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Jurassic monster polar shift confirmed by sequential paleopoles from Adria, promontory of Africa

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Key Points

- We review the status of the Jurassic apparent polar wander path, which has long been controversial.
- We show with new data that the widely used paleomagnetic poles from the Morrison Formation of the Colorado Plateau are overprinted.
- We provide paleomagnetic poles from Adria, promontory of Africa, that confirm the Jurassic monster shift, a major feature of polar wander.

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1029/2018JB017199

Abstract

Jurassic paleomagnetic data from North America have long been contentious, generating ambiguities in the shape of the global-composite apparent polar wander path (APWP). Here we show from a restudy of two subdivisions of the Late Jurassic Morrison Formation at the classic locality at Norwood on the Colorado Plateau that the derived paleopoles reflect variable overprinting probably in the Cretaceous and are of limited value for APW determination. We instead assembled an updated set of Jurassic paleopoles from parauthocthonous Adria, the African promontory, using primary paleomagnetic component directions derived from stratigraphically superposed intervals and corrected for sedimentary inclination error. These paleopoles are found to be in superb agreement with independent igneous paleopoles from the literature across the so-called Jurassic monster polar shift, which in North American coordinates is a jump of ~30° arc-distance from the 190–160 Ma stillstand pole at 79.5°N 104.8°E to a 148±3.5 Ma pole at 60.8°N 200.6°E defined by four Adria sedimentary paleopoles and the published Ithaca, Hinlopenstretet, and Swartsruggens-Bumbeni igneous paleopoles. The implied high rate of polar motion of ~2.5°/Myr across the monster shift is compatible with maximum theoretical estimates for true polar wander (TPW). We include a critique of published Jurassic paleomagnetic data that have been variably used in reference APWPs but that as a result of their low quality muted the real magnitude of the Jurassic monster shift. Finally, we provide paleocontinental reconstructions to describe examples of the bold signature that the monster polar shift left in the distribution of climate-sensitive sedimentary facies worldwide.

1. Introduction and historical perspective on Jurassic polar wander

The Jurassic apparent polar wander path (APWP) has long been controversial [*Courtillot et al.*, 1994; *Hagstrum*, 1993; *Kent and Irving*, 2010], introducing critical uncertainties in the paleogeography of the major continents and relative movements of tectonic terranes. Here we first present a brief updated historical overview of data used in reference APWPs and describe a desultory restudy of the late Jurassic Morrison Formation (Fm.), a prominent source of late Jurassic data for North America. We follow with an analysis of data from Adria, the promontory of Africa [*Channell*, 1996], and make the case that these independent data strongly bolster a new course in the understanding of Jurassic polar wander.

The late Paleozoic through Cenozoic APWP for North America of *Irving and Irving* [1982], obtained using a sliding window average of 30 Myr duration that was incremented in 10 Myr steps (**Fig. 1**), was erected for the Jurassic (nominally 200 to 140 Ma) on ten poles screened for minimum reliability, including three poles from sedimentary rocks on the Colorado Plateau (lower and upper Morrison Fm. [*Steiner and Helsley*, 1975] and the Summerville Fm. [*Steiner*, 1978]). *May and Butler* [1986] subsequently applied the less agnostic paleomagnetic Euler pole (PEP) analysis technique [*Gordon et al.*, 1984] and fit a small-circle paleopole track to seven poles comprised between an Early Jurassic cusp (J1), represented by the Wingate Fm. pole (cited by *Gordon et al.* [1984] from a PhD thesis by *Reeve* [1975]), and a Late Jurassic cusp (J2), represented by the lower Morrison Fm. pole [*Steiner and Helsley*, 1975] (**Fig. 1**). This J1-J2 segment was followed by a barely constrained Late Jurassic–Cretaceous small-circle track from the lower Morrison (J2 cusp) through the upper Morrison pole of *Steiner and Helsley* [1975] and to an average Cretaceous stillstand pole (KA). A total of six Jurassic poles, including those from the lower and upper Morrison Fm. in common with *Irving and Irving* [1982], were from the Colorado Plateau and adjusted by *May and Butler* [1986] for its tectonic rotation (although not by *Irving and Irving* [1982]).

Seemingly small differences between the Jurassic APWPs for North America of *Irving and Irving* [1982] and *May and Butler* [1986] had important tectonic consequences. For example, because the Jurassic APWP of *May and Butler* [1986] placed North America at lower latitudes than the APWP of *Irving and Irving* [1982], this had the effect of decreasing sometimes to statistical insignificance estimates of latitudinal displacement of Cordilleran terranes [*Irving and Wynne*, 1990].

Following the pioneering methodology introduced by *Phillips and Forsyth* [1972], *Besse and Courtillot* [1991] compiled data from all major continents into a master global-composite APWP using established independent plate reconstructions for 200 Ma to Present. In the critical 170–140 Ma time interval, their updated [*Besse and Courtillot*, 2002] global-composite APWP (**Fig. 1**) is dominated by data from sediments from central Europe (8 entries from 142 to 168 Ma from France, Switzerland, Poland; see discussion below in Section 4 and **in Supporting Information 1**). Although used in the earlier version of their APWP [*Besse and Courtillot*, 1991], neither data from either the Colorado Plateau (e.g. Morrison Fm.) nor data more generally used by *May and Butler* [1986] in their PEP analysis were adopted in their updated version [*Besse and Courtillot*, 2002]. The resulting 170–140 Ma portion of the *Besse and Courtillot* [2002] APWP in North American coordinates was found to lie somewhat to the north of the *Irving and Irving* [1982] and *May and Butler* [1986] APWPs but was also generally smooth (**Fig. 1**).

Paleomagnetic directions in igneous rocks with known paleohorizontal can generally record the field in which they were acquired more accurately than sedimentary rocks, which are prone to have inclinations shallower than the ambient field. This is inclination error: *I*-error, which has become much more widely recognized in sedimentary rocks using the elongation/inclination (E/I) statistical method [*Tauxe and Kent*, 2004]. Accordingly, *Kent and Irving* [2010] constructed a global-composite APWP using paleopoles from all major continents preferentially from reasonably well-dated igneous rocks and only those sedimentary units corrected directly for *I*-error using the E/I method of *Tauxe and Kent* [2004]. Jurassic sedimentary data from central Europe and from the Colorado Plateau, including the lower and upper Morrison poles of *Steiner and Helsley* [1975], were thus not included in the final pole compilation.

The scenario thus obtained by *Kent and Irving* [2010] for the Jurassic is characterized by a high latitude stillstand of paleopoles in North American coordinates over northern Siberia from 190 to 160 Ma (**Fig. 1**). This implies that the North American continent was steady relative to lines of latitude and did not experience significant rotation relative to meridians. For example, averaging items #42–53 in Table 5 of *Kent and Irving* [2010] results in a well-grouped 190–160 Ma mean pole at 79.5°N, 104.8°E, A95 = 4.0° (**Table 1**, entry #1; **Fig. 1**). This 190–160 Ma stillstand pole would not substantially change upon exclusion of item #45 of *Kent* *and Irving* [2010], the 169 Ma Moat Volcanics paleopole [*Van Fossen and Kent*, 1990], which according to a recent U-Pb zircon dating study of some White Mountain plutonic rocks [*Amidon et al.*, 2016], could be somewhat older than originally assumed.

This 190–160 Ma stillstand is followed by a prominent jump termed the Jurassic monster polar shift to a well-grouped mean pole at 145 Ma that falls off western Alaska (**Fig. 1**). The jump is partially captured by the intermediate 156.1±1.6 Ma Ontario kimberlites pole 156Ok of *Kent et al.* [2015] based on averaging data from the Peddie kimberlite and Triple B kimberlite with high-precision U-Pb perovskite dates of 154.9±1.1 Ma and 157.5±1.2 Ma, respectively (**Table 1**, entry #2; **Fig. 1**). *Kent et al.* [2015] regarded the stable remanent magnetization retrieved in these kimberlites as a thermochemical magnetization associated with late stage magmatic crystallization of magnetite or magnetite growth during deuteric serpentinization, and in conjunction with the observation that this magnetite carries magnetic component directions of opposite polarity acquired at distinctly different times, they suggested that the process of magnetization acquisition may have been sufficiently long to average out geomagnetic secular variation. The 145 Ma mean pole of *Kent and Irving* [2010] (**Table 1**, entry #3) was originally defined by three igneous poles from three different continents: the Ithaca kimberlite pole 146Ik from North America [*Van Fossen and Kent*, 1993], with an updated U-Pb perovskite age of 146.4±1.4 Ma [*Kent et al.*, 2015] (**Table 1**, entry #4); the combined Swartruggen-Bumbeni pole 145SB from southern Africa [*Hargraves et al.*, 1997], which we assign a nominal age of 145.4±1.4 Ma based on an Ar/Ar date for the Swartruggens kimberlite of 145.0±0.4 [*Phillips*, 1991] and an Ar/Ar date of 145.8±1.3 on the Bumbeni syenite [*Hargraves et al.*, 1997] (**Table 1**, entry #5); and the 144±5 Ma (K/Ar) Hinlopenstretet dikes pole 144Hi from Svalbard [*Halvorsen*, 1989] (**Table 1**, entry #6). Finally, this cluster of three poles defining the reference 145 Ma pole of *Kent and Irving* [2010] is followed by a smaller return shift to the oft-documented stillstand of paleopoles for North America in the Cretaceous as calculated by averaging mean poles of *Kent and Irving* [2010] at 60, 80, 100, and 120 Ma (**Table 1**, entry #7; **Fig. 1**).

