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Key Points:

- U-Pb-dated kimberlites provide reliable paleomagnetic poles for North America
- Kimberlite paleopoles confirm 30° polar shift in Late Jurassic
- Polar shift may represent an episode of true polar wander at 1.5°/Myr

Supporting Information:

- Supporting Information S1

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Tracking the Late Jurassic apparent (or true) polar shift in U-Pb-dated kimberlites from cratonic North America (Superior Province of Canada)

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Abstract Different versions of a composite apparent polar wander (APW) path of variably selected global poles assembled and averaged in North American coordinates using plate reconstructions show either a smooth progression or a large (∼30°) gap in mean paleopoles in the Late Jurassic, between about 160 and 145 Ma. In an effort to further examine this issue, we sampled accessible outcrops/subcrops of kimberlites associated with high-precision U-Pb perovskite ages in the Timiskaming area of Ontario, Canada. The 154.9 ± 1.1 Ma Peddie kimberlite yields a stable normal polarity magnetization that is coaxial within less than 5° of the reverse polarity magnetization of the 157.5 ± 1.2 Ma Triple B kimberlite. The combined ∼156 Ma Triple B and Peddie pole (75.5°N, 189.5°E, A95 = 2.8°) lies about midway between igneous poles from North America nearest in age (169 Ma Moat volcanics and the 146 Ma Ithaca kimberlites), showing that the polar motion was at a relatively steady yet rapid (∼1.5°/Myr) pace. A similar large rapid polar swing has been recognized in the Middle to Late Jurassic APW path for Adria-Africa and Iran-Eurasia, suggesting a major mass redistribution. One possibility is that slab breakoff and subduction reversal along the western margin of the Americas triggered an episode of true polar wander.

1. Introduction

A yawning (30°) gap was revealed in a global composite apparent polar wander (APW) path [*Kent and Irving*, 2010, hereafter K&I] based on paleomagnetic poles from predominantly igneous rocks, and from sedimentary results corrected for inclination error (hereafter *I*-error), assembled in common (in this case, North American) coordinates using plate reconstructions and averaged using a running 20 Myr window. The "monster shift" occurred in the Late Jurassic between mean poles in windows centered at 160 and 145 Ma (mean pole ages of 165 and 146 Ma, respectively) and amounting to polar motion of ∼1.5°/Myr. The shift is not apparent in most published global composite APW paths [e.g., *Besse and Courtillot*, 2002; although see *Schmidt and Embleton*,1982], including the more recently published path of *Torsvik et al*. [2012], which shows a relatively smooth progression of paleopoles from at least 200 to 140 Ma (Figure 1). *Torsvik et al*. [2012, hereafter T+12] attributed the abrupt shift to an artifact stemming from the low number of poles averaged by K&I especially in the 160 Ma time window.

For the 160 Ma mean pole, K&I indeed accepted only four poles whereas T+12 averaged 19 poles. Beside the four igneous poles utilized by K&I, the 19 poles averaged by T+12 included three other igneous poles that had been rejected by K&I because of large uncertainties in age, directional data, or structural coherence. For the 12 sedimentary poles that were summarily excluded by K&I as potentially biased by variable *I*-error, T+12 applied an assumed flattening factor of 0.6 for *I*-error correction to five of them which also happen to be from the Colorado Plateau that has a disputable tectonic coherence with stable North America [*Bryan and Gordon*, 1990; *Kent and Witte*, 1993]. The resulting 160 Ma mean pole of T+12 (70.1°N, 137.5°E, A95 = 4.9°) differs from the 160 Ma mean pole of K&I (78.5°N, 112.5°E, A95 = 7.5°) by some 10.5°, which is significant at the 95% confidence level. For the next younger independent (with 20 Myr window) mean

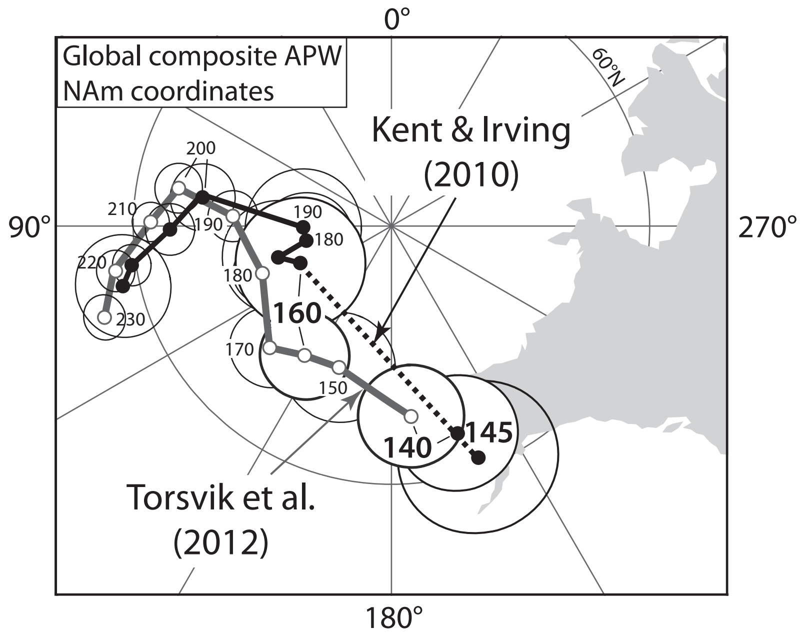

Figure 1. Comparison of global composite APW paths of *Kent and Irving* [2010] and *Torsvik et al*. [2012] between 230 and 140 Ma, both constructed using 20 Myr moving window average of selected paleopoles in common (North American) coordinates and plotted on an equal-area projection with associated circles of 95% confidence. The K&I APW path shows what was referred to as a monster shift between 160 and 145 Ma that is not apparent in the T+12 APW path.

pole at 140 Ma, K&I averaged five igneous poles whereas T+12 averaged seven igneous (two in common with K&I), and two sedimentary poles to obtain a mean (67.9°N, 185.7°E, A95 = 6.0°) that differs from that of K&I (64.7°N, 197.3°E, A95 = 6.8°) but by only 5.6°, which is not significant at 95% confidence. As a result, the difference between the 140 and 160 Ma mean poles in T+12 is only about one-half the arc distance (14.0°) as in K&I (26.7°).

