The Bend: Origin and significance

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ABSTRACT

The origin of the bend in the Hawaiian-Emperor Island seamount chain is the prototypical problem at the heart of the ongoing hotspot debate: Does the bend represent a change in motion between the Pacific plate and underlying hotspot (plume?), or might it represent a change in the intraplate stress field?

Reconstructions of continental plates relative to the Pacific plate produce loci with changes in motion that correspond in age and geometry with the bend, especially the North and South American plates. This implies that the two continental plates moved very slowly relative to the Pacific hotspots, especially between 75 and 30 Ma, and that the Hawaiian-Emperor bend is the result of change of Pacific plate motion relative to the underlying hotspot reference frame (or vice versa). Additional reconstructions imply that the Pacific hotspot frame is distinct from the Atlantic and Indian Ocean hotspots over the same time period.

Passage of some hotspot traces from one plate to another suggests that the hotspots are at least partially sublithospheric phenomena and, therefore, cannot simply represent fractures propagated by intraplate stress fields. Contemporary and paleostress fields correspond to hotspot kinematic models for at least three continental plates. If the stress fields represent drag of the continental plates against the underlying asthenosphere and mesosphere, this suggests that the sublithospheric hotspots are embedded within the mesosphere (and do not move independent of it); both hotspot traces and stresses record the same motion.

The correspondence of North and South American and Hawaiian hotspot motions, combined with the evidence for embedding of the hotspots in the mesosphere, leads to the inference that motion of the two continental plates (along with the Eurasian) constrains the motion of the sub-Pacific mesosphere. Thus, the Pacific and Atlantic-Indian hotspot reference frames are plausibly independent and separated by the deep circum-Pacific subduction zones.

Keywords: plate tectonics, hotspots, Hawaii, plumes, kinematics, plate reconstructions.

INTRODUCTION

In the ongoing debate concerning the origin of island-seamount chains and aseismic ridges (hotspot traces), two end-member models have emerged: propagating fractures induced by intraplate stress and sublithospheric melting anomalies (hotspots and plumes). The prototypical island-seamount chain is the Hawaiian-Emperor chain (Fig. 1). The distinctive bend that connects the Hawaiian ridge with the Emperor seamounts is a natural focus of the debate. In the context of the two models, either "the bend" represents a change in motion of the Pacific plate relative to an underlying melting anomaly or it manifests a migrating stress node controlled by changes in the stress field within the Pacific plate.

By itself, the Hawaiian-Emperor chain does not provide adequate constraints on either model. However, when considered with other inferred traces, a variety of constraints emerges, largely based on apparent age of inception of volcanism along the traces and fundamental plate kinematic concepts and calculations.

PRELIMINARY CONCEPTIONS: A REVIEW

Rigidity

A basic assumption of plate tectonics is "kinematic rigidity" as distinguished from "dynamic rigidity." Kinematic rigidity is an empirical concept. If a body is observed to not deform during translation or rotation, the body is kinematically rigid. Plates are kinematically rigid to the extent that they are observed to not deform internally. Beginning with early preplate tectonics analysis through the most recent reconstructions based on magnetic isochrons and fracture zone offsets, the characterization of most plates as kinematically rigid is still a viable empirical interpretation. Departures from such rigidity within plates (e.g., the Indian and western North American) are approximated through the recognition of additional component plates.

Most deformation within the lithosphere is confined to boundary zones between plates, especially convergence boundaries. Away from convergence boundaries, most lithospheric plates ("lithoplates"; Pilger, 2003b) appear to preserve kinematic rigidity. Thus, the methods of plate reconstructions, using finite rotation parameters (kinematics on a sphere), continue to provide remarkably precise fits of plates to observed geology and geophysics (see, e.g., the synthesis of Müller et al., 1997, and included references).

Reference Frames

Plate reconstructions and kinematics imply the existence of one or more reference frames. One plate can serve as a conventional reference frame for reconstructions of motions of other plates. Earth's rotational and/or geomagnetic poles can serve as partial reference frame(s) (longitudinal ambiguity inhibits completeness). As part of his plume hypothesis, Morgan (1972) proposed that the hotspots (produced by plumes) form a fixed reference frame.

In order for a usable reference frame to exist, (1) it must consist of kinematically rigid reference points and (2) motion of bodies relative to the reference frame must be measurable. Plates are empirically recognized by their kinematic rigidity, while seafloor spreading isochrons and fractures zones record their relative motions. Paleoclimatic and/or paleoceanographic data potentially record the motion of plates relative to the spin axis, while paleomagnetic data reflect plate motions relative to the geomagnetic poles (which may or may not correspond with the spin axis of Earth).

In Morgan's formulation, hotspots move slowly relative to one another and produce volcanic tracks (aseismic ridges, island-seamount chains) by magmatic penetration of overlying

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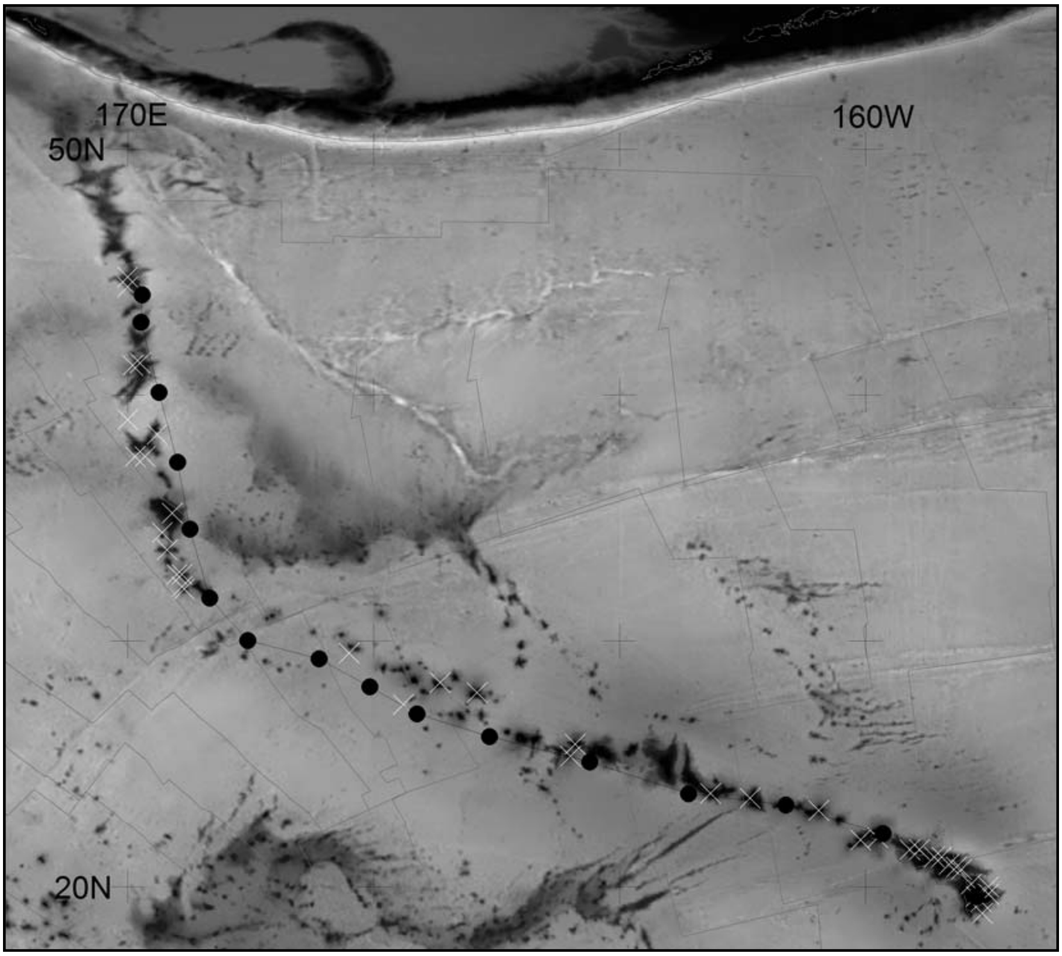

Figure 1. North-central Pacific Ocean bathymetry (after Smith and Sandwell, 1999), equatorial-equidistant map projection (as for all map figures), with predicted locus of Pacific plate relative to a fixed Hawaiian hotspot, calculated at 5 m.y. interval (after Raymond et al., 2000, corrected). Calculation methods are described in the Appendix (in the Data Repository, see text footnote 1).

plates. The tracks, then, record motion of the plates relative to the hotspot reference frame.

