Absolute plate motions and true polar wander in the absence of hotspot tracks

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LETTERS

Absolute plate motions and true polar wander in the absence of hotspot tracks

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The motion of continents relative to the Earth's spin axis may be due either to rotation of the entire Earth relative to its spin axis—true polar wander[1,2]—or to the motion of individual plates[3]. In order to distinguish between these over the past 320 Myr (since the formation of the Pangaea supercontinent), we present here computations of the global average of continental motion and rotation through time[4] in a palaeomagnetic reference frame. Two components are identified: a steady northward motion and, during certain time intervals, clockwise and anticlockwise rotations, interpreted as evidence for true polar wander. We find ~18° anticlockwise rotation about 250–220 Myr ago and the same amount of clockwise rotation about 195–145 Myr ago. In both cases the rotation axis is located at about 10–20° W, 0° N, near the site that became the North American–South American–African triple junction at the break-up of Pangaea. This was followed by ~10° clockwise rotation about 145–135 Myr ago, followed again by the same amount of anticlockwise rotation about 110–100 Myr ago, with a rotation axis in both cases ~25–50° E in the reconstructed area of North Africa and Arabia. These rotation axes mark the maxima of the degree-two non-hydrostatic geoid during those time intervals, and the fact that the overall net rotation since 320 Myr ago is nearly zero is an indication of long-term stability of the degree-two geoid and related mantle structure[5,6]. We propose a new reference frame, based on palaeomagnetism, but corrected for the true polar wander identified in this study, appropriate for relating surface to deep mantle processes from 320 Myr ago until hotspot tracks can be used (about 130 Myr ago).

True polar wander (TPW) occurs because the Earth's spin axis remains always very nearly aligned with its axis of maximum non-hydrostatic moment of inertia—the short axis of the non-hydrostatic degree-two component of the geoid, which is a triaxial ellipsoid. As the geoid changes with time, the solid Earth (presumably down to the core–mantle boundary) rotates uniformly so that these axes remain aligned. Rapid TPW may occur when the short and intermediate axes of the degree-two geoid (with hydrostatic flattening removed) become nearly equal. Then the rotation axis may move along the line between those two axes, leaving the long axis at the Equator. Relating TPW to the Earth is complicated, because on geologic timescales there is presumably no rigid part that can serve as a reference frame for the entire Earth; rather, the Earth's mantle is slowly convecting, and a reference frame with zero net rotation of the convecting mantle can be regarded as most suitable. TPW has been proposed as an explanation for such disparate phenomena as rapid plate velocities, sea-level changes and the Cambrian 'Explosion of Life' (see, for example, refs 7–10). The maximum speed of TPW can be estimated on the basis of how fast the geoid changes and on how fast the Earth's hydrostatic bulge can adjust to a changing rotation axis[11]. This speed limit is estimated to be about 1° Myr^{-1} (refs 12, 13).

Modern reconstructions of the continents to give Pangaea (see, for example, ref. 14) do not look radically different from that of Wegener[3], except that continents are now placed at appropriate latitudes. However, it is not so straightforward to tie the reference frame for the Earth as a whole to observations, and hence to distinguish between absolute plate motions and TPW. Arguably the best reference points are provided by 'hotspots'—regions of intra-plate volcanism, such as in Hawaii, which are thought to be caused by upwellings from the deep mantle[15]. Chains of islands and seamounts that end at active hotspots can be explained by the motion of a rigid plate over fixed hotspots[16]. Because hotspots cannot be absolutely fixed in a convecting mantle, efforts have been made to develop a mantle reference frame in which the motion of hotspots is accounted for[17,18]. Yet their motion is presumably much slower than plate motions, and reference frames with fixed or moving hotspots are both useful in distinguishing absolute plate motions and TPW. Suitable hotspot chains exist back to about 132 Myr ago. For older times, other methods need to be used to distinguish plate motions and TPW[4,5].