K&I did not use an intervening 150 Ma mean pole. This is because only the 157 Ma El Quemado igneous pole from Patagonia [*Iglesia Llanos et al*., 2003] was regarded as acceptable in the more than 20 Myr interval between the 167 Ma Chon Aike pole from Patagonia [*Vizan*, 1998], the 168 Ma Prospect dolerite pole from Australia [*Schmidt*, 1982], and the 169 Ma Moat volcanics pole from North America [*Van Fossen and Kent*, 1990] on one hand (and already included in the 160 Ma mean) and on the other, the 147 Ma Swartruggens-Bumbeni kimberlite pole from southern Africa [*Hargraves et al*., 1997; *Heaman et al*., 2004], the 146 Ma Ithaca kimberlite pole from North America [*Van Fossen and Kent*, 1993] (see below for analysis of U-Pb data), and the 144 Ma Hinlopensretet sills pole from Svalbard [*Halvorsen*, 1989]. The latter three poles form a coherent cluster at ~145 Ma with a mean (61.2°N, 200.2°E A95 = 9.0°, K = 189) that is even more removed from the 160 Ma mean pole (Figure 1) and was used by K&I to delimit the younger end of the monster shift. The 150 Ma mean pole of T+12 was instead based on 15 entries. The only entries that were also accepted by K&I are the 146 Ma Ithaca and 157 Ma El Quemado poles whereas the other three igneous poles as well as the ten sedimentary poles were deemed by K&I insufficiently accurate or precise to be included in a reference APW path.

It would thus appear that the monster shift of K&I could be an artifact of using too few poles, or else was obscured by inclusion of numerous problematical poles in the APW path of T+12. With regard to the latter possibility, we note that the 140, 150, and 160 Ma mean poles of T+12 are the least well defined (have the highest A95s) of any of the 25 mean poles estimated for the entire Mesozoic and Cenozoic (since ~250 Ma), a poor resolution that would be consistent with tracking an episode of proposed fast polar wander by data of insufficient fidelity and age resolution.

The basic pattern of the global APW path for the Jurassic has been a long-standing issue [e.g., *Butler et al*., 1992; *Van Fossen and Kent*, 1992a; *Courtillot et al*., 1994] and now includes the distinct possibility of a major shift [*Kent and Irving*, 2010] that is already apparent in stratigraphically controlled, *I*-error tested and

Table 1. U-Pb Perovskite Dates

Triple B (1–4[a])
Mean = 157.5 ± 1.2 Ma (2σ)
Wtd by data-pt errs only, 0 of 4 rej.
MSWD = 0.23, probability = 0.87
Peddie (1, 3[a])
Mean = 154.9 ± 1.1 Ma (2σ)
Mean = 155 ± 16 [11%] 95% conf.
Wtd by data-pt errs only, 0 of 2 rej.
MSWD = 5.1, probability = 0.024
Williams Brook (1, 2[a]) and Glenwood Creek (1[a])
Mean = 146.4 ± 1.4 Ma (2σ)
Wtd by data-pt errs only, 0 of 3 rej.
MSWD = 0.93, probability = 0.40

[a]See Table S1.

corrected sedimentary poles from the African promontory of Adria [*Channell et al*., 2010; *Muttoni et al*., 2013]. In an effort to better constrain Jurassic APW with new well-dated reference poles of high directional precision and unambiguous tectonic coherence, we collected oriented samples for paleomagnetic study from selected outcrops/subcrops of U-Pb-dated kimberlites in the Timiskaming area of Ontario, Canada. We report results from two kimberlite intrusions: the 154.9 ± 1.1 Ma Peddie kimberlite [*Heaman and Kjarsgaard*, 2000] (revised with new U-Pb age data by *Zurevinski et al*. [2011] and updated analysis below) and the Triple B kimberlite reported here with new U-Pb data at 157.5 ± 1.2 Ma (Table 1), which were made (re)accessible by trenching. Survey samples from the Maclean kimberlite (141.9 Ma) [*Heaman and Kjarsgaard*, 2000] had inexplicably complex magnetizations and these data, in addition to those from a Precambrian dike mistakenly sampled at Buffonta, are not discussed further here.

2. Data

The Peddie and Triple B kimberlites are in the Timiskaming field located in the Superior province of Ontario, Canada (Figure 2). The Peddie (UTM: 599354Easting, 5255182Northing WGS84, Zone 17, equivalent to 47°26′33.03″N, 079°40′56.00″W) is classified as a hypabyssal phlogopite macrocrystic monticellite kimberlite and is hosted by Paleoproterozoic Nipissing diabase dikes [*Kjarsgaard et al*., 2003]. A total of 20 samples, distributed over several meters of outcrop, were taken in a manmade exposure next to a small barrow pit with a cordless drill yielding 19 mm diameter cores that were oriented with a magnetic compass. An exposure of the Triple B kimberlite (UTM: 593292Easting, 5256370Northing, WGS84, Zone 17, equivalent to 47°27′14.73″N, 079°45′44.47″W), classified as an aphanitic to macrocrystic olivine-rich hypabyssal kimberlite intruded into Paleoproterozoic rocks of the Firstbrook Member of the Gowganda Formation, was unearthed from beneath several meters of loose overburden with a backhoe (Figure A2); 15 oriented drill core samples were taken spanning about 5 m of exposure along the bottom of the excavated trench. The previously discovered and dated Seed kimberlite (153.7 ± 1.8 Ma) [*Heaman and Kjarsgaard*, 2000] is located about 270 m to the northwest but was not accessible to sample.

2.1. U-Pb Perovskite Results

Groundmass perovskite was isolated from whole rock kimberlite using standard gravimetric and magnetic mineral separation techniques. The U-Pb perovskite results for four kimberlites are presented in Table 1 and Table S1; the results for Triple B are unpublished and the procedures used are described below. The U-Pb results for the other three kimberlites (Peddie; Glenwood Creek and Williams Brook, which are part of what is also more generally known as the Ithaca kimberlite) were published previously [*Heaman and Kjarsgaard*, 2000; *Zurevinski et al*., 2011] and the results are updated here so that all data have been evaluated using the same data reduction software (YourLab) [*Schmitz and Schoene*, 2007] and can be compared directly. The procedure for determining the U-Pb age of Triple B perovskite fractions was similar to that described by *Heaman and Kjarsgaard* [2000].

