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# Analysis of Ontong Java Plateau palaeolatitudes: evidence for large-scale rotation since 123 Ma?

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## SUMMARY

We have discovered evidence of a previously unrecognized, large-scale rotation of the Ontong Java Plateau (OJP) recorded in its basement palaeolatitudes. When palaeolatitude differences computed among Ocean Drilling Program Sites 807 and 1183–1187 are plotted versus their present-day site latitude differences, a systematic 2:1 slope bias is evident. While it is possible to resolve this bias by introducing *ad hoc* tilt corrections at all six sites, drilling records indicate relatively undisturbed conditions at Sites 1183 and 1185–1187. Of the possible causes of the bias, only whole plateau rotation resolves it while honouring the majority of published palaeolatitudes. This implies that only Sites 807 and 1184 palaeolatitudes, both questioned in the literature, are erroneous. A 9° northward dip previously reported at Site 1184 appears to stem from inclined deposition rather than post-emplacement deformation. We also estimate an 8° southward tilt correction at Site 807 to make the data set self-consistent. Based on the six sites analysed, we find that OJP may have experienced ∼40° of clockwise rotation since its formation at ∼123 Ma. In contrast, available Pacific absolute plate motion (APM) models predict less than 10° of rotation. If our analysis is correct, it suggests that the plateau moved independently of the Pacific Plate early in its history or that Pacific APM models for the Lower Cretaceous are unreliable. While our corrections to Sites 807 and 1184 combined with ∼40° rotation resolve the internal inconsistencies, the mean palaeolatitude value of Ontong Java remains largely unchanged and is still anomalous with respect to the Pacific apparent polar wander path at ∼123 Ma.

**Key words:** Plate motions; Palaeomagnetism applied to tectonics; Ocean drilling; Large igneous provinces.

## 1 INTRODUCTION

Palaeolatitudes obtained from seamount magnetism (e.g. Sager *et al.* 2005), anomaly skewness (e.g. Petronotis *et al.* 1994) and Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP) and International Ocean Drilling Program (IODP) sediment and basalt cores are widely used in constraining plate motion models and defining apparent polar wander paths (APWP), in particular for the Pacific Plate. Models for absolute plate motion (APM), constrained from seamount trail geometries relative to a fixed hotspot reference frame (e.g. Duncan & Clague 1985; Wessel & Kroenke 2008), have also been used to predict APWP (e.g. Sager 2007), and the comparison between observed and predicted APWP is used to assess the validity of the fixed hotspot hypothesis. Of particular importance to the construction of Pacific APWP is the ∼123 Ma Ontong Java Plateau (OJP) (Fig. 1). OJP has been recognized as having outlying palaeolatitude measurements with respect to the Pacific APWP since a basement palaeolatitude of ∼18°S was reported for ODP Leg 130/Site 807 (Mayer & Tarduno 1993). More recently, basement samples from ODP Leg 192 Sites 1183–1187 yielded palaeolatitudes ranging from ∼22°S to ∼34°S, significantly less than those predicted by APM models and coeval palaeopoles from other Pacific sites (Riisager *et al.* 2003, 2004).

Fig. 2 shows an adaptation of the Sager (2006) APWP illustrating the 13°–15° discrepancy in OJP's palaeomagnetic pole. This discrepancy may be one reason why some previous studies concluded that OJP could not be connected to any known mantle plume source (i.e. Neal *et al.* 1997; Kroenke *et al.* 2004) and for others to require a combination of true polar wander and octupole bias effects to link OJP with its only geographically viable source, the Louisville hotspot (Antretter *et al.* 2004). This discrepancy was also cited as further evidence for Late Cretaceous to Eocene movement of Pacific hotspots, which call into question the validity of the fixed-hotspot-derived Pacific APM for this time period (Tarduno 2007).

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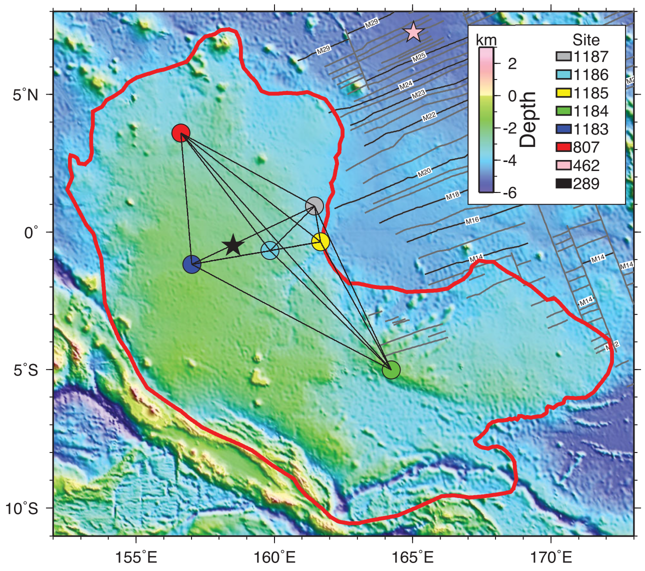


**Figure 1.** Bathymetric map of Ontong Java Plateau (red outline) showing ODP sites analysed in this study (circles). Intersite distances (Fig. 4) are computed along great circle arcs (thin black curves). Phoenix-series magnetic anomalies (grey isochrons, Nakinishi *et al.* 1992) are also shown. Although basement rocks from DSDP Sites 289 and 462 (stars) share similar emplacement characteristics, insufficient flows were sampled to average out palaeosecular variation so these data were not included in this study.

**Table 1.** Published ODP drill locations and palaeolatitudes for Ontong Java Plateau.

| Site | Lon | Lat | Inc | Plat ± $E$ | Age (Ma) |
|---|---|---|---|---|---|
| 807 [1] | 156.620 | 3.600 | −32.9 | −17.9 ± 3.3 | 122.3 [2] |
| 1183 [3] | 157.015 | −1.177 | −46.7 | −27.9 ± 7.2 | 121 [3] |
| 1184 [4] | 164.223 | −5.011 | −53.9 | −34.4 ± 5 | 123.5 [5] |
| 1185 [3] | 161.668 | −0.358 | −40.8 | −23.3 ± 2.2 | 121 [3] |
| 1186 [3] | 159.844 | −0.680 | −43.2 | −25.2 ± 3.5 | 121 [3] |
| 1187 [3] | 161.451 | 0.943 | −39.2 | −22.2 ± 2.3 | 121 [3] |

References: [1] Mayer & Tarduno (1993), [2] Mahoney *et al.* (1993), [3] Riisager *et al.* (2003), [4] Riisager *et al.* (2004), [5] Chambers *et al.* (2004).

Furthermore, claims of high internal consistency among OJP ODP-derived palaeolatitudes (Table 1) have been cited as evidence that other palaeomagnetic data of similar ages, such as Mid-Pacific Mountains and MIT Guyot (Sager 2006), are erroneous (Riisager *et al.* 2003). A recent modification to the Pacific APM incorporating hotspot drift during the Emperor stage (Chandler *et al.* 2012) yields a predicted APWP that is intermediate between the published palaeolatitudes. It is not entirely clear to what extent true polar wander would impact such APWPs. Besse & Courtillot (2002) suggest ∼10° of Pacific true polar wander (in the required sense at OJP) since 123 Ma, which is comparable to the findings of Steinberger & Torsvik (2008) for this time period. In light of the implications for Pacific Plate motion, resolving these contradictions is important.

