential systematic errors. Seamount data showed that the Pacific plate has drifted ~30° northward since Cretaceous time (Francheteau et al., 1970) and that the APWP has a north-south trend from Late Cretaceous to present, a significant bend, and an east-west trend for earlier times (Gordon, 1983; Sager and Pringle, 1988). The ~30° of northward drift interpreted from seamount models by Francheteau et al. (1970) was used by Morgan (1971) as confirmation for his model of Pacific plate motion relative to the hotspots, which implied a similar amount of northward motion.

A compilation of basalt core paleomagnetic data confirmed the ~30° of northward drift of the Pacific plate, as indicated by seamount studies, and suggested southward motion during the Jurassic and Early Cretaceous, giving the APWP an overall "fishhook" shape (Cox and Gordon, 1984). This finding was bolstered by similar results from magnetic lineation skewness and sedimentary core data (Larson and Sager, 1992; Larson et al., 1992). The formation of the fishhook shape by southward followed by northward plate motion is explained in Figure 4.

The fishhook shape is seen in the APWP shown in Figure 3 (poles given in Table 1). This path is based mainly on three studies: Larson and Sager (1992) for the 139 and 145 Ma poles, Sager (2006) for the 123-80 Ma poles, and Beaman et al. (submitted) for the post-80 Ma portion. The 139 and 145 Ma skewness poles from Larson and Sager (1992) are used to define the old end of the APWP, which is poorly known because data of this age are scarce and somewhat contradictory. Early Cretaceous and Jurassic basalt core data give a large range of paleolatitudes that are consistent with the 145 Ma skewness pole, the 123 Ma basalt core pole, or are somewhere in between (Sager, 2006). Since sediment core data also imply southward motion of the Pacific plate for this time (e.g., Larson et al., 1992), I believe that the 145 Ma pole is a reasonable starting point for the Late Jurassic-Early Cretaceous APWP. The amount of southward motion is poorly constrained because of uncertainties about the accuracy of the skewness poles. The exact location of the Late Jurassic age pole is also uncertain because skewness data give two significantly different pole positions depending on whether or not one assumes a contribution from “anomalous skewness” (a cause of mismatch within coeval skewness data sets - the cause of which is poorly understood) (Larson and Sager, 1992). If the skewness poles calculated with a contribution from anomalous skewness are considered, the Pacific APWP fishhook is wide and Late Jurassic-Early Cretaceous poles are located in North America. If the solutions without anomalous skewness are used (as in Fig. 3), the fishhook is narrower and the APWP may double back almost upon itself (Larson and Sager, 1992).

Later paleomagnetic poles are all hybrids, calculated by combining core and magnetic anomaly-derived data in varying amounts; although, the recent studies have minimized the use of non-core data (Sager, 2006; Beaman et al., submitted). For example, the 123 and 113 Ma pole positions were based mainly on basalt core data, which constrain the pole latitude well, but give poor constraint on the pole longitude. Consequently, declinations from seamount magnetic anomaly models of appropriate age were used to help constrain the pole longitudes (Sager, 2006). The 94 and 80 Ma poles are also based on basalt core and seamount model declination data, but with the addition of some sediment core data (Sager, 2006). The 94 Ma pole (Fig. 5; Table 1) is revised here from the 92 Ma pole published in Sager (2006) by including oriented sediment core data from ODP Site 869 (Sager et al., 1995). In the previous calculation, pole error bounds were large because basalt core data near this age are few (Sager, 2006). The addition of the sediment data reduced the error ellipse greatly without changing the pole position significantly.

Paleomagnetic poles for 68, 61, 49, 39, and 30 Ma are based mainly on azimuthally-unoriented sediment core paleomagnetic data, but include information from basalt cores and seamount anomaly model declinations (Beaman et al., submitted). Data from anomaly skewness studies were not included in these pole calculations because Late Cretaceous skewness poles diverge from the APWP determined from other data (Fig. 3). The reasons for this discrepancy are not understood, so it was deemed prudent to use only the most consistent data (Beaman et al., submitted).

Another discrepancy is the separation of the 122 Ma Ontong Java pole from the N-S trend of the APWP (Fig. 3). In analyses of Early Cretaceous basalt core paleomagnetic data, it was found that data from Ontong Java Plateau appear anomalous and show ~10° less northward motion than data from elsewhere in the north Pacific (Sager, 2006). This difference was attributed to tectonic displacement of Ontong Java Plateau from the rest of the Pacific, but there is no good tectonic model to explain this discrepancy. Furthermore, younger Late Cretaceous and early Cenozoic sediment data from Ontong Java Plateau also appear show less northward motion (Hall and Riisager, 2006). It is unclear what has caused this dichotomy, but one implication is that some portion of the Pacific plate may have experienced ~10° less northward motion. Unfortunately, this hypothesis is difficult to test because there are few reliable, well-dated paleomagnetic data from south of the equator. Indeed, as Figure 1 shows, data used to derive the Pacific APWP are located almost entirely in the north Pacific. If the Pacific APWP curves to the west as shown in Figure 3 (dashed line to the Ontong Java Plateau pole) and the total northward motion is thus no more than ~20°, interpretations in this manuscript that rely on poles >80 Ma in age (those farther south) are unreliable. Interpretations for 80 Ma and younger poles, however, will not change significantly.

Pacific Hotspot Models

In the years after Wilson's (1963) hotspot hypothesis was published, alternative models were proposed for the formation of the Hawaiian Islands and Hawaiian-Emperor chain. One considered the melting anomaly to be caused by a propagating crack that caused asthenosphere melting and magma ascension to the surface (Jackson and Shaw, 1975; Jackson et al., 1975). Another called upon a crack and gravitational anchor (i.e., a negatively buoyant melt residuum whose sinking caused local convection and the rise and melting of asthenospheric material) (Shaw, 1973; Shaw and Jackson, 1973). However, once Morgan (1971) published his fixed hotspot model, it was rapidly accepted as the correct explanation based on the simplicity of the model, respect for Morgan's status as one of the formulators of the plate tectonics paradigm, and the fact that it seemed to follow logically from simple plate tectonics (Glen, 2005).

In the three decades plus since Morgan (1971) published his model of Pacific plate motion relative to the hotspots, many other authors have refined the Pacific model or created similar models for other oceans. On the whole, most have been derived in a similar manner: a series of stage rotation poles were determined to fit segments of seamount chains thought to be coeval and stage pole start/stop ages and rotation rates/angles were calculated from often sparse and sometimes inaccurate age data. For the Pacific, the main differences stem from different choices of which segments of seamount chains to be fit and the number and accuracy of age data used to determine pole ages and rotation angles. For example, Morgan (1971) used two rotation poles for his model, using primary trend and age control from the Hawaiian-Emperor chain. At the time, age data for the Hawaiian-Emperor chain were almost nonexistent. As new and revised radiometric dates for these and other Pacific seamounts became available, the model has been revised numerous times (Jarrard and Clague, 1977; Duncan and Clague, 1985; Fleitout and Moriceau, 1992; Wessel and Kroenke, 1997; Harada and Hamano, 2000; Raymond et al., 2000; Wessel et al., 2006).

Many of these models were constructed with a ~43 Ma date for the HEB, based on the once widely-accepted date for that feature from Clague and Dalrymple (1975). Recent geochronology studies indicate that this date is too young (Sharp and Clague, 2006) and many workers now accept an age of 47-50 Ma (e.g., Sharp and Clague, 2006; Wessel et al., 2006). The modeled age of the northern Emperor chain has also seen a significant change. Models published prior to the mid-1990s mostly assumed an age of 70-75 Ma for the northern terminus of the Emperor chain, based on the age of oldest sediments recovered by DSDP drilling from Meiji Seamount, the northernmost Emperor Seamount. Newer models use an age of ~81 Ma, based on radiometric dates from basalts cored from ODP Site 883 on Detroit Seamount (Keller et al., 1995).

It has been and continues to be problematic to make a model for Pacific seamount chains older than the northern Emperor Seamounts (>81 Ma) because the connection between older and younger chains is tenuous. Moreover, older western Pacific seamount chains tend to be short and have overlaps and inconsistencies in trends and age progressions. As a result, it has been difficult to construct a consistent plate motion model (e.g., Koppers et al., 2003). Models that go farther back in time than 81 Ma assume that the Line Islands chain is copolar and coeval to the Emperor Chain and that the Mid-Pacific Mountains (connected to the Line chain) and/or Wake Seamounts show older plate motion over the hotspots (e.g., Duncan and Clague, 1985; McNutt and Fischer, 1987; Wessel and Kroenke, 1997; Kroenke et al., 2004). The Mid-Pacific Mountains/Line Islands bend is assigned an age of ~90 Ma and the Mid-Pacific Mountains and Wake Seamounts trends take the model back to ~140 Ma. Although plausible, this model for earlier Pacific plate motion has significant uncertainties because of the complexity of the Mid-

Pacific Mountains and Line Islands (e.g., Winterer and Sager, 1995) as well as uncertainties in dates and alignments of other pre-81 Ma seamount chains (Koppers et al., 2003).

Recently, several investigators have used a different approach to modeling Pacific plate motion. Rather than determine stage poles based on seamount trends, Harada and Hamano (2000) and Wessel et al. (2006) solved for total reconstruction rotation poles that fit seamount positions within a variable number of linear Pacific chains. Having determined a series of rotation poles, an age model was calculated by fitting an age-distance function to all available seamount dates (Wessel et al., 2006). This approach has distinct advantages: it is less dependent on choices for copolar segments and break points between stage poles and it allows the model to make an optimal fit for all age data.

Two ramifications of the model are important to note. In its construction, all hotspots were considered as equal mantle plumes despite conclusions by others that the constellation of Pacific plumes may contain both primary (deep) and secondary (shallow) sourced plumes (Courtillot et al., 2003). If models of upper mantle flow are correct, differences in source depth could result in different implied volcanic propagation rates for different seamount chains (Doglioni et al., 2005; Cuffaro and Doglioni, this volume). The Wessel et al. (2006) model assumes the same propagation rate for all Pacific hotspots, but perhaps the discrepancies resulting from different source depths are hidden within the relatively large uncertainties in the average pole rotation rates. Another important implication is that the assumption of fixity for Pacific plate hotspots is remarkably good. Deviations of individual seamount chains from small circles concentric around the model rotation poles is very small (typically <1°). Whatever it is that these seamount chains describe, it is consistent. If the model does indeed represent motion of the plate over a series of hotspots, they show very little relative motion.

COMPARISON OF PALEOMAGNETIC AND HOTSPOT MODEL APWP

Pacific paleomagnetic apparent polar wander can be divided into six different phases, shown in Figure 3 by changes in direction or wander velocity. Moving forward in time, segment A consists of southward polar motion that implies southward motion of the Pacific plate during the Late Jurassic and Early Cretaceous. The 139 Ma skewness pole lies between the 123 and 112 Ma poles, seemingly out of order, but this pole has large east-west uncertainty, so it plausibly lies somewhere near the dashed blue line in Figure 3 that represents the short end of the fishhook. Segments B and C show northward motion of the pole and plate during the Mid- and Late Cretaceous. From existing data, it appears the plate turned around at ~123 Ma. Segment C is distinguished from B because the implied rate of polar drift doubled, with the pole shifting at ~1°/Myr between the 94 and 80 Ma poles. Phase D is a stillstand, with the paleomagnetic pole showing negligible motion between 80 and 49 Ma. After 49 Ma, the pole began moving northward again (Segment E) and shifted direction at about 30 Ma (Segment F).