Perovskite recovered from the Triple B sample consisted of minuscule tan fragments; between 300 and 1000 fragments were selected for each analysis (fraction weights varied between 13 and 32 μg). These perovskite fractions contain low to moderate uranium contents (34–53 ppm) and Th/U ratios (5.4–6.0) compared to groundmass perovskite from most kimberlites. The $^{206}Pb/^{238}U$ dates obtained for all four fractions agree within analytical uncertainty and vary between 156.9 ± 2.5 and 158.3 ± 2.5 Ma (2σ). A weighted mean $^{206}Pb/^{238}U$ date for all four fractions is 157.5 ± 1.2 Ma (2σ; mean square weighted deviation (MSWD) = 0.23) and is interpreted as the time of perovskite crystallization and a good estimate for the time of kimberlite emplacement. The slightly revised U-Pb perovskite data for the Peddie, Glenwood Creek and Williams Brook kimberlites are summarized in Table 1. A weighted mean $^{206}Pb/^{238}U$ perovskite date based on two fractions from Peddie is 154.9 ± 1.1 Ma (2σ; MSWD = 5.1) and a composite weighted mean

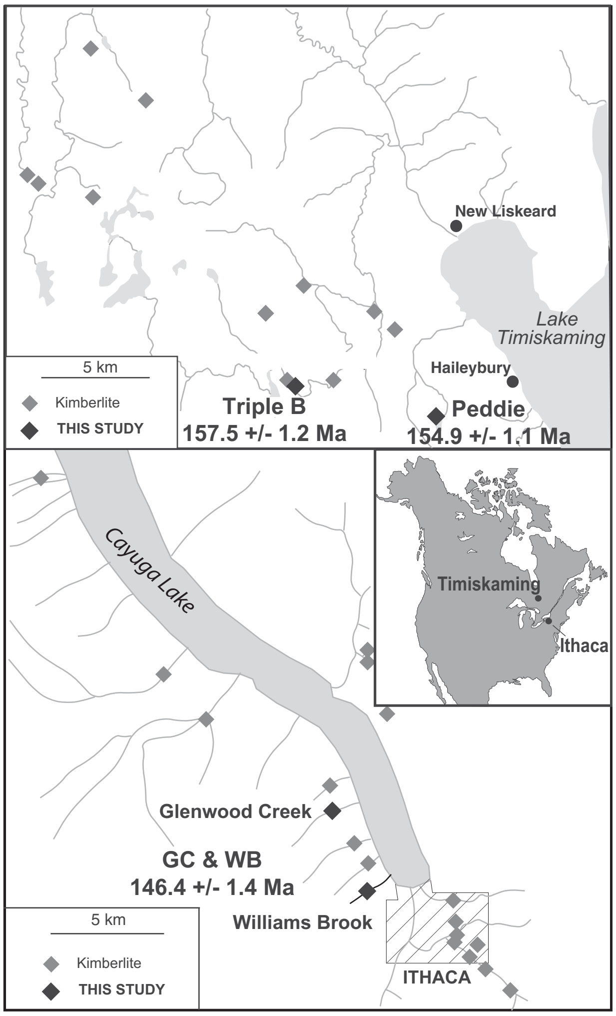

Figure 2. Location maps of (top) the sampled Peddie and Triple B kimberlites near Lake Timiskaming in Ontario, Canada, and (bottom) kimberlites near Ithaca, NY studied previously for paleomagnetism by *Van Fossen and Kent* [1993] and sampled at two localities (Glenwood Creek and Williams Brook) for U-Pb perovskite dating reported here. Inset is map of North America showing the general locations of the Timiskaming and Ithaca sampling areas; see *Heaman et al.* [2004] for general spatiotemporal distribution of kimberlites in North America.

$^{206}Pb/^{238}U$ perovskite date for Glenwood Creek and Williams Brook (outcrop localities of Ithaca kimberlite) is 146.4 $\pm$ 1.4 Ma (2σ; MSWD = 0.93), interpreted as the current best estimate for their emplacement ages.

2.2. Paleomagnetic Results

Laboratory measurements on representative samples are illustrated in Figure 3 (top, Peddie; bottom, Triple B). High field thermomagnetic experiments typically showed a Curie point of close to 575°C indicative of magnetite as the dominant magnetic mineral, sometimes in the presence of a large paramagnetic phase in Peddie even though those thermomagnetic curves tended to be more reversible for than for Triple B. Hysteresis properties suggest that the magnetic mineralogy of the Peddie samples is somewhat finer grained (Mrs/Ms $\sim$ 0.25) and more concentrated (Ms $\sim$ 2.75 emu/g) than the Triple B samples (Mrs/Ms $\sim$ 0.15, Ms $\sim$ 0.5 emu/g).

Progressive thermal and alternating field demagnetizations on companion specimens show that the natural remanent magnetization (NRM) is invariably stable and essentially univectorial with little overprinting in samples from either Peddie and Triple B. Directions are northerly and down (normal polarity) for Peddie (Figure 3, top) and southerly and up (reverse polarity) for Triple B (Figure 3, bottom). All samples but one (which gave a widely discordant direction that we attribute to sample misorientation) from Peddie provided acceptable results. The mean characteristic remanent magnetization (ChRM) based on principal component analysis [*Kirschvink*, 1980] of seven demagnetization steps from 350°C to 575°C (average maximum angular deviation (MAD) less than 2°) for Peddie is Declination = 336.9°, Inclination = 61.9°, a95 = 2.6° for n = 19 samples, and for Triple B is Declination = 162.3°, Inclination = −65.4°, a95 = 3.0° for n = 15 samples. The directions deviate from being coaxial by only 4.2°, which would classify as a Class A reversal test (<5° from antipodal) except the deviation turns out to be significant (95% confidence test angle is 3.8°) [*McFadden and McElhinny*, 1990] because of the high-precision directions.