Here we separate motions of continents in the palaeomagnetic reference frame into a 'mean motion' of all continents and continental motion relative to this mean. The mean motion is determined in a coordinate system illustrated in Fig. 1. West–east motion cannot

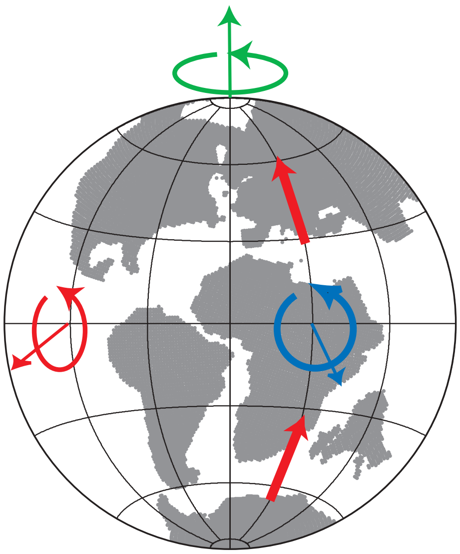

Figure 1 | Coordinate system in which the mean motion (rotation) of continents is described. One axis (blue) is on the Equator at the same longitude as the continents' centre of mass. The second axis (red) is on the Equator 90° away; rotation around this axis corresponds to coherent northward or southward motion of all continents. The third axis (green) is the Earth's spin axis; rotation around it corresponds to west–east motion.

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be determined in the palaeomagnetic reference frame: we additionally assume zero longitudinal motion of the African plate, which gives reasonable results with no large coherent west–east motions of all continents. Here we discuss how the characteristics of the remaining components of motion can be used in distinguishing plate motions and TPW. We restrict our analysis back to 320 Myr ago. Before that, relative motions of terranes that formed Pangaea are uncertain in relative longitude.

Figure 2 shows the cumulative mean rotation of all continents in the palaeomagnetic reference frame around an axis (blue in Fig. 1) in the equatorial plane at the same longitude as their centre of mass equivalent (black continuous line). Figure 3 shows reconstructions of continents in the same reference frame at four time intervals, and confirms that plate motions in that reference frame during these time intervals are indeed dominated by coherent rotation of all continents.

For comparison, Fig. 2 also shows corresponding rotations in two reference frames based on hotspot tracks (black dashed lines)[17–19]. Neither of them exhibits the coherent anticlockwise rotation found in the palaeomagnetic frame. The black dotted line in Fig. 2 shows the corresponding rotation in a palaeomagnetic reference frame where the coherent rotations identified above have been removed: remaining rotations are indeed much smaller.

The mean northward motion of all continents is illustrated by their cumulative mean rotation around an axis (red in Fig. 1) in the equatorial plane at a longitude 90° from their centre of mass equivalent (grey line in Fig. 2). In the palaeomagnetic reference frame, northward motion 320−185 Myr ago is followed by southward motion 185−145 Myr ago and slow overall northward motion after 145 Myr ago. After removing the coherent rotations, the mean motion of all continents becomes more evenly northward (grey dotted line, Fig. 2). This can be regarded as a continuous trend of northward motion (48° since 320 Myr ago, 24° since 240 Myr ago, 12° since 160 Myr ago) at a decreasing rate (from $\sim$0.3° Myr^{-1} during 320−240 Myr ago to $\sim$0.075° Myr^{-1} since 160 Myr ago) overlain by small fluctuations of less than 5° amplitude. For the time interval 130−120 Myr ago, this trend is also confirmed in the reference

