Are the Pacific and Indo–Atlantic hotspots fixed? Testing the plate circuit through Antarctica

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Abstract

It is often assumed that hotspots are fixed relative to one another and thus constitute a global reference frame for measuring absolute plate motions and true polar wander. But it has long been known that the best documented hotspot track, the Hawaiian–Emperor chain, is inconsistent with the internally coherent tracks left by the Indo–Atlantic hotspots. This inconsistency is due either to unquantified motions within the plate circuit linking the Pacific with other plates, for example, between East and West Antarctica, or relative motion between the Hawaiian–Emperor and Indo–Atlantic hotspots. Analysis of recent paleomagnetic results from Marie Byrd Land in West Antarctica confirms that there has been post-100 Ma motion between West Antarctica (Marie Byrd Land) and East Antarctica. However, incorporation of this motion into the plate circuit does not account for the Cenozoic hotspot discrepancy. Comparison of an updated inventory of Pacific and non-Pacific paleomagnetic data does not show a significant systematic discrepancy, which, along with other observations, indicates that missing plate boundaries and other errors in the plate circuit play a relatively small role in the hotspot inconsistency. We conclude that most of the apparent motion between the Hawaiian–Emperor and Indo–Atlantic hotspots is real. The best-estimate average drift rate between these sets of hotspots is approximately 25 mm/yr since 65 Ma, ignoring errors in the plate circuit and a small contribution from Cenozoic motions between East and West Antarctica. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

During the 1960s and 1970s it became evident that the active ends of many volcanic island and seamount chains in the Pacific and elsewhere lie above deep-seated sources of hot rising mantle material [1,2]. Morgan [3,4] boldly proposed that mantle

plumes are fixed relative to one another and therefore constitute a fixed mantle reference frame. From this fixed reference frame the ‘absolute’ motions of lithospheric plates might be measured (e.g. [5,6]). However, tests of hotspot fixity have shown a significant discrepancy between the Hawaiian–Emperor and Indo–Atlantic hotspots (e.g. [7,8]), although the discrepancy has often been ascribed to unquantified plate motions especially within the Antarctic plate [9] or perhaps Pacific plate [10]. In this paper we

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examine the relative fixity of Indo–Atlantic versus Pacific hotspots by testing the global plate circuit through Antarctica.

2. Testing hotspot fixity

Testing the fixity of hotspots requires that the motion of the hotspots relative to their overlying plates and the relative motions of the plates be known. Hotspot to plate relative motions are determined by mapping the age progression of volcanic chains. Plate to plate relative motions are determined from the rate and direction of seafloor spreading on intervening midocean ridges as determined from marine magnetic anomalies and fracture zone trends.

Under the assumption that all hotspots are fixed in the mantle with respect to one another, the motion of a plate over a given hotspot can be considered the *absolute* motion of the plate. If the motion of a second plate relative to the first is known, then the *absolute* motion of the second plate may be simply calculated as the sum of the motion of the first plate relative to the hotspots plus the motion of the second plate relative to the first. Conversely, if the hotspots are fixed, one should be able to predict prior positions of any current hotspot with respect to the second plate. Comparison of predicted positions versus actual mapped hotspot tracks should indicate whether the hotspots have moved relative to one another.

Studies of hotspots in the Atlantic and Indian oceans have found no significant motion (less than 5 mm per year) between these plumes [11,12]. Thus, hotspots responsible for such widely distributed features as the New England Seamounts in the north Atlantic, Tristan da Cunha, Walvis Ridge, and the Rio Grande Rise in the south Atlantic, Réunion Island and the Mascarene Plateau, Ninety East Ridge, the Chagos–Laccadive Ridge, and the Kerguelen Plateau in the Indian Ocean, may constitute a coherent Indo–Atlantic hotspot reference frame, at least within the error bounds.

The Hawaiian–Emperor chain of islands and seamounts on the Pacific plate is an important record of hotspot–plate relative motion. It is quite long (over 5000 km), therefore yielding good spatial resolution, and it is documented with many dates along track [13] extending from the present-day position

of the hotspot beneath Kilauea, to about 43 Ma at the bend between the Hawaiian and Emperor chains, to about 81 Ma at the Detroit Plateau [14] in the north Pacific near the Aleutian Trench (Fig. 1). This classic, well-defined hotspot track is the best choice for comparing Pacific hotspots with Indo–Atlantic hotspots.

Studies comparing Indo–Atlantic hotspot tracks with the Hawaiian–Emperor hotspot track on the Pacific plate have found significant discrepancies between the predicted vs. actual hotspot track [7–10] (Fig. 1). The discrepancy is particularly large prior to the 43 Ma bend in the Hawaiian–Emperor chain, for example the offset between the predicted and actual position of the hotspot around 65 m.y. ago is 14.5° or about 1600 km. This discrepancy may be explained by either unquantified plate motion within the plate circuit linking the north Pacific to the Indian and Atlantic oceans (e.g. [10]) or it may indeed be caused by relative motion between the Indo–Atlantic and Pacific hotspots.