The modest scale of accessible exposure of each kimberlite combined with the small dispersion of ChRM directions (precision parameter, k, is 172 for Peddie and 162 for Triple B) raise the issue of how well the magnetizations average secular variation and represent the time-averaged field. The dominant remanence carrier, magnetite, is not expected to occur in the deep source regions in the upper mantle where kimberlites originate [*Mitchell*, 1986]. The stable magnetite remanence in such kimberlites may thus be regarded as a thermochemical magnetization, resulting from late stage magmatic crystallization of magnetite [*Mitchell*, 1986] or magnetite formed by deuteric fluids associated with serpentinization

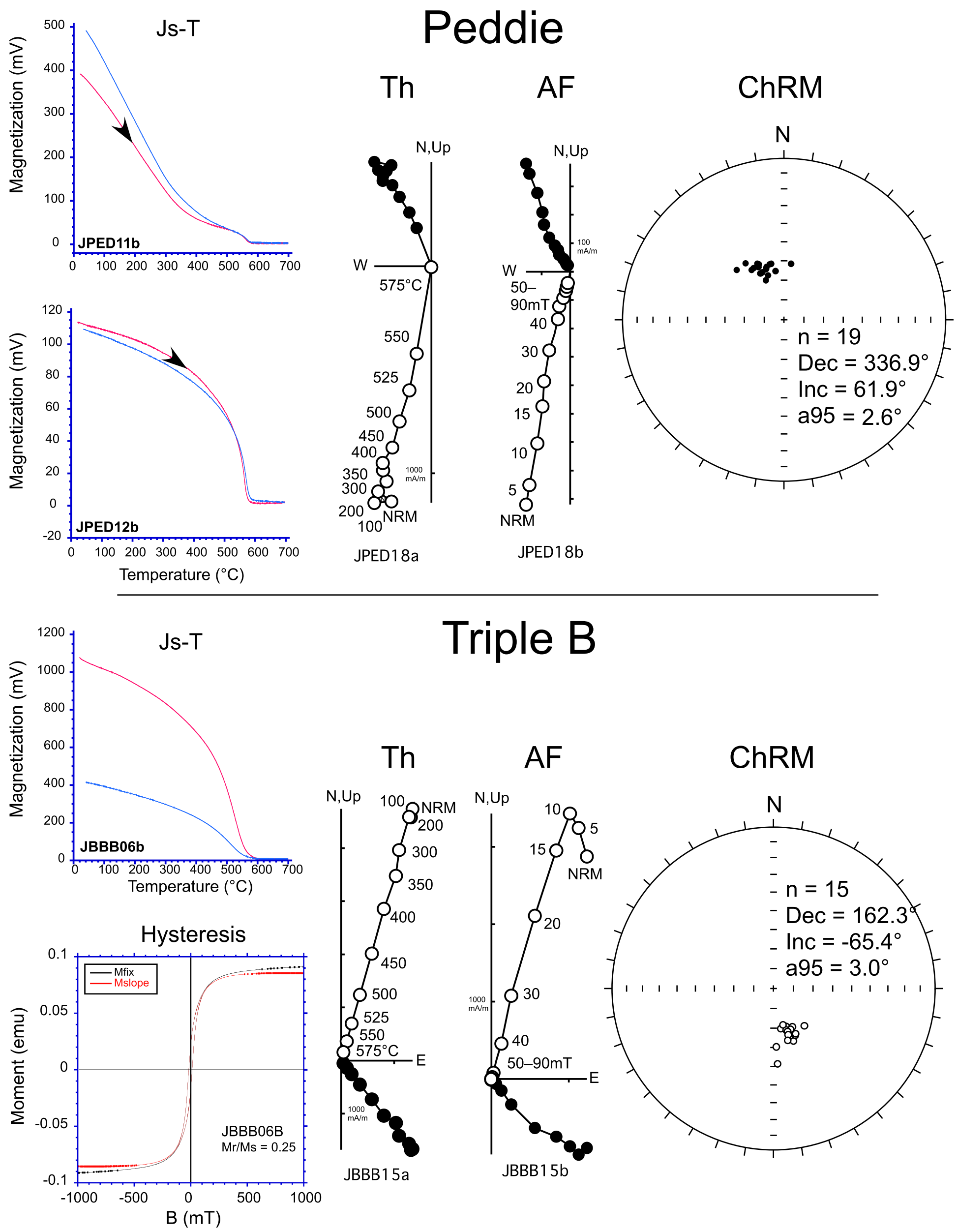

Figure 3. Rock magnetic and paleomagnetic data for Peddie kimberlite (upper diagrams) and Triple B kimberlite (lower diagrams) including examples of high field thermomagnetic (Js-T) heating and cooling curves (25°C/min, in air), an example of an Micromag magnetic hysteresis loop before and after paramagnetic slope correction, and representative vector-endpoint diagrams (open/closed symbols projected on to vertical/horizontal planes) of thermal (Th) and alternating field (AF) demagnetizations of NRM of companion specimens. Characteristic remanent magnetization (ChRM) sample directions are plotted on equal-area projections with filled/open symbols on lower/upper hemisphere.

during emplacement [*Mitchell*, 1986; *Hargraves*, 1989; *Afanasyev et al.*, 2014] so that magnetization acquisition in each kimberlite may have occurred over time scales sufficiently long to allow averaging of geomagnetic secular variation. With opposite polarities, the magnetizations of the Peddie and Triple B kimberlites were certainly acquired at distinctly different times. However, the very similar U-Pb dates make it unlikely to have two very nearly antipodal directions (within 5°) if each did not average significant time. Similar arguments have been made for averaging of paleosecular variation in other kimberlites [e.g., *McFadden and Jones*, 1977]. Moreover, samples taken 12–43 m away from the Peddie kimberlite in the Nipissing diabase host rock show demagnetization behavior compatible with a positive baked contact test (Figure 4).