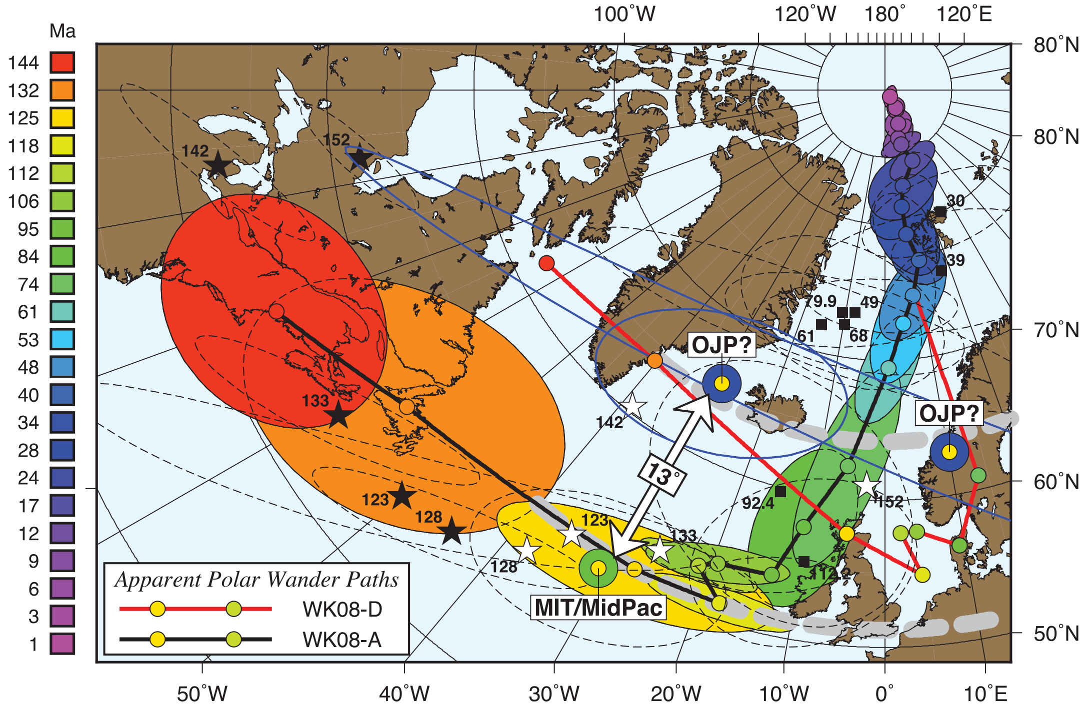


**Figure 2.** OJP palaeomagnetic data diverge from the apparent polar wander paths (APWP) for the Pacific Plate. Small colour-filled circles and corresponding error ellipses are APWP predictions from the WK08-A APM model (Wessel & Kroenke 2008) while the heavy red line is APWP predictions from the WK08-D model (Chandler *et al.* 2012). Black squares are Cretaceous average group palaeomagnetic poles from Sager (2006) with earlier poles from Larson & Sager (1992), here reproduced as stars (black for solutions with anomalous skewness correction, white without skewness correction). Anomalous poles for OJP (122 Ma; large blue and yellow circles) from Sager (2006) (left) and Riisager *et al.* (2004) (right) are also shown, compared to the coeval pole derived from MIT guyot and MidPac mountain samples (Sager (2006); large green and yellow circle). Dashed grey lines indicate the ∼13° offset between WK08-A and OJP. Under a non-zero true polar wander scenario, these polar wander paths would be affected but OJP's palaeolatitude would still be anomalous with respect to other coeval Pacific palaeolatitudes.

**Table 2.** Intersite latitude and palaeolatitude differences*.

| Site | 807 | 1187 | 1185 | 1186 | 1183 | 1184 |
|---|---|---|---|---|---|---|
| 807 | — | 2.7°, 4.3° | 4.0°, 5.4° | 4.3°, 7.3° | 4.8°, 10.0° | 8.6°, 16.5° |
| 1187 | — | — | 1.3°, 1.1° | 1.6°, 3.0° | 2.1°, 5.7° | 6.0°, 12.2° |
| 1185 | — | — | — | 0.3°, 1.9° | 0.8°, 4.6° | 4.7°, 11.1° |
| 1186 | — | — | — | — | 0.5°, 2.7° | 4.3°, 9.2° |
| 1183 | — | — | — | — | — | 3.8°, 6.5° |
| 1184 | — | — | — | — | — | — |

*ODP site rows and columns arranged in descending order according to latitude. Differences computed as row site minus column site and given as Δlatitude, Δpalaeolatitude (negative differences omitted due to symmetry).

We will show that published OJP ODP-derived palaeolatitudes (Table 1) exhibit strong internal bias of a peculiar nature. Below, we present a detailed analysis that suggests this bias can be understood as a combination of unaccounted-for tectonic tilt at Sites 1184 and 807 and a likely large-scale rotation of OJP. We end by discussing how this hypothesis affects our present understanding of the tectonic history of the OJP and the absolute motion of the Pacific Plate.

## 2 ANALYSIS

This analysis begins with the rudimentary observation that differences in palaeolatitude measurements (Δpalaeolatitude) between pairs of Ontong Java's ODP basement rock samples are in general twice as large as differences between the pairs' OJP site latitudes (Δlatitude). Data obtained from Riisager *et al.* (2004) are presented in Table 1 and computed differences are shown in Table 2 and Fig. 3. Error bars are computed as $\sqrt{E^2_{\text{inner}}+E^2_{\text{outer}}}$, where $E$ are error estimates from Table 1. Regression analysis indicates a 2:1 slope (red dashed curve) statistically different from a 1:1 slope, with 95 per cent slope confidence intervals indicated by dashed grey lines. Unless significant plateau rotation or deformation have been involved, we would expect a Δpalaeolatitude versus Δlatitude slope of approximately 1:1. In this regard, the OJP ODP palaeolatitude data show a significant systematic bias.

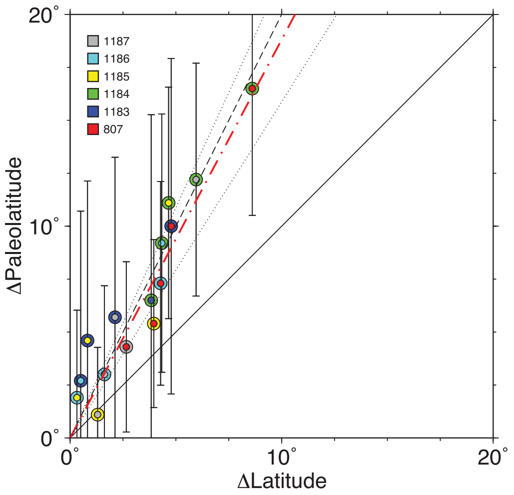


**Figure 3.** ΔPalaeolatitude versus Δlatitude shows a 2:1 slope (dashed black line) rather than the expected 1:1 slope (solid line). Two-tone circles indicate the two ODP sites involved for each data point (see legend for colour codes), with a convention that differences between a pair's site latitudes (and palaeolatitudes) are determined by subtracting values associated with the site indicated by the outer ring colour code from values associated with the site indicated by the inner ring colour code. Error bars are computed as $\sqrt{E^2_{\text{inner}}+E^2_{\text{outer}}}$. Red dashed least-squares regression line indicates statistical difference from 1:1 slope while dotted lines indicate 95 per cent slope confidence intervals.

Furthermore, a geometrically impossible scenario is apparent in the currently accepted OJP palaeolatitudes as approximately half of Δpalaeolatitude distances exceed their respective intersite great circle distances (Fig. 4). Of the eight Δpalaeolatitudes exceeding their intersite distances, fully six pertain to either Site 807 or 1184 and two involve Site 1187. We note that whole plateau rotation alone cannot produce Δpalaeolatitude to intersite distance ratios above 1:1 and that half of the Δpalaeolatitudes do not exceed this ratio. Tectonic tilt has been mentioned in drilling reports for both Sites 807 (Mayer & Tarduno 1993) and 1184 (Mahoney *et al.* 2001); we thus suspect that Sites 807 and 1184 palaeolatitudes could be at fault.

We explored a multitude of causes for the observed slope bias. These scenarios are based upon assumptions (1) that palaeolatitudes across the plateau reflect their depositional environment (i.e. rapid emplacement) and (2) that drilling sampled sufficient basement rock to remove the effects of secular variation. In other words, we assume the magnetic inclination and age measurements are accurate. First, we ruled out whole plateau tilt since it cancels out when computing differences. Likewise, consistent local tilts, although more geologically plausible, would also cancel out in the differences. Site-specific tilt corrections can always be devised to remove the observed bias (i.e. we solve for corrections at each site required to yield in a 1:1 slope), but there is a lack of evidence favouring faulting or tilting at Sites 1183, 1185, 1186 and 1187. We therefore find such *ad hoc* tilts at each site to be an unlikely cause of the systematic bias. If we assume instead that the bias reflects translational deformation of OJP (i.e. the distances between sites have changed), the implication is that up to 50 per cent crustal shortening has occurred (see Fig. 4), constituting a rather unlikely scenario that is unsupported by regional seismic studies (e.g. Mann & Taira 2004). In addition, on a plate with a component of north–south motion, age differences brought about by incorrect age determinations would also produce palaeolatitude differences although it is unlikely that random age biases would result in the observed 2:1 slope. Finally, while most palaeomagnetic studies assume a geocentric axial dipole, there may have been non-dipole components at various times in the past. For instance, Van der Voo & Torsvik (2001) suggested a 10 per cent octupole component might have been present during the Mesozoic and thus possibly during OJP formation. However, our analysis relies on differences between palaeolatitudes so biases from such an octupole component fall in the 0°–2° range and thus do not significantly affect our slopes.