3. Possible sources for apparent inter-hotspot motion

Assuming hotspots are fixed, there are a number of possible sources of error within the plate circuit linking the northern Pacific plate (containing the Hawaiian–Emperor hotspot track) with the Atlantic and Indian Ocean plates (with their hotspot tracks) that could account for the discrepancy in comparisons of the Hawaiian–Emperor hotspot track with the Indo–Atlantic hotspot framework. Two general categories are errors in seafloor spreading models and undocumented plate boundaries or intraplate deformation.

3.1. Seafloor spreading parameters

Seafloor spreading models linking the African and Indian plates to Antarctica and the Antarctic plate to the Pacific are constrained by magnetic anomalies and fracture zone trends. Molnar and Stock [7] and Acton and Gordon [10] estimated errors associated with the seafloor spreading data and concluded that they were not sufficient to account for the hotspot discrepancy. The north–south component of the es-

Fig. 1. A view of the Pacific, showing the Hawaiian–Emperor chain and predicted positions of the Hawaiian–Emperor hotspot track assuming that this hotspot has been fixed with respect to the Indo–Atlantic hotspots.

timated error is approximately 2° to 2.5° , at least a factor of 5 less than the pre-bend (e.g. ca. 65 Ma) discrepancy in the predicted hotspot positions. DiVenere et al. [15] also argued against large errors in published Cretaceous seafloor spreading data because paleomagnetic poles transferred to Antarctica

from North America, Africa, India, and Australia were evenly distributed forming a generally smooth synthetic apparent polar wander (APW) path. Cande et al. [8] presented newly acquired seafloor spreading data linking Antarctica with the Pacific plate. These new data did not remove the hotspot discrepancy.

Using their reconstruction parameters for the south-west Pacific there is a 14.5° discrepancy between the predicted and actual hotspot position at 64.7 Ma (Suiko Seamount, Fig. 1).

3.2. Coherence of the Pacific plate

Another proposal to account for the apparent inter-hotspot discrepancy is an undocumented Cenozoic plate boundary between the north and south Pacific. Gordon and Cox [16] and Acton and Gordon [10] proposed a possible plate boundary somewhere to the north of the Eltanin Fracture Zone (Fig. 1). This proposal followed their conclusion that non-Pacific paleomagnetic poles, transferred into the Pacific coordinate system by removing motion on intervening midocean spreading centers, were offset from like-aged Pacific poles in a systematic manner implying a problem with the global plate circuit. Norton [17], however, asserted to the contrary that the validity of the plate circuit was supported by his comparison of a selection of non-Pacific poles with Acton and Gordon's [10] 65 and 57 Ma Pacific poles, although his conclusion was not based on formal statistical comparison of the poles.

To address this issue, we compare paleomagnetic poles from the Pacific plate with non-Pacific mean poles of Besse and Courtillot [18] and DiVenere et al. [15] transferred into Pacific coordinates (Fig. 2). There is reasonable agreement between the Pacific and non-Pacific poles from 85 Ma through 73 Ma (Fig. 2 and inset). In particular, the ~ 73 Ma Pacific and mean non-Pacific poles (Pac 73 and dk 73) are separated by 5.7° and are not statistically distinguishable. The ~ 76 Ma Pacific skewness-based pole (76v) is separated from the 73 Ma mean non-Pacific pole by a statistically indistinguishable 5.1° . The distance between the 76 Ma Pacific pole and the ~ 69 Ma global mean pole (bc 69) is 5.3° which is the same order as the estimated error.

We also note that the Late Cretaceous paleomagnetic pole from the Chatham Islands off New Zealand (NZ 75), which was based on paleomagnetic laboratory analysis of 84 samples collected from 29 sites in volcanic rocks [19], lies comfortably with the other Pacific poles of similar age. The Chatham Island pole falls within the estimated error ellipses of both the 76 Ma skewness-based (Pac 76v)

and seamount-based (Pac 76s) poles and is therefore not statistically distinct from these.

The general agreement between the north Pacific, New Zealand (south Pacific) and non-Pacific paleomagnetic poles suggests that the Late Cretaceous plate circuit is reasonably well known and contains no significant systematic bias.