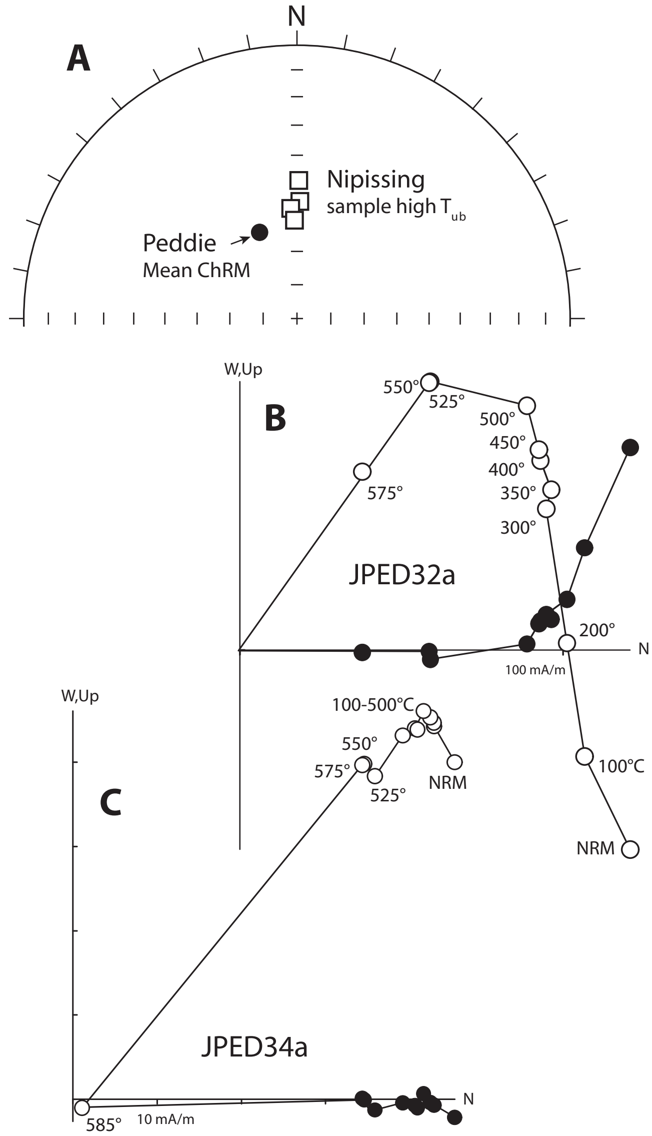

Figure 4. Baked contact test for Peddie kimberlite in four samples in Nipissing diabase taken in available outcrop at ~12 m (samples JPED31, 32, and 33) and from ~43 m (JPED 34) from edge of the ~70 m wide kimberlite body. (a) Equal area projection of high unblocking temperature (525°C–575°C) component of Nipissing samples (open squares plotted on upper hemisphere), which resembles the N1 component for the Nipissing [*Buchan*, 1991], and is far removed from mean ChRM direction (filled circle corresponding to a95 plotted on lower hemisphere) of the nearby Peddie kimberlite (Table 2). Vector endpoint diagram (open/filled symbols projected on vertical/horizontal planes) of thermal demagnetization of a Nipissing sample illustrative (b) of those taken ~12 m away from Peddie and showing evidence of a northerly down overprint to ~500°C that may have been induced by the kimberlite intrusion, followed by a high unblocking temperature component plotted in Figure 4a, and (c) a Nipissing sample taken ~43 m away from Peddie that shows negligible overprinting and only the high unblocking temperature component attributed to the Nipissing N1 direction.

Assuming a geocentric axial dipole model for the time-averaged field, the mean virtual geomagnetic poles (VGPs) for these kimberlites provide estimates of the paleomagnetic (north) pole positions for the stable craton of North America at those times; these poles are located at 73.5°N, 184.1°E, $A95 = 3.7°$ for the 154.9 ± 1.2 Ma Peddie kimberlite and 77.9°N, 198.9°E, $A95 = 4.1°$ for the 157.5 ± 1.1 Ma Triple B kimberlite. The two kimberlites are close in age although the difference in dates (2.4 Myr) is more than either 2σ and hence significant but if the Peddie and Triple B sample VGPs were combined ($n = 34$), the resulting ~156 Ma mean pole position would be at 75.5°N, 189.5°E, $A95 = 2.8°$, $K = 79$.

3. Interpretation of Jurassic Polar Wander

The Peddie and Triple B poles (individually or combined) are significantly different than either the 160 Ma or the 145 Ma mean poles of the K&I global composite APW path but lie close to the connecting trajectory. The combined Peddie and Triple B pole, for example, departs by $16.3° \pm 8°$ with respect to the 160 Ma mean pole (mean age of the four constituent poles is 165.3 Ma) and by $14.8 \pm 9.4°$ with respect to 145 Ma mean pole (mean revised age is 146.0 Ma) (Figure 5). Although the Triple B pole is virtually coincident with the closely grouped set of mean poles (60–120 Ma) that marks the Cretaceous stillstand in APW for North America, the univectorial reverse polarity magnetizations are unlikely to have been acquired in this time interval of predominantly normal geomagnetic polarity that includes the Cretaceous normal superchron. Significantly younger remagnetization of Triple B (or Peddie) is unlikely also because the youngest period of kimberlite magmatism in the region extends from 142 Ma to only 134 Ma [*Heaman and Kjarsgaard*, 2000]. Accordingly, we regard the mean of the dual polarity Peddie and Triple B magnetizations as an accurate estimate of the GAD field for North America at ~156 Ma. The precisely U-Pb-dated Peddie and Triple B

Table 2. Paleomagnetic Results for Characteristic Components[a]

	n	a95 A95	Dec/Lon	Inc/Lat
Triple B (47°27.25′N, 079°45.74′W)				
Mean	15	3.0°	161.9°	−65.4°
VGP	15	4.1	198.9	77.9
Peddie (47° 26.55′N, 079°40.93′W)				
Mean	19	2.6	336.9	61.9
VGP	19	3.7	184.1	73.5
Triple B + Peddie combined				
VGP	34	2.8	189.5	75.5
Nipissing host to Peddie, high T_{ub} (525°C–575°C)				
Mean	4	6.0	359.6	−55.1
VGP	4	7.3	100.7	6.9

[a]n is the number of samples for Fisher mean with a95 (°) the circle of 95% confidence and Dec (°), Inc (°) are the mean declination, inclination with the northerly position of corresponding mean of virtual geomagnetic poles (VGPs) is located at Lon (°E longitude) and Lat (°N latitude) with A95 (°) the associated circle of 95% confidence. See Table S2 for sample-level data.

poles seem therefore to effectively capture the episode of fast APW between 160 and 145 Ma (according to K&I).