Deep Mantle Plumes and a Fixed Reference Frame

Morgan (1972) coupled the proposed fixed hotspot reference with his model for the origin of hotspots: deep mantle plumes. Why might the existence of a fixed hotspot reference frame imply a deep mantle origin of the hotspots?

On an Earth of constant radius, expansion of the Atlantic and Indian Oceans requires contraction of the Pacific and former Tethys Oceans. Global reconstructions indicate that closure of the Pacific is asymmetric (convergence rates vary around the margins of the ocean). The shallow mantle beneath the plates of the Pacific is largely decoupled from mantle beneath the surrounding continental plates, since much of the circum-Pacific (at least the western and eastern Pacific) consists of subduction zones. Thus, as the convergence margins advance on the Pacific basin, the sub-Pacific mantle must also be somehow displaced. (Speculation: The 410 and/or 600 km seismic discontinuities could accommodate such predominantly horizontal, discontinuity-parallel, displacement.)

If hotspots are rooted at shallow depths beneath plates, and sublithospheric mantle is displaced in response to seaward movement of bounding subduction zones, then the Pacific hotspots will move with the displaced surrounding sub-Pacific mantle, thereby moving relative to the hotspots of the Atlantic and Indian Oceans. A shallow, globally fixed set of hotspots seems extremely improbable in light of this.

Evidence for a contemporary, internally fixed hotspot reference frame would violate this geometric requirement. Thus, deep mantle plumes, with rapidly rising material displacing surrounding shallow mantle (not moving with the shallow mantle), could provide the apparently observed hotspot reference frame.

What about the reverse argument? If it could be shown that a global hotspot reference frame *does not* exist, it does not necessarily discount the plume hypothesis. Hotspots could still originate from the deep mantle, but be progressively displaced relative to one another due to deep and/or shallow mantle convection (e.g., Steinberger and O'Connell, 1998, 2000).

Hotspot Reference Frame(s)

Shortly after Morgan introduced the fixed-hotspot/plume hypothesis, Molnar and Atwater (1973) showed that the Hawaiian hotspot appears to have moved relative to the Iceland and Tristan hotspots. Subsequent work, using progressively improved global plate reconstructions, has refined this observation (e.g., Norton, 2000; Raymond et al., 2000). Distinct Pacific, Atlantic-Indian, and (possible) Icelandic hotspot reference frames appear to exist, especially prior to formation of the Hawaiian-Emperor bend (Norton, 2000; Raymond et al., 2000). Within each reference frame, hotspots do not appear to be moving significantly relative to one another; however, there has been significant progressive displacement between the reference frames over the past 75 m.y. (Pilger, 2003a), especially between ca. 75 and ca. 45 Ma.

Further, Morgan (1981) recognized that the hotspot traces of the Atlantic and Indian Oceans and paleomagnetic data from the bordering continents are inconsistent and imply motion relative to one another and (for either or both) Earth's spin axis. Numerous workers have documented discrepancies between paleomagnetic observations from the Emperor Seamount chain and a fixed Hawaiian hotspot (e.g., Kono, 1980; Gordon and Cape, 1981; Tarduno et al., 2003).

Some workers infer from the discrepancies between hotspots and paleomagnetic data that "true polar wander" has occurred. Such an inference is based on the assumption that hotspots indeed form a global reference frame; relative displacement of the hotspot and paleomagnetic references frames would, in this context, imply displacement of the whole Earth relative to the rotation axis and corresponding geomagnetic poles. However, given the discrepancy between the hotspots of the Pacific, those of the Atlantic and Indian Oceans, and Iceland, it is difficult to justify the assumption of a global hotspot reference frame.

Given the various discrepancies among various hotspot sets and paleomagnetic measurements, usage of the term "absolute" motion should probably be discontinued. In contemporary physical science, including the geosciences, there is no preferred reference frame. Alternatively, motions of plates and hotspots could be described in conventional "proper" reference frames (by analogy with astronomy).

Hotspot Sets and Surrounding Mantle

Rarely considered in the hotspot debate is the relation of hotspots to the surrounding "normal" mantle (for exceptions, see Steinberger and O'Connell, 1998, and their later work). Is the mantle convecting with hotspots embedded, like raisins in pudding? Or, are hotspots moving semi-independently of the adjacent non-hotspot mantle, either displacing it or deflecting mantle flow?

In the context of a global hotspot reference frame including deep mantle plumes, semi-independent movement of the hotspots (plumes) would be implied. However, with abundant evidence against such a global reference frame, the question of the relation of hotspots to surrounding mantle material remains open.

Plate Kinematics and Rotation Poles

Bullard et al.'s (1965) invocation of Euler's rotation theorem provided the familiar parameterization for describing rigid motions and reconstructions on a sphere. There are two implementations of the formulation: instantaneous motions and finite reconstructions. In both cases, the center of rotation can be represented as a pole (latitude and longitude) defined by the intersection of the axis of rotation (either instantaneous or finite) with the surface of the sphere. For instantaneous rotations, the third parameter is an instantaneous rate. For finite rotations, a finite angle of rotation is the third parameter.

In terms of kinematics, the familiar principle of structural geology applies: Knowing initial and final configurations does not necessarily provide the relative path of deformation or displacement. Thus, the finite rotation parameters that describe a plate reconstruction do not, in general, describe the path of relative motion of one plate relative to another (or to a hotspot or the geomagnetic pole) in the absence of supporting data.

There is no a priori rationale for poles of motion to remain fixed relative to any pair of plates. Additionally, there is no obvious, similar constraint on plate motions relative to an internal reference frame, either (for example, the geomagnetic poles). Fitting of small circles to island-seamount chains (of the Pacific plate, for example) may approximate kinematics of plate motion relative to a hotspot reference frame, but the viability of such an approximation is subject to debate.

Preliminary Summary and Implications

Lack of internal deformation within a plate is, by definition, an indication of kinematic, if not dynamic, rigidity of the plate. A plate can serve as a reference frame if the record of motion of another object relative to the plate is available. If a set of hotspots can be shown to preserve relative separation distances through time, such a set can also represent a distinct relative reference frame. If such a set of hotspots fixed relative to one another is embedded within the surrounding or underlying mantle (and is not moving relative to the adjacent mantle), the hotspot set and embedding mantle are also, by definition, kinematically rigid.

There is no a priori reason for hotspot reference frames to be fixed relative to the spin axis. However, should the *global set* of hotspots actually form a distinct reference frame, even if it is not fixed relative to the spin axis, such an observation could be indicative of a deep mantle origin of the hotspots, i.e., plumes.

There is no clear reason for fixity of poles (or angular rates) of rotation describing motion between and relative to plates. Similarly, there is no prior reason for motions of plates relative to any other reference frame (e.g., the spin axis, geomagnetic poles, sets of hotspots) to be constrained to fixed poles or constant angular rates. Nor is there any clear reason for the spin axis to correspond to any other plate or hotspot reference frame.

TWO MODELS FOR THE HAWAIIAN-EMPEROR AND OTHER "HOTSPOT" TRACES

Consider the current two classes of models for the origin of "hotspot" traces: (1) propagating fractures within the lithoplate, and (2) surface manifestation of a sublithospheric melting anomaly (deep mantle plumes fall in this category, but other phenomena might also be relevant). Are there existing observations that pertain to distinguishing the applicability of the two models? Is it possible that both model classes are operable, producing similar surface manifestations?

Fracture Mechanisms

The brittle nature of at least the shallow lithosphere implies that some sort of fracturing of lithoplates is required in order for magma to penetrate to the surface, even if the origin of anomalous magmatism is essentially sublithospheric. The question is whether propagating fractures are the "origin" of time-transgressive inception of volcanism along hotspot traces.

In some formulations, the propagating fracture hypothesis involves extensional stresses that brittlely deform the plate and tap into partially molten asthenosphere. If fracturing alone were responsible for apparent age progressions, it is difficult to see how rates of propagation should necessarily be spherically consistent over a plate in either direction or rate, in light of existing models of the driving mechanism for plate tectonics. The apparent (spherically geometric) consistency in the orientation and volcanic inception rate of multiple traces on the Pacific plate (e.g., Raymond et al., 2000; Harada and Hamano, 2000) implies that the melting anomalies are fixed relative to one another.