Most segments of an APWP are thought to result from periods of stable plate motion with changes in APWP direction or speed caused by shifting boundary forces on the plate edges (e.g., Gordon et al., 1984). It appears that a plausible connection can be made between segments of the Pacific APWP and its tectonic history. During the Early Cretaceous, it is likely that the Pacific plate was small (Fig. 6) and surrounded by spreading ridges (Hilde et al., 1976). Without connections to Pacific-rim subduction zones, the plate should have moved relatively slowly and it could have changed directions. This appears consistent with the relatively slow polar motion (~0.5°/Myr) of APWP segments A and B. Sometime during the Mid- or Late Cretaceous, the Pacific plate became engaged with western Pacific subduction zones. The timing of this event is highly uncertain because the record of the western Pacific plate has been subducted, the western extent of the Pacific plate at that time is unknown, and the event probably occurred during the

Cretaceous Quiet Period, so there are no seafloor spreading magnetic lineations to show changes in plate motion. It is plausible that the connection occurred during the Early Cretaceous and explains the turnaround in motion around 123 Ma.

The stillstand from 80-49 Ma implies that the plate moved nearly east west (i.e., the pole of rotation that describes plate motion relative to the spin axis was located near the spin axis) (Fig. 4). This may have occurred because the western edge of the Pacific plate began to subduct while the northern edge was still separated from northern subduction zones by an intervening plate (Fig. 6), which seems to have been the case until well into the Cenozoic (e.g., Lonsdale, 1988). Northward motion would have resumed (segment E) when the Pacific plate northern edge began to subduct into the Aleutian Trench. Dating of the Aleutian Arc implies that this occurred during the Eocene (Scholl et al., 1986), which coincides with the recommencement of polar wander between 49-39 Ma (Fig. 3). The shift in APWP direction around 30 Ma may have resulted from changing plate boundary forces once the eastern Pacific plate came into contact with North America and the San Andreas transform system began to form (Atwater, 1989).

Despite differences in data and methods used to derive models of Pacific plate motion relative to the hotspots, APWP predicted by these models are similar. The models all show predicted pole positions trending southward in the north Atlantic, more-or-less along the prime meridian (Fig. 7). Scatter in predicted pole positions increases with age; for 20 Ma, the 95% confidence circle of the mean of predicted poles is only ~2°, but for 80 Ma, this has increased to ~6°. All models show rapid polar motion throughout the Late Cretaceous and Cenozoic, many with a kink in the path corresponding to the HEB. The total displacement from the spin axis is ~12° for 40 Ma and ~30° at 80 Ma, the difference reflecting polar motion during the time of the Emperor chain formation.

Predicted polar wander prior to the Emperor chain is poorly known and most plate motion models do not treat this period. Two models are plotted in Figure 3 (Duncan and Clague, 1985; Wessel et al., 2006) and both show the APWP bending to the west at ~100 Ma. The earlier model is simpler and uses a single rotation pole to describe Early Cretaceous plate motion, whereas the latter contains several kinks where different sets of seamount trends define segments of the rotation model (Wessel et al., 2006).

Comparison of the paleomagnetic APWP with the predicted APWP from hotspot models shows excellent correlation for the past ~50 Myr, but significant discrepancies for earlier times (Fig. 3). The Wessel et al. (2006) predicted APWP has a 30 Ma pole well within the 95% confidence ellipse of the 30 Ma paleomagnetic pole; the 40 Ma predicted pole is very close to the 39 Ma paleomagnetic pole; and the 50 Ma predicted pole is within the confidence ellipse of the 49 Ma paleomagnetic pole. In other words, the two paths are statistically indistinguishable for much of the Cenozoic.

A major offset between predicted and measured polar paths occurs from 80 to 49 Ma, during which time the paleomagnetic APWP shows a stillstand while the hotspot-derived APWP indicates significant polar motion. Even with the large paleomagnetic pole confidence ellipses and allowing for several degrees of uncertainty in the predicted pole position (Wessel et al., 2006), the two paths appear distinct by 61 Ma (Fig. 8). In all, the hotspot model predicted APWP shows a maximum difference of 15° compared to the paleomagnetic APWP. This difference implies ~19° of southward motion for the Hawaiian hotspot from 80-49 Ma because the paleomagnetic data imply that the plate did not move northward during the time that the Emperor Seamounts formed. (Note: Because of spherical geometry, offset values are different depending on the location of the points being compared. Thus, the offset between paleomagnetic poles in the north Atlantic is different from the offset in seamount locations in the central Pacific.)

Farther back in time, the details of the hotspot model predicted APWP diverge from one another and the paleomagnetic APWP because of the poorly-known connections to earlier seamounts. Neither predicted APWP implies a spurt of rapid apparent polar wander to match that observed between the 94-80 Ma paleomagnetic poles. Prior to that time both predicted APWP trend westward, broadly consistent with the hook in the paleomagnetic APWP. The Wessel et al. (2006) model comes closest to matching the paleomagnetic data, with the predicted APWP implying slow polar motion and slow northward motion of the plate from about 125-90 Ma. The oldest part of the predicted APWP implies mostly E-W polar motion with a slight southward component and thus the predicted model implies a turnaround in plate motion at about the same time as indicated by paleomagnetic data. Although the 145 Ma paleomagnetic pole suggests a large difference between the predicted and paleomagnetic polar paths, the accuracy of paleomagnetic poles of this age is uncertain and the discrepancy is much less for the 139 Ma pole.

DISCUSSION

On the whole, the trend of the paleomagnetic APWP and that predicted from hotspot-derived plate motion models are broadly similar. The hotspot-derived plate motion models predict a large amount (~40°) of northward motion of the Pacific plate since Mid-Cretaceous time, similar to the paleomagnetic APWP. Furthermore, hotspot-derived models that describe motion prior to the Emperor chain predict a significant change in apparent polar wander direction, with earlier polar motion nearly east-west (Duncan and Clague, 1985), perhaps with a slight component in the north-south direction indicating Late Jurassic-Early Cretaceous plate motion to the south (Wessel et al., 2006). Although there appears to be general agreement, there are large offsets (>5°) between the paleomagnetic and hotspot-model predicted APWP (Fig. 8). Both APWP show a Cretaceous turnabout in plate motion, but paleomagnetic data may indicate greater southward motion of the plate during the Late Jurassic-Early Cretaceous and that the APWP bend is sharper. Furthermore, the hotspot-model predicted APWP indicates relatively uniform northward motion, with over 30° of polar motion since 80 Ma, whereas the paleomagnetic APWP shows significant changes in the rate of polar motion with rapid polar wander between 94-80 Ma and a stillstand from 80-49 Ma. The paleomagnetic data imply only ~17° of northward motion since 80 Ma.

Which APWP Differences are Significant?

Although there is >5° offset between hotspot-predicted and paleomagnetic APWP poles for much of Pacific plate history, it is not immediately clear how large a difference is significant. The paleomagnetic poles have been calculated with usually >10 different data from different locations; thus, they represent a large area average. Uncertainty (95% confidence) ellipses are mostly <5° on the minor semi-axis and <10° on the major semi-axis. Moreover, the short axis is usually aligned nearly north-south, so the uncertainty is least in the direction corresponding to paleolatitude differences. Hotspot-predicted poles are outside the paleomagnetic pole confidence ellipses for the 61, 68, 80, 94, and 145 Ma poles, but within the uncertainties of the 30, 39, 49, 113, 123, and 139 Ma poles (Figs. 3, 8). Those hotspot-predicted poles that are within the paleomagnetic pole confidence ellipses of the same age are not statistically distinct.

Uncertainties for the hotspot-predicted pole positions are not determined for most models; however, Wessel et al. (2006) estimated errors for their model for the present back to 67 Ma. Typical 95% uncertainty ellipses are highly elongated along the direction of plate motion but narrow in the perpendicular direction because the minor semi-axis is controlled by the easily measured seamount chain geometry whereas the major semi-axis is constrained by sparse age data that define the volcanic migration rate along track. Uncertainty ellipses for the older, Emperor chain poles are ~8° in length versus 2-3° in width and slightly smaller for the late Cenozoic. Taking into account these estimated errors, the hotspot-predicted and paleomagnetic poles for 61 Ma may not be distinct because there is probably a significant overlap of uncertainty ellipses. Uncertainties were not estimated for older hotspot model poles (Wessel et al., 2006), but if similar to those for 67 Ma, the differences between 68 and 94 Ma poles may not be as significant as suggested by Figure 8 because the hotspot-model predicted poles have large N-S uncertainties (and confidence ellipses would overlap at least a little). However, given the large distance between the hotspot-model predicted and paleomagnetic poles for 80 Ma, this offset is large enough to be distinct.

Given the large uncertainty for the paleomagnetic APWP prior to ~123 Ma and the significant uncertainties in connecting pre-Emperor age (~81 Ma) seamounts to Late Cretaceous-Cenozoic plate motion models, the cause and significance of the differences between observed and predicted APWP are unclear. There may well be significant differences in the amount of northward motion and timing implied by the two different polar paths, but conclusions based on those differences are premature given the data and model uncertainties. More paleomagnetic data are needed for the Late Jurassic and Early Cretaceous as are better models of hotspot motion for the same period.

Although the preceding discussion seems to suggest that the two polar paths are almost indistinguishable, the APWP differences for the Late Cretaceous are both large and systematic.

Furthermore, implications for the motion of the Pacific plate imply markedly different tectonics for this time period.

Implications of Late Cretaceous-early Cenozoic Polar Wander

As noted previously, the paleomagnetic and hotspot model predicted APWP are indistinguishable for times 49 Ma and after. In contrast, the most notable and significant differences occur from 94-49 Ma. The distance between the 94 and 80 Ma paleomagnetic poles (~13°) and the age difference imply rapid northward polar motion at ~1°/Myr (Sager, 2006). Although there is relatively large uncertainty in the distance of polar motion (±7°) and the ages of poles (2-3 Myr), the finding of rapid polar motion seems robust, having been noted in other analyses of similar data sets (e.g., Cottrell and Tarduno, 2003) and in a largely independent paleomagnetic data set derived from seamount magnetic anomalies (Sager and Koppers, 2000). The reason for the rapid polar motion is not known. It implies rapid northward motion of the Pacific plate (Cottrell and Tarduno, 2003), but there is no indication that during the Mid-Cretaceous the Pacific plate was engaged on its northern boundary in a subduction zone that would have given it a large northward component of motion (Fig. 6). Sager and Koppers (2000) contended that the rapid polar motion resulted from TPW. Although some investigators found paleomagnetic evidence from global composite APWP to support this idea (Prévot et al., 2000), others disagree (e.g., Torsvik et al., 2002; Cottrell and Tarduno, 2003). The result is that there is no consensus for about the source of this rapid polar shift.