The El Quemado igneous pole from Patagonia (South America), dated at 156.5 ± 1.9 Ma on the basis of $^{40}Ar/^{39}Ar$ analyses on one partially altered sample [*Iglesia Llanos et al.*, 2003] and included in the 160 Ma mean pole of K&I, indeed plots with the constituents of that mean pole, for example, the 169 Ma Moat volcanics pole, rather than near either the Triple B or Peddie poles of ostensibly more similar ages (Figure 5). The El Quemado Formation could be a few million years older with updated monitor standards [*Kuiper et al.*, 2008], it may have suffered a relatively minor yet crucial resetting of its geochronological clock, or its magnetic directions were affected by local tectonic rotations [*Rapalini*, 2007], emphasizing the tight age and structural control needed to resolve events during such an interval of rapid polar shift. It is also now clear that attempts [*Kent and Irving*, 2010] to use practically the only available data for the Late Jurassic of North America from the Morrison Formation, by applying an arbitrary *I*-error correction to the sedimentary results and further

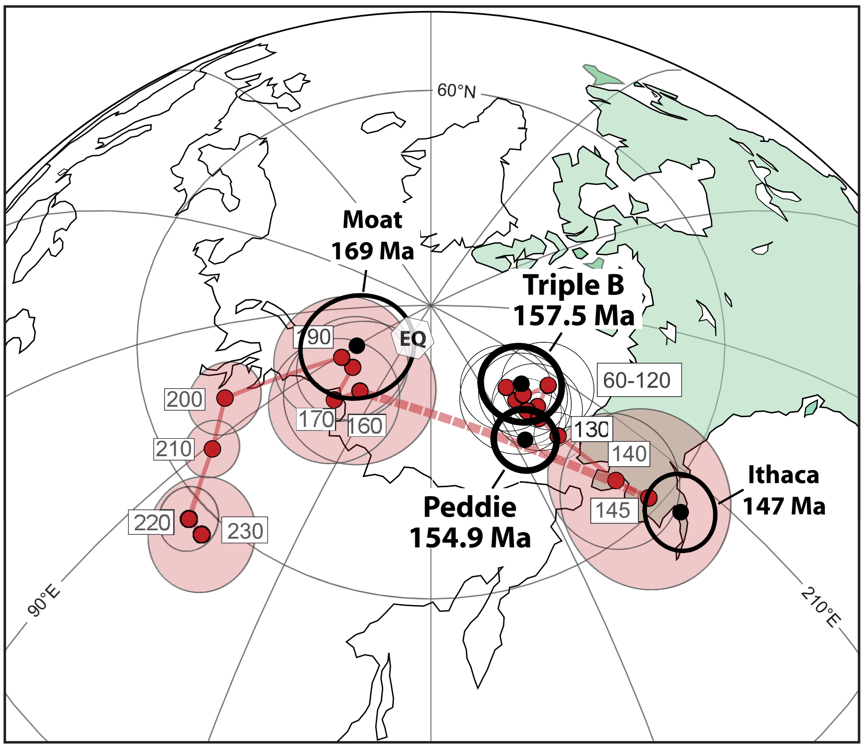

Figure 5. Pole positions with circles of 95% confidence for Triple B and Peddie kimberlites compared to global composite APW path of *Kent and Irving* [2010] with mean poles in 20 Myr windows (except 145 Ma mean; see text) from 230 to 60 Ma in North American coordinates. Also shown for reference are the accepted poles from North America nearest in age to the Triple B and Peddie kimberlite poles from the 169 Ma Moat volcanics [*Van Fossen and Kent*, 1990] and the 146 Ma Ithaca kimberlite [*Van Fossen and Kent*, 1993], which are included in the 160 and 145 Ma mean poles, respectively, that bracket the monster polar shift (dashed line). The pole from the El Quemado Formation of Patagonia [*Iglesia Llanos et al.*, 2003] plots in North American coordinates (labeled EQ: 84.4°N 122.5°E) near the older end of the polar shift, suggesting that its age is somewhat older than cited (156.5 ± 1.9 Ma) or its direction may have been biased by local tectonic rotations [*Rapalini*, 2007].

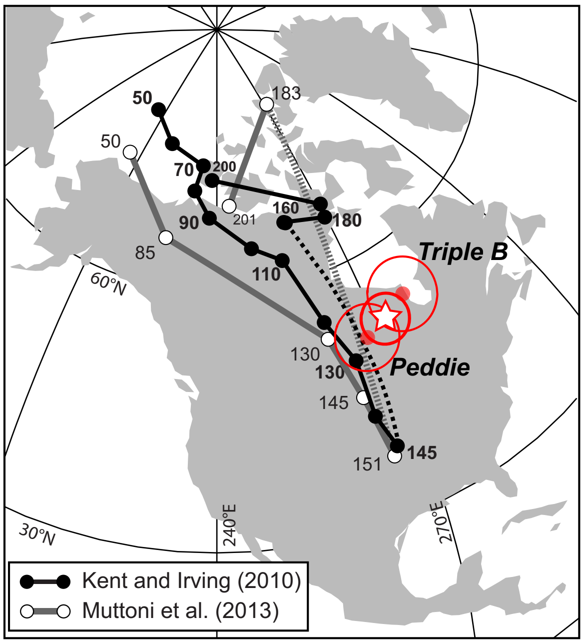

Figure 6. Global composite APW path [*Kent and Irving*, 2010] with monster shift between 160 and 145 Ma (dashed segment) transferred to NW Africa coordinates compared to an independent APW path for Adria-Africa built largely from well-dated and E/I corrected sedimentary poles from the Southern Alps of Italy [*Muttoni et al.*, 2013] that also shows evidence of a polar shift (dashed segment) sometime between 183 and 150 Ma. The poles for the Peddie and Triple B kimberlites and their mean (star) with associated A95s are plotted in same NW Africa coordinates.

adjusting them for rotation of the Colorado Plateau, should be considered futile as these data are amply superseded by the Triple B and Peddie kimberlite results.