Torsvik et al. [2012] elaborated on a previous pole compilation [*Torsvik et al.*, 2008] to generate a global-composite APWP using data from all major continents. The critical 170–140 Ma portion of their APWP is based chiefly on data from sediments from the Colorado Plateau, including the lower and upper Morrison paleopoles [*Steiner and Helsley*, 1975] as well as other entries used in *May and Butler* [1986] all corrected by 5.4° to account for the clockwise rotation of the Colorado Plateau citing *Bryan and Gordon* [1990] (who actually estimated the rotation was 5° +2.4°/ -2.3°), in conjunction with entries from sediments from central Europe similar to those used by *Besse and Courtillot* [2002] (see discussion below in Section 4 and **in Supporting Information 1**). Acknowledging the necessity to do something about *I*-error with the general unavailability of sample or site level data from often vintage publications, *Torsvik et al.* [2012] assumed for selected (but hardly all) sedimentary entries a nominal correction factor, f = 0.6.

The overall result was that the APWP of *Torsvik et al.* [2012] tends to lie slightly to the south of *Besse and Courtillot* [2002] and even more to the south of *Kent and Irving* [2010] **(Fig. 1**). A notable feature is for around 145 Ma where the constituent paleopoles of *Kent and Irving* [2010] occupy the easternmost longitudes of all considered APWPs. *Torsvik et al.* [2012] included only one pole (Ithaca kimberlites of New York [*Van Fossen and Kent*, 1993]) and *Besse and Courtillot* [2002] two poles (Ithaca pole and a pole from Hinlopentretet dikes of Svalbard [*Halvorsen*, 1989]) of the three poles used by *Kent and Irving* [2010] to define the 145 Ma cusp (Ithaca, Hinlopentretet, and the Swartruggens and Bumbeni kimberlites of southern Africa [*Hargraves et al.*, 1997]). But by averaging these three poles with other data in a broad 20 Myr moving time window, the APWPs of *Besse and Courtillot* [2002] and *Torsvik et al.* [2012] show an attenuated cusp compared to the hybrid APWP of *Kent and Irving* [2010], which also used a 20 Myr moving time average for temporally well distributed selected data as in the Late Triassic and Early to Middle Jurassic (230 to 160 Ma), but a discrete non-overlapping time average (such as had been sometimes more generally used for APWP construction, for example, by *Van der Voo* [1993]) for the more spatiotemporally isolated poles defining the 145 Ma mean pole.

As pointed out by *Torsvik et al.* [2012], the *Kent and Irving* [2010] hybrid APWP for the Jurassic differs strongly from their and most other published paths APWPs (e.g., *Besse and Courtillot* [2002]), which was attributed to the small number of poles used by *Kent and Irving* [2010] that were also not averaged in a 20 Myr window over the cusp interval. However, including for the sake of averaging larger numbers of poles that are likely to be variably biased by undiagnosed errors and possibly by overprinting from earlier and less adequate laboratory procedures (see discussion below and **in Supporting Information 1**) will tend to attenuate and obscure the full expression of important features of APW such as the Jurassic monster polar shift. Nevertheless, it is obviously critical that such features are tested with new data. With this in mind, we attempted a renewed study of a key unit for the Jurassic APWP of North America, the Late Jurassic age Morrison Fm., at the same locale where it had been studied by *Steiner and Helsley* [1975]. We then proceed to describe a much more fruitful and independent source of Late Jurassic data from Adria, the promontory of Africa, that has largely been ignored in global-composite APWPs. We review paleopoles from magneto-biostratigraphic sections from the literature that have been already corrected for sedimentary inclination shallowing, and provide a new set of paleopoles from existing magneto-biostratigraphic sections that we corrected for inclination shallowing, in order to provide better insights into the Late Jurassic polar motion.

2. The Morrison conundrum

A key example of the broad influence of biased paleopoles on APWP construction is provided by the classic lower and upper Morrison Fm. paleopoles from North America [*Steiner and Helsley*, 1975], which have been used widely since *Irving and Irving* [1982], are critical to the PEP analysis of *May and Butler* [1986], and are included in the recent global-composite APWP of *Torsvik et al.* [2012]. The lower Morrison is comprised of the basal Tidwell Member, dominated by siltstones and gray limestone beds with occasional ash layers, overlain by the Salt Wash Member, which is a fluviatile unit dominated by channel sandstones. The upper Morrison is comprised of the Brushy Basin Member, a unit dominated by floodplain mudstones with volcanic ash layers. Ar/Ar ages on sanidine crystals extracted from the ash layers allowed dating of the basal Tidwell Member to 155 Ma and the base and top of the Brushy Basin Member to 150 and 148 Ma, respectively [*Kowallis et al.*, 1998].

Steiner and Helsley [1975] sampled the lower and upper Morrison Fm. in the Norwood area on the Colorado Plateau (**Fig. 2A**) and obtained paleopoles (**Fig. 3**, S&H75) that were not corrected for Colorado Plateau rotation, which was not recognized before [*Hamilton*, 1981]. *May and Butler* [1986] corrected these poles [*Steiner and Helsley*, 1975] by 3.8° to account for the then-estimated clockwise rotation of the Colorado Plateau [*Bryan and Gordon*, 1986], and used the lower Morrison pole (**Fig. 3**, M&B86) to define their critical J2 cusp (**Fig. 1**) and along with the upper Morrison pole to help define the ensuing J2-KA PEP track (**Fig. 1**). *Bazard and Butler* [1994] produced a paleopole (**Fig. 3**, B&B94) from the upper Morrison Fm. (Brushy Basin Member) from Montezuma Creek, Utah, that is virtually undistinguishable from the upper Morrison paleopole of *Steiner and Helsley* [1975] from Norwood, Colorado, that is also on the Colorado Plateau and subject to correction to correction for its tectonic rotation.

Kent et al. [2010] attempted to reconcile these lower and upper Morrison paleopoles with their global-composite APWP by applying to the *Steiner and Helsley* [1975] data an assumed inclination flattening correction of f = 0.55 and a much larger (13°) restorative counterclockwise Colorado Plateau rotation relative to cratonic North America [*Kent and Witte*, 1993; *Steiner*, 1986; *Steiner*, 1988]. The thus doubly-'corrected' upper Morrison (149 Ma) pole was found to lie encouragingly close to the 145 Ma mean pole at the terminus of the Jurassic monster shift (**Fig. 3**, K&I10); however, the doubly-'corrected' lower Morrison (155 Ma) pole was found to still lie off any beaten APW track (**Fig. 3**, K&I10).

Another set of data from the Morrison Fm. was reported from the Front Range east of the Colorado Plateau [*Van Fossen and Kent*, 1992] (**Fig. 2A**). The Front Range Morrison (its type locality) is thought to be stratigraphically equivalent to the Brushy Basin Member of the upper Morrison Fm. from the Colorado Plateau localities, according to *Bazard and Butler* [1994], but gave a paleopole that, with some uncertainties related to differential local structural rotations of the sampled sites, was found to lie at much more northern latitudes (**Fig. 3**, VF&K92: 83.7°N 150.4°E) than the Morrison paleopoles from the Colorado Plateau. Nonetheless, persistent uncertainties in paleopole position, lack of direct *I*-error assessment, and suspicion of remagnetization led *Kent and Irving* [2010] to exclude all these Morrison Fm. data [*Bazard and Butler*, 1994; *Steiner and Helsley*, 1975; *Van Fossen and Kent*, 1992] from their composite APWP.

3. New paleomagnetic data from the Morrison Formation

In an attempt to better constrain the significance of the lower and upper Morrison paleopoles with regard to the Jurassic monster shift in which they should temporally fall and the North American APWP in general, we revisited the classic locality near Norwood, Colorado [*Steiner and Helsley*, 1975] where we sampled the same flat-lying lower and upper Morrison Formation. The aim was to perform an E/I test as well as the 'correction-by-site' method [*Tauxe and Kent*, 2004] for direct assessments of the inclination flattening factor.

On roadcuts along State Highway 145 east of Norwood, we sampled the lower Morrison Fm. (Salt Wash Member) at 11 stratigraphically superposed sites (JMA–JML) and the upper Morrison Fm. (Brushy Basin Member) at 18 stratigraphically superposed sites (JBA–JBR) (**Fig. 2B**). A total of 152 (with 100 from JMA and JMB devoted to the 'correction-by-site' E/I test) and 37 standard (10 cc) paleomagnetic core samples from the lower and upper Morrison Fm., respectively, were subjected to progressive thermal demagnetization in an ASC Model TD48-SC thermal demagnetizer and measurement of the resulting natural remanent magnetization (NRM) with a 2G Enterprises Model 760 DC SQUID superconducting rock magnetometer, all located in a magnetically shielded room with ambient fields nominally less than 300 nT (thermal demagnetization data in **Supporting Information 2**, Table S1 for sites JMA–JML and Table S2 for sites JBA–JBR).