If the cause is TPW, the shift should be found in paleomagnetic data across the globe. Comparing Pacific paleomagnetic poles with others from the rest of the globe can be difficult because of the differing plate motions. A number of authors have made inter-plate comparisons by removing plate motions defined relative to the hotspots. Having done so, the remaining polar wander is sometimes interpreted as TPW (i.e., wander of the spin axis relative to the hotspots/mantle). Figure 9 shows that two global average, mantle APWP indicate motion of the spin axis toward the Pacific Ocean during the Late Cretaceous and early Cenozoic. Figure 10 explains how a shift of the spin axis toward the Pacific causes apparent northward motion of the plate, which is what the 94-80 Ma pole shift suggests. The Besse and Courtillot (2002) APWP implies ~8° of motion from 90-67 Ma and the Prévot al. (2000) APWP indicates ~16° from 80-65 Ma. Both curves were constructed with 20-Myr averages, which tend to smooth abrupt changes in polar wander. Nevertheless, if the hotspot based plate motion models used in those studies for backtracking the paleomagnetic data are correct, both APWP support the idea that the rapid 94-80 Ma shift in Pacific paleomagnetic poles may have been caused by a shift in the spin axis, i.e., TPW.

The finding of a polar stillstand from 80-49 Ma is startling because it implies a very different tectonic motion than previously thought during the period corresponding to formation of the Emperor Seamounts. The nearly north-south trend of these seamounts (and other similar chains, e.g. Wessel et al., 2006) has been used to infer that Pacific plate motion was largely north-south during this period. Indeed, this implied northward drift is so ingrained that dozens of western Pacific tectonic models have incorporated this ~20° of northward motion (e.g., Hilde et al., 1976; Engebretson et al., 1984). In contrast, the paleomagnetic APWP implies negligible (~4° or less) north-south motion during the Emperor Seamounts period. This is a drastic difference with revolutionary implications. If the paleomagnetic APWP is correct, many tectonic models will have to be rethought.

Paleolatitudes for the Hawaiian-Emperor chain (estimated from the distance between seamounts and the APWP poles; Fig. 11) agree with the paleolatitude trend in basalt core data from the Emperor chain (Tarduno et al., 2003). Agreement is not surprising because the Emperor data were used in the APWP calculations, but the point is that a larger set of paleomagnetic data from widespread locations say the same thing as data from drill cores recovered from four Emperor Seamounts. The paleolatitude of the plate and Hawaiian hotspot apparently changed in the same linear manner during the time corresponding to 80-49 Ma poles. After this time, the implied hotspot paleolatitude was the same as its present location, in agreement with published findings (e.g., Sager, 1984; Sager et al., 2005).

In a graph of total northward motion (Fig. 11), paleomagnetic data agree with the hotspot-predicted latitude of the Hawaiian-Emperor seamounts (Wessel et al., 2006) from 30-49 Ma. In contrast, the 61-80 Ma poles predict little northward drift while the hotspot-predicted northward drift increases rapidly, leading to an offset of up to ~18° at 80 Ma. Equatorial-band sediments from Cretaceous DSDP cores from the western Pacific (see Sager, 1984) agree with the amount of northward drift implied by the paleomagnetic poles (Fig. 11). Recent estimates of paleolatitude from equatorial-band sediments for the Cenozoic (Parés and Moore, 2005) show a similar trend as the paleomagnetic poles and seamount chains, but with an offset of ~3° to the south. The agreement of two independent types of paleolatitude data (paleomagnetic and paleoequator) imply that the paleomagnetic data are accurate; although, the 3° Cenozoic offset suggests a potential for a small, systematic bias in one or the other. One possibility is that the equatorial sediment band, which is related to equatorial currents, may not have been precisely at the equator. Another is that the geocentric axial dipole assumption for paleomagnetic data may be slightly inaccurate owing to long-term non-dipole components in the time-averaged geomagnetic field (McElhinny et al., 1996; Courtillot and Besse, 2004).

The simplest explanation for the discrepancy between paleomagnetic and hotspot-predicted APWP for this period is that the hotspot moved rapidly south while the plate moved mostly east-west. Two mechanisms for such a shift have been proposed. Some investigators have argued that the hotspot itself shifted ~13° in latitude as a result of flow in the mantle (e.g., Tarduno et al., 2003; Steinberger, 2000; Steinberger and O'Connell, 2000; Steinberger et al., 2004). Others have posited TPW, a shift of the entire mantle (and embedded hotspots) relative to the spin axis (e.g., Gordon and Cape, 1981; Duncan and Storey, 1992). With paleomagnetic and paleolatitude data from only one plate, it is difficult to distinguish between these two hypotheses. TPW should give a coherent shift of hotspots over the entire globe, whereas mantle flow should yield globally-inconsistent motions (Fig. 2).

In order for TPW to cause the observed apparent southward motion of the hotspot, the spin axis must have moved away from the Pacific (Figs. 9, 10). Of the two global synthetic APWP shown in Figure 9, one implies a small shift (~8°) of the spin axis away from the Pacific from 65-45 Ma (Prévot et al., 2000), but the other does not (Besse and Courtillot, 2002). Given the magnitude of the shift implied by Pacific paleomagnetic data, it seems probable that such a large shift would appear prominently in global pole compilations, even with severe averaging. Furthermore, TPW as an explanation for the southward motion of the Hawaiian hotspot is unsatisfying because it does not explain the HEB. With TPW, the Pacific plate and mantle would move together and there would be no cause for an apparent change of plate motion relative to the Hawaiian hotspot. Thus, if TPW is posited to be the reason that the paleolatitudes change, then the HEB then implies the coincident action of some other phenomenon.

Hotspot motion within the mantle as an explanation for the apparent rapid hotspot drift also has difficulties. The paleomagnetic data imply ~19° of paleolatitude change for the

Hawaiian hotspot whereas favored mantle flow model explain only ~12-13° (Steinberger, 2000; Steinberger and O'Connell, 2000; Steinberger et al., 2004; Steinberger and Antretter, 2006). It is unclear whether such models can readily explain the ~50% greater amount of paleolatitude shift with reasonable adjustments to model parameters. Even more problematic than the drift rate is the direction of hotspot motion. Existing mantle flow models have the Hawaiian hotspot moving south or southeast, responding to mantle flow toward eastern Pacific upwelling. The north-south trend of apparent hotspot motion during the formation of the Emperor Seamounts, however, implies a significant westward component of hotspot velocity (Steinberger et al., 2004).

The motion of the hotspot relative to the mantle, ${}_{m}\mathbf{V}_{h}$ (bold indicates a vector), is the difference of the vector representing plate motion relative to the hotspot, ${}_{h}\mathbf{V}_{p}$, and the vector representing plate motion relative to the mantle, ${}_{m}\mathbf{V}_{p}$ (Fig. 12). The trend of the Emperor Seamounts gives an estimate of ${}_{h}\mathbf{V}_{p}$ for the Late Cretaceous and early Cenozoic. Although the velocity of the Pacific plate relative to the mantle is unknown, it can be assumed that it was either similar to the late Cenozoic motion (NNW) or nearly east-west because of the paleomagnetic paleolatitude constraints (i.e., negligible northward motion). Given paleomagnetic pole uncertainties, these two assumptions may not be significantly different. Either is reasonable because the plate was probably engaged in western Pacific subduction zones that would have pulled it westward, but probably not yet subducting into the Aleutian Trench to provide a northward component of motion (Fig. 6). The vector diagram in Figure 12 indicates that if the Pacific plate had a significant westward motion, the hotspot must have had a similar component of westward motion so that the two nearly canceled to produce seamounts with a nearly north south trend. The amount of westward hotspot motion inferred therefore depends on the amount of westward motion assumed for the plate. The length and age span of the Hawaiian chain gives approximate average progression rate of 78 km/Myr, whereas the Emperor chain suggests an average progression rate of 62 km/Myr. Adding these estimated vectors gives a velocity of ~67 km/Myr at an azimuth of ~224° (Fig. 12), nearly at right angles to the predicted direction of Hawaiian hotspot motion (Steinberger, 2000). Although this estimate is crude because of the gross averages for velocity vectors and planar approximation, it clearly shows that the hotspot probably moved in a southwesterly direction.

In sum, large differences between measured and hotspot-predicted APWP for the Late Cretaceous to early Cenozoic are a challenge for existing explanations of hotspot drift during the formation of the Emperor chain. Both TPW and hotspot motion caused by mantle flow have drawbacks. Neither is disproven, certainly, but perhaps these difficulties indicate that other hypotheses should be considered more carefully. Several authors in this volume (Foulger, this volume; Norton et al., this volume; Smith et al., this volume; Stuart et al., this volume) and elsewhere (Natland and Winterer, 2005) suggest that the Hawaiian-Emperor chain (and other Pacific seamount chains) could have formed from a propagating crack that was initiated by and whose path has been determined by changing stresses applied by shifting plate boundary forces. A crack, for example, might not suffer from the problem that the paleolatitude shift of the Emperor seamounts was rapid and that the HEB implies an abrupt change in hotspot motion.

Comparison of Pacific and Antarctic APWP

Several studies have used motion models of Indian and Atlantic ocean plates relative to the hotspots to predict the motion of the Pacific plate relative to the hotspots (Stock and Molnar, 1987; Cande et al., 1995; DiVenere and Kent, 1999; Raymond et al., 2000). This is done by connecting the plates by models of relative motion derived from spreading boundaries. For the Pacific plate, the most direct connection to plates outside the Pacific rim is through Antarctica.

The idea is that if the hotspots constitute a fixed constellation of mantle position markers, motion of the Pacific plate reconstructed from Indian and Atlantic plate motion will match that derived from hotspot tracks on the Pacific plate itself. Such analyses are usually able to match the younger Hawaiian Seamounts reasonably well, but fail to show the amount of northward motion suggested by the Emperor Seamounts (Stock and Molnar, 1987; Cande et al., 1995; di Venere and Kent, 1999; Raymond et al. 2000). One interpretation is that this shows inter-hotspot motion, but another is that the plate circuit is flawed because relative motion has occurred on an undefined plate boundary hidden within Antarctica or the southern Pacific plate (Acton and Gordon, 1994).

With a refined Pacific paleomagnetic APWP, it is possible to test the Antarctic plate circuit by rotating the APWP into the Antarctic reference frame (closing up the opening of the Pacific-Antarctic ridge) and comparing with the Antarctic APWP. Because the Antarctic APWP is poorly defined owing to sparse data, the comparison must be made with a composite APWP constructed for the continents and rotated to Antarctica (Besse and Cortillot, 2002). This synthetic APWP is located mostly in east Antarctica, on the Atlantic side of the 120° and 300° meridians (Fig. 13). In contrast, Pacific APWP south poles are rotated 8°-14° toward Antarctica by closure of Late Cretaceous and Cenozoic spreading on the Pacific-Antarctic ridge (using the spreading model of Cande et al. (1995), updated by Tebbins and Cande (1997), with the Late Cretaceous pole of Mayes et al. (1990)). Except for the 80 Ma pole, the rotated Pacific poles are all on the Pacific side of the 120° and 300° meridians, separated by ~10° from the Antarctic APWP. The uncertainty ellipses for the 39-68 Ma Pacific poles do not overlap the uncertainty circles of coeval poles for the Antarctic APWP and probably would not overlap significantly even if uncertainties for the plate rotations were explicitly included. The systematic offset has been noted by other authors (Acton and Gordon, 1994; Andrews et al., 2004) and probably indicates problems with the plate circuit through Antarctica. It is unclear whether the problem occurs with the spreading models for the Pacific-Antarctic or Southwest Indian Ridge (which brings the continental APWP to Antarctica from Africa) or whether the problem is poorly documented plate boundaries in the south Pacific plate or Antarctica (Acton and Gordon, 1994). Whatever the cause, the systematic mismatch of most Pacific and Antarctic paleomagnetic poles suggests that reconstructions of Pacific hotspot tracks using Indo-Atlantic plate motions and a plate circuit through Antarctica (or vice versa) and interpretations of inter-hotspot motion made from them may not be reliable.