In an earlier contribution, Pilger and Handschumacher (1981), following a line of reasoning introduced by Solomon and Sleep (1974), suggested that plate deformation due to extensional stress fields within plates might be the origin of melting anomalies. In this formulation, extensional failure of the plate results in lithospheric thinning, depressurization at the base of the lithosphere, and enhanced melting at the asthenosphere-lithosphere boundary. Pilger and Handschumacher suggested that once formed, this melting anomaly could become self-perpetuating and provide a focus for further extension of the plate, with propagation in the greatest principal horizontal compressive stress (σ_1) direction. If viscous drag of the plate against the asthenosphere and/or mesosphere is an important contributor to intraplate stress, then σ_1 would be parallel to plate motion relative to the underlying asthenosphere/mesosphere, and induced fracture propagation would occur opposite to the direction of plate motion. The rate of propagation would equal that of the rate of plate motion if the melting anomaly was embedded in the underlying mesosphere and the mesosphere was itself not deforming significantly.

More important than the existence of a set of melting anomalies that are fixed relative to one another, Pilger and Handschumacher (1981) showed that two proposed hotspot traces—the Tuamotu Ridge (Pacific plate) and Nazca Ridge (Nazca-Farallon plate)—apparently formed from the same melting anomaly, when the anomaly was located beneath the Pacific-Nazca (Farallon) spreading center. Figure 2 illustrates the evolution of the spreading center, melting anomaly, and ridges, based on plate reconstructions of mapped magnetic isochrons. Propagating fracture zones, by themselves, cannot have produced the "mirror-image" Tuamotu and Nazca Ridges. Spreading centers are themselves too weak to allow transmission of obliquely oriented stresses across the boundaries they form; conversely, the divergent kinematics across spreading centers would produce significantly greater levels of stress in "normal" lithosphere than that attributable to intraplate forces. It is difficult to see how symmetrical and obliquely oriented stresses could be propagated across a spreading center, thereby producing fracturing and a consequent, corresponding pair of aseismic ridges. Conversely, the divergent kinematics across spreading centers would produce significantly greater levels of stress in "normal lithosphere" away from the ridges than that attributable to intraplate forces. Thus, a sublithospheric melting anomaly seems to be required.

The geometry and apparent age progressions of several other inferred hotspot traces imply that the melting anomalies responsible for them have passed beneath spreading centers. These include the Kerguelen-Ninetyeast, Reunion-Chagos-Laccadive, and Great Meteor–New England–White Mountain. That is, the older portions of these inferred traces exist on one plate, while the younger portions are beneath another. Thus, a fracture-only mechanism for these traces is inadequate.

Certainly, there is evidence for apparently fracture-controlled volcanism. The Puka-Puka ridge of the south-central Pacific demonstrates an apparent rapid propagation (Sandwell et al., 1995), at a much higher rate than most other island-seamount chains and aseismic ridges of the Pacific. The Puka-Puka ridge, however, is a much smaller feature than the other traces, perhaps precisely because there was less potential magma (normal asthenosphere only) to feed the fractures presumed to form the ridge. That is, the fractures could not tap a concentrated zone of melt within the sublithospheric mantle, because they propagate faster than the plate is moving relative to the underlying mesosphere.

Based on continental analogies, a fracture-driven origin for the Hawaiian-Emperor chain might be expected to produce intersecting features. The more northerly trending Emperor Seamounts might be expected to extend farther south of the bend. Similarly, the Hawaiian chain might be expected to extend farther to the west of the bend. However, we do not observe any obvious intersection of the two chains—we see a junction: the bend. Again, this suggests a sublithospheric melting anomaly.

There is a continental example of possibly fracture-related magmatism that bears on the question of whether a self-perpetuating melting anomaly is necessary. Crustal extension responsible for the East African Rift may predate volcanism. While progressive extension is difficult to demonstrate, it is apparent that recent extensional deformation without contemporaneous volcanism is occurring to the south of the rift (e.g., Zoback et al., 1989). Conversely, analysis of isotopic age dating of volcanics from the rift region indicates time-transgression from north to south at a rate consistent with the motion of the African plate in the Atlantic-Indian Ocean hotspot reference frame (Pilger, 2003a). Pilger suggested that crustal extension may have thinned the African plate enough to produce partial melting by depressurization of a particularly fertile region of the sub-African plate asthenosphere/mesosphere. Such a zone of melting could then become self-perpetuating. The pattern of volcanic migration, since it corresponds with predicted plate motions, does not support proposals that call for a spreading plume head (e.g., Ebinger and Sleep, 1998). Conversely, fracturing alone cannot explain the propagating magmatism; crustal thinning and, possibly, mantle fertility, are also required.

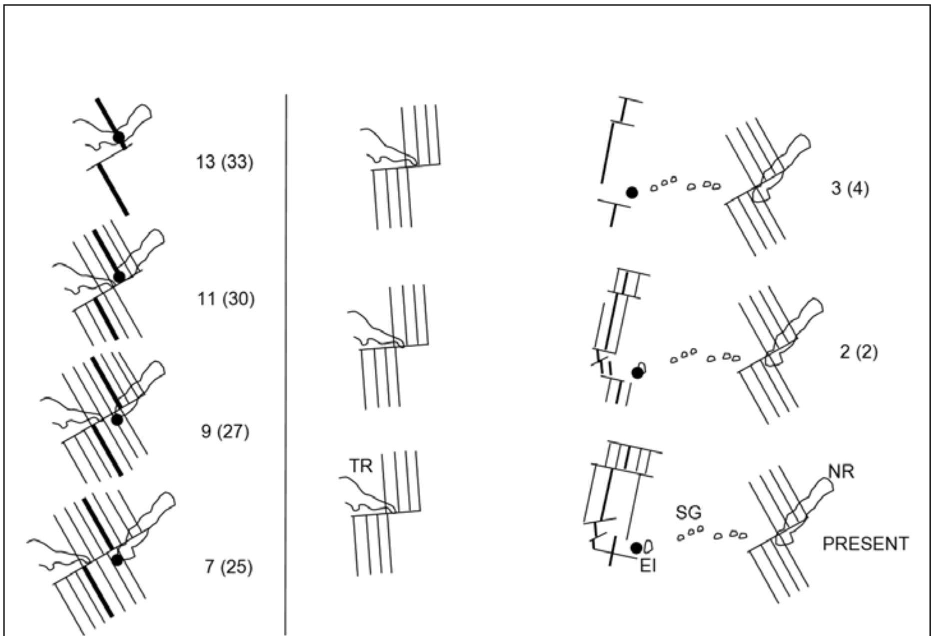

Figure 2. Schematic evolution of east-central Pacific Ocean from magnetic isochron 13 to present, based on plate reconstructions of Pilger and Handschumacher (1981). Note that the isochron fracture-zone reconstructions also result in juxtaposition of Tuamotu ridge (T.R.) and Nazca ridge (N.R.) at the Pacific-Nazca (-Farallon) spreading center until isochron 11. This implies generation of the ridges by a melting anomaly beneath the spreading center (from at least isochron 21 to isochron 11). It is difficult to see how oblique propagating fractures could produce the "mirror-image" ridges without a sublithospheric melting anomaly. E.I.—Easter Island; S.G.—Sala-y-Gomez Island-Seamount Chain.

Hotspot Kinematics

One of the objections to the plume hypothesis is that if the Hawaiian-Emperor chain's origin is a plume, and, therefore, the bend records a change in motion of the Pacific plate relative to the plume, a similar change in motion of the

Pacific plate relative to other plates should be observed (e.g., Hamilton, 2003). While such changes in plate motion are physically implausible (e.g., Anderson, 2002), evidence for rapid relative plate motion changes is abundant in the Pacific, including the formation of the Nazca and Cocos plates at ca. 25 Ma, so this latter inference has documented counter-examples. There are some implicit assumptions in the first objection: (1) Deep mantle plumes and an absolute motion reference frame are coupled hypotheses (as Morgan originally proposed). (2) If the Pacific plate changes its motion relative to the "plume," adjacent plates do not change their motion relative to the plume. (3) Motion of the Pacific plate relative to adjacent plates did not change at the same time the Hawaiian-Emperor bend formed.