After removal of spurious 'A' component directions between room temperature and 100°C, NRM demagnetization trajectories of the samples typically showed the occurrence of a pervasive 'B' component up to 600–650°C (**Fig. 4A**) with directions oriented north-and-down (positive inclinations) that could be isolated in a total of 140 lower and upper Morrison samples. These 'B' component directions (**Supporting Information 2**, Table S3) are relatively well clustered around a mean of Declination, D = 6.2°E, Inclination, I = 63.9° (radius of 95% confidence circle, $\alpha 95$ = 2.1°; **Fig. 4B**). What are optimistically regarded as characteristic component ('Ch') directions were isolated in a very narrow temperature range from 600–650°C to 680°C, consistent with hematite as carrier of the remanence (see also *Bazard and Butler* [1994]), in 40 samples from the lower Morrison and only 6 in the upper Morrison (**Fig. 4A**). These occasional 'Ch' component directions (**Supporting Information 2**, Table S4) are commonly oriented southeast-and-up (negative inclinations) or northwest-and-down, which are interpreted as recording reverse and normal geomagnetic polarity, respectively, but are distinctively not antipodal (**Fig. 4B**). The overall mean obtained by averaging the n=40 'Ch' component directions (after inverting the reverse polarity directions) from the lower Morrison is

D = 298.9°E, I = 35.9° (α95 = 7°; **Fig. 4B**). Due to the paucity of 'Ch' component directions that could be isolated and the negative reversal test that they provided, no E/I test for a direct assessment of the flattening factor could be performed.

The 'B' component mean direction defines a high-latitude pole (81.2°N 281.1°E) that, when rotated 13° counterclockwise to account for Colorado Plateau rotation, falls at 80.2°N 219.1°E (**Fig. 3**, solid star of 'This Study'). This is in the vicinity of the 120–60 Ma Cretaceous stillstand paleopole for cratonic North America (**Table 1**, entry #7; **Fig. 3**). Based on this correspondence, we tentatively interpret the 'B' component as an overprint that may be associated with deep weathering at the K-1 unconformity that often truncates the top of the Morrison Fm. and that may correspond to a ~20 Myr hiatus after which the Early Cretaceous Burro Canyon and Cedar Mountain formations were deposited [*Kowallis et al.*, 1998]. Alternatively, the overprint may represent (thermo)chemical diagenetic formation of hematite from fluids activated by the Late Cretaceous Laramide orogeny, whose remagnetization effects have been described from throughout western North America [*Muttoni et al.*, 2001a] even though other redbeds from the Colorado Plateau such as the Late Triassic Chinle Fm. [*Kent et al.*, 2018] usually do not show such pervasive overprinting. Interestingly, *McWhinnie et al.* [1990] reported a paleomagnetic study on the Jurassic Twin Creek Fm. from the frontal segment of the Idaho-Wyoming Overthrust Belt, some 600 km to the NNW of Norwood and just off the Colorado Plateau ('Wyoming Salient' in upper left inset of **Fig. 2A**), that revealed the presence of a pervasive remagnetization component carried by authigenic magnetite that yielded a pole (83°N 286°E) that is virtually undistinguishable from the 'B' component pole of this study without correction for Colorado Plateau rotation, implying the 'B' component was acquired after the rotation occurred.

The 'Ch' component mean direction from the lower Morrison defines a pole (34.6°N 160.9°E) that, even when rotated 13° counterclockwise to correct for Plateau rotation as for the 'B' paleopole, falls at 23.9°N 168.3°E, well to the south of any known Morrison paleopole from the literature (**Fig. 3**, empty hexagon of 'This Study'). We interpret the anomalous lower Morrison pole position as an artifact, reflecting a bias caused by a partially unremoved overprinting of the few 'Ch' component directions of reverse polarity by the superposed northerly and steep-down ‘B’ component. The unblocking temperature spectra of the ‘Ch’ directions are either very narrow, limiting our confidence in component extraction (e.g., **Fig. 4A**, sample JBI01), or they tend to partially overlap with the unblocking spectra of the pervasive ‘B’ component, as revealed by the slightly curved path that magnetic directions follow during transition from ‘B’ to ‘Ch’ component endpoints. This curvature due to partial mixing of components, particularly visible in the inclination values, would explain the observed bias towards easterly and shallow-up ‘Ch’ directions (e.g., **Fig. 4A**, sample JMB11a). This distortion of the ‘Ch’ component directions induced by the pervasive ‘B’ component overprint seems to be present also in the *Steiner and Helsley* [1975] data: their normal and reverse polarity mean directions, even of the well-grouped sites, are almost never truly antipodal (see their Figure 6). Moreover, we suspect from our experience that some of the normal polarity directions that they assumed were primary are in fact ‘B’ component overprints. Averaging various populations of heavily overprinted ‘Ch’ directions and/or a mixture of ‘Ch’ and ‘B’ directions is bound to result in a variety of variably biased paleopoles strung out from 60°N to less than 30°N as observed after over 40 years of research on the Morrison Fm. (**Fig. 3**).

4. The contribution of Adria

Finding that the paleomagnetic directions from the Morrison Fm. at the classic localities on the Colorado Plateau are too heavily overprinted and of scarce significance for constraining the Late Jurassic monster shift, we looked elsewhere for reliable Late Jurassic data. We scrutinized the global paleomagnetic database (GPDP) used in *Besse and Courtillot* [2002] and *Torsvik et al.* [2012] in search of alternative paleopoles, struggling with entry numbers that differ from one version of the database to another. According to our analysis, described in **Supporting Information 1** and associated **Figs. S1 and S2**, the Late Jurassic time interval is relatively deficient in reliable paleopoles in both of these compilations, which are dominated by relatively low-quality (q-factor typically only 3 out of 7) Jurassic paleopoles from mostly sedimentary units in published work going as far back as the 1970’s from central Europe, the Colorado Plateau and Louisiana, Tunisia and Brazil, whose inclusion and averaging had the effect to smear out what we consider the real magnitude and rapidity of the Jurassic monster plate shift.

We therefore turn our attention to Adria, the promontory of Africa, that can be rotated into North America coordinates using standard Central Atlantic reconstruction parameters for northwest Africa. Paleomagnetic data from Adria (see *Channell* [1996] for a first compilation) have been largely neglected in mainstream APWPs, such as by *Besse and Courtillot* [2002], *Kent and Irving* [2010], and *Torsvik et al.* [2012], and are therefore totally independent from them. Nevertheless, *Channell et al.* [2010] and *Muttoni et al.* [2013] have shown that Triassic and Jurassic poles from Adria map close to global-composite APWPs, a correspondence also noted by *Kent et al.* [2015]. Here we show in detail that Jurassic data from Adria can be used to assess and refine the character of Jurassic APWP, especially the disputed Jurassic monster shift of *Kent and Irving* [2010].

The African affinity of parautochthonous regions of Adria is well documented since *Channell and Horvath* [1976] and *Channell* [1996]. Permian to Paleogene paleomagnetic poles from the Trento Plateau (including the Dolomites) and the bordering Belluno Basin and eastern Lombardian Basin in the Southern Alps (**Fig. 2C,D**), obtained from well-dated magneto-biostratigraphic sequences corrected for inclination shallowing or from radiometrically dated igneous rocks, show coherence with coeval data from Africa [*Muttoni et al.*, 2013]. Thus, these areas of northeastern Italy, as well as other foreland areas of the Alpine-Apennine orogeny around the Adriatic Sea, e.g. Istria, Gargano-Apulia, and Iblei in southeastern Sicily **(Fig. 2C**), are interpreted as parautochthonous with respect to the African craton [*Muttoni et al.*, 2013; *Muttoni et al.*, 2003; *Channell et al.*, 2010].

The Trento Plateau, where most of the data considered in this study come from, is a sector of the Southern Alps where Alpine shortening was broadly oriented N-S and involved thick piles of Triassic platform carbonates overlying a 2 km-thick Permian volcanic unit resting above the Variscan crystalline basement, which together conferred rigidity to the thrust sheets and prevented large and systematic vertical axis rotations [*Muttoni et al.*, 2013]. Tectonic deformation involving various degrees of vertical axis rotations is more typical of the thin-skinned and largely basement-free Apennine thrust belt (**Fig. 2C**) and thus magneto-biostratigraphic studies from the Apennines [*Lowrie and Alvarez*, 1977; *Satolli and Turtù*, 2016] were not considered here for reference paleopoles because separate adjustments (rotations) of variable degrees would be required for incorporation into a global-composite APWP. In any case, we stress that these data from the allochthonous Apennines define altogether an APWP that is markedly African in aspect [*Channell*, 1996; *Satolli et al.*, 2007], thus confirming the substantial tectonic coherence of parauthocthonous Adria and Africa and the confinement of systematic rotations to the Apenninic sector of Adria.

We consider key mean paleopoles from the Trento Plateau and bordering Lombardian and Belluno basins from sedimentary units straddling the Middle Triassic, Middle and Late Jurassic, Early Cretaceous, and Paleogene (see descriptions below). Paleopoles across the critical Jurassic interval were derived from various stratigraphic sections (Torre de' Busi, Vignola = Colme di Vignola, Branchetto = Passo del Branchetto, Bombatierle, Foza, Frisoni, Sciapala; **Fig. 2D**) that have been previously studied for magnetostratigraphy and nannofossil biostratigraphy, and securely tied to the M-sequence of marine magnetic anomalies [*Channell et al.*, 1995] as far back as CM22 [*Channell et al.*, 2010]. We express the chronology of these sections (and poles) relative to the updated (after *Channell et al.* [1995]) M-sequence of *Malinverno et al.* [2012] (MHTC12) down to CM30 (**Fig. 5)**. For sections (or portions of sections) older than CM22, the chronostratigraphy of the sections (and related poles) was estimated using three key biostratigraphic events: first occurrence FO of *Conusphaera mexicana minor*, FO of *Faviconus multicolumnatus*, and last occurrence LO of *Cyclagelosphaera wiedmanni*), which have proven particularly useful to subdivide the Oxfordian–Kimmeridgian interval in the Tethys realm, and two of which – *C. mexicana minor* FO and *F. multicolumnatus* FO – have been correlated to the M-sequence at CM22 and CM25A, respectively, using magnetostratigraphy from the expanded S'Adde section from Sardinia [*Muttoni et al.*, 2018] **(Fig. 5**). The LO of *C. wiedmanni* is estimated at ~156 Ma and traced onto MHTC12 at CM30 (**Fig. 5**) based on Ar/Ar dating (156.1±0.89 Ma) of an ash level at the top of the *Rosso Ammonitico Medio* (RAM) unit at the Kaberlaba section [*Pellenard et al.*, 2013] that was traced by means of lithostratigraphy to the nearby (1 km apart) Bombatierle section of this study, where the LO of *C. wiedmanni* is recorded also at the top of the RAM unit [*Channell et al.*, 2010].