SUMMARY AND CONCLUSIONS

Comparison of the Pacific plate paleomagnetic APWP with an APWP derived from models of plate motion relative to the hotspots show differences of up to 15°. Cenozoic poles from 30-49 Ma agree within uncertainties, indicating no significant difference between the paleomagnetic and hotspot reference frames for that period. Uncertainties in Late Jurassic and Early Cretaceous paleomagnetic poles and plate motion models relative to the hotspots make the significance of offsets between the two reference frames prior to ~123 Ma uncertain, even though those differences range from 6°-9°. The offset during the period 112-61 Ma appears significant and shows a maximum for the 80 Ma pole. Whereas the hotspot plate motion model shows nearly constant northward motion from ~95 Ma into the Cenozoic, the paleomagnetic APWP has a period of rapid polar wander from 94-80 Ma, followed by a stillstand from 80-49 Ma. The cause of the rapid polar motion from 94-80 Ma is uncertain, although comparison with global paleomagnetic polar wander curves suggests that it may have resulted at least partly from TPW. It is less clear whether TPW is an adequate explanation for the offset between reference frames for 80-49 Ma. Although one global TPW curve shows similar spin axis motion, TPW does not readily explain the large implied difference in plate motion relative to the hotspots implied by the HEB. A change in hotspot motion is a simpler explanation. Paleomagnetic data indicate that the 80 Ma offset is 15° between APWP, implying ~19° of southward motion of the Hawaiian hotspot. This is considerably (~50%) greater than the southward drift implied by previous studies. Furthermore, consideration of average velocity vectors for the Pacific plate and Hawaiian hotspot indicate that the hotspot had a westward velocity that nearly equaled the westward motion of the Pacific plate. The rapid implied drift of the hotspot relative to the mantle may prove challenging to explain by mantle flow because the implied drift velocity is ~50% greater than published models and it is almost at right angles to modeled flow directions. If neither TPW nor mantle flow are an adequate explanation for the apparent hotspot drift, it is appropriate to consider other explanations.

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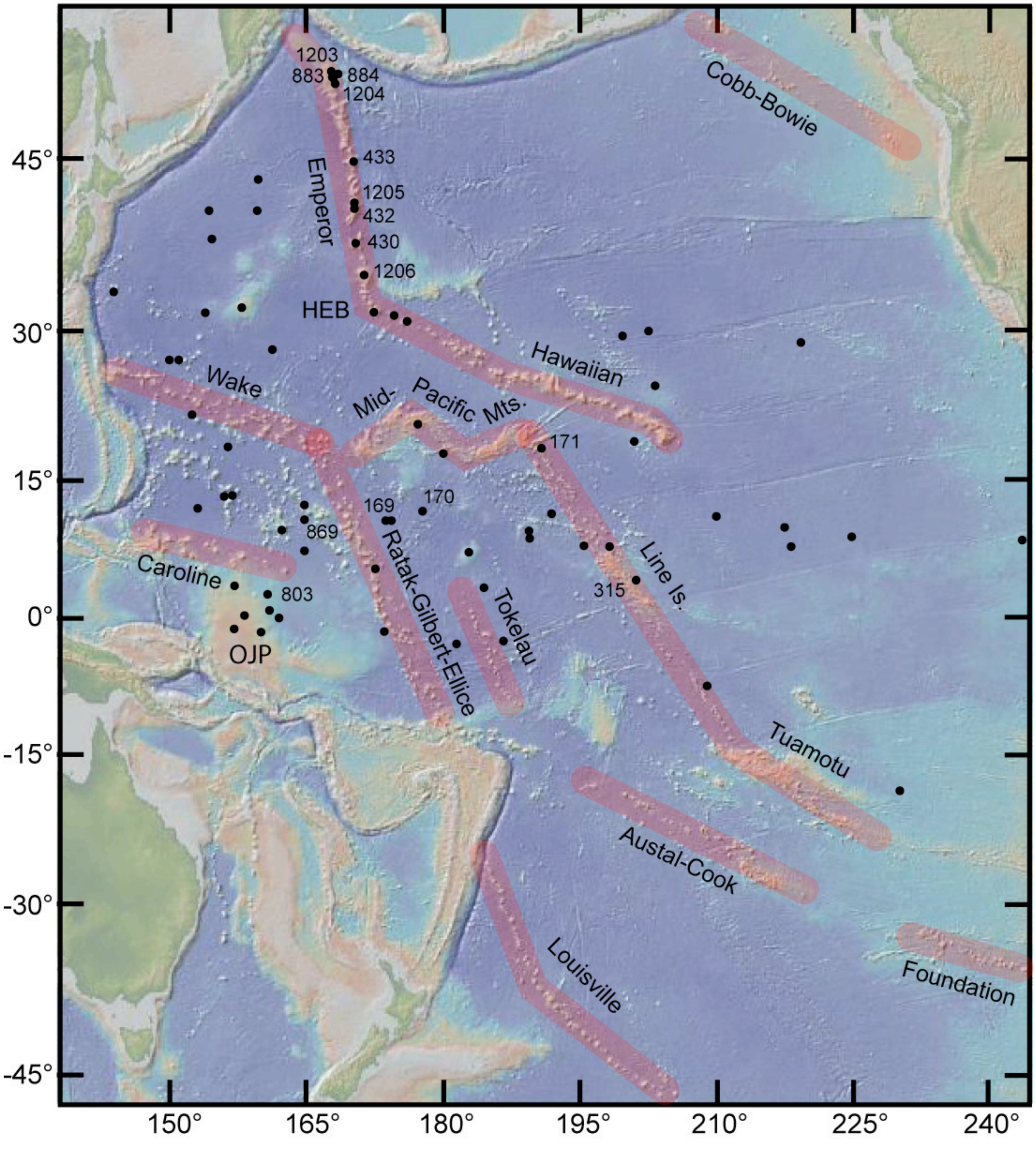
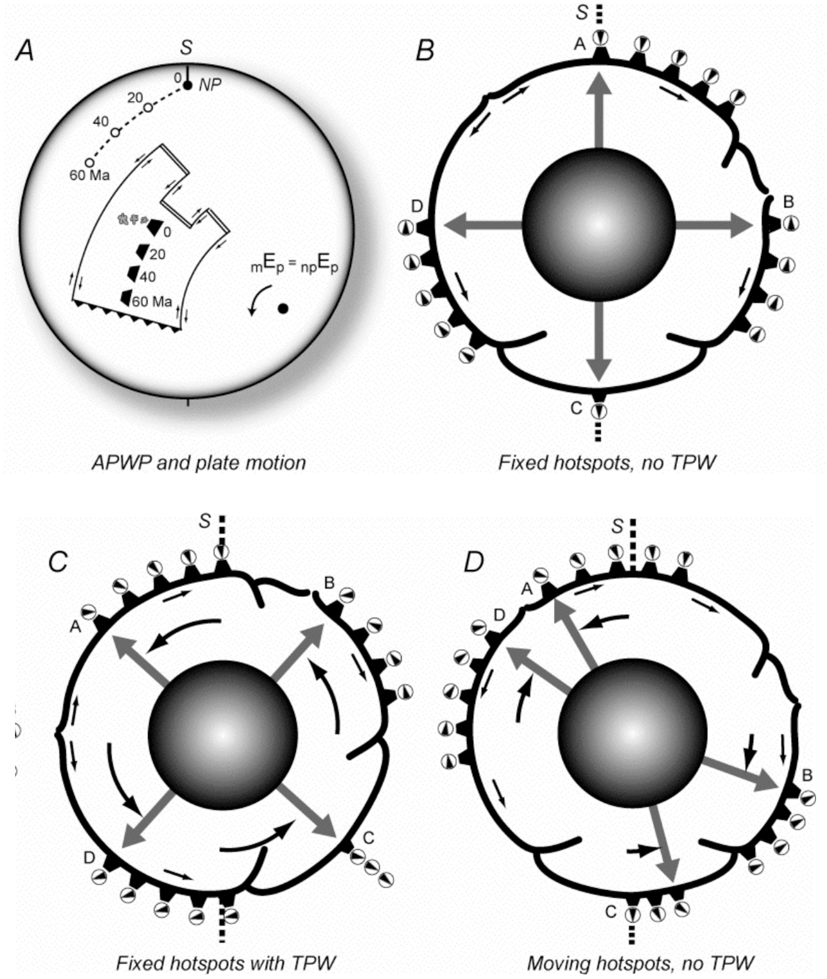


Figure 1. Hotspot seamount chains on the Pacific plate. Shaded areas show seamount chains mentioned in text. HEB is the Hawaiian-Emperor Bend. OJP is Ontong Java Plateau. Dots show sampling locations for paleomagnetic data used in apparent polar wander path calculations (Sager, 2006; Beaman et al., submitted). Numbers denote DSDP and ODP sites on the Emperor chain and other data used for revision of 94 Ma pole (Table 1). Note that sample locations are largely restricted to the northern hemisphere.