Relative to assumption 1, numerous workers have advanced alternative plume models that do not require a fixed hotspot reference frame. The rationale for a fixed plume reference frame is inconsistent with such alternative models; but should a single hotspot reference frame be demonstrated, it would be difficult to explain without deep mantle plumes. Conversely, should several distinct hotspot reference frames be demonstrated, their existence does not necessarily imply or preclude the existence of deep mantle plumes.

In terms of assumption 2, a documented age of the bend is critical, as is analysis of plate kinematics for not only adjacent oceanic, but continental plates as well. Further (assumption 3), the "absence" of change of Pacific plate motions relative to adjacent plates should be more closely examined.

Norton (1995, 2000) recognized that synthetic loci of adjacent *continental* plate motion relative to the Pacific plate possess trends very similar to that of the Hawaiian-Emperor chain, especially the North America–Pacific and South America–Pacific loci. However, the distinct "bend" in the two synthetic loci is ca. 47 Ma, which is 4 m.y. older than the commonly accepted age of 43 Ma for the bend. Preliminary redating of samples from the Emperor Seamounts now suggests that the age of the bend may indeed be closer to 47 or 48 Ma (Sharp and Clague, 2002), as postulated by Pilger and Handschumacher (1981) and Pilger (1984). Thus, there is a kinematics-age correspondence of the bend with some surrounding plates, contrary to previous interpretations.

What about the adjacent oceanic plates? What does the asserted absence of apparent changes in Pacific-Farallon or Pacific-Antarctic plate motions near 47 Ma imply? Naively, one could infer that all three plates changed motion relative to the Hawaiian hotspot, as well as North and South America. Equivalently, the sublithospheric mantle that includes the hotspot changed its motion relative to the oceanic plates. However, it is worth taking a closer look at the kinematic calculations, especially of East to West Antarctica motion documented by Cande et al. (2000), subsequent to Norton's work.

Figures 3 and 4 illustrate calculated loci, anchored at Hawaii, of the Pacific plate relative

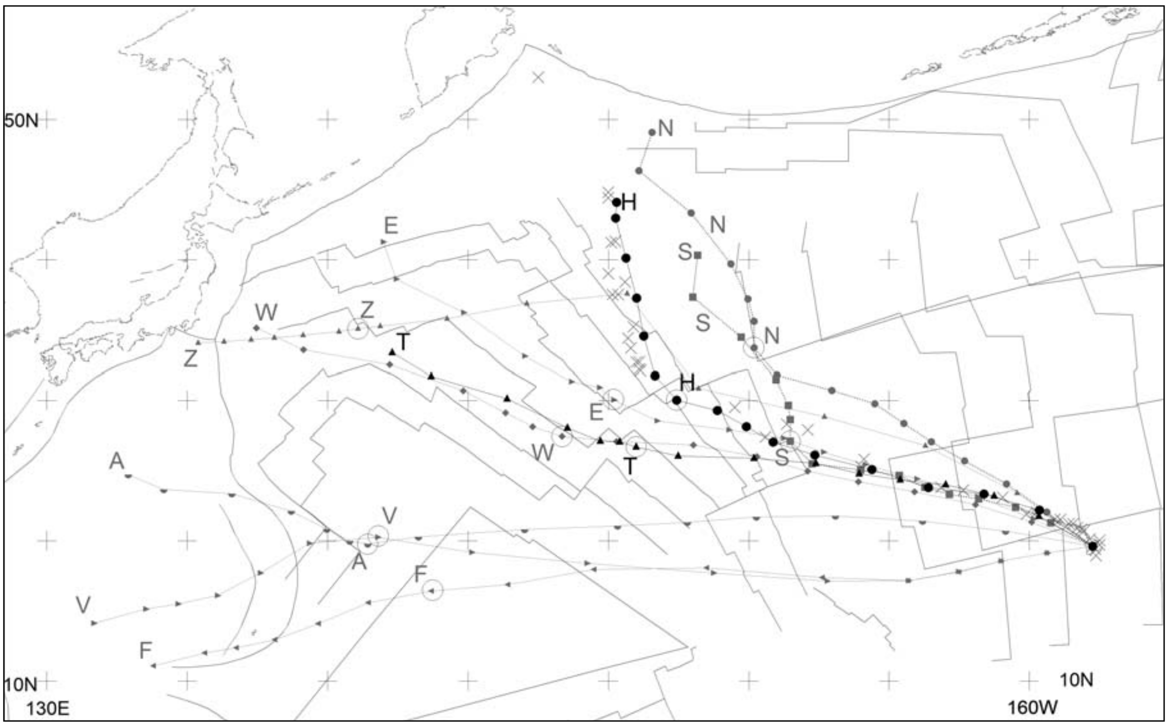

Figure 3. Loci of several plates and Hawaiian and Tristan (Atlantic-Indian Ocean) hotspot frames relative to a fixed Pacific plate: A—Australian, E—Eurasian, H—Hawaiian hotspot (model of Raymond et al., 2000), N—North American, S—South American, T—Tristan hotspot, W—West Antarctic, plus Pacific plate relative to adjacent (fixed) oceanic plates: F—Farallon, V—Vancouver, and Z—Nazca. Reconstructions are at 5 m.y. intervals, calculated from Hawaii. Loci are constructed as if each plate or hotspot frame incorporates present-day Hawaii and shows the hypothetical path of the plate or frame relative to the fixed plate over the past 75 m.y. (straight-line segments connect each calculated point). Reconstruction parameter sources are in Table DR1 and plate circuits in Table DR2, both in the Data Repository (see text footnote 1). Calculation methods and parameters are in Appendices 1 and II in the Data Repository. Magnetic isochrons and plate boundaries are from Müller et al. (1997). Note changes in apparent plate motion between 45 and 50 Ma (that is, close to the age of the Hawaiian-Emperor bend), especially within the North and South American loci. Farallon and Vancouver loci also show slight changes. See Figure 4 for a close-up of the younger portions of some of the critical loci.

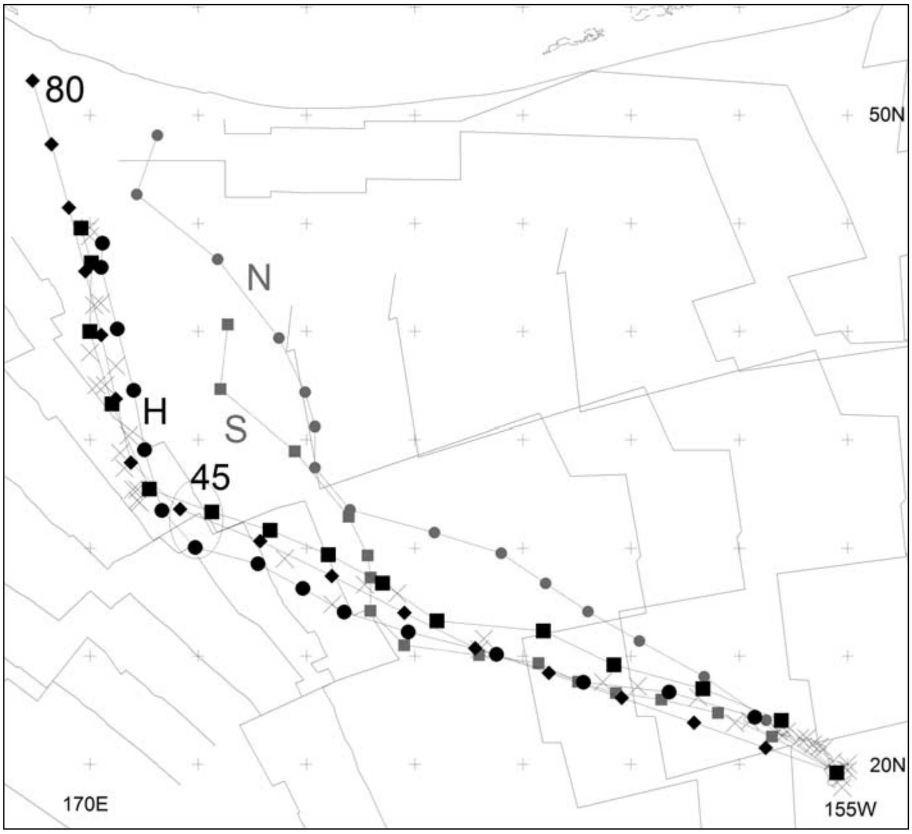

Figure 4. Close-up of Figure 3, for Pacific plate motion relative to North American (N) and South American (S) plate and Hawaiian (H) hotspot reference frames (with two more models shown). Reconstructions are at 5 m.y. intervals, calculated from Hawaii. For Pacific hotspot: Harada and Hamano (2000) circles with fine dotted line; Norton (2000) squares with bold dotted line; Raymond et al. (2000) diamonds with solid line. Pacific–North American and Pacific–South American: circles with solid lines. Note that the model for Harada and Hamano's parameters extends to only 70 Ma, not 75 Ma. Note subparallelism of North and South American loci with loci for the Hawaiian hotspot, between ca. 25 and ca. 75 Ma (see also Norton, 1995), and, especially corresponding "bends" in the loci between 45 and 50 Ma. Numbers are ages in Ma.