According to this chronostratigraphic framework for the Jurassic, and the available chronostratigraphy for the bracketing Triassic and Cretaceous–

Paleogene, paleomagnetic poles from Adria sites considered in this study (**Fig. 2D**) are as follows, older to younger (**Table 1**, **Fig. 5**):

Pole 238Dol (**Table 1**, entry #8) is based on magnetostratigraphic data from radiometrically (U-Pb) constrained sections from the Trento Plateau: Belvedere [*Brack and Muttoni*, 2000], Froetschbach [*Muttoni et al.*, 1997], Margon [*Gialanella et al.*, 2001], and Stuores [*Broglio Loriga et al.*, 1999], straddling altogether the Ladinian–Early Carnian (238±3 Ma). Paleopoles from these sections, which were previously corrected for inclination shallowing [*Muttoni et al.*, 2013, Table 1, entries #21–24], yield a mean paleopole (**Table 1**, entry #8) that is virtually coincident with a paleopole from Middle Triassic sediments at Al-Azizia and Kaf Bates in Libya [*Muttoni et al.*, 2001b] that was corrected for inclination shallowing by *Muttoni et al.* [2013, Table 1, entry #25].

Poles 158Bomb and 158Foz (**Table 1**, items #9 and #10) are based on magnetostratigraphic data from the pre-*C. wiedmanni* LO interval of the Bombatierle and Foza sections, respectively [*Channell et al.*, 2010]. These poles are here checked for antipodality using the bootstrap reversal test [*Tauxe*, 2010] and corrected for inclination flattening (f = 0.7 and f = 0.6, respectively) with the E/I method (**Supporting Information 3, Figs. S3 and S4**). Although a magnetostratigraphic correlation to the MHTC12 sequence is difficult to perform, these poles should be pre-CM30 in age (>156 Ma) based on the Ar/Ar age estimate of the *C. wiedmanni* LO (see above), and have thus been assigned a nominal age of ~158 Ma (**Fig. 5**). They have been rotated from Northwest African to North American coordinates using a rotation pole interpolated between those for magnetic anomaly M25 [*Roest et al.*, 1992] and the Blake Spur Magnetic Anomaly (BSMA) [*Klitgord and Schouten*, 1986].

Pole 154Vig (**Table 1**, item #11) is based on magnetostratigraphic data from levels of the Colme di Vignola section older than the *F. multicolumnatus* FO and younger than the *C. wiedmanni* LO, not recorded in the section despite relatively dense sampling [*Channell et al.*, 2010]. This pole is here checked for antipodality and corrected for inclination flattening (f = 0.8) (**Supporting Information 3, Fig. S5**). As for poles described above, a magnetostratigraphic correlation of the interval defining pole 154Vig to the MHTC12 sequence was not possible to perform. In any case, this pole should broadly correspond to CM30–CM25 based on the correlation of *F. multicolumnatus* FO to CM25A and of *C. wiedmanni* LO (not recorded) to CM30 (see discussion above; **Fig. 5**), and therefore, its age has been estimated to be on the order of 154±2 Ma. It was rotated to North America at M25 time [*Roest et al.*, 1992].

Poles 150Branch and 150Sci (**Table 1**, items #12 and #13) are based on magnetostratigraphic data from the post-*F. multicolumnatus* FO and pre-*C. mexicana minor* FO interval of the Branchetto and Sciapala sections, respectively [*Channell et al.*, 2010]. Both sets of data are here corrected for inclination flattening (f = 0.9 and f = 0.7, respectively) and checked for antipodality, albeit the Branchetto data were found negative with the bootstrap reversal test [*Tauxe*, 2010] (**Supporting Information 3, Figs. S6 and S7**, respectively). These poles should broadly correspond to CM25–CM22 based on biostratigraphy (*F. multicolumnatus* FO in CM25A and *C. mexicana minor* FO in CM22; see above), and have thus been assigned an estimated age of 150±3 Ma (**Fig. 5**). They were rotated to North America at M25 time [*Roest et al.*, 1992].

Pole 147VFF (**Table 1**, item #14) is based on magnetostratigraphic data from the CM22 interval at Vignola, Foza, and Frisoni [*Channell et al.*, 2010]. These data have been previously checked for inclination flattening obtaining f = 1 for all intervals [*Muttoni et al.*, 2013, Table 1, entries #44–46] (note that at Vignola, f was initially estimated at 0.9 by *Channell et al.* [2010]) and averaged into an Early Tithonian mean pole [*Muttoni et al.*, 2013, Table 2] that is adopted here. This mean pole has been assigned a nominal age of 147±1 Ma (**Fig. 5**) and has been rotated to North America at M21 time [*Roest et al.*, 1992].

Poles 154Vig, 150Branch, 150Sci, and 147VFF can be averaged into an overall mean pole termed 150Adria (**Table 1**, item #15).

Pole 143BVFF (**Table 1**, item #16) is based on magnetostratigraphic data from the CM21–CM20 and CM19–CM17 intervals at Torre de' Busi, Vignola, Foza, and Frisoni [*Channell et al.*, 2010]. These data were previously checked for inclination shallowing (f comprised between 0.8 and 1.0 [*Muttoni et al.*, 2013, Table 1, entries #47–52] and averaged into a mid-Tithonian–Berriasian mean pole [*Muttoni et al.*, 2013, Table 2] that is adopted here. This mean pole, broadly corresponding to CM21–CM17, has been assigned an age of 143±3 Ma (**Fig. 5**), and has been rotated to North America at M21 time [*Roest et al.*, 1992].

Pole 128Mai (**Table 1**, item #17) is based on magnetostratigraphic data from the Trento Plateau and Lombardian Basin: Capriolo [*Channell et al.*, 1987], Cismon [*Channell et al.*, 2000], Polaveno and San Giovanni [*Channell and Erba*, 1992], and Val del Mis [*Channell et al.*, 1993], straddling the Maiolica Limestone of Hauterivian–Barremian (Early Cretaceous) age from CM11 to CM1 (128±7 Ma). These entries, previously corrected for inclination shallowing [*Muttoni et al.*, 2013, Table 1, entries #55–59], yield a mean paleopole (**Table 1**, item #17) that is consistent with coeval paleopoles from the Etendeka Large Igneous Province of Namibia [*Muttoni et al.*, 2013, Table 1, entries #60–61].

Pole 50Sca (**Table 1**, item #18) is based on magnetostratigraphic data from the Belluno Basin and Trento Plateau: Cicogna [*Dallanave et al.*, 2009], Alano di Piave [*Agnini et al.*, 2011], and South Ardo [*Dallanave et al.*, 2012], straddling the Scaglia Formation of Paleocene–Eocene age from C29 to C17. These paleopoles, which show no statistical difference despite covering a large chronostratigraphic interval (50±15 Ma), were previously corrected for inclination shallowing [*Muttoni et al.*, 2013, Table 1, entries #68–70], and yield a mean paleopole (**Table 1**, item #18) that is consistent with paleopoles from Africa [*Muttoni et al.*, 2013, Table 1, entries #71–72].

In summary, bracketed between Middle Triassic paleopole 238Dol and Paleogene paleopole 50Sca, there are a total of 8 Jurassic–Early Cretaceous paleopoles from parauthocthonous Adria ranging in age from 158 Ma to 128 Ma that have been correlated to the M-sequence by means of magnetostratigraphy or traced onto it by means of biostratigraphy (**Fig. 5**). Some of these paleopoles are comparable in age to the three clustered poles used by *Kent and Irving* [2010] to give the mean position at 145 Ma (see below).

5. The Jurassic monster polar shift

Paleopoles from parauthochtonous Adria have been plotted relative to the completely independent APWP of *Kent and Irving* [2010] in common North American coordinates to assess the timing and tempo of the Jurassic monster polar shift (**Fig. 6**).

Adria pole 238Dol at 238±3 Ma lies close to the 230 Ma mean pole of *Kent and Irving* [2010], providing a first-order anchor point (see also *Muttoni et al.* [2013] for other anchor points) to validate the comparison of younger poles, especially those in the ensuing critical Jurassic time interval (**Fig. 6A**). This agreement is further substantiated by data from the E/I corrected Middle Triassic Al-Azizia and Kaf

Bates pole from northern Libya [*Muttoni et al.*, 2001b], which upon rotation to North American coordinates, falls in the narrow space between pole 238Dol and the 230 Ma mean pole of *Kent and Irving* [2010].

The Early–Middle Jurassic (190–160 Ma) high-latitude stillstand (in North American coordinates) (**Fig. 6A**; **Table 1**, entry #1) is followed by the Jurassic monster shift to the 145 Ma mean cusp pole [*Kent and Irving*, 2010] (**Fig. 6A**; **Table 1**, entry #3) as defined by the Ithaca, Swartruggens-Bumbeni, and Hinlopenstretet igneous poles (**Table 1**, entries #4–#6), with the 156.1±1.6 Ma Ontario kimberlites pole (156Ok) of *Kent et al.* [2015] (**Table 1**, entry #2) bridging the gap between the 190–160 Ma stillstand and the 145 Ma cusp poles (**Fig. 6A**).