APWP and plate motion

Fixed hotspots, no TPW

Fixed hotspots with TPW

Moving hotspots, no TPW

Figure 2. Cartoon showing relationships among polar wander, hotspot drift, and true polar wander (TPW). A: Movement of a plate relative to the spin axis is described by a rotation pole $_{np}E_p$. The apparent polar wander path (APWP) traces a small circle segment concentric on the rotation pole for the time period for which the rotation pole applies. If a hotspot forms a seamount chain and there is no drift of the hotspot relative to the spin axis, the seamounts formed by the hotspot also trace a small circle concentric on the same rotation pole. If there is no TPW, the spin axis is fixed relative to the mantle and the rotation pole describing the motion of the plate relative to the mantle, $_mE_p$, is the same as $_{np}E_p$. B: If hotspots (points A through D) are fixed relative to the mantle and there is no TPW, all hotspot paleolatitudes will remain the same through time. The arrows indicate the paleomagnetic inclination which is zero (horizontal magnetization) at the equator (hotspots B and D) and vertical at the poles (hotspots A and C). C: If the hotspots A through D are fixed relative to the mantle, but the mantle shifts relative to the spin axis (i.e., TPW), seamount paleolatitudes (and paleomagnetic poles) will change through time, but in a globally coherent manner. D: If there is no TPW, but the hotspots move independently relative to the spin axis with time, the hotspot paleolatitudes (and paleomagnetic poles) shift with time, but in a manner that is not consistent across the Earth. (redrawn from Carlson et al., 1988)

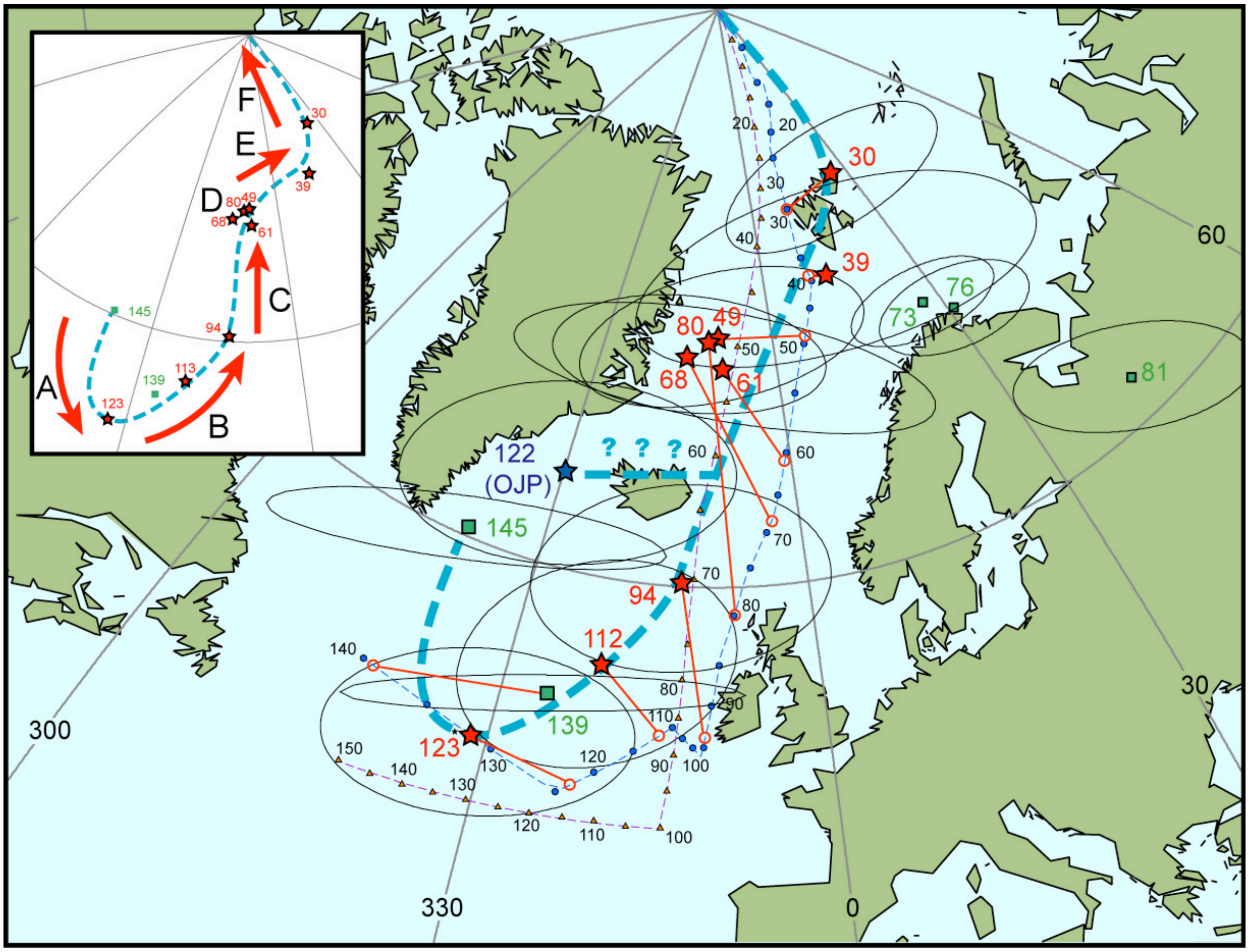


Figure 3. Pacific apparent polar wander path. Red stars denote pole positions defining the most likely APWP (Sager, 2006; Beaman et al., submitted), shown by the blue, heavy dashed line. Poles are surrounded by 95% confidence ellipses and labeled by age in Myr. Blue star denotes Ontong Java Plateau pole, which is considered anomalous (Sager, 2006). Green squares show poles determined from magnetic lineation skewness (73, 76, and 81 Ma poles from Petronotis and Gordon (1999), Vasas et al., (1994); 139 and 142 Ma poles from Larson and Sager (1992)). The Late Cretaceous skewness poles are considered anomalous (Beaman et al., submitted). Thin dashed lines show predicted polar wander path from plate/hotspot motion models of Duncan and Clague (1985) (purple with triangles) and Wessel et al. (2006) (blue with dots). Triangle and dot symbols show predicted pole positions at 5-Myr intervals, labeled every 10 Myr. Red lines show offset between paleomagnetic and hotspot model predicted poles. Inset sketch map shows interpreted phases of polar wander. Plot is an equal area map. Numbers are pole ages in Ma.

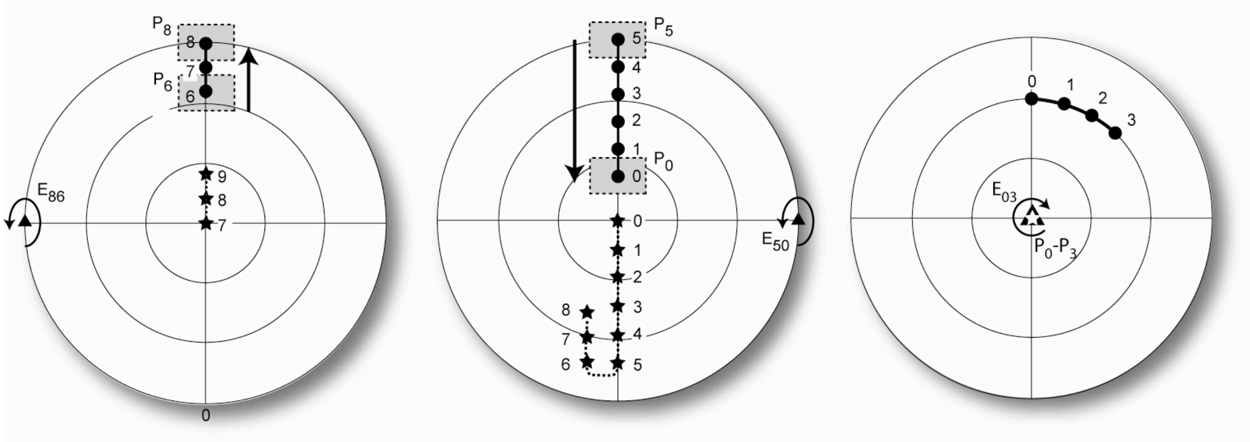


Figure 4. Cartoon explaining APWP “fishhook” shape. Plots show geographic pole viewed from above. Left: Southward drift of plate from ages 8 to 6, described by rotation around Euler pole E_{86}, moves plate from locations P_6 to P_8. Points 6 to 8 (filled circles) show motion of marker point on plate. This motion causes APWP (stars) with ages increasing toward the plate. Middle: Northward drift of plate from ages 5 to 0, described by rotation around Euler pole E_{50}, moves plate from locations P_5 to P_0. Points 5 to 0 show motion of marker point on plate. This motion causes APWP with ages increasing away from plate. Overall shape of APWP is a fishhook, that indicates southward motion followed by northward motion of plate. Right: If the Euler pole (E_{03}) coincides with the spin axis, no polar wander occurs and the time series of paleomagnetic poles does not appear to move (a stillstand). If later plate tectonic motion occurs such that the recorded Euler pole is moved away from the spin axis, the APWP will have a cluster of poles ($P_3 = P_2 = P_1 = P_0$), at some point that is not at the spin axis.

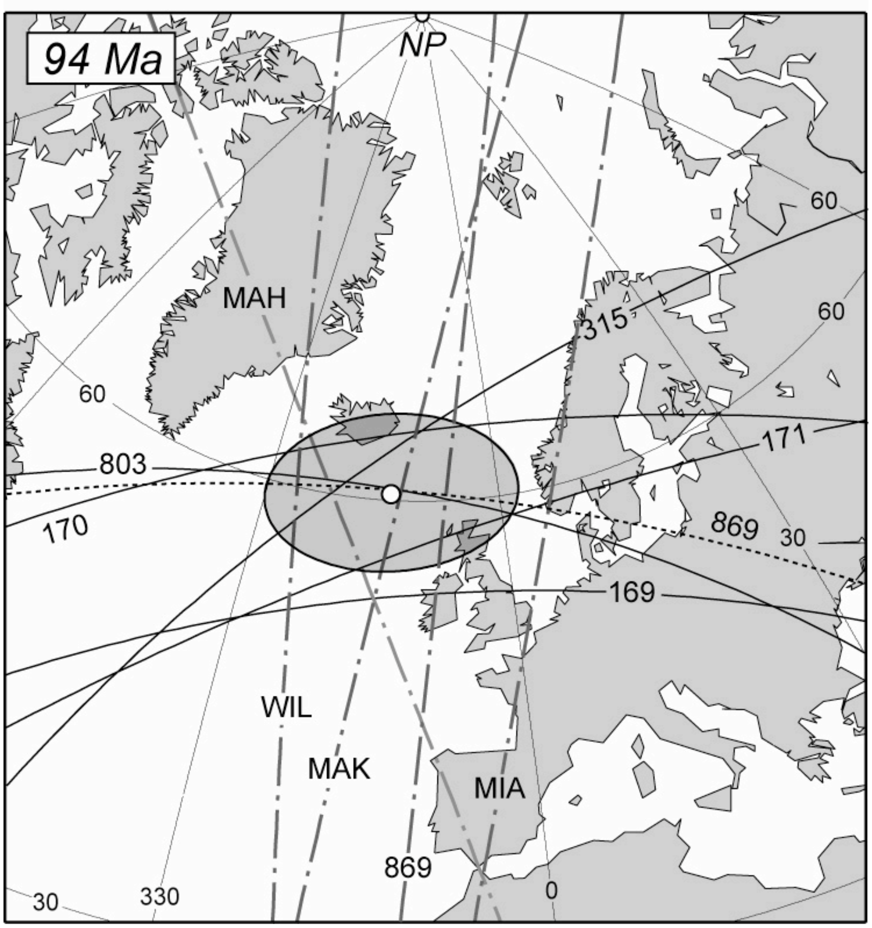


Figure 5. Revised Late Cretaceous mean paleomagnetic pole for 94 Ma. Data used for the pole calculation are the same as those for the 92 Ma pole of Sager (2006) but with the addition of sedimentary inclination and declination data from ODP Site 869 (Sager et al., 1995). Solid arcs show the locus of the paleomagnetic pole inferred from the mean paleomagnetic inclination from basalt or igneous core data. Dashed arc shows the same from Site 869 sediment data. Nearly vertical dash-dot lines show pole location inferred from seamount anomaly model declination data. Open circle is mean pole position and surrounding ellipse is 95% confidence region (Table 1). Numbers give DSDP and ODP site numbers. MAH, WIL, MAK, and MIA are abbreviations for seamount names (see Sager (2006) for data and sources). Equal area projection.