There is some disagreement between younger Pacific and non-Pacific results. The 65 Ma and 57 Ma Pacific poles are far-sided by statistically significant 6° to 10° with respect to the non-Pacific APW path. This might suggest post 57 Ma 'extension' between the Pacific and Indo-Atlantic. Earlier seamount-based 26 and 39 Ma Pacific poles cited by Acton and Gordon [10] also indicated a similar far-sided offset from the non-Pacific poles. However, a more recently reported 32 Ma skewness-based Pacific pole [20], which is being incorporated into revised analyses of Pacific plate motions [21], is near-sided by about 6° with respect to non-Pacific poles, which would suggest post-32 Ma 'convergence' between the Pacific and Indo-Atlantic. It would seem very fortuitous for these consecutive and undocumented Cenozoic tectonic deformations within the plate circuit to have disturbed and then realigned the Cretaceous paleomagnetic poles. Instead, one may consider the uniform reliability of the Pacific paleopoles to be suspect.

The Pacific APW path relies heavily on indirect magnetic measurements rather than on laboratory analysis of remanent magnetization in rock samples. This is necessary because of the paucity of land on the Pacific plate and the difficulty of direct sampling of ocean crust. Many Pacific paleomagnetic poles are based on results from inversions of seamount magnetic anomalies. Seamount poles are prone to bias from induced magnetization, magnetic overprints, and incorporation of dual polarity which are very difficult to adequately address [22,23]. Small degrees of non-uniformity in the magnetization of a seamount, that may be due to secular variation during the period of volcanic extrusion, variations in rock types and their resultant magnetic properties, and structural complexities, can yield sizable errors of 10° or more in mean poles determined assuming uniform seamount magnetization [22]. Paleomagnetic poles have also been derived from the skewness of marine magnetic anomalies on the Pacific plate [20,24–27].

Fig. 2. Comparison of north Pacific paleomagnetic results with a paleomagnetic pole from New Zealand (south Pacific) and non-Pacific poles with alpha 95 confidence ellipses: *bc 8–bc 81*, 8–81 Ma segment of Besse and Courtillot [18] global, non-Pacific, synthetic APW path transferred to Antarctica [15] and to the Pacific using Cande et al. [8]; *NZ 75*, [19] ca. 75 Ma result from Chatham Islands, south Pacific; *Pac 32* through *Pac 76v* are Pacific anomaly skewness poles; *Pac 32*, [20]; *Pac 57*, [26]; *Pac 65*, [24]; *Pac 73*, [25]; *Pac 76v*, [27]; *Pac 76s*, [23] Pacific seamount-based pole; *Pac 81*, co-latitude circle from Detroit Seamount [47]. Inset: comparison of 73 to 81 Ma north Pacific results, the New Zealand 76 Ma pole, and alternative 73 and 85 Ma non-Pacific global mean poles: *dk 73* and *dk 85* are, respectively, 73 Ma and 85 Ma non-Pacific global mean poles of DiVenere et al. [15] transferred into Pacific coordinates using Cande et al. [8].

Unfortunately, skewness poles can also be biased to varying degrees by anomalous skewness [28]. Solutions for the anomalous skewness are model-dependent and appear to vary with spreading rate and reversal rate due to non-vertical polarity boundaries in the middle and lower oceanic crust [29,30], crustal motion on rotational faults [28], or even anomalous

geomagnetic field behavior [31]. The accuracy of skewness poles is probably of the same order as Cenozoic seamount poles, both being affected by systematic biases that are imprecisely known.

Pending extensive confirmation of these remote-sensed data from seamount magnetic anomalies and seafloor magnetic anomalies by direct paleomagnetic

sampling and updating of vintage land-based paleomagnetic results (e.g. Chatham Islands), there is as yet no reason to believe that the development of the Pacific APW path is converging on a robust configuration adequate for high resolution comparisons. For example, the high precision (small 95% confidence ellipse) 26 Ma and 39 Ma Pacific poles ($81.1^\circ\text{N}/2.4^\circ\text{E}$, $dp/dm = 7.1^\circ/1.2^\circ$; $78.0^\circ\text{N}/7.1^\circ\text{E}$, $dp/dm = 2.6^\circ/0.9^\circ$ respectively [10]) are in direct conflict with the 32 Ma pole of Johnson and Gordon [20] ($85.7^\circ\text{N}/88.1^\circ\text{E}$). The 32 Ma pole is offset 9.6° from the 26 Ma pole and 12.1° from the 39 Ma pole, well outside the error ellipses of the 26 and 39 Ma poles.

Perhaps most troubling about the current Pacific APW path is the uneven spacing of the age progression of the mean poles implying periods of rapid APW punctuated by stillstands with respect to the spin axis (e.g. [26]). However, the rate of motion of the Pacific plate over the Hawaiian–Emperor hotspot from the Late Cretaceous through the Cenozoic varies only gradually, without a sense of the implied surges in polar motion (Fig. 3). A fortuitous combination of erratic hotspot and plate motion would seem to be required to account for the gradual age progression of the hotspot track.