Although other mechanisms are able to reduce the slope bias, they require that measured palaeolatitudes and/or ages be at fault. The only mechanism that simply explains the observed palaeolatitude discrepancies is rotation of the whole plateau. For maximum consistency, palaeolatitude corrections for two sites were required. The literature contains references to tilted basement rocks at Site 1184 (9° northward dip, Mahoney *et al.* 2001) and at Site 807. As indicators of tilt, Mayer & Tarduno (1993) cited the fact that Site 807 sits in a graben, has shallowing inclination with depth, and a 21° discrepancy between reconstructed and mean measured inclination. However, the latter argument was questioned by Sager (2006) as this discrepancy is shared with other OJP palaeolatitudes. On the other hand, Sites 1183, 1185, 1186 and 1187 presumably sampled undisturbed rocks. This duality of tilted and undisturbed samples led us to devise a geological scenario where the observed slope bias would be the result of a combination of rotation of

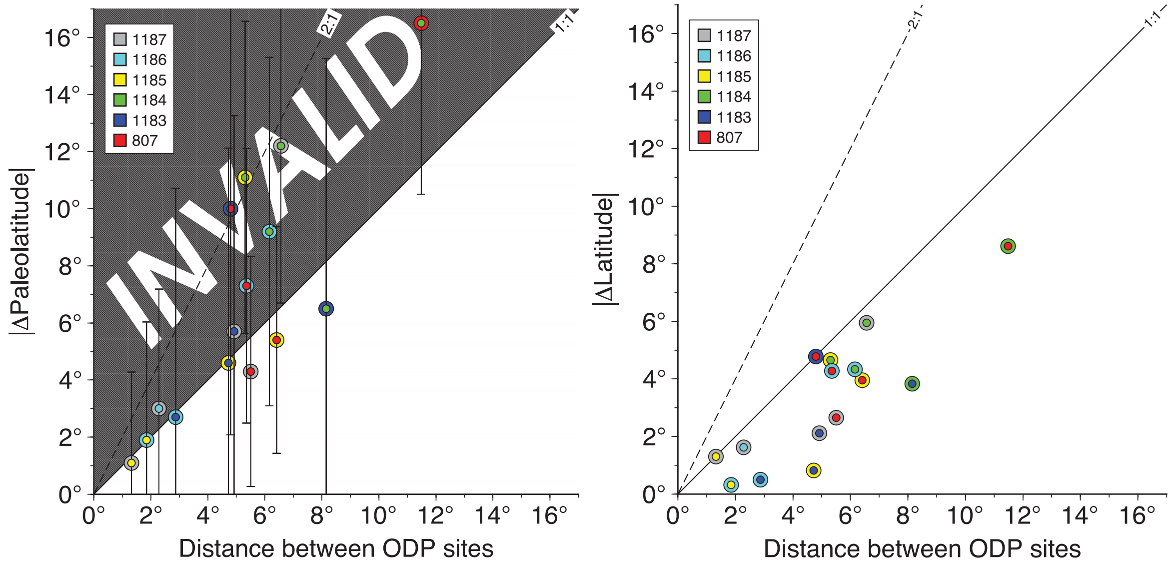


**Figure 4.** About half of OJP Δpalaeolatitudes violate the basic geometrical principle that intersite Δpalaeolatitudes should not exceed their respective great circle distances (left-hand panel). Δlatitude versus great circle distance naturally exhibits no such phenomenon. If all palaeolatitudes were valid, crustal shortening of ∼50 per cent would be implied (right-hand panel).

the whole plateau as well as tilt adjustments for Sites 807 and 1184.

Quantification of plateau rotation involves both present and past positions of Ontong Java's ODP site locations. Palaeosite positions are determined from their published palaeolatitudes and from modelled palaeolongitudes. We first determine the mean present ODP location (160.137°E, 0.447°S) using the undisturbed OJP ODP Sites, 1183 and 1185–1187. We next determine the mean palaeosite position (141.009°W, 24.650°S) by computing the mean of undisturbed published palaeolatitudes and by reconstructing the mean present longitude to its 123 Ma location using the WK08-D Pacific APM model of Chandler *et al.* (2012). APM influence is minimized by limiting its use to mean palaeosite longitude derivation; different APM models only affect the results insignificantly. The difference in present and palaeomean site positions is the constant ($\Delta$longitude $= 58.854°$, $\Delta$latitude $= -24.203°$) used for translating present site locations to overlie the palaeosite distribution (see Fig. 5). The mean present site location serves as the vertical axis about which OJP rotations are performed. Rotations about the present mean site location are then translated by the difference in mean site positions to overlie the palaeosite distribution. These modelled palaeosite locations provide palaeolongitudes for both the observed and modelled data sets (hence differences in reconstructions from different APM models would cancel out). For context, an interpreted OJP perimeter (Chandler *et al.* 2012) is also translated and rotated by the same amounts (see Figs 5–7). Finally, we produce candidate models at all rotation angles and determine optimum rotations by minimizing modelled palaeolatitude versus observed palaeolatitude $\chi^2$ misfit, calculated as $\sum_{i=1}^{N}(e_i/E_i)^2$ where $N = 6$, $e_i = |plat_{obs} - plat_{model}|_i$ and $E_i$ are published palaeolatitude errors from Table 1. Note that the actual plateau rotation axis may have differed from ours, but such differences simply amount to a translation which cancels when differences between sites are computed.

Assuming OJP deformation has occurred outside its perimeter and that the interior remains relatively undisturbed, we expect agreement between modelled and observed palaeo-ODP site positions. In addition to plateau rotation, tilt corrections may also be derived on the basis of this assumption. We therefore compute tilt corrections by determining model versus palaeolatitude inclination differences for ODP Sites 807 and 1184. While the study by Mayer & Tarduno (1993) mentioned possible tectonic tilt at Site 807 but made no such correction, the Site 1184 palaeolatitude derivation by Riisager *et al.* (2004) did not mention whether palaeoinclination was adjusted. We therefore considered both horizontal and tilted emplacement of Site 1184 tuff deposits due to uncertainty in whether it was applied in previous studies. If beds were deposited horizontally, then the 9° northward tilt observed by Mahoney *et al.* (2001) would imply a comparable increase in Site 1184's inclination. Conversely, if layers were deposited at an angle, and if the published 1184's palaeolatitude was corrected based on the horizontal assumption, then 1184's inclination needs to be reduced.

Figs 6 and 7 illustrate the improved agreement between modelled and palaeolocations that is attained by plateau rotation ($\omega$ denotes rotation angle). Unfilled coloured circles are palaeosite locations as published by Riisager *et al.* (2004) whereas filled circles are our tilt-corrected palaeosite locations. Arrows show the magnitude and sense of the two tilt corrections. Open squares are the present ODP sites after rotation and translation and serve as predicted palaeosite locations based on the prescribed rotation angle. Significant reduction in $\chi^2$ misfit is apparent for panels with non-zero rotation angle. Figs 6 and 7 differ in their handling of Site 1184. In Fig. 6, we show how removing the Mahoney *et al.* (2001) 9° tilt adjustment from Site 1184's inclination, coupled with plateau rotation, dramatically improves agreement to its expected location. In Fig. 7, Site 1184's tilt adjustment is estimated independently from the palaeoinclination data as simply the difference between predicted and observed values.