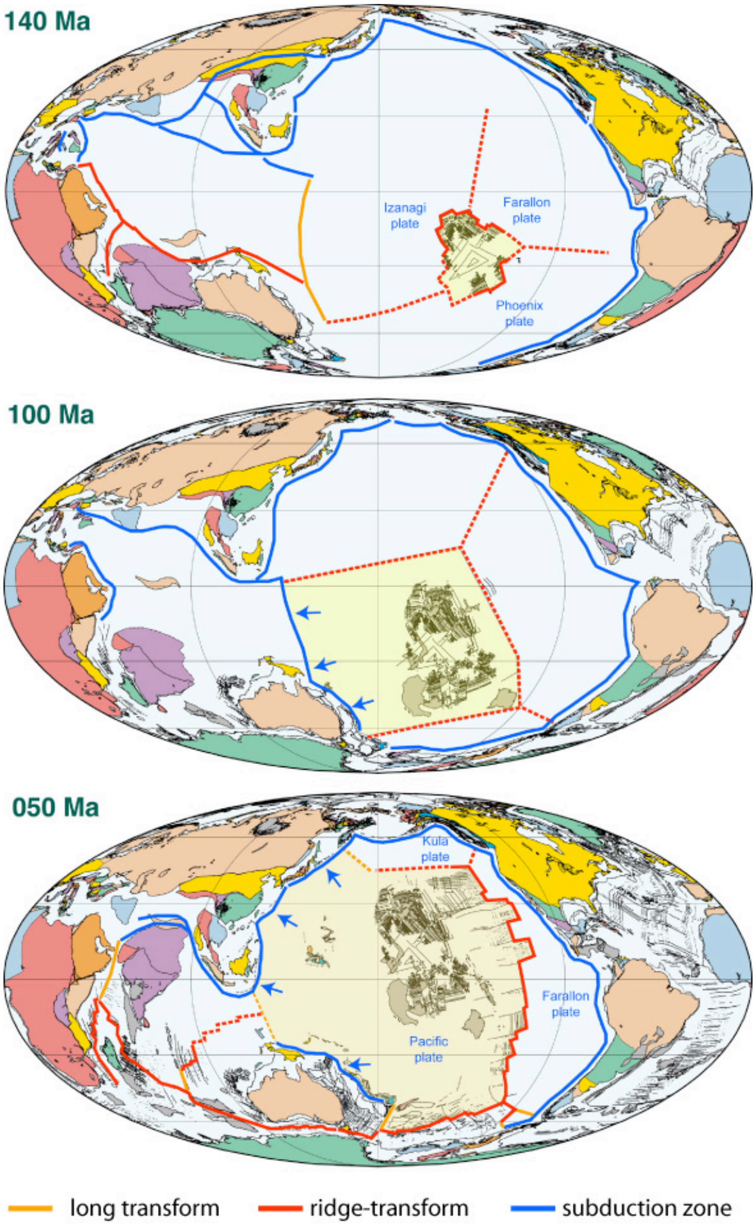


Figure 6. Sketch maps showing plate boundaries surrounding the Pacific plate at three times in the past. Dashed lines show most uncertain boundaries. Blue arrows show subduction of Pacific plate. Reconstructed continents and magnetic lineations from Lawver et al. [2003]. Pacific lineations and features were backtracked relative to the Indo-Atlantic plates using a plate circuit. Plate boundaries were taken from many sources.

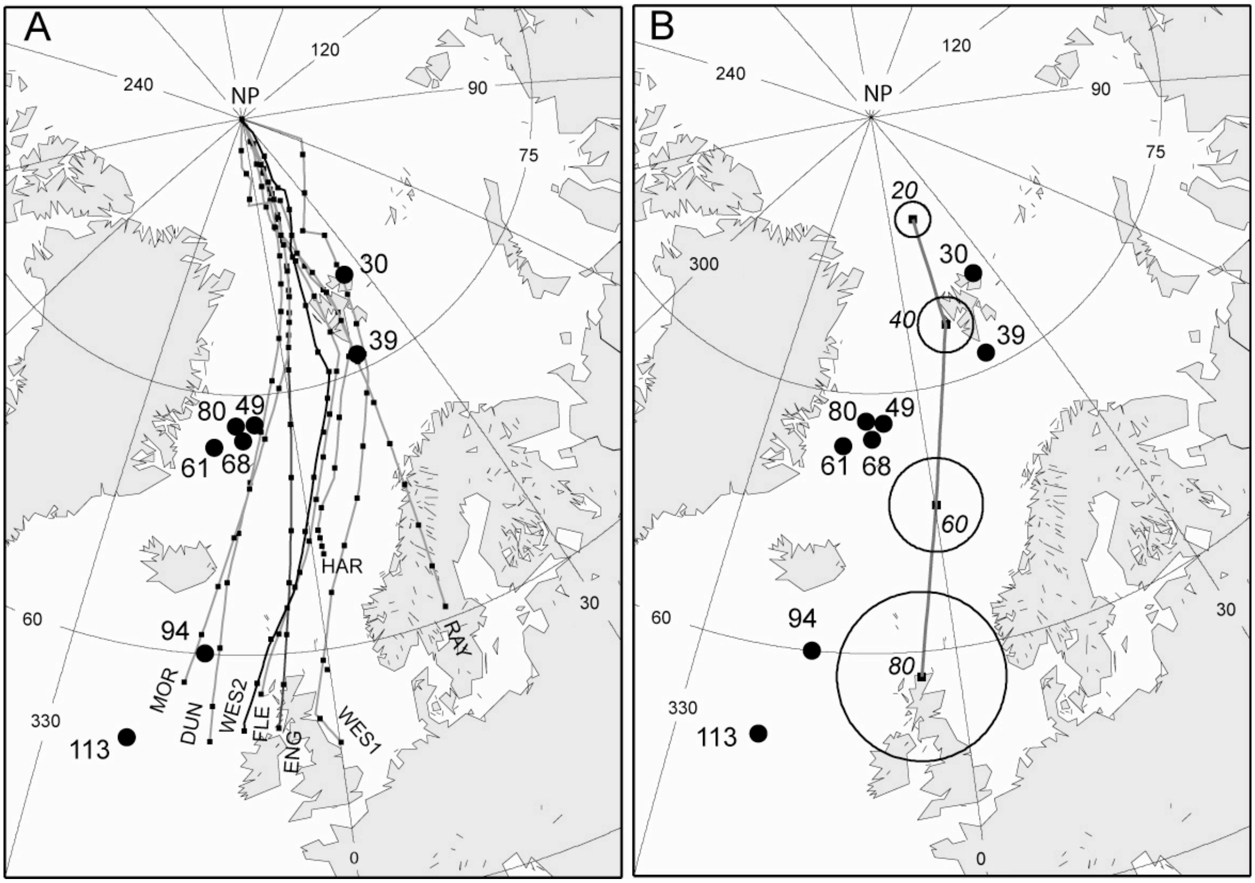


Figure 7. Predicted Pacific APWP from various models for the last 80 Ma assuming hotspots fixed relative to the spin axis. Filled circles are paleomagnetic mean poles (Fig. 3), labeled by age in Myr. A shows APWP predicted by each model, with dots at 5 Myr intervals. B shows average positions (and 95% confidence region around the mean) for the 20, 40, 60, and 80 Ma predicted poles. Abbreviations for models are MOR (Morgan, 1971), DUN (Duncan and Clague, 1985), WES1 (Wessel and Kroenke, 1997), WES2 (Wessel et al., 2006), FLE (Fleitout and Moriceau, 1992), ENG (Engebretson et al., 1984), HAR (Harada and Hamano, 2000), RAY (Raymond et al., 2000). Numbers are pole ages in Ma.

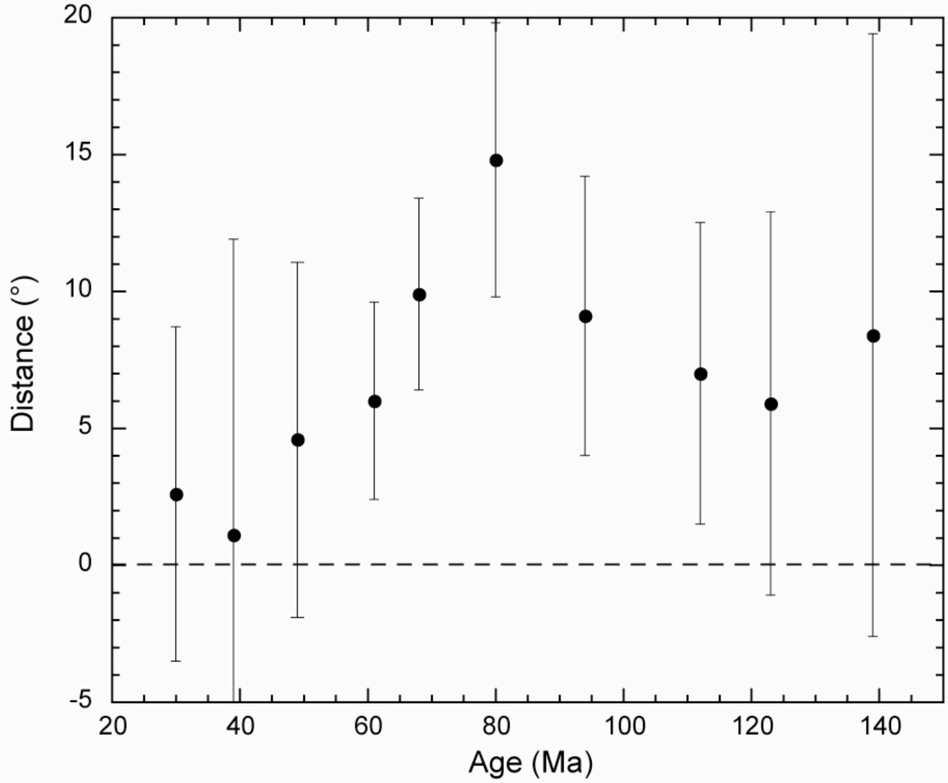


Figure 8. Arc distance between a paleomagnetic pole (Table 1) and its corresponding position on the hotspot model APWP (calculated from Wessel et al., 2006). Error bars are an estimate the of amount of paleomagnetic pole 95% confidence ellipse traversed along great circle path connecting the two points. Dashed line at zero represents agreement of the two poles. Uncertainty in hotspot the model is not represented.