Adria paleopoles confirm and serve to refine the timing (see **Fig. 5** for poles chronology) of this overall APW pattern accurately and independently from the items originally defining the features. In particular, pole 158Foz falls at the edge of the Early–Middle Jurassic stillstand whereas the nearly coeval pole 158Bomb (both poles dated to around 158 Ma), falls close to the ~156 Ma Ontario kimberlites pole (156Ok). The Adria poles in (bio)stratigraphic superposition thus seem to delineate an onset of rapid polar motion in the 158–156 Ma time frame (**Fig. 6A)**.

The resolution of the polar motion is manifest by the extraordinary concordance of the just younger poles from Adria with the 145 Ma mean pole position [*Kent and Irving*, 2010], i.e., the 154Vig pole (154±2 Ma), the 150Sci pole (150±3 Ma), the 150Branch pole (150±3 Ma), and the 147VFF pole (147±1 Ma) (**Fig. 6A**). The mean of these four Adria paleopoles in North American coordinates (**Table 1**, entry #15) is indistinguishable from the mean of the three igneous poles (146Ik, 145SB, and 144Hi) that originally defined the 145 Ma mean pole of *Kent and Irving* [2010] (**Table 1**, entry #3). Together, the seven poles ranging in age from 144 Ma to perhaps 154 Ma yield a well-grouped overall mean pole – termed 148Cusp – located at 60.8°N, 200.6°E (**Table 1**, entry #19). This mean pole is attributed a nominal age of 148±3.5 Ma calculated as the mean of the dates for the 7 constituent poles (± 2 standard deviations) and whose close agreement in pole space might even suggest a pause in polar motion of ~10 Myr duration.

The contribution of poles from parauthochtonous Adria extends across the Jurassic–Cretaceous boundary (**Fig. 6B)**. The 143BVFF pole at 143±3 Ma (**Table 1**, entry #16) marks practically a rebound from the 148Cusp pole toward the 120–

60 Ma Cretaceous stillstand (in North American coordinates) (**Table 1**, entry #7). Pole 128Mai from Early Cretaceous (128±7 Ma) magneto-biostratigraphic sections of the Maiolica Limestone (**Table 1**, entry #17) falls on the 130 Ma reference pole just to the south of the North American Cretaceous stillstand pole, whereas the 50Sca pole (50±15 Ma) from Paleocene–Eocene sections of the Scaglia Formation (**Table 1**, entry #18) falls close to the 50 Ma reference pole just to the north of the North American Cretaceous stillstand pole (**Fig. 6B).**

6. Discussion

We reconstructed the paleogeography of major continents from 190 to 60 Ma across the Jurassic monster shift using paleopoles discussed in this study coupled with reconstruction parameters from the literature, essentially corresponding to those summarized in Table 4 of *Kent and Irving* [2010] (**Fig. 7**).

From 190 to 160 Ma, North America, with Greenland and Eurasia attached, remained relatively fixed relative to the spin axis (stillstand) (**Fig. 7A, B).** The ensuing Jurassic monster shift can be described geometrically as a ~30° rotation of the reconstructed continents in unison about a Euler pole centered on the equator in the Bight of Benin of western Africa [*Kent et al.*, 2015] (**Fig. 7B, C**). This happens to be virtually the same Euler pole location used by *Torsvik et al.* [2012] to explain true polar wander (TPW). They argued that an Euler pole at about this location would have remained close to the center of masses of the African and Pacific Large Low Shear-wave Velocity Provinces (LLSVPs), which are associated with large-scale geoid highs and thus likely to constrain any whole-mantle rotations to the axis of minimum moment of inertia. Supporting evidence that the monster shift represents an episode of whole-mantle TPW rather than motion of the reconstructed continents relative to Earth's mantle, or APW, is the coherency of paleomagnetic results from practically the only available drill site recovering Late Jurassic sediments and igneous basement from the Pacific plate [*Fu and Kent*, 2018].

A gross estimate of the rate for the monster polar shift is 30° in 12 Myr (~160 Ma to 148Cusp), or about 2.5°/Myr. Taking into account only the best-dated (U-Pb perovskite) kimberlite poles [*Kent et al.*, 2015] from Ontario (156.1±1.6 Ma, with an associated A95 uncertainty of 2.8°), and from Ithaca (146.4±1.4 Ma, with an A95 of 3.8°), the mean rate of polar motion would be 1.9°/Myr (min = 0.8°/Myr, max =

4.3°/Myr). These mean estimates are close to a theoretical limit for TPW of 2.4°/Myr as calculated by *Tsai and Stevenson* [2007]. We stress that better age constraints are needed to pin down angular velocities more precisely within the Jurassic monster shift, for example, if the motion first accelerated and then decreased. A suggested geodynamic trigger for such an episode of TPW [*Kent et al.*, 2015] is the break-off and sinking of a cold, dense subducting slab through the mantle at an optimal distance from the Euler pole [*Greff-Lefftz and Besse*, 2014], such as apparently occurred at about the right time in the America Cordillera [*Sigloch and Mihalynuk*, 2013].

After this large perturbation, a slower essentially return polar motion of about 10° in ~10 Myr occurred from the 148Cusp to pole 143BVFF at 143 Ma and continued up to the start of the Cretaceous stillstand (in North American coordinates) (**Fig. 7D**); this retromotion may reflect plate motion of North Amercia but could also include an episode of TPW, a polar shift common to all tectonic plates, which may have been forced by the initiation of eastward subduction in the American Cordillera [*Sigloch and Mihalynuk*, 2013] and/or slab breakoff during the latest Jurassic–earliest Cretaceous closure of the Mongol-Okhotsk Ocean [*Van der Voo et al.*, 2015]. Subsequent motions of the major continental plates through the Cretaceous stillstand (in North American coordinates) from about 120 to 60 Ma occurred essentially due to Atlantic and India Ocean openings (**Fig. 7E**) with negligible contribution of TPW as essentially precluded by the stillstand.

Regardless of its ultimate geodynamic forcing, the Jurassic monster shift left an important albeit underestimated legacy in the evolution of sedimentary basins and climate-dependent sedimentary facies when viewed in the framework of Earth's dominantly zonal climate [*Manabe and Bryan*, 1985]. For example, northern Adria (e.g., Trento Plateau, **Fig. 7A**) experienced rapid southward motion of up to 20° from the mid-latitude temperate belt in the Early Jurassic to tropical paleolatitudes in the Late Jurassic (**Fig. 7F**). Elaborating on *Muttoni et al.* [2005], we consider this motion as a main controlling agent on the style of deposition in pelagic settings on Adria (e.g., Lombardian Basin) whereby radiolarian oozes (Radiolarites) were deposited as Adria migrated to tropical (or even subequatorial) paleolatitudes, in general agreement with modern-day depositional settings controlled by zonal circulation patterns, e.g., in subequatorial upwelling belts or regions of coastal upwelling related to the seaward deflection of western boundary currents. A similar plate-tectonic stratigraphic approach has been used by *Mattei et al.* [2014] to explain the first-order depositional history of central Iran (**Fig. 7A**) whereby coal-bearing sedimentation stopped and carbonate platform productivity and evaporitic sedimentation ensued on the adjacent margin as Iran drifted from the humid temperate belt to arid tropical latitudes during the Jurassic monster shift (**Fig. 7F**).

But perhaps the most startling implication of the monster shift is the role it seems to have played in the generation and preservation of fossil fuels. According to *Muttoni and Kent* [2016], the Callovian–Oxfordian Tuwaiq Mountain and Hanifa formations, which represent the main source rocks of Jurassic oil in the Persian Gulf (e.g., Ghawar oil field, **Fig. 7A**), were deposited when eastern Saudi Arabia resided near the intertropical convergence zone (ITCZ) straddling the equator (**Fig. 7B, F**), whereas the anhydrites of the overlying Tithonian Hith Fm., representing the main seal cap, were deposited as Saudi Arabia (Ghawar) rapidly drifted to the arid southern tropics as a consequence of the monster shift (**Fig. 7C, F**). This tightly sequenced sediment package resulted in some of the world's largest oil fields, such as Ghawar. On the other side of Gondwana, the Neuquén Basin of Argentina (**Fig. 7A**) resided at paleolatitudes higher than ~35°S within the presumed temperate humid belt of the southern hemisphere during most of the Mesozoic and Cenozoic (**Fig. 7F**). A single northward incursion to ~30°S towards the austral arid belt occurred at 148 Ma and broadly coincided with the deposition of the Auquilco evaporites that seal the underlying Los Molles marine shales, an important source rock of oil in the Neuquén Basin [*Muttoni and Kent*, 2016]. And in North America, the Gulf of Mexico ('Gulf' in **Fig. 7A**) resided at 10–15°N within the presumed boreal arid tropical belt during the Middle Jurassic when the Louann Salt was deposited. During the late Jurassic polar shift, the Gulf drifted to ~30°N into a presumed more temperate belt, and the Late Jurassic Smackover and Bossier source rocks were deposited (**Fig. 7F**) [*Muttoni and Kent*, 2016]. Other examples of abrupt sedimentary facies changes associated with the Late Jurassic monster polar shift can be expected to emerge.