## 3 RESULTS

The $\chi^2$ misfits computed for the full range of rotation angles are shown in Fig. 8. In Fig. 8(a), we see a misfit reduction of one order of magnitude from ∼1 at 0° rotation to the minimum misfit value of

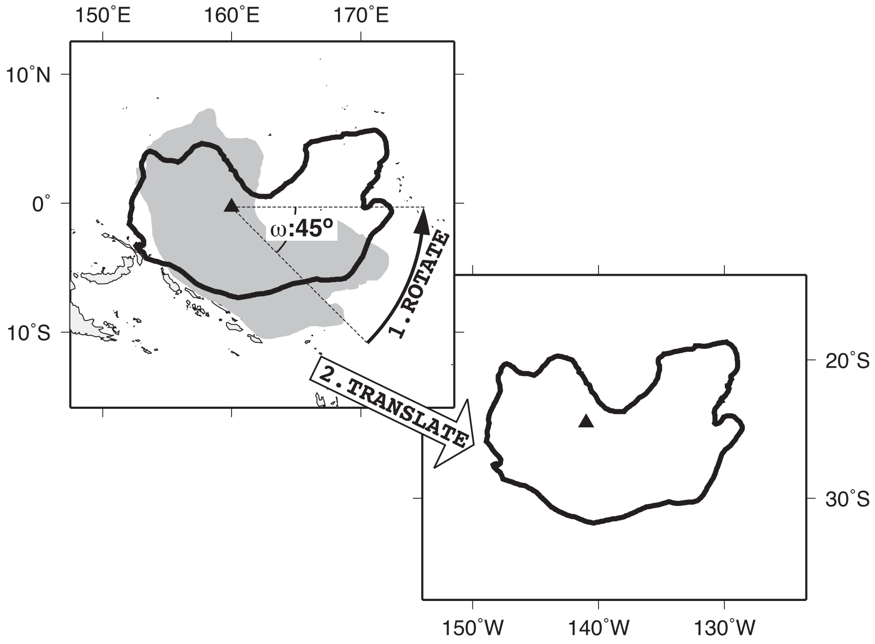


**Figure 5.** We model the full range of rotations (45° shown here) by first rotating present-day Ontong Java about its mean undisturbed ODP Site location (black outline and triangle in upper left map), then reconstructing to its palaeolocation (black outline and triangle in lower right map) where palaeolatitude and palaeolongitude are determined from OJP's undisturbed palaeolatitudes and WK08-D APM, respectively.

0.101 occurring at 37° rotation. However, rotation angles between 25° and 50° achieve nearly identical misfit reduction, implying that the true plateau rotation was likely within this range. Fig. 8(b) shows similar $\chi^2$ misfit results for the alternative scenario in which neither 807 nor 1184 are involved in misfit calculations. Based solely on the undisturbed sites located closer to the mean site location, this scenario suggests a similar rotation but with a larger range of acceptable rotations. Here, the minimum misfit of 0.057 occurs at 52° rotation angle. Of course, the closer clustering of data points to the rotation axis means the uncertainty in the rotation angle is likely to be higher, as reflected in the broadening of the $\chi^2(\omega)$ curve.

Tectonic reconstructions at these preferred rotation angles are shown in Fig. 9. Improvement between expected (squares) and observed (circles) palaeolatitudes is seen at all sites in Fig. 9(a); however, aside from Site 1186, expected and observed sites do not overlie one another. This scenario implies an ∼8° southerly tilt correction for Site 807, yielding an estimated −41° inclination and −23.5° palaeolatitude. Site 1184, after removing the 9° tilt correction from the published measurement, has −44.9° inclination and −26.5° palaeolatitude.

At 52° rotation (Fig. 9b), further improvement is seen to the point where measured palaeolatitudes overlie (within 1° of one another) their expected locations directly at Sites 1183, 1185 and 1186. This scenario implies ∼10° southerly and ∼12° northerly tilt corrections for Sites 807 and 1184, respectively. For Site 807, the inclination and palaeolatitude corresponding to the 52° rotation tilt correction estimates are −42.9° and −24.9°. For Site 1184, the inclination and palaeolatitude estimates are −41.9° and −24.1°. Therefore, at the 37° rotation angle, Site 807 plots just 3° north of Site 1184, whereas the 52° rotation scenario suggests Site 1184 was 0.8° north of Site 807 at 123 Ma. This is in stark contrast to the currently accepted 16.5° palaeoseparation between Site 807 to the north and Site 1184 to the south, respectively.

The process of slope bias removal by plateau rotation and tilt correction is further illustrated graphically in Fig. 10. In each graph, two-tone colour-filled circles are modified by rotations and/or tilt adjustments, whereas unfilled coloured circles are the original biased data, which do not vary. Except in cases of tilt correction, Δpalaeolatitudes do not change. In essence, the colour-filled two-tone circles move only in the horizontal direction as the plateau is rotated. In Fig. 10(a), the plateau has been rotated 37°, causing the redistribution of Δlatitudes shown. The interior sites (excluding 807 and 1184) now cluster along the ∼1:1 slope line. Similar ∼1:1 slopes are also evident for the subset of Site 1184 points (green) although the 1184 distribution is offset from the origin by a constant vertical offset that is related to its erroneous palaeolatitude measurement. Fig. 10(b) shows the effect of removing the 9° Site 1184 tilt correction from the Riisager *et al.* (2004) palaeolatitude. The 1184 subset of points has now been shifted vertically to the origin and shares a similar ∼1:1 slope with the interior undisturbed points. Fig. 10(c) shows a similar effect when applying our 8.2° southerly tilt correction estimate to Site 807's palaeolatitude, namely that the 807 subset (red points) are shifted down to the origin and share identical slope with the other OJP points. We note that this scenario reduces the slope bias from slope ∼2 (as in Fig. 3) to ∼1.3, a substantial improvement given only six ODP sites.

Fig. 10(d) shows the effect of a 52° plateau rotation on the biased background points. A similar observation can be made, that interior points are now aligned along the 1:1 slope line. Sites 1184 and 807 subsets are again offset vertically due to their erroneous palaeolatitude measurements. Applying our estimated tilt corrections to Site 1184 (Fig. 10 e) and 807 (Fig. 10f) palaeolatitudes results in a further reduction of slope bias from 2 to 1.2.

## 4 DISCUSSION

The OJP rotation hypothesis clearly depends on the accuracy of ODP basement age and palaeolatitude measurements for its plausibility. Our rotations would be affected and possibly invalidated should ages or palaeolatitudes be shown to differ significantly from their currently accepted values. Site 1184 age and palaeolatitude