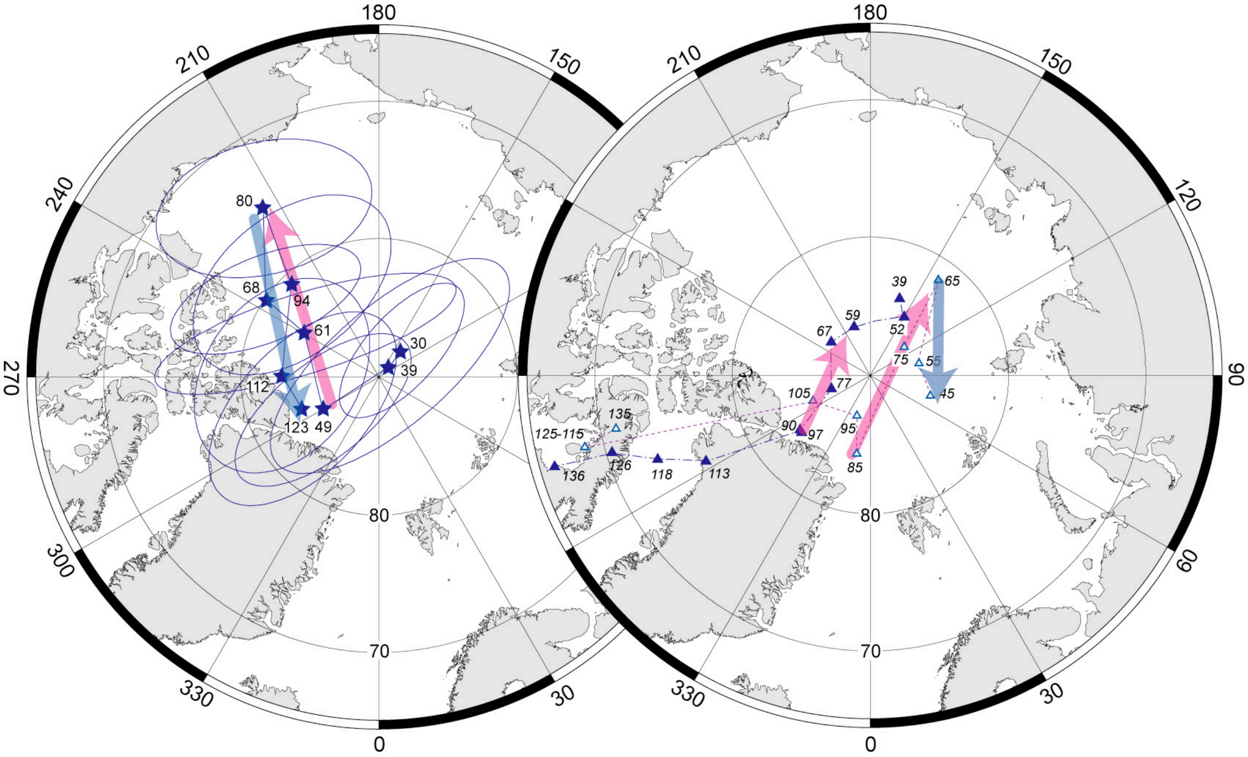


Figure 9. Polar wander in the hotspot reference frame. Left: Pacific paleomagnetic poles (stars) and 95% confidence ellipses (Table 1) were reconstructed using a hotspot-based plate motion model (Wessel et al., 2006). Right: Global TPW curves. Filled triangles and dotted line show a composite apparent polar wander path constructed from continental plates, reconstructed into the African plate reference frame, and backtracked using a model of drift of the African plate relative to the hotspots (Besse and Courtillot, 2002). Open triangles and dash-dot line show another, similar polar wander path constructed using only volcanic rock paleomagnetic data (Prévot et al., 2000). If the hotspots form a mantle reference frame (i.e., have small relative motions), there has been no TPW, and long-term non-dipole geomagnetic field components are small, the paleomagnetic poles should reconstruct to the spin axis. Polar wander in the hotspot reference frame is frequently interpreted as true polar wander (e.g., Andrews, 1985; Gordon, 1987; Besse and Courtillot, 2002). Pink arrows show implied spin axis motion toward the Pacific hemisphere whereas light blue arrows show motion in the opposite sense. Numbers are pole ages in Ma.

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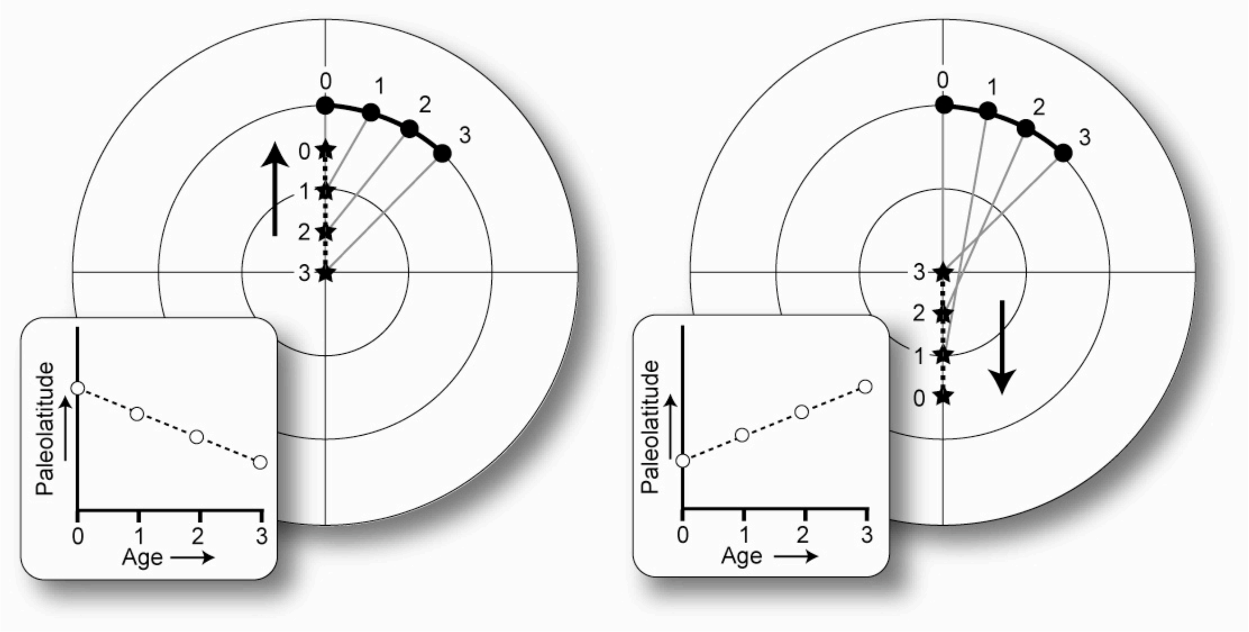

Figure 10. Cartoon explaining the effect of TPW on paleolatitude. Plots show the geographic pole (looking down from above) and polar wander (movement of the spin axis) in the hotspot reference frame, calculated by backtracking paleomagnetic poles using models of plate motion relative to the hotspots. Filled circles represent a seamount chain that has been created by a hotspot at location 0. Plate motion has no northward component, so the Euler pole describing the plate motion relative to the hotspot is located at the spin axis and older seamounts have the same latitude as the hotspot. If TPW moves the spin axis (paleomagnetic poles) toward the hotspot (left), paleolatitudes appear to increase for younger seamounts (inset). If TPW moves the spin axis away from the hotspot (right), paleolatitudes appear to decrease in younger seamounts. The example on the right mimics observations of paleolatitudes in the Emperor Seamounts (Tarduno et al., 2003), implying the paleolatitude shift can be explained by motion of the spin axis toward the Pacific.

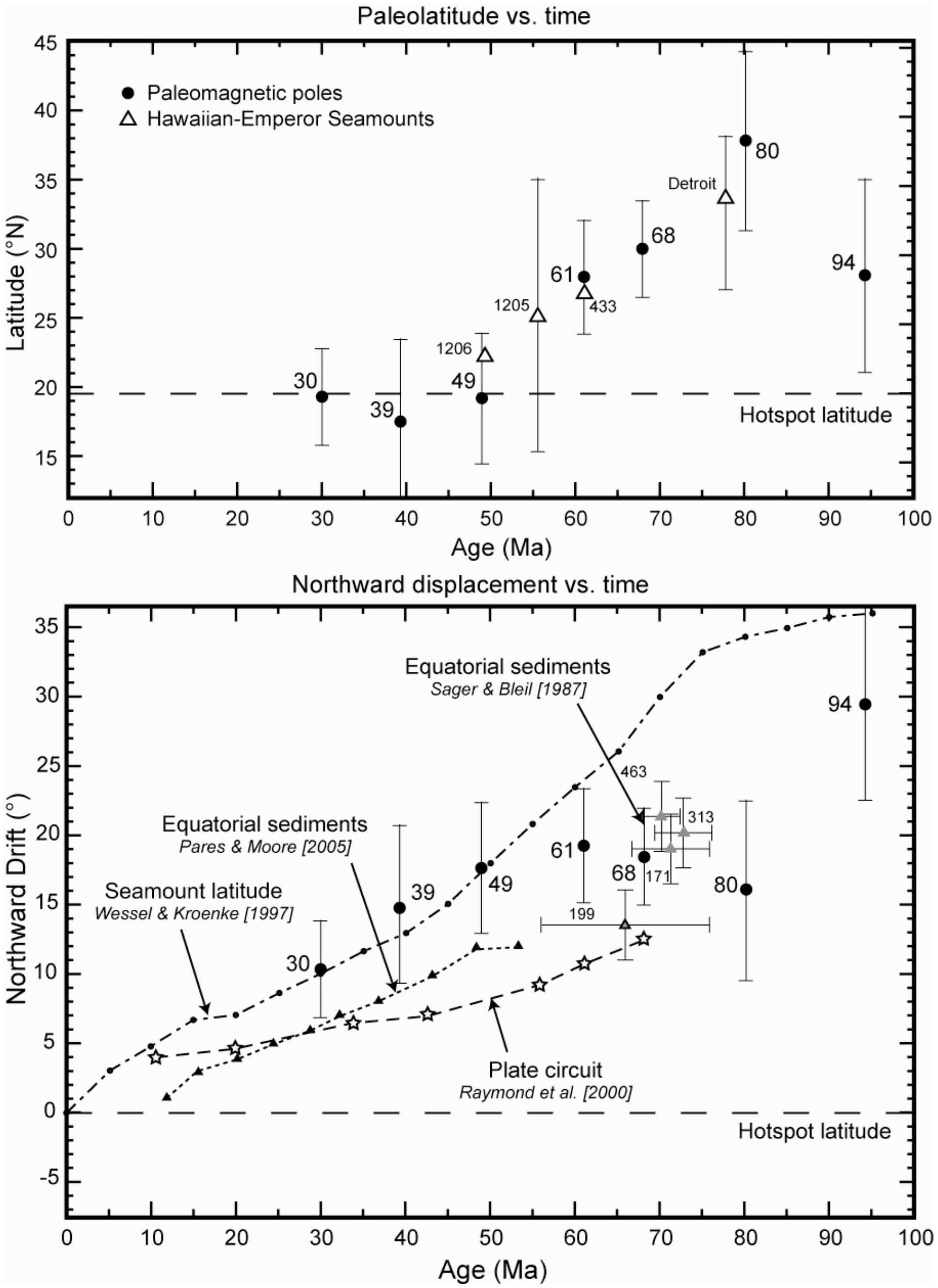

Figure 11. Paleolatitude (top) and northward drift (bottom) implied by Pacific paleomagnetic data versus age. (Top) Filled circles show estimated paleolatitudes of Hawaiian-Emperor seamounts determined by distance from paleomagnetic poles to seamount sites (estimated from Wessel et al. (2006) model). Open tiangles show paleolatitudes from DSDP/ODP basalt drill cores (Tarduno et al., 2003). (Bottom) Filled circles show northward drift implied by paleomagnetic poles. Dash-dot line and dots show northward drift of Hawaiian-Emperor Seamounts with time (from Wessel et al., 2006). Small dashed line and triangles denote northward drift shown by equatorial sediments (Parés and Moore, 2005). Gray triangles show additional estimates of northward drift from equatorial sediments (Sager and Bleil, 1987). Heavy dashed line and stars are estimates of seamount latitude from plate circuit model of Raymond et al. (2000). Numbers are pole ages.