Largely independent data from the Adria promontory of Africa [*Muttoni et al.*, 2013] and from the Late Jurassic Garedu Formation of Iran, a part of Eurasia since the Triassic [*Mattei et al.*, 2014], have already been found to be compatible with the monster shift of Jurassic APW. When placed in common coordinates using plate reconstructions, precisely dated Jurassic sedimentary poles corrected for *I*-error from parautochthonous (relative to Africa) regions of Adria (e.g., the Southern Alps) agree remarkably well with the K&I APW path, both showing a comparable rapid polar shift in the Late Jurassic to a cusp at 145–150 Ma, close to the Jurassic/Cretaceous boundary [*Muttoni et al.*, 2013] (Figure 6). The low paleolatitude based on paleomagnetic results corrected for *I*-error from the Kimmeridgian-Tithonian (Late Jurassic, ~150 Ma) Garedu Formation of Eurasian Iran agrees with paleogeography predicted from the monster shift and account for the rapid temporal change of climate-sensitive facies in Iran [*Mattei et al.*, 2014]. A rapid paleolatitudinal change of similar age was previously invoked to explain the sudden and widespread deposition of Jurassic radiolarian cherts throughout the Mediterranean and Middle Eastern region [*Muttoni et al.*, 2005]. The consistency of paleomagnetic evidence from North America, Africa and Eurasia strongly suggests that the monster shift in the Late Jurassic may be a global phenomenon and thus a candidate for true polar wander.

4. Candidate for True Polar Wander?

The common motion (i.e., rotation about an equatorial Euler pivot) of all lithospheric plates and the mantle with respect to Earth's spin axis (closely approximated by the time-averaged geomagnetic field from dynamo action shaped by Coriolis effects in the fluid outer core according to the geocentric axial dipole hypothesis [*Hospers*, 1954; *Runcorn*, 1959]) is commonly referred to as true polar wander. TPW arises from changes in the planetary moment of inertia from uncompensated redistributions of mass [*Gold*, 1955; *Goldreich and Toomre*, 1969; *Tsai and Stevenson*, 2007]. The separate motion of each lithospheric plate (e.g., continent crust and immediately underlying mantle) with respect to Earth's spin axis is called apparent polar wander (APW) and reflects plate driving forces like ridge push and slab pull [*Forsyth and Uyeda*, 1975]. TPW is occurring today, as directly measured by astronomic observations [*Dickman*, 1979; *Gross and Vondrák*, 1999] and modeled according to mass anomalies from the unloading of Pleistocene ice sheets to account for a polar motion of order 10 cm/yr, the short-term equivalent of ~1°/Myr [e.g., *Sabadini et al.*, 2002; but see *Mitrovica and Wahr*, 2011]. This is comparable to more sustained rates of relative plate motions reflected in APW, for example, the northward flight of India and its convergence with Asia at ~1°/Myr in the Cenozoic [*Patriat and Achache*, 1984; *Cande and Stegman*, 2011]. However, discerning common polar motion as a component of TPW is highly problematical due to disconnections in global plate circuits [*Gordon*, 2000; *Raymond et al.*, 2000] and the practical difficulties of obtaining estimates of polar motion (i.e., paleomagnetic pole positions) from a sufficient number of lithospheric plates, especially oceanic plates, which, moreover,

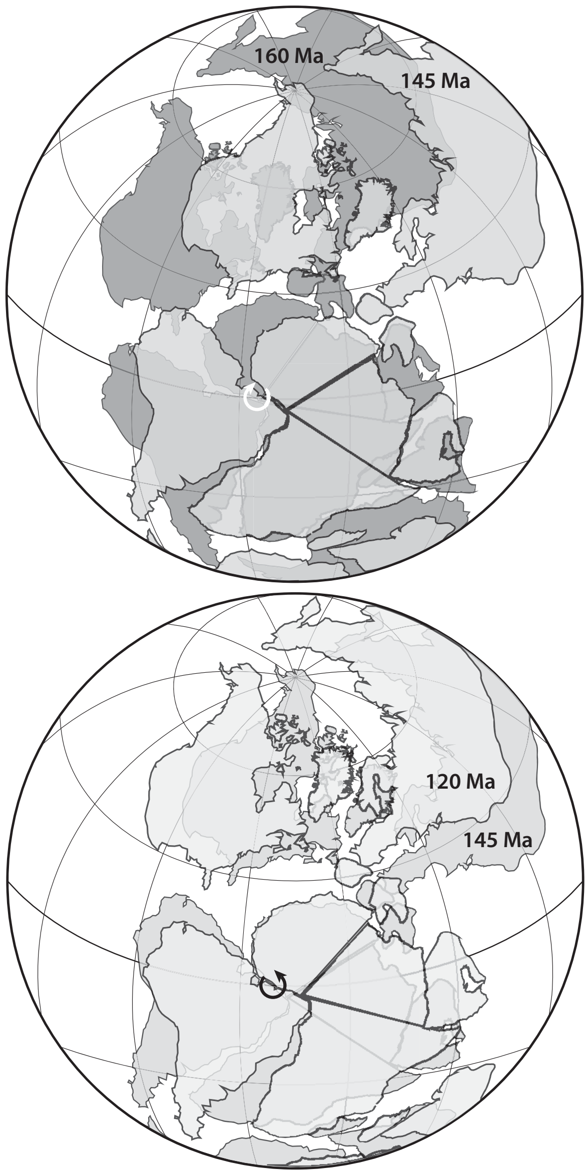

Figure 7. (top) Paleocontinental reconstructions on equal-area projections bracketing the monster shift in K&I mean poles for 160 Ma (darker shading) and for 145 Ma (superposed outlines with lighter shading), and (bottom) the immediately succeeding interval from 145 Ma (darker shading) to 120 Ma (superposed outlines with lighter shading). The Euler equatorial pivot for both the 160–145 Ma polar shift and the 145–120 Ma shift of opposite sense is located in the vicinity of the Bight of Benin of western Africa (partial circles with arrows in directions of apparent rotations of the continents). Maps were drawn with PaleoMac [*Cogné*, 2003], using relative plate motions from *Besse and Courtillot* [2002] and mean global composite paleopoles for 120, 145, and 160 Ma from *Kent and Irving* [2010].

are inevitably subducted. Attempts to construct a mantle reference frame from hotspot tracks are usually only since ~120 Ma [*Muller et al*., 1993] and inevitably stumble over the large-scale motions between the Atlantic and Pacific hotspots [*Tarduno and Gee*, 1995; *Van Fossen and Kent*, 1992b] that probably reflect more complicated processes like mantle winds [*Steinberger and O'Connell*, 1998].