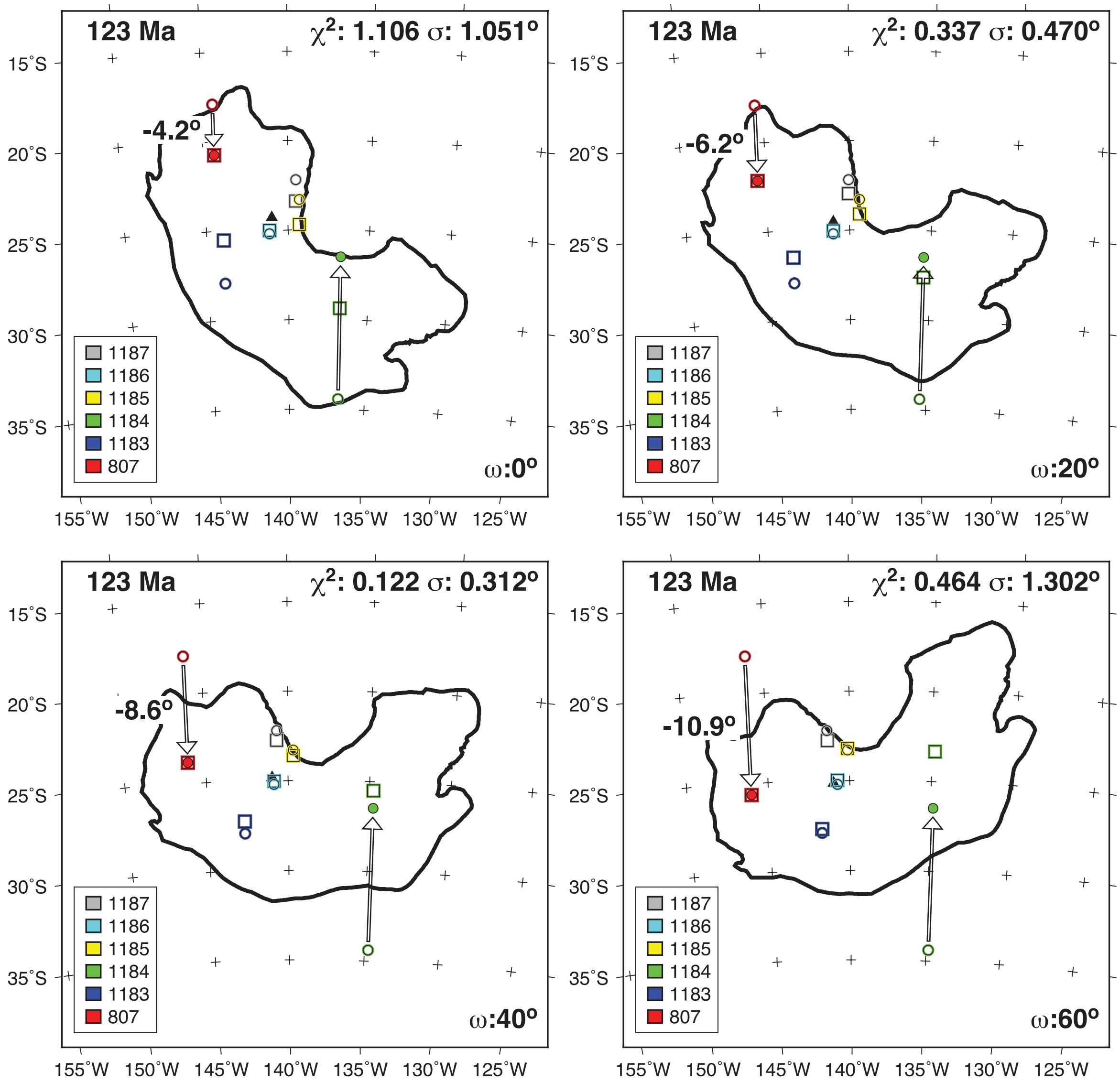


**Figure 6.** Map view comparison of translated and rotated ODP/DSDP drill site positions (squares) to the set of OJP palaeolatitude measurements (circles). Rotation is about the mean ODP/DSDP site location (black triangle). $\chi^2$ and $\sigma$ represent modelled versus observed palaeolatitude misfit and misfit standard deviation, respectively. Here, Site 807's tilt adjustment is being estimated, hence the site is not included in misfit calculations. Site 1184 is tilt corrected northwards by 9° and is a leverage point controlling misfit minimization. Misfit decreases as rotation angle ($\omega$) approaches 40° when it begins increasing (see Fig. 8).

measurements, in particular, have both been problematic according to the literature. Whereas other OJP basement samples were basaltic lavas, mid-Eocene fossil-bearing tuff was sampled at Site 1184 (Mahoney *et al.* 2001). A subsequent $^{40}$Ar/$^{39}$Ar analysis of plagioclase crystals separated from the volcanoclastic matrix yielded a Cretaceous age of 123.5 Ma, leading Chambers *et al.* (2004) to rule out the Eocene age. Similarly, while Site 1184's palaeolatitude has been reported as 34.4° S (Riisager *et al.* 2004), our analysis suggests this measurement is too far south by 8°–11°. However, our analysis suggests that the 1184's palaeomagnetic measurement is likely precise with the bias being in the 9° tilt adjustment. Removing this tilt adjustment reconciles Site 1184's palaeolatitude with other undisturbed sites (at 37° rotation) and implies northward inclination of tuff beds at emplacement with a likely vent to the south. We note in the event that Site 1184 data are found to be unreliable, the remaining OJP data still support rotation. Indeed, our alternative analysis does not include Site 1184 in $\chi^2$ misfit calculations and suggests 52° rotation although its uncertainty increases somewhat. Assuming Site 1184's palaeolatitude to be accurate, the 37° rotation scenario is preferable to the less constrained 52° rotation scenario, suggesting ~40° of clockwise rotation since 123 Ma.

In exploring potential causes for the observed Δpalaeolatitude versus Δlatitude slope bias, we derived a set of six *ad hoc* tilt adjustments, that when applied to the published measurements, resolved the slope bias without the explicit need for plateau rotation. In support of this interpretation is the fact that these tilt adjustments (see Table 3's *ad hoc* column) result in palaeolatitudes that are within the published uncertainty range for each of the six sites. However, these *ad hoc* tilt corrections suggest modification of all published palaeolatitudes in such a way as to bring them in line with expected values for an unrotated plateau. Therefore, the *ad hoc* method holds the model fixed while adjusting the observations. This method is clearly the inverse of our rotation hypothesis, which finds optimum model rotations relative to fixed observations. In addition, inspection of

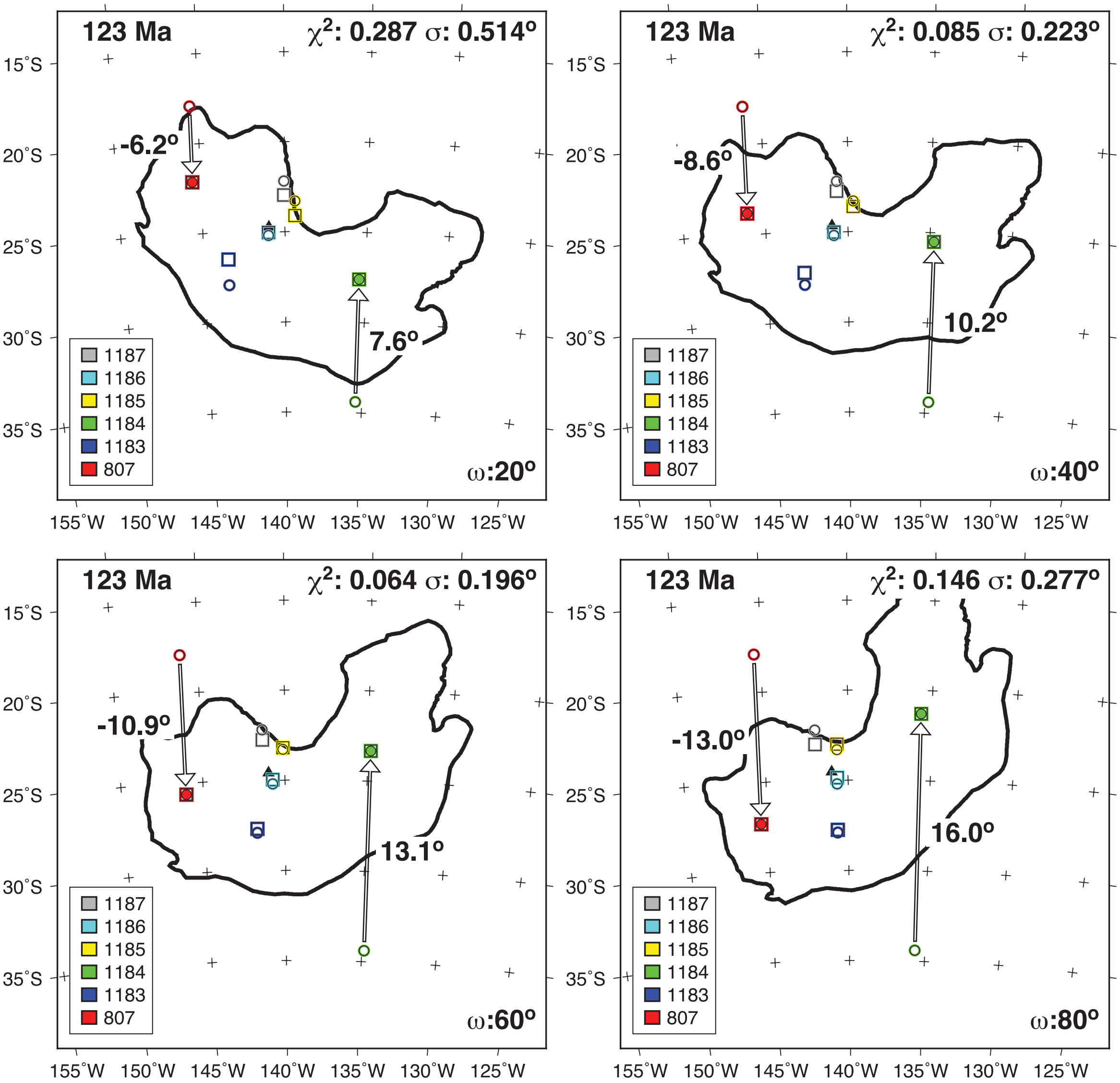


**Figure 7.** The magnitude of rotation based solely on the undisturbed sites is determined by excluding Sites 1184 and 807 from misfit calculations. In this case, misfit decreases as rotation angle approaches 60° then begins to increase (see Fig. 8). Tilt correction estimates for Sites 807 and 1184 are derived as a result. See Fig. 6 caption for symbol descriptions.