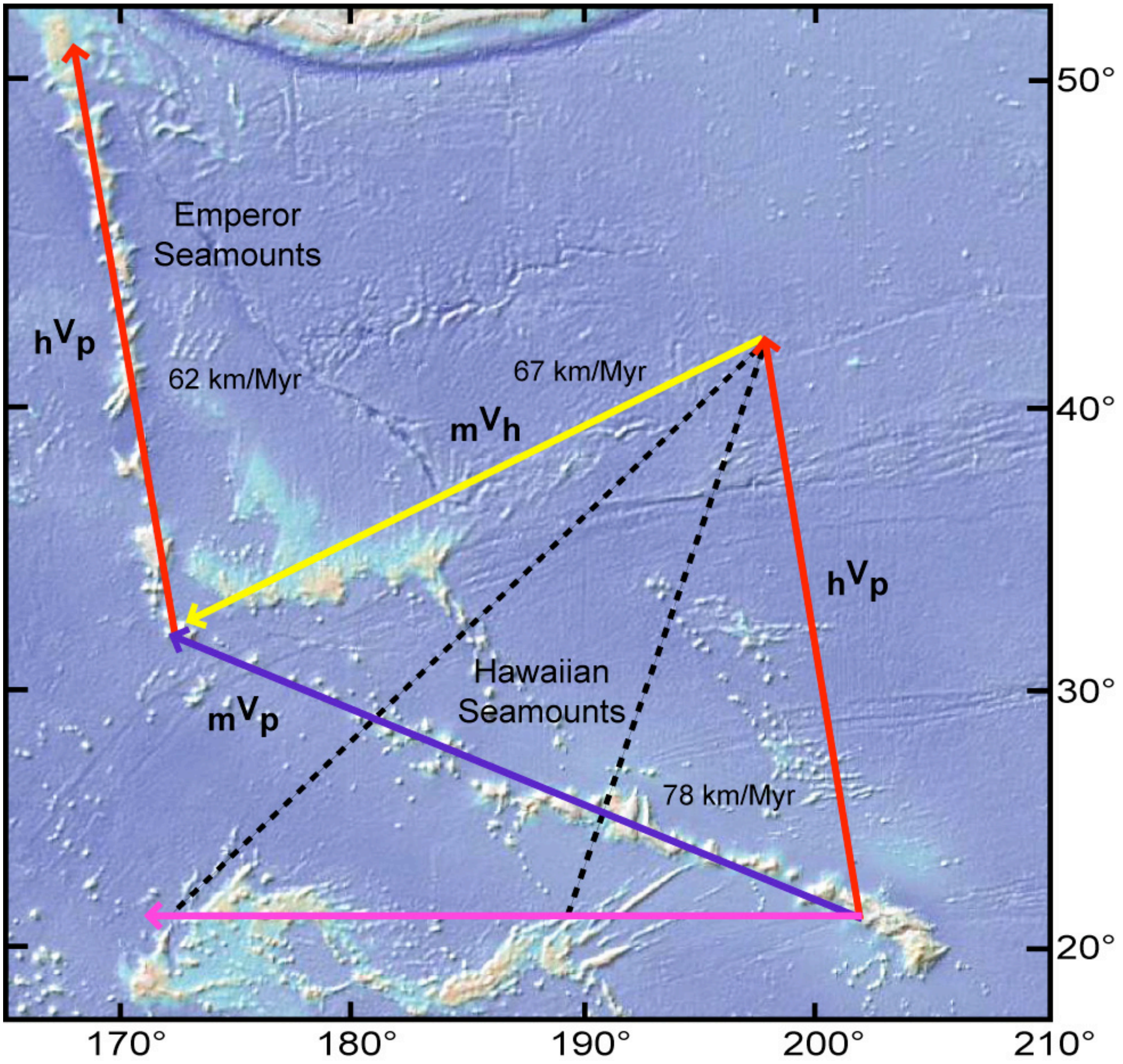

Figure 12. Sketch of motion vectors indicating Hawaiian hotspot drift during the formation of the Emperor Seamounts. Motion of plate relative to hotspot, ${}_hV_p$ (red vector), given by trend of Emperor Seamounts. Motion of plate relative to mantle (assumed fixed relative to spin axis), ${}_mV_p$ (purple vector), is assumed to be same as at present (Hawaiian Chain). Sum is motion of hotspot relative to the mantle, ${}_mV_h$ (yellow vector), which has a large westward component. Horizontal vector at bottom (magenta) shows Pacific plate motion if the plate had no northward component of velocity. Dashed line vectors show predicted motion of hotspot relative to mantle if Pacific plate motion had no northward component. Different dashed lines correspond to different westward velocities. Background is a shaded relief plot of Hawaiian-Emperor Chain bathymetry.

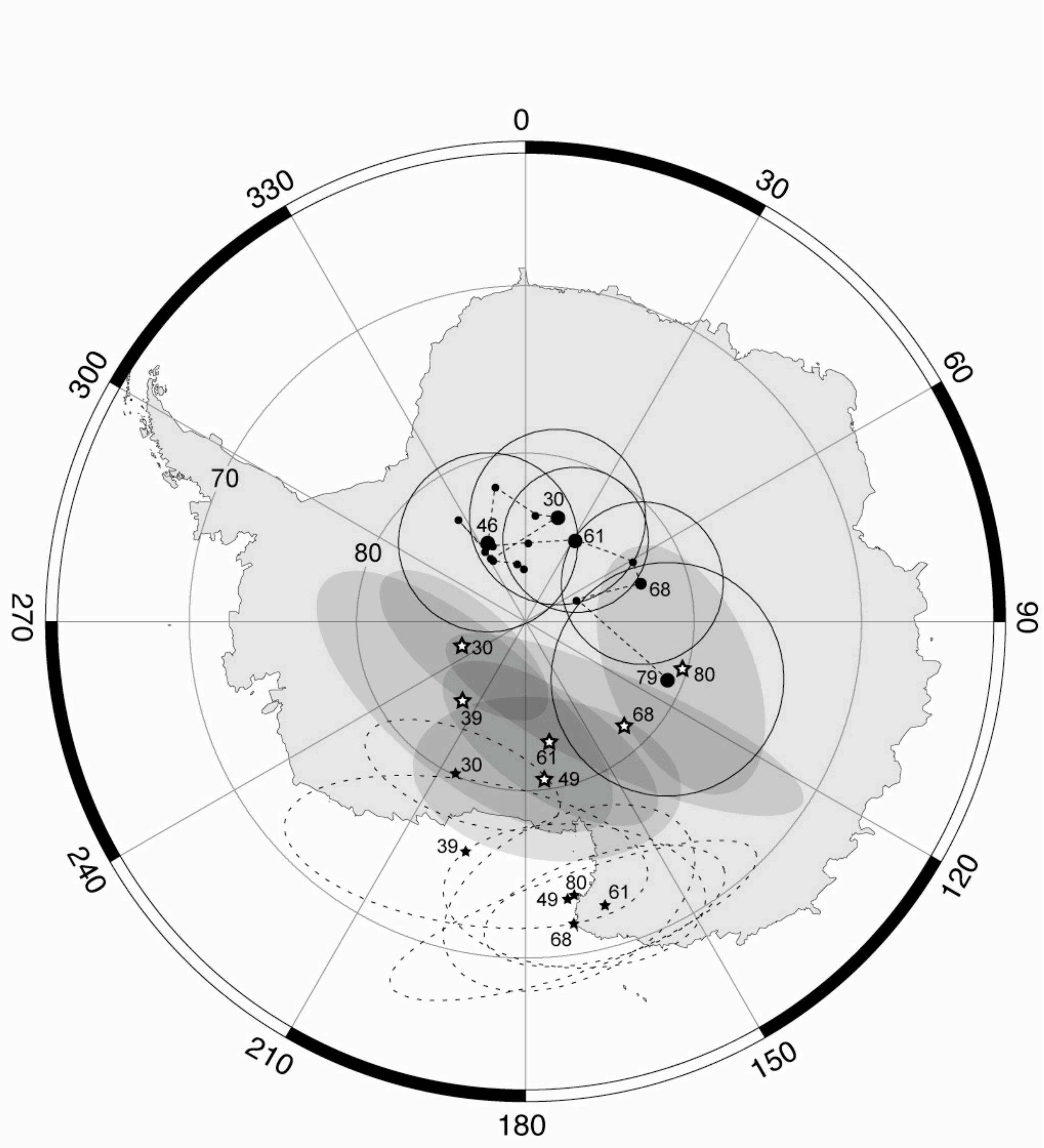

Figure 13. Comparison of the Antarctic and Pacific plate apparent polar wander paths. Antipoles of Pacific paleomagnetic poles are shown as solid stars, with 95% confidence ellipses traced by dashed lines. Open stars and gray confidence ellipses show the same poles rotated into the Antarctic reference frame using a model of the relative motion of the Pacific and Antarctic plates derived from seafloor spreading on the Pacific-Antarctic ridge (Cande et al., 1995; Tebbens and Cande, 1997; Mayes et al., 1990). Antarctic polar wander path (small and large filled circles connected by dotted line) is synthetic polar wander path for continents rotated into Antarctic reference frame (Besse and Courtillot, 2002). Large circles are 95% confidence regions for Antarctic poles. Numbers are pole ages in Ma.

Table 1. Pacific paleomagnetic poles.

Age (Ma)	Pole location		95% Confidence				Data Weights (%)		
± std. dev.	Lat(°N)	Lon(°E)	Maj.	Min.	Azim.	N	S	B	D
[†]29.5 ±2.5	80.1	24.4	6.1	2.6	91	15	87	13	0
[†]39.2 ±2.3	75.8	14.6	10.8	4.3	96	9	69	0	31
[†]48.6 ±3.8	73.4	350.0	7.7	3.4	77	13	77	10	13
[†]61.2 ±3.2	71.8	350.9	11.4	2.9	101	14	38	17	45
[†]68.3 ±1.7	72.4	344.5	7.3	3.1	91	10	71	3	26
[*]79.9 ±2.8	73.2	349.2	7.9	4.8	106	15	17	41	42
94.2 ±2.6	60.5	345.9	8.2	5.1	83	11	36	21	43
[*]112.2 ±3.6	55.6	334.9	7.7	5.5	67	11	0	53	47
[*]120.5 ±1.8 (OJP)	65.3	331.0	9.0	4.9	75	10	0	50	50
[*]122.7 ±4.4	50.0	329.1	8.6	4.6	77	40	0	55	45
[§]136-141	53.0	334.0	11.1	1.0	78				
[§]142-149	60.4	321.5	10.8	1.7	74				

Table head abbreviations. Std. dev. = standard deviation; Maj. = major semi-axis of confidence ellipse; Min. = minor semi-axis of ellipse; Azim. = azimuth of major semi-axis, clockwise from north; Data weights are percentage of weight for a particular data type in the determination of the pole location; N = total number of independent data; S = sediment core data weight; B = basalt core data weight; D = seamount model declination data weight. Poles from (*) Sager (2006), (†) Beaman et al., submitted, (§) Larson and Sager (1992), with 94.2 Ma pole revised as explained in text.