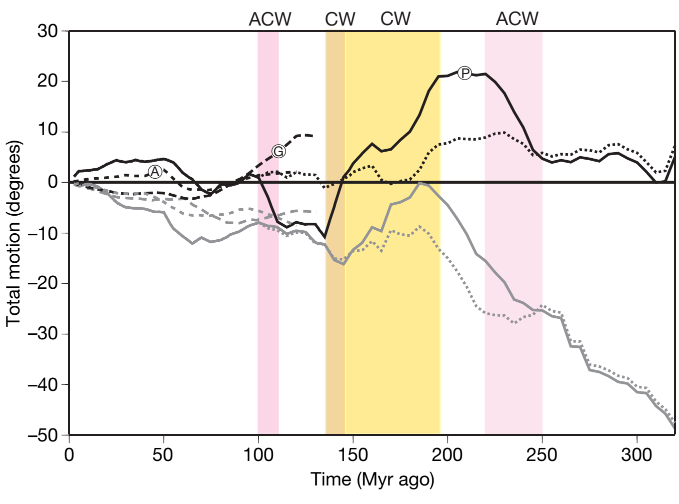

Figure 2 | Cumulative rotation and north–south motion averaged for all continents. Black lines show rotation around an equatorial axis (blue in Fig. 1) at the same longitude as the centre of mass of all continents, with positive values for a given time corresponding to clockwise (CW) rotation since that time. Grey lines show rotation around an equatorial axis (red in Fig. 1) orthogonal to the first axis, with negative values for a given time corresponding to northward motion of continents since that time. Continuous lines are computed in the palaeomagnetic reference frame (P), long dashed lines in the global mantle reference frame[17,19] (G), short dashed lines in the Africa mantle reference frame[18,19] (A), dotted lines in a new reference frame, similar to the palaeomagnetic one, except that the following rotations around an equatorial axis at constant rate have been subtracted from African plate motion: 18° anticlockwise (ACW) 250−220 Myr ago and clockwise 195−145 Myr ago around an axis at 15° W; 10° clockwise 145−135 Myr ago and anticlockwise 110−100 Myr ago around an axis at 37.5° E.