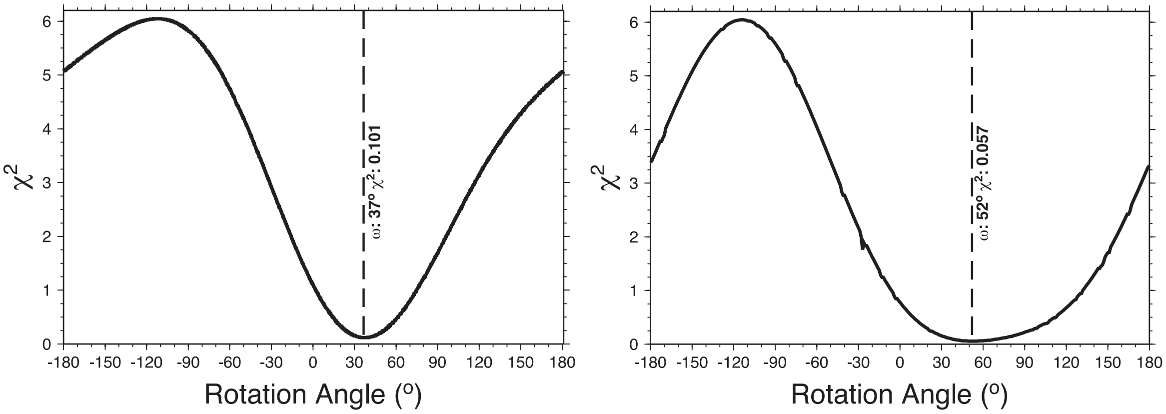


**Figure 8.** $\chi^2$ misfit versus rotation angle shown for both rotation angle estimations. Minimum misfit occurs at 37° clockwise rotation when our corrected Site 1184 palaeolatitude is included in misfit calculations (left-hand panel). A broader range of low misfit and a global minimum of 52° is found by excluding this site (right-hand panel).

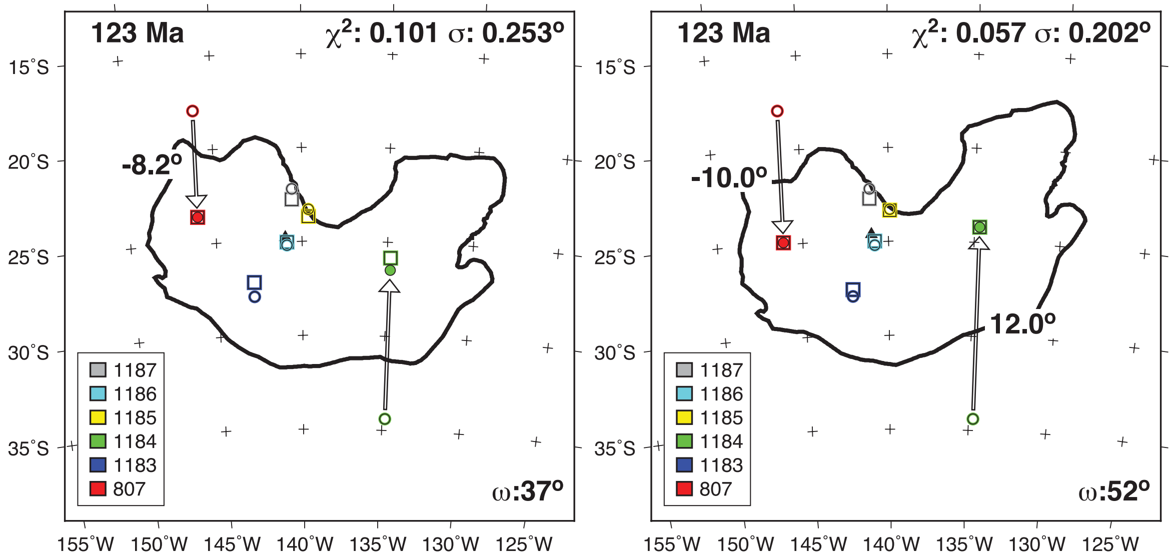
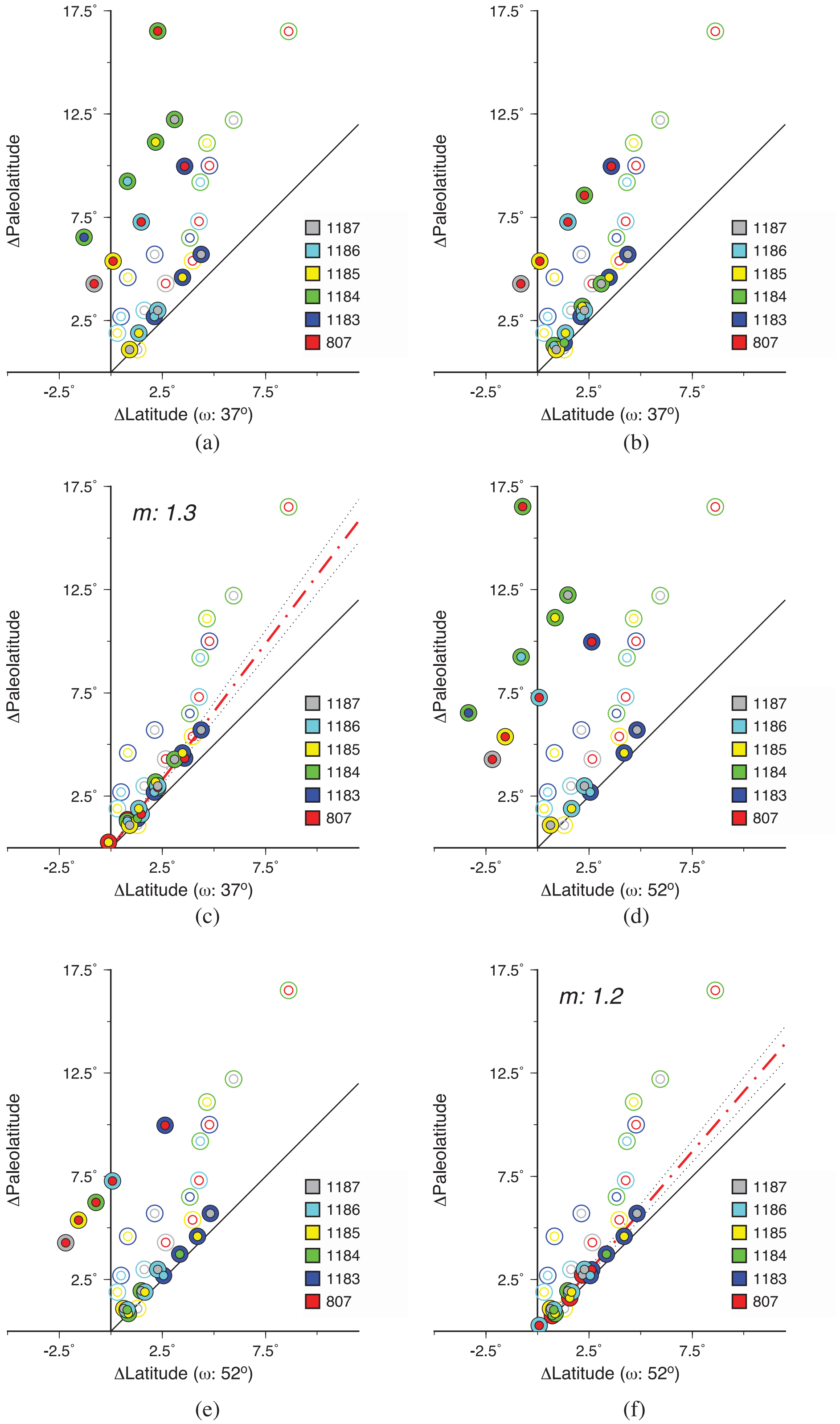


**Figure 9.** Improved agreement between expected and observed palaeolatitudes is seen at optimum rotation angles whether Site 1184 is included (left-hand panel) or not (right-hand panel).

*ad hoc* corrections for the undisturbed sites presented in Table 3 reveals magnitudes and directions that correspond to rotation in the opposite sense. While we must acknowledge such a possibility, we consider such a contrived set of inclination adjustments to be much less likely than the rotation hypothesis which requires tilt adjustment at the very sites that mention tectonic tilt in their original drilling reports. Also shown in Table 3 are misfits between modelled and observed palaeolatitudes ($e_i$) at angles $\omega = 0^\circ$, 37° and 52°. These $e_i(\omega)$ values exhibit the misfit reductions attained at each of the undisturbed sites through the whole plateau rotation. We are unable to explain the dichotomy between relatively large palaeolatitude measurement uncertainties and the strong agreement between observed and modelled palaeolatitude locations. One would not expect a single rotation to cause most of the palaeolatitudes to agree if the source of data scatter were random. Our results possibly indicate that palaeolatitude measurements may be better defined than suggested by their respective and conservative error estimates.