Recent work by Yan and Carlson [32] indicates

that the Louisville hotspot in the south Pacific has been fixed with respect to the Hawaiian–Emperor hotspot during the past 67 million years and that the Pacific plate has experienced less than 0.3% total strain during that time. According to this analysis less than 30 km (less than one-third degree) of relative motion could have occurred between Suiko Seamount in the north Pacific and the Chatham Islands in the south Pacific. This would seem to preclude separate north and south Pacific plates during the Cenozoic or at least limit the amount of relative motion between them.

As a final note on the suggestion of separate north and south Pacific plates, Petronotis et al. [26] saw no evidence in their analysis of magnetic anomaly 25r for a north–south Pacific split and they freely incorporated data from north and south of the Eltanin Fracture Zone in determination of their 57 Ma Pacific pole.

4. Implications of paleomagnetic results from Marie Byrd Land

In the absence of separate Pacific plates, the other potentially important source of error in the global

Fig. 3. Age progression along the Hawaiian–Emperor hotspot track. Distances are along-track distance from Kilauea. Data are from Clague and Dalrymple [13] except Detroit Seamount [14].

plate circuit that could account for the Indo–Atlantic to Pacific hotspot discrepancy is Cenozoic motion between East and West Antarctica (e.g. [9]). This possibility has often been discussed given the remoteness of this area and the documentation of independent motions of West Antarctic crustal blocks during the Mesozoic (e.g. [15,33,34]). The Marie Byrd Land (MBL) sector of West Antarctica in particular is the crucial link connecting the Pacific plate with East Antarctica and the Atlantic/Indian bordering plates. Seafloor spreading on the Pacific–Antarctic Ridge between MBL and New Zealand began in the Late Cretaceous just prior to Chron 34 [35] and documents relative motion between the Pacific plate and West Antarctica. All other boundaries around the Pacific plate have been subduction or transform boundaries for most or all of the past 85 Ma.

DiVenere et al. [15] produced an improved 100 Ma paleomagnetic pole for MBL, sampling many of the same units as a prior study by Grindley and Oliver [36] as well as a number of new units, and avoiding some structural complications that may have affected the previous results. Comparison of these new paleomagnetic results from MBL and an independently constructed non-Pacific global synthetic APW path for East Antarctica [15] reveals that there has been significant motion of the Pacific-bordering blocks of West Antarctica, and particularly MBL, with respect to East Antarctica since about 100 Ma.

The cumulative post-100 Ma motion of MBL with respect to East Antarctica can be constrained by these paleomagnetic measurements as well as the geologic evidence for Late Cretaceous through Recent extension in the Ross Sea and sub-glacial basins between East Antarctica and MBL (e.g. [37–40]). We can therefore calculate the potential contribution of MBL–East Antarctic motion to the Pacific plate circuit to see if it can account for the hotspot discrepancy.

Any number of Euler poles describing the post-100 Ma motion of MBL with respect to East Antarctica will satisfy the paleomagnetic constraints. However, if MBL–East Antarctic motion is also responsible for the discrepancy between the predicted and actual Hawaiian–Emperor hotspot track then it is possible to define a common Euler pole that will

account for both the MBL–East Antarctic relative motion and the Pacific vs. Indo–Atlantic hotspot discrepancy. We choose to solve for the post-64.7 Ma offset of Suiko Seamount vs. the predicted 64.7 Ma hotspot position because Suiko Seamount is the oldest dated edifice in the Hawaiian–Emperor chain for which there is a seafloor spreading model [8] constrained by fracture zone trends and magnetic anomalies on both sides of the ridge to link the Pacific with Antarctica. The best-fit Euler pole is determined from the intersection of the perpendicular bisector to the ~ 100 Ma paleomagnetic poles for East Antarctica and MBL [15] and the perpendicular bisector to the position of Suiko Seamount with respect to MBL at 64.7 Ma and the predicted hotspot position at 64.7 Ma (Fig. 4). The error space for the Euler pole was estimated using the circles of confidence about the 100 Ma MBL and East Antarctic poles and a 2° allowance for errors in the positions of the hotspots. The best-fit Euler pole, 38°N , 170°E , with its estimated 95% error space is shown in Fig. 4.

The best-fit Euler pole is incorporated into the plate circuit accounting for East Antarctic–Pacific relative motion. We predict past positions of the Hawaiian–Emperor hotspot by summing the motion of the Pacific plate with respect to the Indo–Atlantic hotspots, with and without including possible post 64.7 Ma relative motion of MBL with respect to East Antarctica (Fig. 5). We use the rotation parameters of Müller et al. [12] for Indo–Atlantic hotspots to East Antarctica and Cande et al. [8] for MBL to Pacific. Assuming no Cenozoic motion between MBL and East Antarctica, the predicted track falls well off the actual hotspot track during the early Cenozoic as noted above. The discrepancy between the predicted and actual hotspot position at 64.7 Ma is progressively reduced by increasing the amount of MBL–East Antarctic rotation about the best-fit Euler pole. Error envelopes for the predicted 64.7 Ma hotspot position were produced for 5° , 10° , 15° , and 20° rotations of MBL to East Antarctica (Fig. 5, inset).