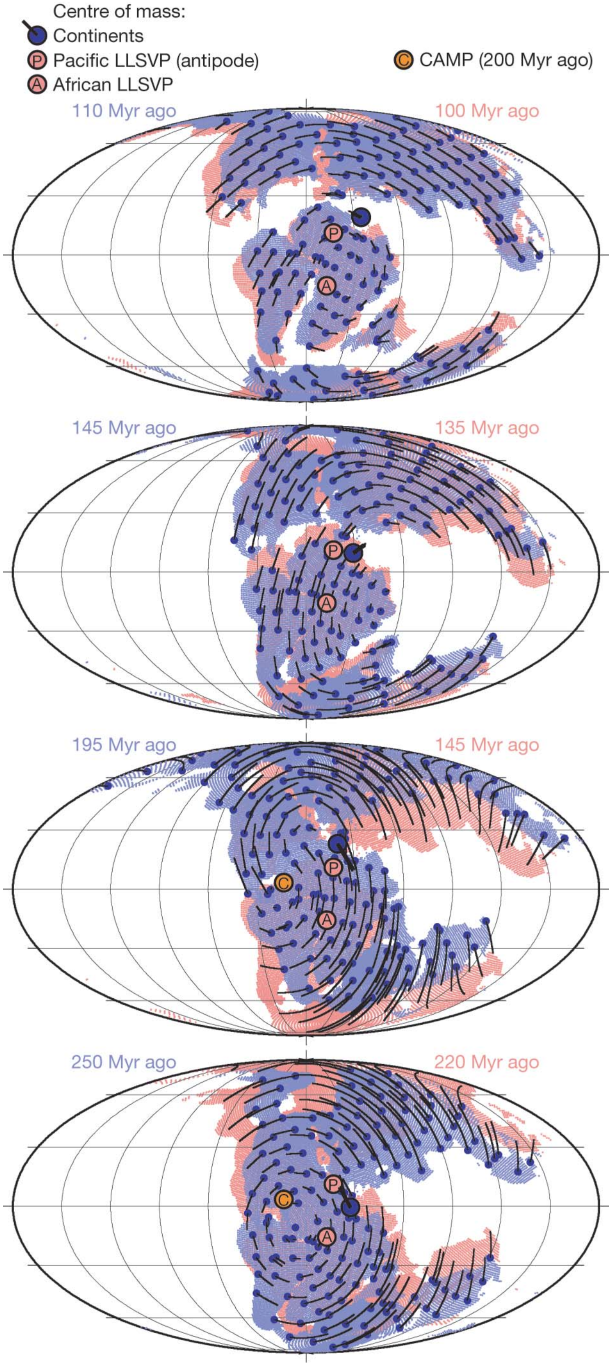

Figure 3 | Motions of continents reconstructed in the palaeomagnetic reference frame during four time intervals. Total motions are shown as black lines, connected to blue dots (locations at the beginning of the time intervals). Large blue dots with thick black lines indicate location and motion of the centre of mass of all continents. Centres of mass of African and Pacific large low-shear-velocity provinces (LLSVPs) are determined from regions with $<-1\%$ velocity anomaly in the lowermost two layers ($\sim$300 km) of the 'smean'[27] tomography model. Eurasia is shown for reasons of simplicity as a coherent plate, but in the lowermost diagram, for example, north and south China may not have been part of Eurasia/Pangaea[14]. CAMP, central Atlantic magmatic province. (Table 1 lists the Euler rotations of South Africa in the global palaeomagnetic reference frame[19] used in this figure. The complete list in 5 Myr intervals is given in table 8 of ref. 19. These are finite rotations to move the (African) plate back from its present position to the past position at the given age. Since the longitude of a plate is not constrained palaeomagnetically, Euler pole latitude is arbitrarily set to zero.)

frames based on hotspots. There is some leeway in the location of the curve that represents the mean motion of continents (grey dotted line, Fig. 2), as there is a trade-off between the amount of northward motion and the longitude of the axes of the subtracted rotations.

Figures 2 and 3 are based on a global compilation of palaeomagnetic data and a global apparent polar wander path constructed in South African coordinates after correction for relative movements. Significant episodes of TPW should be recognizable for all locations on Earth and witnessed as rotations (derived from palaeomagnetic declinations) in the same sense on one hemisphere but with variable magnitude around an equatorially located Euler pole. As a sensitivity test for our TPW model, we calculated the rotation rates (in degrees per Myr) and sense for major plates with reasonable data coverage (Fig. 4). If TPW was much greater than 'continental drift', all plates on the same hemisphere should show the same sense of rotation, and with few exceptions we observe periods of systematic anticlockwise (110–100 Myr ago, 250–220 Myr ago) or clockwise (145–135 Myr ago, 195–145 Myr ago) rotation that conform to our TPW model. The 250–220 Myr ago phase of TPW has more speculatively been proposed[20], while the phase 110–100 Myr ago is implied in a comparison of hotspot and palaeomagnetic reference frames[19,21].

It is expected that episodes of rather 'fast' TPW (up to about $1^\circ\,\mathrm{Myr}^{-1}$, during time intervals when the two larger principal non-hydrostatic moments of inertia of the Earth become nearly equal) will be separated by longer time intervals of relatively slow TPW. The mean continental rotations depicted with the continuous black line in Fig. 2 and discussed above show just that characteristic, and we hence attribute their cause to be TPW. The absence of the youngest of these rotations (110–100 Myr ago) in any hotspot-based reference frame confirms our interpretation. The event of two non-hydrostatic moments of inertia becoming nearly equal does not need a specific trigger and there is hence no need to look for correlation with any other geologic events.

Under the interpretation of TPW, the axes of coherent continent rotation correspond to maxima of the degree-two non-hydrostatic geoid. For the youngest of these rotations (110–100 Myr ago), this axis is close to the centres of the two large low-shear-velocity provinces (LLSVPs) of the lowermost mantle beneath the Pacific and Africa, ~180° apart in longitude. The shape and extent of the LLSVPs resembles the present-day geoid highs, in particular if those features of the geoid clearly related to subduction are disregarded[22]. These axes of coherent continent rotation are 5–10° further west in a hybrid reference frame based on hotspot tracks back to 100 Myr ago and the palaeomagnetic frame before that[19], bringing the axes for the latter two time intervals (145–135 Myr ago and 110–100 Myr ago) even closer to the LLSVP centres. This proximity is a further indication of the long-term stability of LLSVPs.

The present-day long axis of the degree-two geoid does not match the LLSVP centres, as there are additional geoid highs clearly related to subduction, in particular in Indonesia and South America. During the earlier two interpreted TPW episodes, additional geoid highs due to subduction beneath the western edge of Pangaea may have caused a different location of the degree-two geoid high. For a strong increase of mantle viscosity with depth, a negative density anomaly in the lower mantle—for example, a plume head—would also cause a positive contribution to the geoid at spherical harmonic degree two[23]. The reconstructed eruption location of the central Atlantic magmatic province—potentially the largest[6] of all large igneous provinces—200 Myr ago is almost exactly the same as the inferred rotation axis of Pangaea 250–220 Myr ago, and given approximate estimates of plume head rise times, the plume head of the central Atlantic magmatic province is likely to have been in the lower mantle 250–220 Myr ago.