The less likely interpretation requiring tilt adjustments of all OJP basement palaeolatitudes implies little change to the tectonic history of the Pacific Plate. Ontong Java remains an enigmatic piece of Pacific crust with palaeolatitudes that do not conform to the conventional Pacific APWP. Under this scenario, the primary implication is of extensive plateau deformation not previously recognized or of significant unaccounted for secular variation. In contrast, the rotation hypothesis requires significant revision of Pacific Plate history. The rotations predicted by our models are unprecedented among Pacific Plate motion models. For instance, the WK08-A (Wessel & Kroenke 2008), OMS-05 O'(Neill *et al.* 2005) and WK08-D (Chandler *et al.* 2012) APMs predict OJP rotations of 4° clockwise, 2.8° counter-clockwise and 13° counter-clockwise to have occurred since 123 Ma (Chandler *et al.* 2012). The WK08-D APM was favoured by (Chandler *et al.* 2012) for including Emperor-stage Hawaiian plume drift, requiring little to no true polar wander, and for best reconciling Ontong Java–Manihiki–Hikurangi superplateau reconstructions with palaeolatitude evidence. However, the rotation predicted by WK08-D is in the opposite sense (i.e. counter-clockwise). If the rotation predicted by APM models is valid, the implication is that OJP's orientation relative to Pacific was $\sim$50°–65° different than today. Either (1) all published Pacific APM models are unreliable for the Lower Cretaceous or (2) there was relative motion between OJP and the Pacific since the time of OJP formation. While the palaeolatitude evidence favours plateau rotation, we are unable to determine whether this rotation involved the whole Pacific or former microplates (e.g. OJP) that were later accreted to the Pacific Plate. Although a 37°–52° rotation of the whole Pacific Plate seems unlikely, mantle convection modelling by Shephard *et al.* (2012) failed to reconcile mantle tomography profiles with Pacific motion predicted by current APM models, suggesting a possible Pacific history much different than our current understanding. The more likely scenario involves decoupling between Pacific and Ontong Java, although no obvious palaeo-Pacific–OJP plate boundary is apparent and it is uncertain whether this decoupling took the form of microplate rotation or reflects tectonic interactions with the Pacific or the encroaching Australian Plate.

Clockwise OJP rotation is not incompatible with the recent hypothesis that Ontong Java formed simultaneously with Manihiki and Hikurangi plateaus as part of the Ontong Java Nui superplateau (Taylor 2006); (Chandler *et al.* 2012). Manihiki's Site 317 palaeolatitude (Cockerham & Jarrard 1976) is the sole sample-based palaeolatitude measurement for testing the compatibility of these two hypotheses. Cockerham & Jarrard (1976) reported a 20° palaeolatitude difference between DSDP Site 317's volcaniclastic-basalt basement and overlying carbonate sediments. The authors favoured the carbonate palaeolatitude and offered either tectonic tilt of the basement strata or a failure to average out secular drift as reasons for Site 317's 47.5°S basement palaeolatitude. Cockerham & Jarrard (1976) further acknowledged the possibility that compaction of overlying sediments could have altered the sedimentary palaeoinclination by $\sim$20°. Another Site 317's palaeolatitude study by Cockerham & Hall (1976) reported that tectonic tilting likely occurred between the time of carbonate and volcanoclastic sediment deposition and that the carbonate palaeolatitude estimate suffered from an inclination error requiring further study. Although Manihiki's Site 317 palaeoinclination measurement is of poor quality (e.g. only seven independent flow units were sampled), as shown in Fig. 11(a), the Manihiki carbonate palaeolatitude is in good agreement with the superplateau hypothesis at 37° rotation (1184 is tilt



(a) (b)

(c) (d)

(e) (f)

**Figure 10.** Depiction of slope bias removal showing least-squares regression estimates for slope (*m*). The slope bias can be removed by (a) rotating OJP 37°, (b) removing Site 1184's published 9° tilt correction (implies emplacement-induced dip) and (c) applying an 8.2° southerly tilt adjustment to Site 807. (d) Further improvement is seen with 52° plateau rotation along with (e) a 12° northward tilt adjustment for 1184 tuff beds and (f) a 10° southerly tilt correction for Site 807. Original and biased data are plotted as unfilled circles while filled circles are subject to rotation and/or tilt correction.

**Table 3.** Predicted and published OJP palaeoinclination discrepancies at different modelled rotations.

| Site | *Ad hoc* | $e_i$ ($\omega = 0^\circ$) | $e_i$ ($\omega = 37^\circ$) | $e_i$ ($\omega = 52^\circ$) |
|---|---|---|---|---|
| 807 | −3.2 | −4.2 | −8.2 | −10.0 |
| 1183 | 2.0 | 3.0 | 0.9 | 0.4 |
| 1184 | 4.7 | 5.5 | 9.8 | 12.0 |
| 1185 | −1.8 | −1.9 | −0.5 | −0.1 |
| 1186 | −0.2 | 0.2 | 0.2 | 0.3 |
| 1187 | −1.6 | −1.6 | −0.8 | −0.7 |

*Note:* $e_i$ are differences between predicted and published OJP palaeoinclination and *ad hoc* are zero-mean tilt corrections yielding 1:1 Δpalaeolatitude versus Δlatitude slope.

corrected here, Site 317's volcanic palaeolatitude is not shown). Furthermore, if we include Site 317 while omitting Sites 807 and 1184 in misfit calculations, we estimate a Site 317-optimized superplateau rotation of 35°, statistically identical to the OJP-only rotation. However, should the carbonate palaeolatitude be erroneous due to tilt or compaction, the 47.5° basement palaeolatitude would favour the WK08-D reconstruction (Chandler *et al.* 2012) and not the rotation/superplateau reconstruction shown in Fig. 11(a). Higher quality basement palaeolatitudes are clearly needed for Manihiki to resolve the compatibility of the OJP rotation and OJP–Manihiki–Hikurangi superplateau hypotheses.

Although no clear Pacific/Ontong Java suture is apparent in regional bathymetry, the large magnitude of rotation required by the palaeolatitudes and evidence against such large Pacific Plate rotations implies decoupling. This is not a new suggestion: The ∼15° offset between OJP's palaeolatitude and that implied by other 123 Ma samples elsewhere has long been a puzzle. Acton & Gordon (1994) suggested motion between the south and north Pacific was required to reconcile palaeomagnetic data from the Pacific with other plates. Larson & Sager (1992) postulated a missing 'Stealth Plate' that once separated the Mesozoic magnetic lineation sets (Japanese, Hawaiian and Phoenix lineations) to explain the missing 15°. Sager (2006) revisited this consideration in light of the improved OJP palaeolatitude estimates and reaffirmed the possibility of a tectonic disconnect between OJP and the rest of the Pacific, despite the difficulty in envisioning a tectonic scenario for it. We consider our inferred large-scale rotation to also support decoupling between OJP and the Pacific during or shortly after plateau formation.

The possibility of an OJP decoupling has implications for studies of Pacific apparent polar wander curves, which have included Ontong Java as a constraint (albeit anomalous) for the ∼120–125 Ma time frame. High internal consistency among OJP palaeolatitudes has been used to question the veracity of palaeolatitudes at MIT Guyot and the Mid-Pacific Mountains and presented as evidence against fixity of Pacific hotspots (Riisager *et al.* 2003). However, with a decoupled Ontong Java, OJP palaeolatitudes would no longer be suitable as constraints for Pacific APWP. MIT Guyot and the Mid-Pacific Mountains, which show much better agreement with the overall Pacific APWP trend (Fig. 2), would then become the primary constraints for Pacific APWP at ∼123 Ma. Nevertheless, even after tilt adjustment, the OJP palaeolatitudes are still significantly further north than the nearest likely source (Louisville hotspot). If we consider a Pacific APM such as the WK08-D, which accepts a greatly reduced north–south motion during the Emperor stage, then the corresponding predicted Pacific APWP (red line; Fig. 2) for 125 Ma is half-way between the MIT Guyot/Mid-Pacific mountains and OJP palaeolatitudes. However, it is at present not clear how to reconcile the proposed Emperor-stage hotspot drift (>14°; Tarduno *et al.* 2003) with the apparent lack of significant drift for the Louisville hotspot as implied by IODP Leg 330 results (Koppers *et al.* 2012). More work is clearly needed on refining the Pacific APM back to 125 Ma.

The tilt adjustment estimates for Sites 807 and 1184 have little impact on OJP's mean palaeolatitude. This is largely because these corrections have similar but oppositely oriented magnitudes that move each site closer to the mean. In comparison to the currently accepted 25.2°S mean palaeolatitude, we find mean values of 24.8°S and 24.6°S for plateau rotations of 37° and 52°, respectively. However, should 10 per cent octupole bias be present during formation then the mean palaeolatitude would shift ∼5° further south (Van der Voo & Torsvik 2001; Antretter *et al.* 2004).