Twenty-two degrees of MBL–East Antarctic relative rotation about the best-fit Euler pole are required to bring the predicted hotspot location into exact coincidence with the actual 64.7 Ma hotspot location. Approximately 16° of MBL–East Antarctic rotation are required to move the predicted hotspot

Fig. 4. Best-fit Euler pole solution showing intersection of perpendicular bisectors and error space; *MBL 100* and *EAnt 102* are the circa 100 Ma mean poles for Marie Byrd Land and East Antarctica, respectively [15].

location near to the limit of error in the model, as follows. The distance between the predicted (with 16° MBL rotation) and actual 64.7 Ma hotspot position in Fig. 5 is 3.3° . The north–south component of the error as estimated by Acton and Gordon [10] due to the cumulative plate rotations plus uncertainty in the location of the African hotspots is of the order of

2° to 2.5° (their Fig. 6). Here we allow another 1° for the effective uncertainty in the position and age of the Hawaiian–Emperor hotspots at 64.7 Ma.

The tectonic consequences of the hypothetical MBL–East Antarctic rotations are shown in Fig. 6. Rotations of 16° and 22° about the best-fit Euler pole result in very large to complete overlap of MBL

Fig. 5. Predicted vs. actual Hawaiian–Emperor hotspot track, without and with 5°, 9°, 16°, and 22° rotations of MBL to East Antarctica about the best-fit Euler pole: 350/–38. Inset shows error envelopes related to error in determining the best-fit Euler pole for 5°, 10°, 15°, and 20° rotations of MBL to East Antarctica.

with East Antarctica. The 16° and 22° models, which reconcile the hotspot discrepancy within statistical uncertainty, are therefore completely unacceptable from a geologic point of view.

A smaller, 9°, rotation results in complete closure of the Ross Sea, matching the shorelines of MBL and East Antarctica. This smaller rotation would also satisfy the MBL–East Antarctica paleomagnetic constraints [15]. Closure of the Ross Sea is a maximum geometric constraint for possible MBL–East Antarctica rotations but this 9° rotation is not sufficient to bring the predicted and actual hotspot locations into agreement (Fig. 5). The residual 8.6° arc distance between the predicted and the actual 64.7 Ma hotspot position is well outside the estimated errors (approximately 3° to 3.5° as above). Furthermore, while this solution may appear reasonable to account for part of the hotspot discrepancy this construction assumes that all MBL–East Antarctic motion occurred after

65 Ma and complete closure of the Ross Sea before that time, neither of which is very likely.

The amount and timing of extension in the Ross Sea between MBL and East Antarctica is not precisely known. Crustal thickness arguments suggest a maximum of 275–350 km extension [15,40] across the 750–1000 km wide Ross Sea. DiVenere et al. [15] preferred a somewhat larger extension to balance the geologic and paleomagnetic evidence. Their model is approximately equivalent to the 5° solution shown in Fig. 6. It is likely that much of the extension took place during the Cretaceous accompanying rifting, beginning about 100 Ma [41], and separation of New Zealand around 85 Ma just prior to Chron 34 [35]. Lawver and Gahagan [42] proposed that most MBL–East Antarctic motion ceased by the time New Zealand separated from MBL based on a neat fit of the Campbell Plateau into the present Antarctic continental margin. In any case, major extension in the

Fig. 6. Consequences of hypothetical MBL to East Antarctic rotations of 5°, 9°, 16°, and 22° about best-fit Euler pole: 350/−38.

Ross Sea apparently ended by mid-Late Oligocene when the large rift basins in the central and eastern Ross Sea were buried with sediments. Since that time, extension has been restricted to a narrow basin adjacent to the Transantarctic Mountains [43]. Regardless of the timing of extension, the occurrence of continental (albeit stretched) basement beneath the Ross Sea [43] makes complete geomet-

ric closure of MBL to the Transantarctic Mountains unlikely.

Therefore, the actual contribution of MBL–East Antarctic motion to the post-65 Ma hotspot discrepancy is likely less than the 5° solution shown here. If all of this Ross Sea extension did occur after 65 Ma then MBL–East Antarctic motion could account for, at most, little more than 20% of the 14.5° offset

between the predicted vs. actual ~ 65 Ma position of the Hawaiian–Emperor hotspot. Alternatively, if most of the extension in the Ross Sea finished by the time of New Zealand separation during the Cretaceous, then Cenozoic motion between MBL and East Antarctica could account for even less of the hotspot discrepancy. For example, if only 20% of the Ross Sea extension occurred after 65 Ma, this motion could account for only about 4% of the hotspot discrepancy.