The Jurassic monster shift also had important tectonic implications. For example, the Mt. Tatlow reference locality in southern British Columbia (**Fig. 7A**) would have migrated rapidly from ~44°N at 160 Ma to ~68°N at 148 Ma to then migrate south to ~60°N by 120 Ma (**Fig. 7F**); this change of motion of the western margin of North America from clockwise (monster shift) to counter-clockwise (post-shift rebound) caused a switch from sinistral to dextral convergence with the approaching Wrangellia and Stikinia exotic terranes, in line with geologic evidences as documented in *Kent and Irving* [2010].

7. Conclusions

We have elaborated on the character of the Jurassic global-composite APWP, which has long been a matter of debate (e.g., *May and Butler* [1986] vs. *Besse and Courtillot* [2002] vs. *Kent and Irving* [2010] vs. *Torsvik et al.* [2012]) and showed that:

- Paleopoles from the Late Jurassic Morrison Fm. from the Colorado Plateau (e.g., *Steiner and Helsley* [1975]), which have often been used in reference APWPs since *May and Butler* [1986], are affected by a pervasive overprint of presumably Cretaceous age, precluding E/I analysis of *I*-error, and are therefore of limited value for APWP determination. The inclusion in reference APWPs of low-quality Jurassic paleomagnetic data from the Colorado Plateau as well as central Europe has tended to obscure what appears to be a real pronounced feature referred to as the Late Jurassic monster polar shift.
- Reliable Jurassic paleopoles that have hardly been taken into consideration for construction of global-composite APWPs come from parauthocthonous Adria in the Southern Alps of Italy, which is a tectonic promontory of Africa and can thus be incorporated directly in plate reconstructions. Following *Channell et al.* [2010] and *Muttoni et al.* [2013], we obtained a revised set of seven Late Jurassic paleopoles ranging in age from 143 Ma to 158 Ma, bracketed by paleopoles at 50 Ma, 128 Ma, and 238 Ma for control, from parauthocthonous Adria in the Southern Alps that are based on detailed sampling from strata with unambiguous time order that allowed their magneto-biostratigraphies to be correlated to the reference M-sequence time scale and the directions to be checked and corrected for *I*-error.
- These parauthocthonous Adria paleopoles provide an excellent confirmation of the magnitude and timing of the so-called Jurassic monster shift between nominally 160 Ma and 145 Ma, which is a unique feature of the global APWP

revealed only when a strict selection of well-dated and inclination flattening-free paleopoles are used *[Kent and Irving*, 2010; *Kent et al.*, 2015; this study].

- In North American coordinates, the Jurassic monster shift is a jump of ~30° arc-distance from the 190–160 Ma stillstand pole at 79.5°N 104.8°E A95=4.0° to the 148±3.5 Ma 148Cusp pole at 60.8°N 200.6°E A95=3.1°, the latter defined by the cluster of four Adria paleopoles (northwest Africa) and the Ithaca (North America), Hinlopenstretet (Eurasia), and Swartsruggens-Bumbeni (southern Africa) igneous paleopoles. The mean rate of polar motion calculated using the well-dated (U-Pb perovskite) Ontario [*Kent et al.*, 2015] and Ithaca [*Van Fossen and Kent*, 1993] kimberlites poles from North America is 1.9°/Myr.
- The Late Jurassic monster shift was common to the assembled continents, now including parauthocthonous Adria of northwest Africa, and most probably represents an episode of true polar wander (TPW), a rotation of the whole Earth about a pivot on the Equator located, in this case, in the region of western Africa and that may have been triggered by an abrupt mass anomaly, such as the break-off and sinking into the mantle of a subducting slab. An episode of TPW is compatible with the only available data from the Pacific oceanic realm [*Fu and Kent*, 2018].
- The Jurassic monster shift controlled the first-order depositional architecture of several sedimentary basins worldwide through globally synchronous and rapid variations of paleolatitude of sign and magnitude that depend on the position relative to the equatorial Euler rotation pole. The geocentric axial dipole (GAD) assumption at the basis of these paleolatitude estimates remains valid for TPW, as a mechanism to account for the Jurassic monster shift, insofar as the geodynamo in the fluid outer core will tend to align with the rotation axis (due to the Coriolis effect) providing a stable reference frame for paleolatitude estimates even as the whole mantle-lithosphere rotates.

Acknowledgments

The data used in this paper can be found in the supporting information. We thank the Associate Editor Mark Dekkers, reviewer Marco Maffione, and an anonymous reviewer for insightful comments on the submitted version of this manuscript. DK thanks the US National Science Foundation, the Rutgers Board of Governors, and Lamont-Doherty Earth Observatory for support. LDEO Contribution #0000.

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Table 1. Paleomagnetic poles discussed in the text.

Item#, Pole name & Chron		Age (Ma / relative)	N/n	f	Long NW Africa	Lat NW Africa	A95 □95	K k	Long N America	Lat N America	R
(1) 190–160Stillstand		190–160	12	n. r.			4.0	121.5	104.8	79.5	
(2) 156Ok		154.9±1.1 & 157.5±1.2	2/34	n. r.			2.8		189.5	75.5	
(3) 145K&I [mean of (4)-(6)]		145±2	3	n. r.			9.0	189	200.2	61.2	
(4) 146Ik		146.4±1.4	7	n. r.			3.8		203.1	58.0	
(5) 145SB		145.0±0.4 & 145.8±1.3	6	n. r.			6.3		209.6	63.1	
(6) 144Hi		144±5	17	n. r.			7.5		188.0	61.5	
(7) 120–60Stillstand		120–60	4	n. r.			1.7	2938	192.8	75.9	
(8) 238Dol		238±3 / Ladinian-Carnian	4	0.6-0.9	213.0	59.4	10.3	81	98.4	53.9	$
(9) 158Bomb	pre-CM30	~158 / Callovian	1/54	0.7	266.5	56.8	4.3	21	164.7	77.5	#
(10) 158Foz	pre-CM30	~158 / Callovian	1/100	0.6	254.9	64.8	3.7	16	119.7	76.8	#
(11) 154Vig	CM25–CM30	154±2 / Oxfordian	1/74	0.8	267.5	38.1	2.9	33	195.8	60.9	§
(12) 150Branch	CM22–CM25	150±3 / Kimmeridgian	1/54	0.7	275.1	34.7	3.5	32	209.0	58.7	§
(13) 150Sci	CM22–CM25	150±3 / Kimmeridgian	1/45	0.9	270.3	38.5	3.4	41	200.0	61.8	§
(14) 147VFF	CM22	147±1 / Early Tithonian	3	1.0	265.4	37.6	4.1	895	198.1	60.3	ç
(15) 150Adria [mean of (11)-(14)]		150±6	4		269.6	37.3	4.3	459	200.9	60.5	
(16) 143BVFF	CM17–CM21	143±3 / Mid Tithon.–Berrias.	6	0.8-1.0	263.5	45.3	3.1	463	190.4	67.4	ç
(17) 128Mai	CM1–CM11	128±7 / Hauteriv.-Barrem.	5	0.6–0.9	260.0	51.2	9.2	70	190.4	71.3	&
(18) 50Sca	C17–C29	50±15 / Paleocene–Eocene	3	0.4–0.6	210.1	74.5	3.7	1113	181.5	75.8	£
(19) 148Cusp [mean of (4)-(6) & (11)-(14)]		148±3.5 / Oxfordian-Tithonian	7				3.1	392	200.6	60.8	

Chron = Chron attribution of mean pole; Age = numerical (Ma) and/or relative age of mean pole; N = number of independent poles used to calculate the mean pole; if N=1 and N=2, the mean pole is calculated on the n paleomagnetic directions; f = flattening factor calculated using the elongation/inclination (E/I) statistical method of Tauxe and Kent [2004] (n. r. = flattening correction not required); Long, Lat NW Africa = longitude (°E) and latitude (°N) of mean pole in Northwest African (Adria) coordinates; A95/α95 = radius of 95% confidence circle (A95 when N≥3, α95 when N=1 and N=2); K/k = Fisher precision parameter (K when N≥3, k when N=1 and N=2); Long, Lat N America = longitude (°E) and latitude (°N) of pole in North American coordinates; R = Northwest African (Adria) to North America rotation parameters (see below).

Item#:

1) Paleopole calculated by averaging paleopoles #42–53 in Table 5 of Kent and Irving [2010]. **2)** Ontario kimberlite pole of Kent et al. [2015]. **3)** 145 Ma pole of Kent and Irving [2010] obtained by averaging the following items 4–6. **4)** Ithaca kimberlite pole [Van Fossen and Kent, 1993] with updated U-Pb perovskite age [Kent et al., 2015]. **5)** Swartruggen-Bumbeni pole [Hargraves et al., 1997] rotated to North America by Kent and Irving [2010]) using Roest et al. [1992]. **6)** Hinlopentretet dikes pole, Svalbard [Halvorsen, 1989] rotated to North America by Kent and Irving [2010]. **7)** Mean pole calculated by averaging poles of Kent and Irving [2010] at 60, 80, 100, and 120 Ma in North American coordinates. **8)** Paleopole based on unflattened (E/I corrected) data of entries #21–24 of Table 1 of Muttoni et al. [2013] from the Belvedere [Brack and Muttoni, 2000], Froetschbach [Muttoni et al., 1997], Margon [Gialanella et al., 2001], and Stuores [Broglio Loriga et al., 1999] sections of Ladinian–Early Carnian age. This mean paleopole differs by 0.6° from the Ladinian–Early Carnian mean paleopole of Table 2 of Muttoni et al. [2013] that includes also one entry from Al-Azizia and Kaf Bates sediments from Libya (#25 of Table 1 of Muttoni et al. [2013]). **9)** Paleopole from this study obtained by unflattening (E/I correcting) data of Channell et al. [2010] from the pre-C. wiedmanni LO interval of the Bombatierle section. **10)** Paleopole from this study obtained by unflattening (E/I correcting) data of Channell et al. [2010] from the pre-*C. wiedmanni* LO interval of the Foza section. **11)** Paleopole from this study obtained by unflattening (E/I correcting) data of Channell et al. [2010] from the pre-*F. multicolumnatus* FO interval of the Colme di Vignola section. **12)** Paleopole based on unflattened (E/I corrected) data of entry #43 of Table 1 of Muttoni et al. [2013] from the ~post-*F. multicolumnatus* FO and pre-*C. mexicana minor* FO interval of the Passo del Branchetto section of Channell et al. [2010]. **13)** Paleopole from this study obtained by unflattening (E/I correcting) data of Channell et al. [2010] from the post-*F. multicolumnatus* FO and pre-*C. mexicana minor* FO interval of the Sciapala section. **14)** Paleopole based on unflattened (E/I corrected) data of entries #44–46 of Table 1 of Muttoni et al. [2013] from the CM22 interval of the Colme di Vignola, Foza, and Frisoni sections of Channell et al. [2010]. **16)** Paleopole based on unflattened (E/I corrected) data of entries #47–52 of Table 1 of Muttoni et al. [2013] from the CM17–CM19 and CM20–CM21 intervals of the Torre de' Busi, Colme di Vignola, Foza, and Frisoni sections of Channell et al. [2010]. This paleopole is equivalent to the Early Tithonian mean paleopole of Table 2 of Muttoni et al. [2013]. **17)** Paleopole based on unflattened (E/I corrected) data of entries #55–59 of Table 1 of Muttoni et al. [2013] from the ~CM11–CM1 interval at Capriolo [Channell et al., 1987], Cismon [Channell et al., 2000], Polaveno and San Giovanni [Channell and Erba, 1992], and Val del Mis [Channell et al., 1993] sections straddling the Maiolica Limestone. This mean paleopole differs by 1.6° from the Hauterivian–Barremian mean paleopole of Table 2 of Muttoni et al. [2013] that includes also entries from Africa (#60–61 of Table 1 of Muttoni et al. [2013]). **18)** Paleopole based on unflattened (E/I corrected) data of entries #68–70 of Table 1 of Muttoni et al. [2013] from the ~C17–C29 interval at South Ardo [Dallanave et al., 2012], Cicogna [Dallanave et al., 2009], and Alano di Piave [Agnini et al., 2011] sections straddling the Scaglia Formation. This mean paleopole differs by 2.1° from the Paleocene–Eocene mean paleopole of Table 2 of Muttoni et al. [2013] that includes also entries from Africa (#71–72 of Table 1 of Muttoni et al., [2013]).

R:

$ = Lottes and Rowley [1990] at Pangea fit: Lat. = 66.4°N, Long. = 345.9°E, Rot. = −75.1°. # = Euler pole at Lat. = 66.8°N, Long. = 344.9°E, Rot. = -67°, interpolated between Roest et al. [1992] at anomaly M25 and Klitgord and Schouten [1986] at BSMA. **§** = Roest et al. [1992] at anomaly M25: Lat. = 66.7°N, Long. = 344.1°E, Rot. = −64.9°. **ç** = Roest et al. [1992] at anomaly M21: Lat. = 66.2°N, Long. = 341.7°E, Rot. = −62.1°. **&** = Euler pole at Lat. = 66°N, Long. = 341°E, Rot. = -56°, interpolated between poles at anomalies M0 and M11 [Roest et al., 1992]. **£** = Muller et al. [1993] at anomaly 21 (Africa to Hotspot + Hotspot to North America = Africa to North America: Lat. = 75.70°N, Long. = 356.26°E, Rot. = -15.49°).

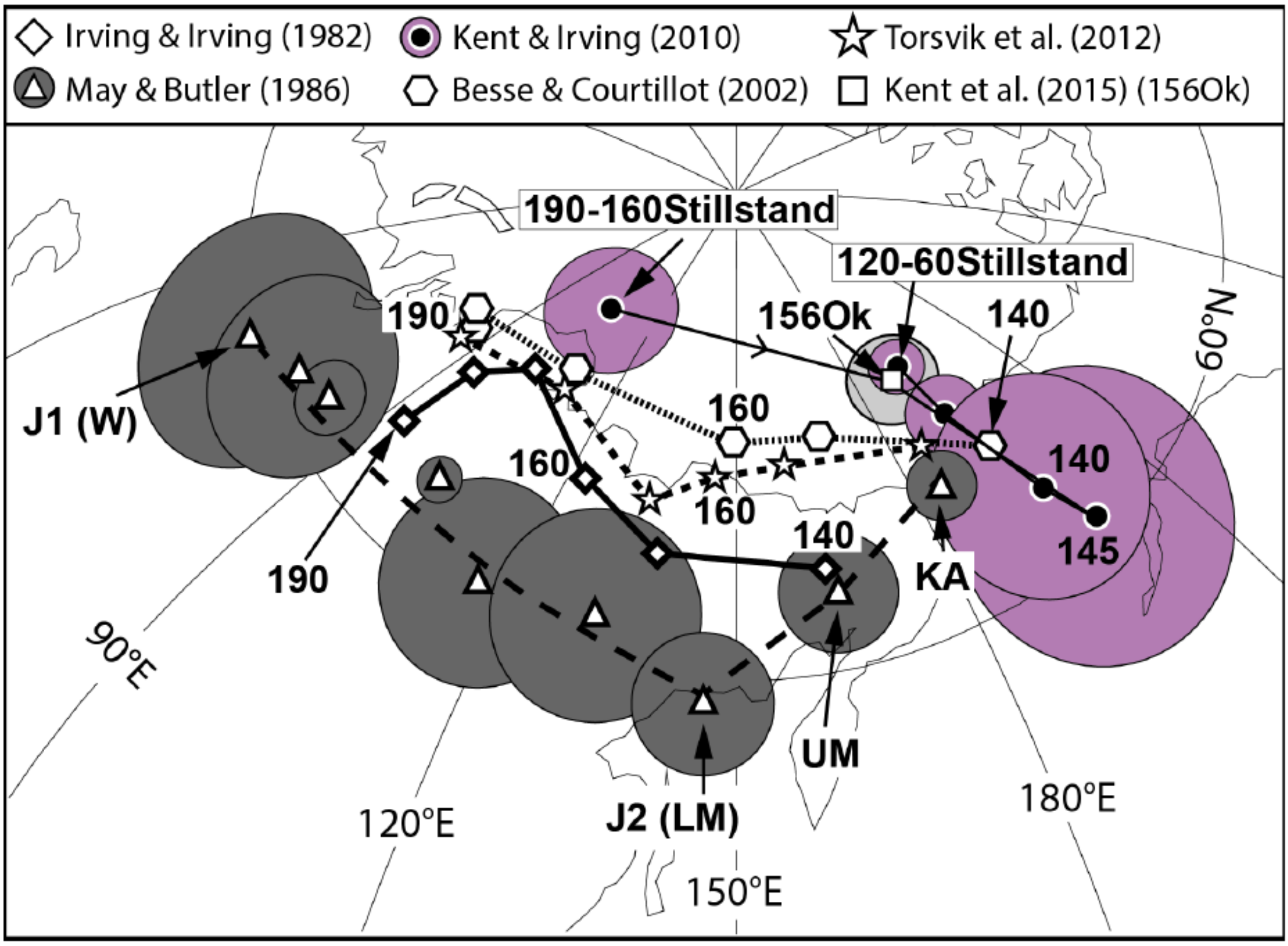

Figure 1. Comparison of some published reference APWPs in North American coordinates straddling the Jurassic–Cretaceous. For the *May and Butler* [1986] APWP, poles J1(W), J2(LM), UM, and KA are respectively the J1 (Wingate) cusp pole, the J2 (lower Morrison) cusp pole, the upper Morrison pole, and the Cretaceous average pole; the lower and Morrison poles are those of *Steiner and Helsley* [1975] corrected for 3.8° clockwise rotation of the Colorado Plateau (as for other poles from the Colorado Plateau used in *May and Butler*, 1986). The *Kent and Irving* [2010] APW path occupies the northernmost latitudes over Siberia in the Early Jurassic (190–160 Ma Stillstand pole) and shows a prominent polar shift through the Ontario kimberlites pole (156Ok) [*Kent et al.*, 2015] and ending in a cusp over western Alaska at 145 Ma, in turn followed by a return shift to the Cretaceous 120–60 Ma Stillstand pole. See text for discussion.