to adjacent plates, both oceanic and continental, and the postulated Pacific hotspot reference. Figure 3 is comparable to Figure 10 in Norton (2000), but includes only those plates adjacent to the Pacific plate. Figure 5 illustrates loci of the North and South American plate, plus the "Hawaiian" hotspot reference frame (as defined by the hotspots of the Pacific Ocean; Pilger, 2003a) relative to the Pacific plate, anchored at some of the principal hotspots of the Pacific Ocean. In addition, Figure 5 includes reconstructed continental subduction margins of the circum-Pacific; initially, the margin (corresponding roughly to the continental volcanic arc) was restored to the "Tristan" hotspot reference frame (as defined by the hotspots of the Indian and North and South Atlantic Oceans and named after Tristan da Cunha; Pilger 2003a), according to the plate on which it is located; subsequently, the margin was restored to the Hawaiian hotspot reference frame. Note clustering of the restored margins, especially between 40 and 80 Ma.

How were the rotational parameters of the loci calculated? The Pacific hotspot locus is based on the parameters of Raymond et al. (2000, modified), interpolated using methods described by Pilger (2003a). The parameters used in calculating the Pacific plate relative to other plates involved spline interpolation of plate reconstruction parameters (sources are listed in Table DR1[1]) at 5 m.y. intervals (using the method of Pilger, 2003a) and, for the continental plates, combination of the splined parameters through plate circuits (Table DR2 [see footnote 1]). The circuits were Pacific-Antarctic-Australian, Pacific–Antarctic–African–North American, Pacific–Antarctic–South American, and Pacific–Antarctic–African–North American–Eurasian (within the Antarctic plate, relative motions of East and West Antarctica between chrons 13 and 21 were also incorporated). Note that *no hotspot frame* is part of any of the circuits connecting the Pacific and continental plates. Table DR3 (see footnote 1) lists the resulting interpolated parameters. Description of the reconstruction method and uncertainties are included in the Appendix (in the Data Repository, see footnote 1).

Consider the oft-claimed absence of changes in motion of the Pacific plate relative to adjacent oceanic plates. In reality, there *are* apparent changes between 45 and 50 Ma (Fig. 3) in the motion direction and rate of the Pacific plate relative to the Farallon, Nazca, and Antarctic plates (with which the Pacific plate shares divergent boundaries), calculated close to the Hawaiian-Emperor locus. (Prior to ca. 25 Ma, the Nazca plate was part of the Farallon plate.) The changes relative to the Farallon and Nazca plates are not in the same sense as that relative to the Hawaiian hotspot, however. The sense of change relative to Antarctica (and Australia, too) is similar in sense, if not rate, to the Hawaiian-Emperor bend.

What is particularly striking is the strong similarity in orientation change observed for the Pacific plate relative to the North American and South American plates (between 45 and 50 Ma; if the interpolations were performed at 1 instead of 5 m.y. intervals, the ca. 47–48 Ma change recognized by Norton [2000] would be evident). The implications of this observation are that North America and, to a lesser extent, South America, were moving fairly slowly relative to the Hawaiian hotspot until ca. 25 Ma. This correlation implies a potential kinematic significance of the bend.

The locus of Pacific-Hawaii motion in Figures 3–5 is based not only on the Hawaiian-Emperor island-seamount chain, but also the Louisville Seamounts. Further, the Pacific hotspot parameters are largely consistent with most of the young island-seamount chains of the Pacific (Raymond et al., 2000; Pilger, 2003a). Thus, between ca. 70 and ca. 30 Ma, North and South America were moving very slowly relative to the hotspots of the Pacific.

Embedded Hotspots

Is there genetic significance in the kinematic correspondence of North America and the Hawaiian hotspot reference frame? Some workers (subconsciously, perhaps) seem to visualize hotspots (or plumes) as moving independently

[1]GSA Data Repository item 2007006, a description of plate reconstruction methods, sources, and calculated parameters, is available on the Web at http://www.geosociety.org/pubs/ft2007.htm. Requests may also be sent to editing@geosociety.org.

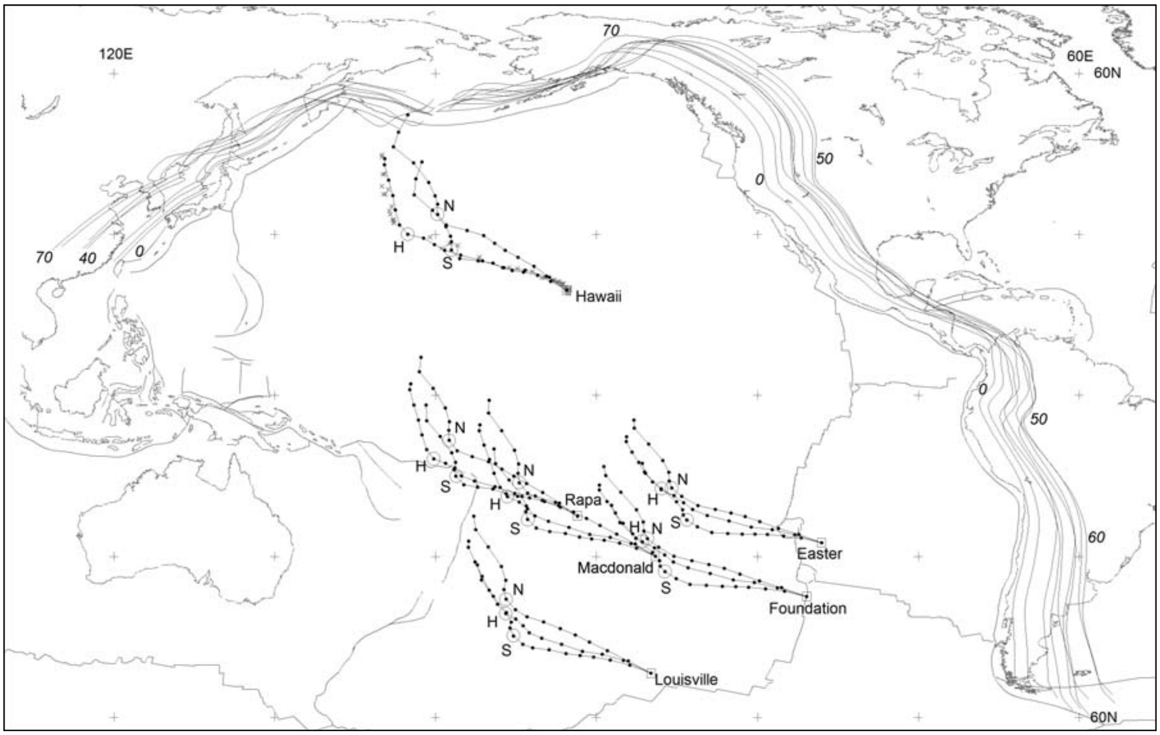

Figure 5. Reconstructed loci of North American (N), South American (S), and Pacific hotspots (H) relative to the Pacific plate, anchored at five postulated hotspots (Hawaii, Easter, McDonald, Rapa, and Louisville). Circled points are 45 Ma. Generalized continental, sublithospheric subduction margin of the circum-Pacific is restored to the Hawaiian hotspot frame and 10 m.y. intervals (contour labels in Ma); note clustering of restored margins, especially between 75 and 40 Ma. "X" indicates locations of dated samples from various hotspot traces. Magnetic isochrons and plate boundaries are from Müller et al. (1997). Reconstruction sources, circuits, and parameters are in Tables DR1–3 in the Data Repository (see text footnote 1).

of the surrounding mantle. There is indirect evidence, however, that the mantle surrounding hotspots also comprises part of the reference frame that hotspots imply.