While evidence favours our combined rotation and 807/1184 tilt correction model, we acknowledge that large uncertainties in palaeolatitudes allow contributions from other sources, including insufficient sampling to remove secular variation effects along with

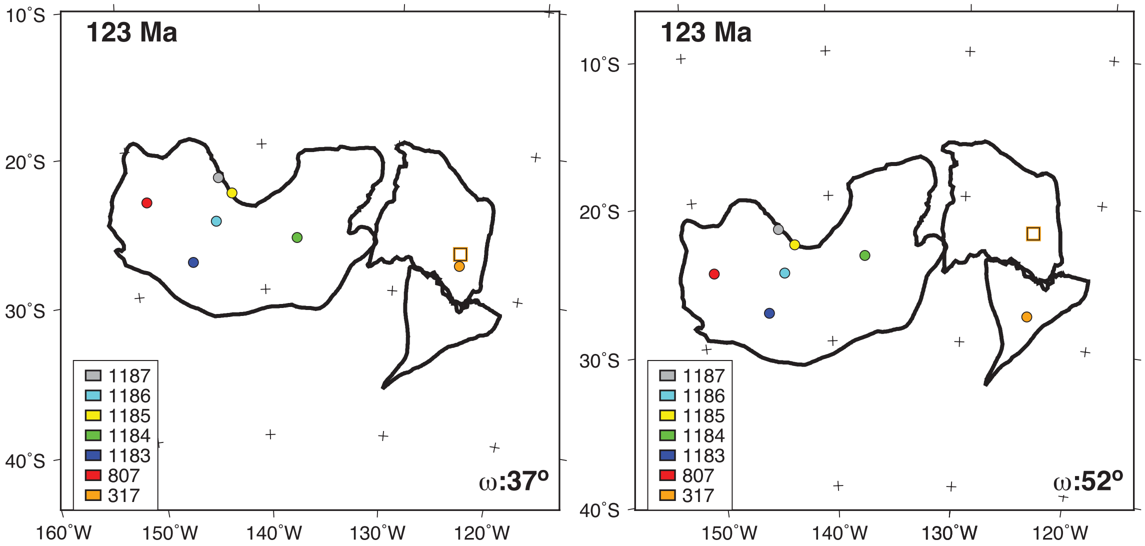


**Figure 11.** 123 Ma reconstruction of the Ontong Java Nui superplateau (Chandler *et al.* 2012) at 37° (left-hand panel) and 52° (right-hand panel) rotation. The palaeolatitude determined from DSDP Site 317 carbonate sediments (Cockerham & Jarrard 1976) favours the 37° scenario.

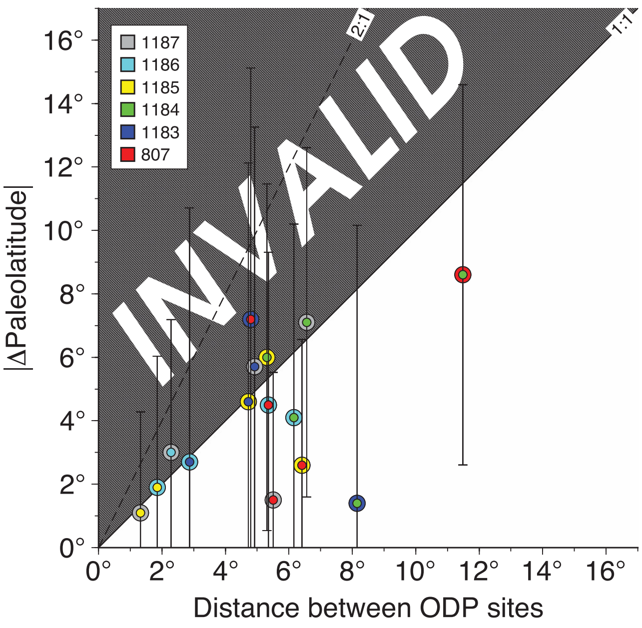


**Figure 12.** ODP Sites 807 and 1184 appear to be erroneous whether or not OJP rotation occurred. Here, it is assumed that no rotation occurred so Sites 807 and 1184 are tilt corrected using their respective tilt correction estimates ($e_i$ at 0° in Table 3). The majority of Δpalaeolatitudes no longer exceed their respective intersite distances.

the possibility that a slope statistically indistinguishable from 1:1 could be drawn if Site 1184 were omitted from the analysis or if Sites 807 and 1184 were tilt corrected in the absence of rotation. In particular, the number of statistically distinct magnetic units at each site is relatively low (i.e. five to seven for Sites 1184–1187 and eight for Site 807) which may not be enough to average out secular variation (Sager 2006). Figs 12 and 13 depict the effects of rotationless tilt corrections of Sites 807 and 1184 using their respective $e_i$ ($\omega = 0°$) tilt correction estimates shown in Table 3. A reduction from eight to five invalid Δpalaeolatitudes is apparent in Fig. 12. Although the regression slope apparent in Fig. 13 is statistically indistinguishable from a 1:1 slope, internal bias is still evident for three subsets; the undisturbed sites (1183 and 1185–1187) fall along the 2:1 slope curve and the 807 and 1184 subsets remain parallel to the 2:1 slope curve, indicating that the internal bias is not resolved through tilt correction of Sites 807 and 1184 alone.

## 5 CONCLUSION

We have presented a simple geological model that reconciles Ontong Java ODP site locations with their respective palaeolatitude measurements and that suggests $\sim 40°$ of clockwise rotation since 123 Ma. Aside from Sites 807 and 1184, of which tilt corrections have been estimated, we find OJP's palaeolatitudes to be internally consistent when coupled with previously unrecognized rotation of the plateau. The reduction in palaeolatitude error and resultant determination that the adjusted palaeolatitudes are no longer anomalous, provide evidence for either significant rotation of the Pacific Plate since the time of OJP formation or for decoupled movement between the Pacific Plate and Ontong Java. The latter hypothesis, favoured by other coeval palaeopoles, calls into question the suitability of Ontong Java palaeolatitudes as constraints for Pacific APWP. Although there is strong support for rotation among the OJP palaeolatitudes, the hypothesis is complicated by a lack of an obvious Pacific–OJP palaeoplate boundary. Furthermore, Manihiki's sole basement palaeolatitude, although of questionable validity, indicates a palaeoposition that is incompatible with the rotation magnitudes implied by this analysis. More high-quality basement palaeolatitudes at Ontong Java and particularly for the Manihiki and Hikurangi plateaus will be required to confirm or reject the rotation hypothesis and to revise the Cretaceous history of the Pacific Basin.

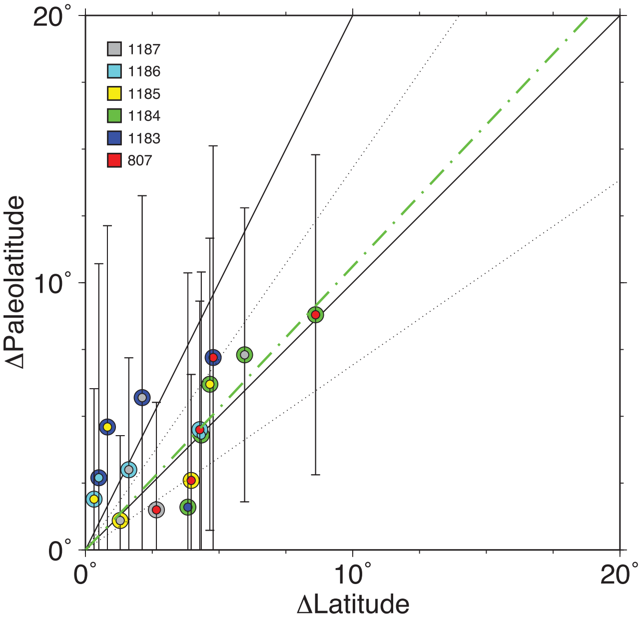


**Figure 13.** Assuming no rotation occurred, Sites 807 and 1184 are adjusted according to their respective $e_i$ ($\omega = 0°$) tilt correction estimates from Table 3. Although statistical equivalence to 1:1 slope is found (green dashed regression line), greatly increased 95 per cent slope confidence intervals (dotted lines) indicate that considerable error has been introduced. Furthermore, 2:1 slopes are evident in the undisturbed (1183 and 1185–1187), 807 (red), and 1184 (green) subsets, suggesting that the bias is not resolved through tilt correction alone.

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