Motions of continents since 130 Myr ago in a mantle reference frame have typically been rather steady. Therefore, interpreting the northward drift as motion of plates over the mantle makes sense kinematically. Furthermore, the reconstructed Pangaea location approximately overlies the African LLSVP, which is expected to correspond to a past geoid high, and therefore large motions of the Earth's spin axis towards it or away from it are not expected. Therefore, and because of the different expected characteristics of TPW (short episodes of faster motion between longer times of little motion), we regard it as unlikely that the steady northward drift represents TPW. Geometrically, a long-term northward motion of continents is linked to the preferred occurrence of spreading ridges in the Southern Hemisphere[24]. Dynamically, it may be related to the centres of the two LLSVPs of the lowermost mantle, and hence the centres of presumed large-scale mantle upwellings overlying them (beneath Africa and the South Pacific superswell), being located south of the Equator. Thus there is more upward flow in the Southern Hemisphere, and flow at shallow depth more towards the north.

The remaining fluctuations may well be due to TPW, but their magnitude of 5° or less is similar to the uncertainty of palaeomagnetic reconstructions of continents relative to the spin axis, and it is hence difficult to assess whether they are real features.

Differences between the reference frame proposed here and the palaeomagnetic frame are sufficiently small that conclusions obtained with the latter[6] should largely remain valid. The proposed

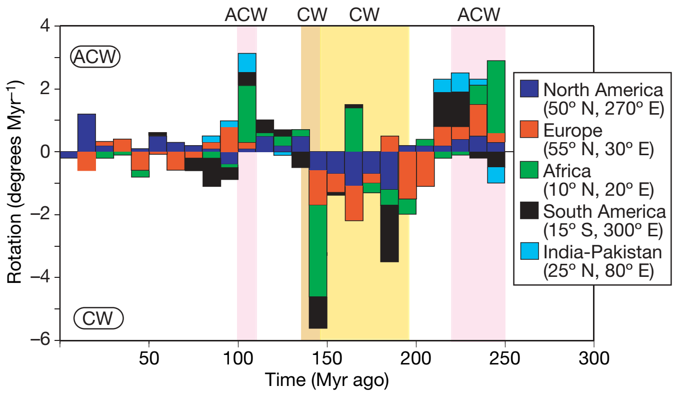

Figure 4 | Mean rotation of North America, Europe, Africa, South America and India-Pakistan since 250 Myr ago, based on palaeomagnetic declinations. We first calculated running-mean apparent polar wander paths for each plate (20 Myr window), and based on a geographic location (approximately the centre of the plate, as listed in the key) we computed mean declinations in 10 Myr intervals (bins). Declination (plate rotation) differences between successive 10 Myr bins were calculated, separated into clockwise and anticlockwise rotations, and plotted as rotation (in degrees per Myr; vertical axis). Rotation rates for each plate were then stacked. Some cases appear not to fit with the proposed TPW—for example, India-Pakistan rotating in the opposite sense 250–240 Myr ago and Africa rotating in the opposite sense 170–160 Myr ago. The latter can be explained by poor data from Africa at that time, that is, very few reliable poles and with a large scatter for the resulting mean pole (95% confidence oval of 40°). Note that some plates have near-zero rotation rates at certain intervals, and will not show up here.

Table 1 | Euler rotation parameters for South Africa

	Palaeomagnetic		TPW corrected		
Age (Myr)	Longitude (degrees)	Angle (degrees)	Latitude (degrees)	Longitude (degrees)	Angle (degrees)
100	150.8	22.3	0.0	150.8	22.3
110	169.2	32.1	3.9	153.0	26.7
135	172.6	42.1	2.1	161.0	35.9
145	155.2	38.1	-2.6	154.6	38.2
195	147.9	17.8	-2.6	155.7	35.5
220	127.2	27.2	0.3	141.6	43.1
250	145.4	40.4	4.0	145.6	40.8

Parameters are shown for palaeomagnetic[19] and TPW corrected reference frames. Note that in the former frame, latitude is zero for all ages.