Gravity lineations above the east-central Pacific are observed to be parallel with plate motion in the hotspot reference frame (e.g., Haxby and Weissel, 1986). Further, wavelengths of the lineations imply a shallow origin (e.g., McAdoo and Sandwell, 1989; Winterer and Sandwell, 1987). If the lineations reflect intraplate stresses, their orientations imply that the stress field may involve drag of the plate against the underlying asthenosphere/mesosphere. Conversely, if the lineations are a manifestation of enhanced magmatism across paleotransform faults (Raddick et al., 2002), this too implies relative fixity of the magma sources within the surrounding sublithospheric mantle.

Intracontinental contemporary stress and paleostress fields within North America, South America, and Africa are consistent with the instantaneous plate motion in the Atlantic-Indian Oceans hotspot reference frame (e.g., Zoback et al., 1989; Pilger, 2003a). If the stress fields are an effect of lithospheric drag against the asthenosphere and mesosphere, this implies that the hotspots from which traces the plate motions are derived are "embedded" within the surrounding sublithospheric mantle.

KINEMATIC CORRESPONDENCE

If the calculated loci of Pacific, North American, and South American plate motion relative to the Hawaiian hotspot are even approximately accurate, what does the presence of corresponding "bends" in each locus imply? Before this question can be addressed, it is appropriate to also consider the calculated motions of the plates relative to the hotspots of the Atlantic and Indian Oceans.

As a culmination of previous models, Müller et al.'s (1993) parameters for the hotspots and plates of the Atlantic and Indian Ocean provide a remarkable fit to the physiographic expression of the inferred hotspot traces. Some of the isotopic ages from the traces are "too old," especially for Kerguelen, Reunion, and (especially) Great Meteor (Pilger, 2003a), but when the recalculations and data filtering of Baksi (1999) are taken into account, there are few such anomalies.

Loci of plate and Hawaiian hotspot motion relative to the Tristan hotspot set (Pilger, 2003a; after Tristan da Cunha hotspot) (Figs. 6 and 7) have been calculated in a similar fashion to the Pacific loci in Figure 3, except that all were calculated in the Tristan reference frame. The plate hotspot parameters for Africa were combined with plate-to-plate parameters, again using spline interpolation. The circuits were North American–African–Tristan, South American–African–Tristan, Antarctic-African-Tristan, and Pacific-Antarctic-African-Tristan (Table DR2, see footnote 1).

What is of particular interest is the subparallelism of the Pacific and North American loci relative to the Tristan reference frame in the interval ca. 75 to ca. 30 Ma. Relative to the sublithospheric Tristan hotspots, the North American plate and the sublithospheric Hawaiian hotspot set were moving "together" (which is equivalent to the prior observation of little relative motion between the North American lithoplate and the Hawaiian hotspots). The subducting Farallon and Kula plates separated North and South America from the sub-Pacific lithospheric mantle during this time period. The

Figure 6. Loci of the several plates and Hawaiian hotspot relative to the Tristan (T) hotspot reference frames: A-T—Australian, E-T—Eurasian, H-T—Hawaiian hotspot, N-T—North American, P-T—Pacific, S-T—South American, W-T—West Antarctic, plus Pacific plate relative to Hawaiian hotspot (P-H). Reconstructions are at 5 m.y. intervals, calculated from Hawaii. Loci represent hypothetic motion path of plate or frame relative to Tristan hotspot reference frame. Magnetic isochrons and plate boundaries are from Müller et al. (1997). The discrepancy between the Pacific loci relative to the Hawaiian and Tristan hotspot reference frames is a measure of the relative independence of the two reference frames. Note sub-parallelism of South and North American–Tristan loci with Hawaiian-Tristan locus. This parallelism is the transformed equivalent to that in Pacific plate frame (Fig. 4). Numbers are ages in Ma.

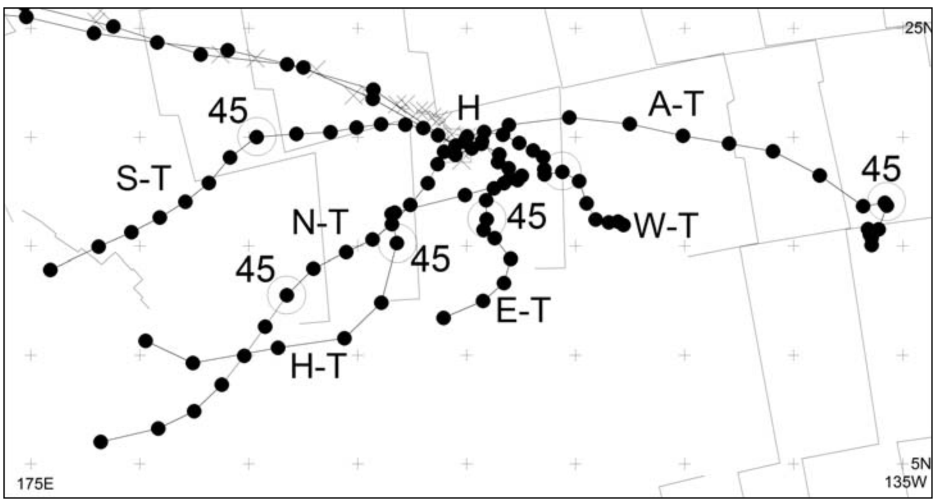

Figure 7. Close-up of Figure 6. Note subparallelism of Hawaiian-Tristan and North American–Tristan loci between ca. 30 and 75 Ma. A-T—Australian, E-T—Eurasian, H-T—Hawaiian hotspot, N-T—North American, S-T—South American; H—hotspot. Numbers are ages in Ma.

calculated kinematics implies that the subduction zones beneath North America were being displaced along with the plate.

Could these calculations imply that the upper mantle in which the Pacific hotspots are embedded was being displaced as a result of North and South America's displacement of the Farallon and Kula subduction zones? Conversely, was the southwesterly movement of Pacific upper mantle (relative to Tristan) "pulling" North and South American along? In either case, the coupling of the Americas with Pacific upper mantle implies that any changes in motion of the oceanic plate relative to the Hawaiian hotspot set would also be reflected in changes relative to the American plates. The clustering of restored continental subduction margins in Figure 5 is an additional manifestation of these calculations.

THE BEND-KINEMATIC SIGNIFICANCE

Most hotspot traces appear to have a sub-lithospheric origin—they cannot be attributed to self-propagating extensional fractures. In some cases, their initial formation appears to have been due to active or passive lithospheric thinning (Pilger and Handschumacher, 1981; Raddick et al., 2002; Pilger, 2003a). Perhaps others do, indeed, represent deep mantle plumes. In either case, the hotspots can be grouped into a minimum of three geographically distinct groups that demonstrate minimal internal deformation (Pilger, 2003a) but have moved relative to one another on a time scale of tens of millions of years.

In either case, whether their origins are deep or shallow, the groups of hotspots appear to be "embedded" in surrounding shallow mantle. Intraplate stress fields, Pacific gravity and bathymetry lineations, and migrating volcanic "curtains" (East Africa and eastern Brazil; Pilger, 2003a) are all consistent with plate motions relative to one of the hotspot reference frames.

The bend in the Hawaiian-Emperor island-seamount chain represents change in relative motion of the Pacific plate relative to the underlying upper mantle in which the Hawaiian and other Pacific hotspots are embedded. The plate reconstruction evidence assembled by Norton (2000) implies an age for the bend of ca. 47–48 Ma within the time scale of Cande and Kent (1995). Consistency with preliminary redating of Emperor Seamounts (Sharp and Clague, 2002) provides additional support for the age.