Torsvik et al. [2012] pointed to a 10 Myr interval (110–100 Ma) in the Early Cretaceous, with a calculated polar motion of 1.12°/Myr about an equatorial axis at 17°E, as the fastest episode of TPW in the past 250 Myr. This interpretation assumed that the African plate stays fixed on the equator over the Atlantic Large Low Shear wave Velocity Province (LLSVP), which along with its antipodal Pacific LLSVP counterpart, were thought to be the predominant long-lived sources of mantle plumes. However, a 100–110 Ma major episode of TPW seems puzzling in the context of the well-known stillstand of polar motion from 60 to 120 Ma with respect to North America [*Globerman and Irving*, 1988; *Van Fossen and Kent*, 1992b]. This putative episode of TPW would require North America to have drifted precisely in opposition to the fast polar shift from 110 to 100 Ma yet to have stayed essentially stationary just before and for a considerable period afterward to explain its constant (within ~5°) colatitude (i.e., angular distance from the paleomagnetic pole or spin axis) during the entire Cretaceous stillstand. Alternatively, there was no TPW: North America remained stationary with respect to the paleomagnetic axis during the entire stillstand, whereas Africa experienced large APW, reflecting its drift from North America as the Atlantic opened. The paleomagnetic evidence alone does not seem to provide a means to determine which alternative is more likely to be operative.

The monster 30° polar shift in the Late Jurassic is a more plausible candidate for an episode of TPW. This polar shift is observed widely in paleomagnetic data (thus far from Adria (Africa), Iran (Eurasia), perhaps in Australia, as well as North America) and progressed at a fast clip (~1.5°/Myr) for a prolonged (~20 Myr) interval and is not so readily accounted for by relative plate motions, which were limited in the early stages of Pangea breakup. The bracketing mean poles at 160 and 145 Ma are highly coherent amongst several continents: the four available entries for 160 Ma from South America, North America, and Australia are significantly better grouped after plate tectonic restoration (as indicated by the higher-precision parameters, $K_2/K_1 = 153/23 = 6.7$ compared to 95% confidence limit of 4.3) and the same is true for the three available entries for 145 Ma from Europe, North America, and southern Africa ($K_2/K_1 = 189/7 = 27$ compared to 99% confidence limit of 16) [*Kent and Irving*, 2010]. Accurate plate reconstructions and recordings of a predominantly geocentric axial dipole field best explain such internal consistency.

We can speculate what might have triggered this episode of unusually fast TPW or APW. The growth of continental ice sheets in the Late Jurassic [*Frakes and Francis*, 1988] that were large and persistent enough to trigger and sustain TPW of this magnitude seems very unlikely. The polar shift occurs within a ~50 Myr gap in the occurrence of large igneous provinces (LIPs)–between the 133 Ma Parana-Entendeka and 183 Ma Karoo-Ferrar continental flood basalts–both centered in Africa and splayed over a few then-adjoining continents [*Courtillot and Renne*, 2003]. Thus, a LIP also does not seem to provide a viable mechanism to trigger a major episode of TPW in the Late Jurassic and Early Cretaceous.

A beguiling option is that slab break off and flip in subduction polarity in the Americas Cordillera starting about 165 Ma [*Sigloch*, 2011; *Sigloch and Mihalynuk*, 2013] were able to induce and sustain the fast polar shift between 160 and 145 Ma. The detached slab sinking through the upper to the lower mantle may produce a change in sign in the effect of the mass anomaly on the geoid, as suggested by models of *Greff-Lefftz and Besse* [2014], and this could explain the sharp polar wander cusp at ~145 Ma. The Euler pivot for the polar shift from 160 to 145 Ma is in the vicinity of what is now the Bight of Benin of western Africa (Figure 7, top), about the same place where the pivot also seems to be located for the rotation in the opposite sense between 145 and 120 Ma (Figure 7, bottom). This geometry is ostensibly consistent with the quasi-stationary African assumption [*Torsvik et al.*, 2012]. However, the apparent centrality of Africa may simply reflect that the sources of major plate driving torques or mass anomalies are located in the subduction complexes around the periphery of the dispersing Pangea continent [e.g., *Greff-Lefftz and Besse*, 2014], which is also where latitudinal changes were most pronounced during these polar shifts. Finally, if the monster shift does represent a major episode of TPW, it may have influenced geomagnetic field behavior such as reversal frequency [*Courtillot and Besse*, 1987; *Biggin et al.*, 2012].

5. Summary and Conclusions

1. Two new well-dated (U-Pb perovskite) paleomagnetic poles from the 154.9 ± 1.1 Ma Peddie and the 157.5 ± 1.2 Ma Triple B kimberlites from the stable craton of North America provide critical constraints on the Late Jurassic portion of APW, which is notably deficient in reliable pole data but may include a huge (~30°) polar shift.
2. The Triple B and Peddie poles fall approximately midway on the APW track between the 145 and 160 Ma global mean poles of K&I and therefore imply that the monster shift occurred at a relatively steady rate of ~1.5°/Myr over this time interval.
3. A very similar polar shift has been reported in independent, stratigraphically well-dated paleomagnetic poles from Adria, a promontory of Africa, and Iran, a part of Eurasia.
4. The tempo and geographical scale of the monster shift suggest it might represent an episode of TPW, the rotation of the whole mantle with respect to Earth's spin axis, or else a major change in plate driving forces effecting the collage of continents.
5. Possible mass or plate driving perturbation(s) that may have triggered this polar shift could be slab break off and flip in subduction polarity along the Americas Cordillera, or subduction-related processes elsewhere on the periphery of the Pangea supercontinent during breakup and dispersal.

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