We conclude in this analysis that the often-cited East–West Antarctic motions cannot account for the apparent motion between the Hawaiian–Emperor hotspot and the Indo–Atlantic hotspots. Incorporation of the error about the best-fit Euler pole (Fig. 5, inset) does not significantly alter these conclusions. For example, selection of an Euler pole from the large end of the error envelope about the best-fit Euler pole (Fig. 4) would increase the displacement of the predicted hotspot position generally, but not directly, toward the actual hotspot position, but would not make sense geologically (i.e., it would imply extension south of MBL and no extension but major shearing in the Ross Sea).

5. Discussion

Since plumes that feed hotspots must rise through a convecting mantle one might expect hotspots as a general rule to be in motion. In this regard it is surprising to find that hotspots within the Atlantic and Indian realm show no significant relative motion. Steinberger and O’Connell [44] modeled plumes in a convecting mantle. They showed that plumes under one plate could move together as a group relative to plumes under another plate (e.g. Pacific and African plates) as a result of return flow in the lower mantle.

Paleomagnetic studies have considered the changing paleolatitudes along hotspot tracks to examine the question of hotspot motions. Van Fossen and Kent [45] showed that north and south Atlantic hotspots moved southward as a coherent group during the Cretaceous while the Louisville hotspot in the south Pacific also moved southward. This is counter to the true polar wander explanation for changing hotspot latitudes but is evidence for relative hotspot motions. Tarduno and Gee [46] compared the pa-

leolatitudes of some Cretaceous age Pacific guyots with the present latitude of active hotspots that they assumed had formed the guyots. From their comparison with Atlantic hotspots they also concluded that there must have been large-scale motions between Pacific and Atlantic hotspots. Tarduno and Cottrell [47] comparing the paleolatitudes obtained for Detroit and Suiko seamounts with the hotspot’s present latitude argued against true polar wander as the source of latitude change but rather that it was likely caused by southward motion of the Hawaiian–Emperor hotspot relative to the Pacific plate between 81 and 43 Ma. Finally, Norton [17] found no global tectonic events or plate reorganizations that appeared to be related to the 43 Ma bend and concluded that the Hawaiian–Emperor hotspot must have been in motion prior to the 43 Ma bend.

The question of East–West Antarctic motions and their relevance to the global plate circuit and the hotspot discrepancy has previously been addressed by looking at motions implied along the Alpine Fault in New Zealand from Australia–Antarctic–Pacific reconstructions [8,10,48]. Depending on the plate reconstruction used, various amounts of Cenozoic motions between East and West Antarctica could be called upon to alleviate implied geologic misfits in New Zealand caused by the reconstructions. Acton and Gordon [10] found that East–West Antarctic motions could not remove all of the hotspot discrepancy without causing significant reconstruction misfits in New Zealand.

In our test of the Antarctic segment of the plate circuit, we show that Cenozoic relative motions between East and West Antarctica can account for little more than about 20% of the apparent motion between the Hawaiian–Emperor hotspot and the Indo–Atlantic hotspots. The residual offset between the predicted and actual hotspot position cannot be explained by reconstruction uncertainties of the magnitude usually discussed (e.g. [7,10]). It is therefore concluded that the apparent post-65 Ma hotspot motion is not an artifact of errors in the plate circuit. Therefore, inter-hemispheric relative motion between the Indo–Atlantic hotspots and Pacific hotspots (at least the Hawaiian–Emperor hotspot) appears likely. More specifically, Cenozoic motion between MBL and East Antarctica accounts for approximately 5 mm/yr of the average appar-

ent post-65 Ma drift rate of 25 mm/yr between the Hawaiian–Emperor hotspot and the Indo–Atlantic hotspot framework (approximately 1 mm/yr if 20% of the Ross Sea extension occurred after 65 Ma).

The greatest uncertainty remains the Pacific APW path which is based largely on paleopoles derived from remote-sensed data. More paleomagnetic results based on laboratory analyses of oriented samples from the north Pacific and the south Pacific are needed to validate the Pacific APW path and confirm the relationship between the Pacific and non-Pacific plates.