Unfortunately, there are no island-seamount chains on the unsubducted Nazca plate old enough to correspond to the Hawaiian-Emperor bend for an additional test. Nevertheless, calculations of Nazca (Farallon) plate motion in the

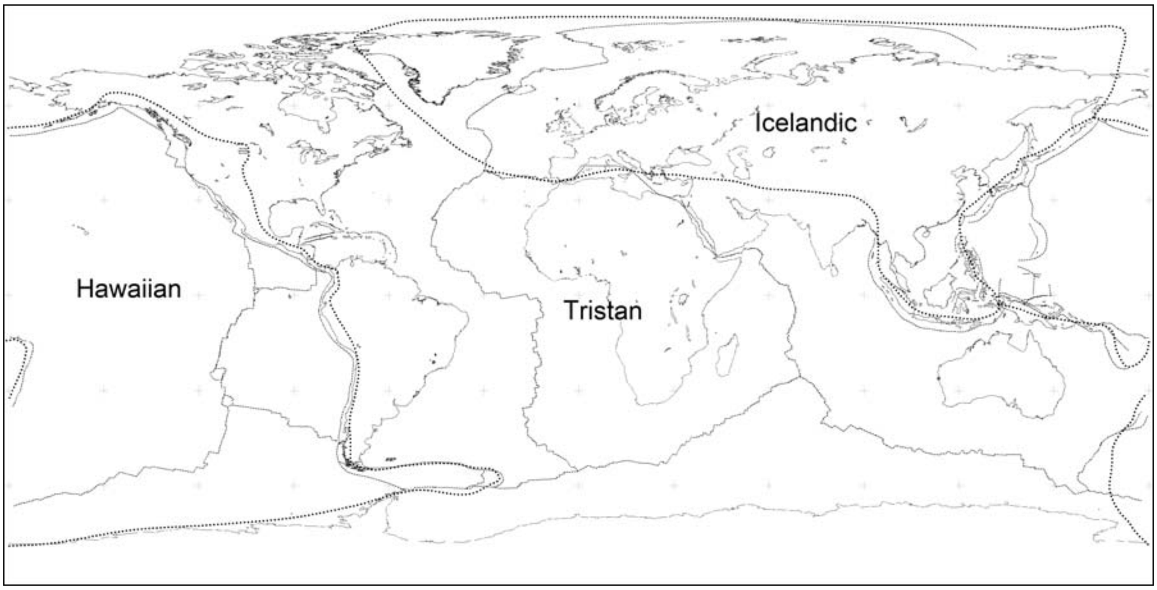

Figure 8. Proposed mesoplate boundaries (dotted polylines) modified from Pilger (2003a, 2003b) to correspond with Liu et al.'s (2003) calculated high-stress boundaries (see also Liu, 2003; and Horowitz et al., 2001) and intraplate stress boundaries in western North America (Pilger, 2003a).

early Cenozoic do imply such a bend in the projected Nazca ridge (produced by the Easter hotspot), corresponding to the zone of low-angle subduction beneath the Peruvian Andes (Pilger, 1984). Relative buoyancy of the subducting Nazca ridge is the probable origin of the low-angle subduction segment.

Since the Pacific plate changed its motion relative to the surrounding plates and underlying mantle at the time of the Hawaiian-Emperor bend, the remaining question is fundamentally dynamic. Why did it change its motion relative to Hawaii (and the Americas) from northerly to west-northwesterly?

SUMMARY AND PROSPECTS

The Hawaiian-Emperor bend is a kinematic feature. It represents a change in Pacific plate motion relative to a melting anomaly (the Hawaiian hotspot) embedded, along with other such anomalies, within the underlying mantle and relative to adjacent oceanic and continental plates. The adjacent oceanic plates also appear to have changed their motion relative to the underlying mantle at the same time, while the North and South American plates show no significant change relative to the Pacific hotspots.

The existence of a region of upper mantle with embedded hotspots that collectively form a detectable reference frame led Pilger (2003a) to propose the term "mesoplate." Mesoplates are kinematically (if not dynamically) rigid layers within the upper mesosphere, bounded on top by the solidus and overlying asthenosphere, and bounded at depth, possibly, by one of the seismic discontinuities (410 or 600 km). Lateral boundaries are largely controlled by subduction zones. Three mesoplates, corresponding with three hotspot sets, are presently defined: Tristan, Hawaiian, and Icelandic. Each is named after a prominent hotspot in the set. The mesoplate formulation is a convenient heuristic for broadening the recognition of the three hotspot reference frames to include the upper mantle within which they are embedded. Figure 8 illustrates the inferred boundaries of the three principal mesoplates, modified based on a recent proposal by Liu (2003) and Liu et al. (2003).

As an example of further application of the mesoplate concept, Figure 9 is a schematic illustration of the interaction of the plates of the Pacific with North America and the two underlying mesoplates. In essence, this formulation is an extension of plate tectonics to three deeper, sublithospheric plates, separated from lithoplates by the asthenosphere.

From ca. 75 to ca. 30 Ma (Fig. 10) North America and the Hawaiian mesoplate were moving to the southwest relative to the Tristan

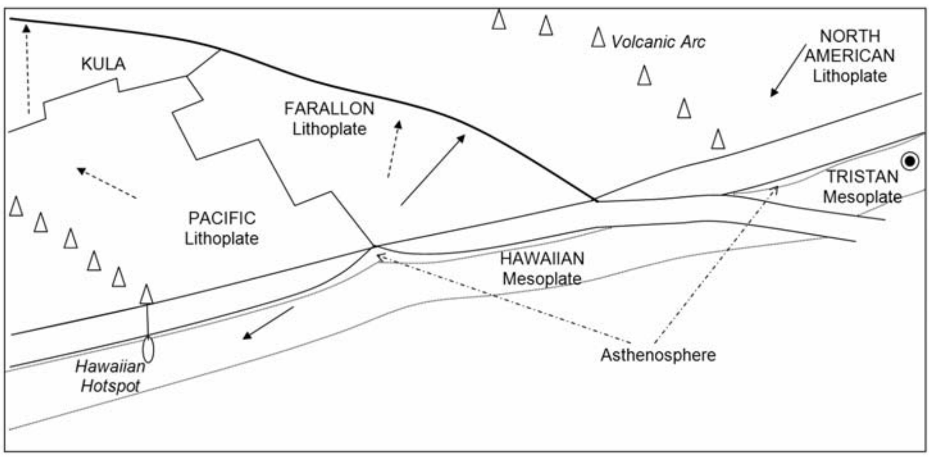

Figure 9. Schematic illustration of interaction of Pacific, Farallon, Kula, and North American lithoplates and Hawaiian and Tristan mesoplates (reference frames) in the early Cenozoic (ca. 60 Ma). For convenience, Tristan mesoplate is fixed. Arrows indicate motion of Hawaiian mesoplate and lithoplates relative to Tristan.

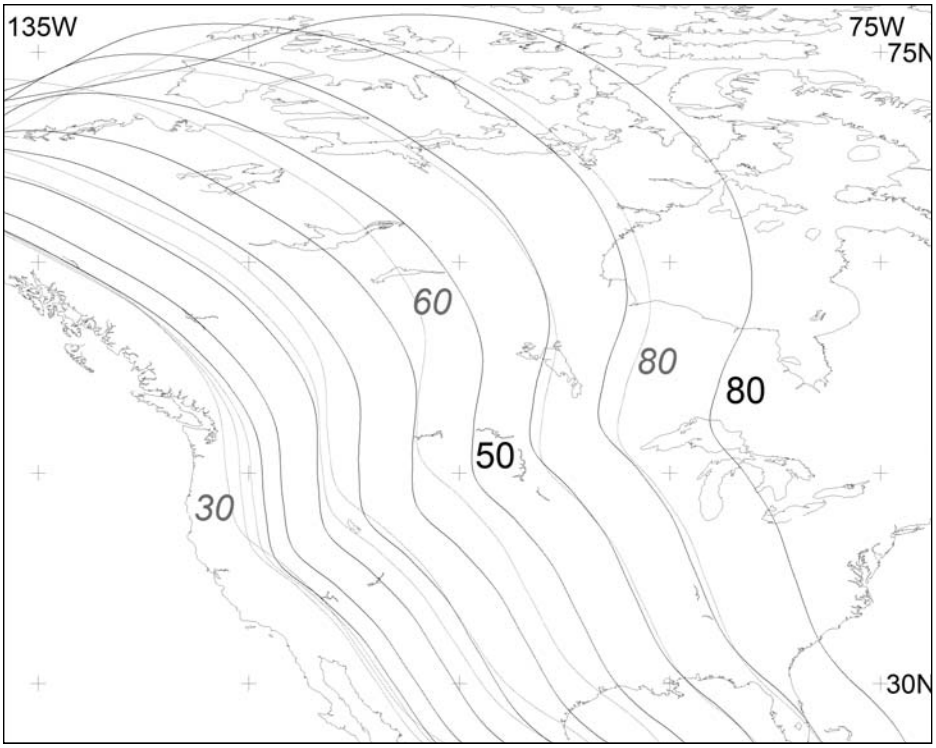

Figure 10. Reconstructions of the western margin of the North America at 10 m.y. intervals. Solid lines—North American lithoplate relative to the Tristan mesoplate (hotspot reference frame). Dashed lines—Hawaiian mesoplate relative to Tristan mesoplate. Note western migration of both reconstructed margins between ca. 75 and 30 Ma. This implies that relative motion of North America and the Hawaiian mesoplate during this time was minimal. Numbers are ages in Ma.

mesoplate (Pilger, 2003b). The Farallon and Kula plates were undergoing subduction beneath North America during this period. Between ca. 75 and ca. 45 Ma, low-angle subduction apparently occurred (Cross and Pilger, 1978) accompanied by Laramide tectonism. The calculated kinematics imply a growing gap between the Tristan and Hawaiian mesoplates between ca. 75 and 30 Ma, conceivably filled, in part, by the low-angle subducting Farallon plate.