TPW events would cause up to 30° latitude difference between time intervals 220–195 Myr ago and 135–100 Myr ago at locations reconstructed approximately 90° from the reconstructed location of North Africa. Results remain tentative as they are derived from continental motions only, and possible changes in relative motion between continental and oceanic plates[20] will need to be further studied in order to assess whether or not the coherent rotations found do indeed correspond to TPW. As we approach the centenary of Wegener's Pangaea[3], we are finally realizing the full spectrum of available palaeogeographic and kinematic tools, integrated with a fully dynamic global framework.

METHODS SUMMARY

Relative plate motions since 320 Myr ago have been compiled by Torsvik *et al.*[19]. For absolute plate motions, we use their palaeomagnetic reference frame[19]. After 130 Myr ago, we also use the 'global mantle'[17,19] and 'Africa mantle'[18,19] reference frames for comparison. For each plate, we only consider the 'continental' part, with elevation > -200 m. From the present-day positions and past motions of continents, their positions through time are determined. From these continent distributions and motions, the quantities equivalent to centre of mass, inertia tensor I and angular momentum $\mathbf{L}$, of all continents, but with mass replaced by area, relative to the centre of the Earth, are computed. By inverting the relation $\mathbf{L} = I\boldsymbol{\omega}$, the mean rotation $\boldsymbol{\omega}$ of all continents is determined. At each time, three components are determined in an orthogonal coordinate system, with one axis along the Earth's spin axis, and one at the same longitude as the equivalent to the centre of mass of all continents. These components are integrated through time, yielding cumulative rotations. These approximately represent finite rotations, but not exactly, as the centre of mass longitude also changes with time in our reference frame, although not by much. In both the palaeomagnetic reference frame and the modified reference frame proposed here, the cumulative rotation around the Earth's spin axis (corresponding to mean west–east motion of all continents, which is not determined palaeomagnetically) is very small over the period 320–130 Myr ago (less than 5° fluctuations), which appears reasonable.

Figures were prepared using the GMT[25] and GMAP[26] software.

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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METHODS

We express Euler rotations for times t_A as 3×3 rotation matrices[28] A, that is, a point on the plate at present at location $\mathbf{x}$ (in cartesian coordinates) was at $A\mathbf{x}$ at time t_A. Points on other plates are reconstructed by combining rotations of plates relative to each other (compiled in table 1 of ref. 19) with the Euler rotations of South Africa (Table 1).

Maps in Fig. 3 are computed by rotating all points on a one-degree grid with elevation > -200 m from their present location to the location at that time. Present-day NUVEL[29] plate boundaries are used to assign points to plates. This procedure is obviously not exactly correct—for example, Greenland has not always been part of the North American plate. However, this simplification affects our results only in a minor way.

In order to obtain the TPW corrected rotations, we first compute stage rotations, that is, finite rotations for 5 Myr time intervals. With the Euler rotations for times t_A and t_B expressed as rotation matrices A and B, the stage rotation to move the plate from its position at t_A back to its position at t_B is then $S_{AB} = BA^{-1}$. Stage rotations are again expressed as rotation vectors. TPW corrections, which are derived by visual inspection of Figs 2 and 3, and specified in Fig. 2 legend (description of dotted line), are then applied by vector subtraction in cartesian coordinates. TPW corrected stage rotations for time intervals $t_B - t_A$ are again expressed as rotation matrices[28] $S_{AB,corr}$. The TPW corrected rotation matrix for t_B is then $B_{corr} = S_{AB,corr}A$, and corrected finite rotations are computed successively backward in time. We note that, even though TPW corrections for the time 145 Myr ago, and for times 250 Myr ago and before, are not intended, our procedure also yields slightly different TPW corrected Euler rotations for these times. However, differences are much smaller than for those times where the corrections are indeed intended.

Dotted lines in Fig. 2 are computed using the TPW corrected reference frame in the same way as continuous lines were computed with the palaeomagnetic reference frame.

Torsvik *et al.*[6] concluded that reconstructed large igneous province (LIP) eruption sites overlay the edges of LLSVPs, using four different reference frames after 132 Myr ago and the palaeomagnetic frame before that. The change of reference frame before 132 Myr ago only possibly affects the central Atlantic magmatic province (CAMP) at 200 Myr ago and the Karroo LIP at 182 Myr ago. As explained, the reconstructed CAMP location coincides with the axis of added rotation and hence remains unaffected; Karroo is rotated by about 8°, leaving it close to the LLSVP margin.

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