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References

- [1] J.T. Wilson, A possible origin of the Hawaiian Island, *Can. J. Phys.* 41 (1963) 863–868.
- [2] J.T. Wilson, Evidence from ocean islands suggesting movement in the Earth, *Philos. Trans. R. Soc. London, Ser. A* 258 (1965) 145–165.
- [3] W.J. Morgan, Convection plumes in the lower mantle, *Nature* 230 (1971) 42–43.
- [4] W.J. Morgan, Deep mantle convection plumes and plate motions, *Am. Assoc. Pet. Geol. Bull.* 56 (1972) 203–213.
- [5] R.G. Gordon, D.M. Jurdy, Cenozoic global plate motions, *J. Geophys. Res.* 91 (1986) 12389–12406.
- [6] C.Y. Yan, L.W. Kroenke, A plate tectonic reconstruction of the southwest Pacific, 0–100 Ma, *Proc. ODP, Sci. Results* 130 (1993).
- [7] P. Molnar, J. Stock, Relative motions of hotspots in the Pacific, Atlantic and Indian Oceans since late Cretaceous time, *Nature* 327 (1987) 587–591.
- [8] S.C. Cande, C.A. Raymond, J. Stock, W.F. Haxby, Geophysics of the Pitman Fracture Zone and Pacific–Antarctic plate motions during the Cenozoic, *Science* 270 (1995) 947–953.
- [9] R.A. Duncan, Hotspots in the southern oceans — an absolute frame of reference for motion of the Gondwana continents, *Tectonophysics* 74 (1981) 29–42.
- [10] G.D. Acton, R.G. Gordon, Paleomagnetic tests of Pacific plate reconstructions and implications for motion between hotspots, *Science* 263 (1994) 1246–1254.
- [11] R.A. Duncan, M.A. Richards, Hotspots, mantle plumes, flood basalts, and true polar wander, *Rev. Geophys.* 29 (1991) 31–50.
- [12] R.D. Müller, J.-Y. Royer, L.A. Lawver, Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracks, *Geology* 21 (1993) 275–278.
- [13] D.A. Clague, G.B. Dalrymple, in: E.L. Winterer, D.M. Husson, R.W. Decker (Eds.), *The Eastern Pacific Ocean and Hawaii*, Vol. N, *The Geology of North America*, Geological Society of America, Boulder, CO, 1989, pp. 188–217.
- [14] R.A. Keller, R.A. Duncan, M.R. Fisk, Geochemistry and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of basalts from ODP Leg 145 (north Pacific transect), *Proc. ODP, Sci. Results* 145 (1995) 333–334.
- [15] V. DiVenere, D.V. Kent, I.W.D. Dalziel, Mid-Cretaceous paleomagnetic results from Marie Byrd Land, West Antarctica: a test of post-100 Ma relative motion between East and West Antarctica, *J. Geophys. Res.* 99 (1994) 15115–15139.
- [16] R.G. Gordon, A. Cox, Paleomagnetic test of the Early Tertiary plate circuit between the Pacific basin plates and the Indian plate, *J. Geophys. Res.* 85 (1980) 6534–6546.
- [17] I.O. Norton, Plate motions in the north Pacific: the 43 Ma nonevent, *Tectonics* 14 (1995) 1080–1094.
- [18] J. Besse, V. Courtillot, Revised and synthetic apparent polar wander paths of the African, Eurasian, North American and Indian plates and true polar wander since 200 Ma, *J. Geophys. Res.* 96 (1991) 4029–4050.
- [19] G.W. Grindley, C.J.D. Adams, J.T. Lumb, W.A. Watters, Palaeomagnetism, K–Ar dating and tectonic interpretation of Cretaceous and Cenozoic volcanic rocks from Chatham Islands, New Zealand, *N. Z. J. Geol. Geophys.* 20 (1977) 425–467.
- [20] B.C. Johnson, R.G. Gordon, Recent Pacific plate standstill? a 32 Ma paleomagnetic pole for the Pacific plate determined from magnetic anomaly skewness and implications for motion of the Pacific hotspots relative to the spin axis since mid-Tertiary time, *Eos* 77 (46) (1996) F157.
- [21] R.G. Gordon, K.E. Petronotis, G.D. Acton, B. Johnson, S. Vasas, Pacific plate apparent polar wander from 81 Ma to 32 Ma from skewness of marine magnetic anomalies, *Eos* 78 (46) (1997) F183.
- [22] R.L. Parker, L. Shure, L.A. Hildebrand, The application of inverse theory to seamount magnetism, *Rev. Geophys.* 25 (1987) 17–40.
- [23] W.W. Sager, M.S. Pringle, Mid-Cretaceous to Early Tertiary apparent polar wander of the Pacific plate, *J. Geophys. Res.* 93 (1988) 11753–11771.
- [24] G.D. Acton, R.G. Gordon, A 65 Ma palaeomagnetic pole for the Pacific plate from the skewness of magnetic anomalies 27r–31, *Geophys. J. Int.* 106 (1991) 407–420.
- [25] K.E. Petronotis, R.G. Gordon, A Maastrichtian palaeomagnetic pole for the Pacific plate from a skewness analysis of marine magnetic anomaly 32, *Eos* 75 (44) (1994) 204.
- [26] K.E. Petronotis, R.G. Gordon, G.D. Acton, A 57 Ma Pacific plate palaeomagnetic pole determined from a skewness