ADDITIONAL DISCUSSION

In the past few years there have been a number of contributions to the kinematic significance of the Pacific hotspot traces beyond those cited herein. Koppers et al. (2001) reached a different conclusion regarding Pacific seamount trails than that advanced most recently by Raymond et al. (2000), Norton (2000), and Harada and Hamano (2000). However, Koppers et al.'s analysis incorporated assumptions that limit its applicability. As a kind of "null" hypothesis, they assumed that Pacific motion in a fixed hotspot frame also intrinsically includes fixed stage rotation poles and constant stage rotation rates, rather than potentially continuously changing parameters. This assumption therefore required somewhat arbitrary assignment of seamount chain segments to corresponding stages. Further, they fitted the consequent rotation rates to all available $^{39}Ar/^{40}Ar$ data from the seamount chains, rather than, for example, the oldest dates from a particular sample location; thus, they implicitly assumed that each island or seamount had a very short duration of magmatism and that available samples accurately represent the magmatic history of the island or seamount. In sum, then, Koppers et al. tested a composite hypothesis of fixed hotspots, constant stage poles and rates, consistent magmatic histories, and representative sampling, not just the fixed hotspot hypothesis alone. Subsequently, Koppers et al. (2004) also inferred from new dating of the Louisville chain that the resulting apparently "nonlinear" rate of magmatic migration along the chain is a departure from a "fixed" hotspot model: "These results indicate that the Louisville age progression should be interpreted on the basis of both plate and hot spot motion" (Koppers et al., 2004, abstract, p. 1). It is not clear why constant motion rates are an essential part of any fixed hotspot model.

After the initial version of this paper was submitted for review, O'Neill et al. (2005) published an interesting analysis of the relative motions of hotspots by combining reconstruction parameters (similar to those presented here) with mantle convection models that incorporate embedded plumes. The convective model, building on the previous work of Steinberger and O'Connell (e. g., 1998, 2000) and Koppers et al. (2004), incorporates tomographic velocity models of the mantle (converted to density) and plate motions calculated from plate reconstructions. In this manner, they attempted to fit plumes to the Hawaiian-Emperor island-seamount chain and the traces of the Atlantic and Indian Ocean by combination of plate reconstructions and calculated plume motions. Because other island-seamount chains of the Pacific were not incorporated in their latest model (which differs from that presented in Koppers et al., 2004, for Hawaii and Louisville), it is difficult to evaluate its larger applicability. However, it is apparent that magnitude of relative motion of the Hawaiian hotspot to the other modeled plumes is the most significant among all of the traces they analyzed. For the plumes of the Atlantic and Indian Ocean, O'Neill et al. were unable to distinguish between a fixed model (Müller et al., 1993) and their moving plume model for the past 75 m.y.

It is tempting to speculate that the plate motions incorporated into O'Neill et al.'s convective model may well be its most important component. That is, the apparent modeled motion of the Hawaiian hotspot is quite similar to that inferred in the present paper; in Figure 11, note the gross similarity of the locus of the Hawaiian hotspot in the mean mantle reference frame of O'Neill et al. (2005) and that of the hotspot relative to the Tristan hotspot reference frame. As might be expected, the convective modeled locus is smoother than the kinematically calculated locus. Since the hotspots (or plumes) beneath the Pacific plate (Hawaiian set) have apparent minimal motion relative to one another over the past ~75 m.y., but significant movement relative to the Atlantic-Indian Ocean (Tristan) set (e.g., Raymond et al., 2000), it will be interesting to see if further modeling applications can "reproduce" the other long-lived hotspot traces of the Pacific (Louisville, Macdonald, and Rapa).

One of the more difficult aspects of the evaluation of any hotspot kinematic and convective model is the availability, precision, and accuracy of isotopic dating of hotspot samples. Baksi (1999) has questioned some published dates

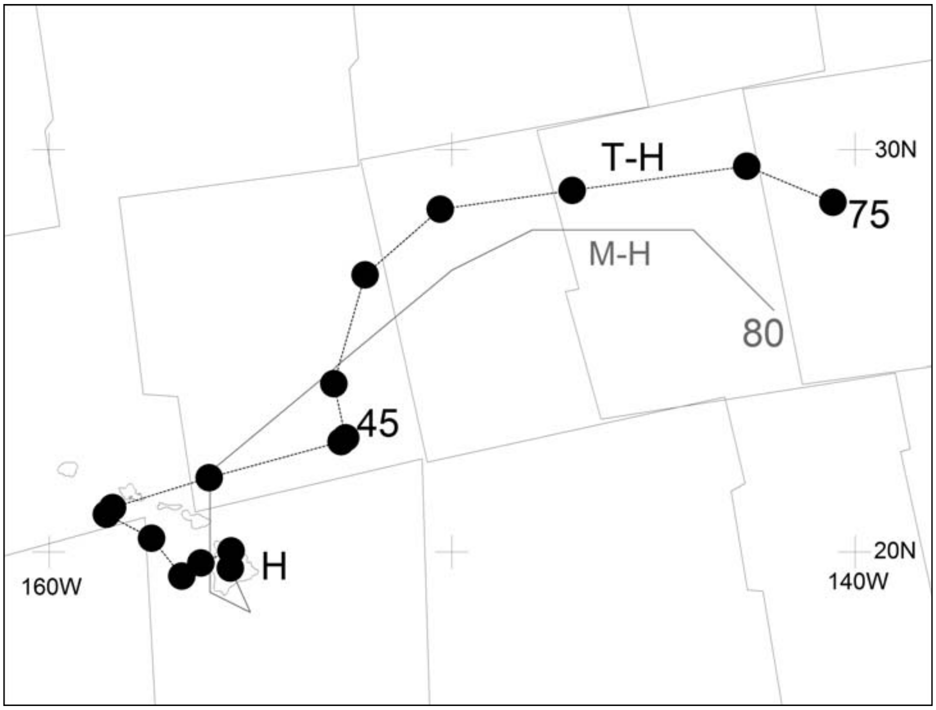

Figure 11. Loci of Hawaiian hotspot (H) relative to Tristan hotspot reference frame (T-H; dashed line and solid circles; this paper) and relative to the mean convective frame of O'Neill et al. (2005) (M-H: solid gray line, after their Fig. 17). Dates of end of loci (75 and 80) and intermediate point (45) are in Ma. Latitude and longitude graticules are spaced at 10º intervals. Because the published locus of O'Neill et al. (their Fig. 17) was shown in color gradations, precise ages cannot be shown.

from several hotspot traces; the numerical results he has recalculated and found acceptable actually fit the hotspot model of Müller et al. (1993) better than the originally published dates as noted above. Many of those published dates that Baksi rejected on statistical grounds also showed the poorest fit to the hotspot model. (O'Neill et al. [2005] incorporated the original dates in their revised model, while acknowledging the possible problems noted by Baksi.) The more recent, apparently higher quality dating by, e.g., Koppers et al. (2001, 2004), is certainly helpful.

Insofar as the Hawaiian-Emperor bend is concerned, the possibility that the bend is older than the previous, widely accepted age of 43 Ma rests on (1) new dating so far reported in abstracts only (Sharp and Clague, 2002), and (2) the kind of analysis presented here. It is hoped that improved dating will further the advancement of our understanding of hotspot traces and their relation to processes in the underlying asthenosphere and mesosphere.

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