- analysis of crossing of marine magnetic anomaly 25r, *Geophys. J. Int.* 118 (1994) 529–554.
- [27] S.M. Vasas, R.G. Gordon, K.E. Petronotis, New paleomagnetic poles for the Pacific plate from analysis of the shapes of anomalies 33n and 33r, *Eos* 75 (44) (1994) 203.
- [28] S.C. Cande, A palaeomagnetic pole from Late Cretaceous marine magnetic anomalies in the Pacific, *Geophys. J. R. Astron. Soc.* 44 (1976) 547–566.
- [29] S.C. Cande, D.V. Kent, Constraints imposed by shape of marine magnetic anomalies on the magnetic source, *J. Geophys. Res.* 81 (1976) 4157–4162.
- [30] J. Arkani-Hamed, Remanent magnetization of the oceanic upper mantle, *Geophys. Res. Lett.* 15 (1988) 48–51.
- [31] S.C. Cande, Anomalous behavior of the paleomagnetic field inferred from the skewness of anomalies 33 and 34, *Earth Planet. Sci. Lett.* 40 (1978) 275–286.
- [32] C.Y. Yan, R.L. Carlson, The Cenozoic ‘fixity’ of the Hawaii and Louisville hotspots, and the rigidity of the Pacific plate, *Eos* 77 (17) (1996) S91.
- [33] D.R. Watts, A. M. Bramall, Palaeomagnetic evidence for a displaced terrain in Western Antarctica, *Nature* 293 (1981) 638–641.
- [34] A.M. Grunow, D.V. Kent, I.W.D. Dalziel, Mesozoic evolution of West Antarctica and Weddell Sea Basin: new paleomagnetic constraints, *Earth Planet. Sci. Lett.* 86 (1987) 16–26.
- [35] C.L. Mayes, L.A. Lawver, D.T. Sandwell, Tectonic history and new isochron chart of the South Pacific, *J. Geophys. Res.* 95 (1990) 8543–8567.
- [36] G.W. Grindley, P.J. Oliver, Paleomagnetism of Cretaceous volcanic rocks from Marie Byrd Land, in: R.L. Oliver et al. (Eds.), *Antarctic Earth Science*, Australian Academy of Science, Canberra, 1983, pp. 573–578.
- [37] E.S. Stump, P.G. Fitzgerald, Episodic uplift of the Transantarctic Mountains, *Geology* 20 (1992) 161–164.
- [38] D.D. Blankenship, R.E. Bell, S.M. Hodge, J.M. Brozena, J.C. Behrendt, C.A. Finn, Active volcanism beneath the West Antarctic ice sheet and implications for ice-sheet stability, *Nature* 361 (1993) 526–529.
- [39] J.C. Behrendt, D.D. Blankenship, C.A. Finn, R.E. Bell, R.E. Sweeney, S.M. Hodge, J.M. Brozena, CASERTZ aeromagnetic data reveal late Cenozoic flood basalts(?) in the West Antarctic rift system, *Geology* 22 (1994) 527–530.
- [40] J.C. Behrendt, A. Cooper, Evidence of rapid Cenozoic uplift of the shoulder escarpment of the Cenozoic West Antarctic rift system and a speculation on possible climate forcing, *Geology* 19 (1991) 315–319.
- [41] S.D. Weaver, B.C. Storey, R.J. Pankhurst, S.B. Mukasa, V.J. DiVenere, J.D. Bradshaw, Antarctica–New Zealand rifting and Marie Byrd Land lithospheric magmatism linked to ridge subduction and mantle plume activity, *Geology* 22 (1994) 811–814.
- [42] L.A. Lawver, L.M. Gahagan, constraints on timing of extension in the Ross Sea Region, *Terra Antarct.* 1 (1994) 545–552.
- [43] A.K. Cooper, F.J. Davey, K. Hinz, Crustal extension and origin of sedimentary basins beneath the Ross Sea and Ross Ice Shelf, Antarctica, in: M.R.A. Thomson, J.A. Crame, J.W. Thomson (Eds.), *Geological Evolution of Antarctica*, Cambridge University Press, New York, 1991, pp. 285–291.
- [44] B. Steinberger, R.J. O’Connell, Advection of plumes in mantle flow: implications for hotspot motion, mantle viscosity and plume distribution, *Geophys. J. Int.* 132 (1998) 412–434.
- [45] M.C. Van Fossen, D.V. Kent, Paleomagnetism of 122 Ma plutons in New England and the Mid-Cretaceous paleomagnetic field in North America: true polar wander or large-scale differential mantle motion? *J. Geophys. Res.* 97 (1992) 19651–19661.
- [46] J.A. Tarduno, J. Gee, Large-scale motion between Pacific and Atlantic hotspots, *Nature* 378 (1995) 477–480.
- [47] J.A. Tarduno, R.D. Cottrell, Paleomagnetic evidence for motion of the Hawaiian hotspot during formation of the Emperor seamounts, *Earth Planet. Sci. Lett.* 153 (1997) 171–180.
- [48] J. Stock, P. Molnar, Revised history of early Tertiary plate motion in the south-west Pacific, *Nature* 325 (1987) 495–499.