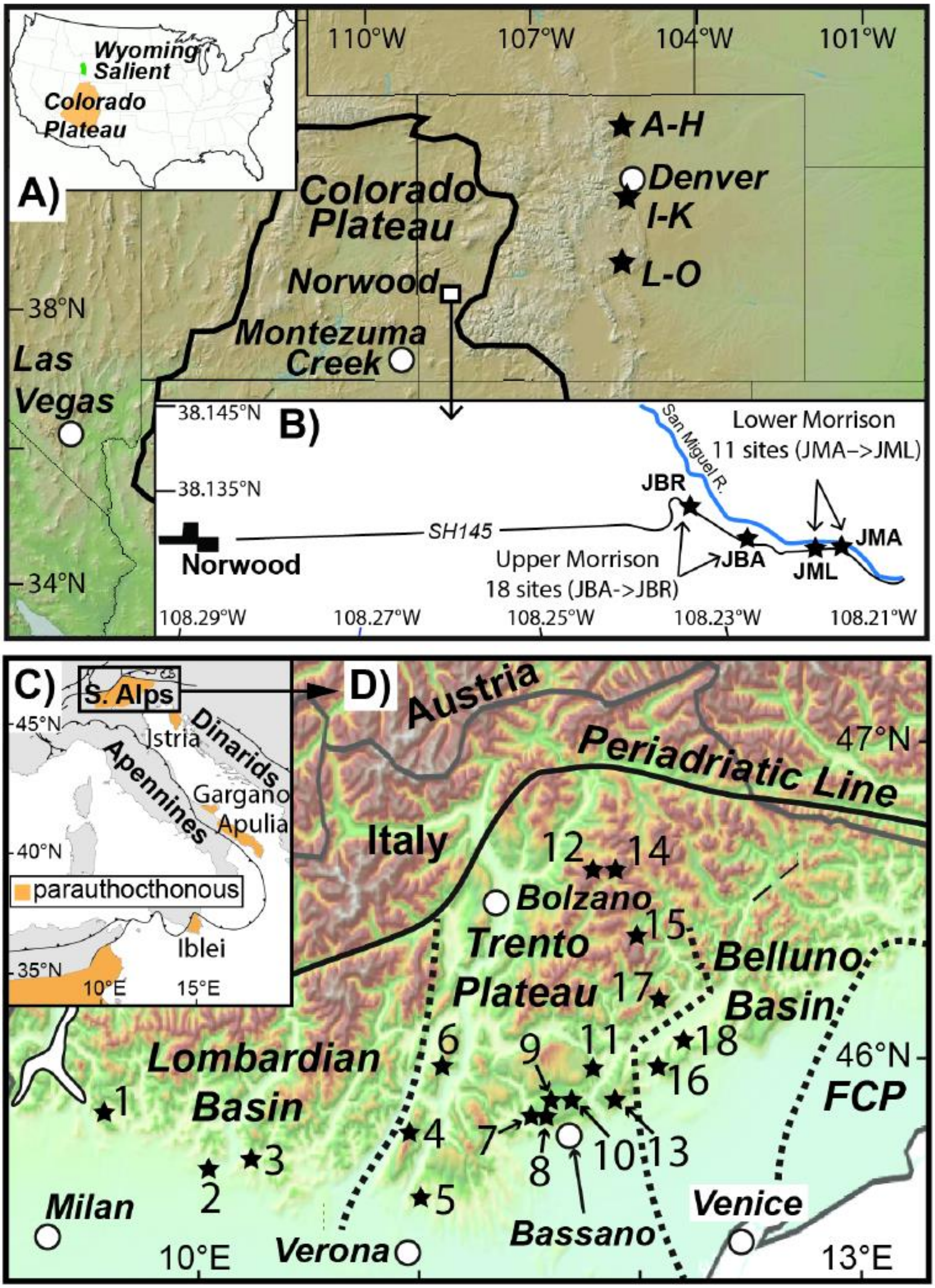

Figure 2. (A) Simplified elevation map of southwestern USA showing outline of Colorado Plateau with indication of sampling area of this study near Norwood and

of *Van Fossen and Kent* [1992] in the Front Range off the Colorado Plateau (sites A-H, I-K, L-O). (B) Detailed location map of the Norwood area with sites from the lower and upper Morrison Formation sampled in this study. (C) Italian peninsula and north Africa showing the distribution of regions that are considered essentially stable (parauthocthonous) relative to the African craton: the central-eastern Southern Alps (S. Alps in figure), Istria, Gargano, Apulia (and in general the Adriatic foreland between the Apennine and the Dinaric thrust-and-fold belts), and Iblei in Sicily. These regions constitute parauthocthonous Adria discussed in the text (as opposed to allochthonous Adria in the Apennines). (D) The central-eastern Southern Alps with main paleogeographic features (Lombardian Basin, Trento Plateau, Belluno Basin, and Friuli Platform – FCP) and locations of sites considered in this study: 1) Torre de' Busi, 2) Capriolo, 3) Polaveno and San Giovanni, 4) Colme di Vignola (abbr. Vig), 5) Passo del Branchetto (abbr. Branch), 6) Margon, 7) Bombatierle (abbr. Bomb), 8) Sciapala (abbr. Sci), 9) Foza (abbr. Fo), 10) Frisoni, 11) Cismon, 12) Froetschbach, 13) Alano, 14) Stuores, 15) Belvedere, 16) South Ardo, 17) Val del Mis, 18) Cicogna.

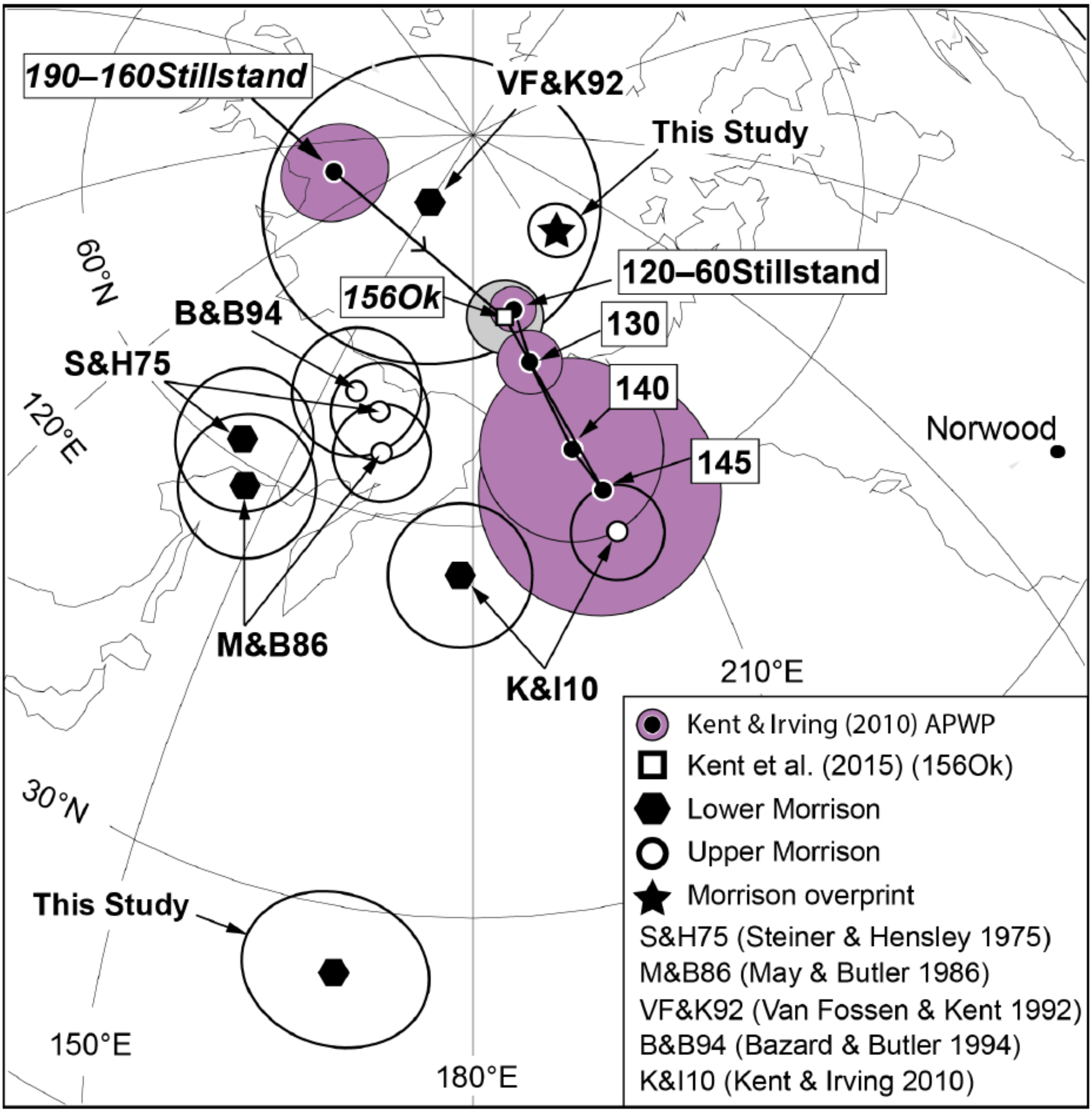

Figure 3. Paleopoles from the lower and upper Morrison Formation from the literature compared to the *Kent and Irving* [2010] APWP in North American coordinates from the 190-160 Ma stillstand in the Early Jurassic to the 145 Ma cusp pole and the ensuing Cretaceous stillstand. The Ontario kimberlites pole (156Ok) [*Kent et al.*, 2015] is also indicated. *Steiner and Helsley* [1975] paleopoles are without Colorado Plateau rotation. *May and Butler* [1986] paleopoles are those of *Steiner and Helsley* [1975] corrected for 3.8° clockwise rotation of the Colorado Plateau. *Kent and Irving* [2010] paleopoles are those of *Steiner and Helsley* [1975] but with 13° Colorado Plateau rotation and an assumed flattening factor f = 0.55.

Van Fossen and Kent [1992] lower Morrison paleopole is from the Front Range near the type area of the Morrison Fm. [*Peterson and Turner*, 1998] but off the Colorado Plateau (and it is therefore nor corrected for Colorado Plateau rotation). The lower Morrison paleopole of this study and the Morrison 'B' component overprint paleopole of this study are also indicated before and after 13° clockwise rotation of the Colorado Plateau.

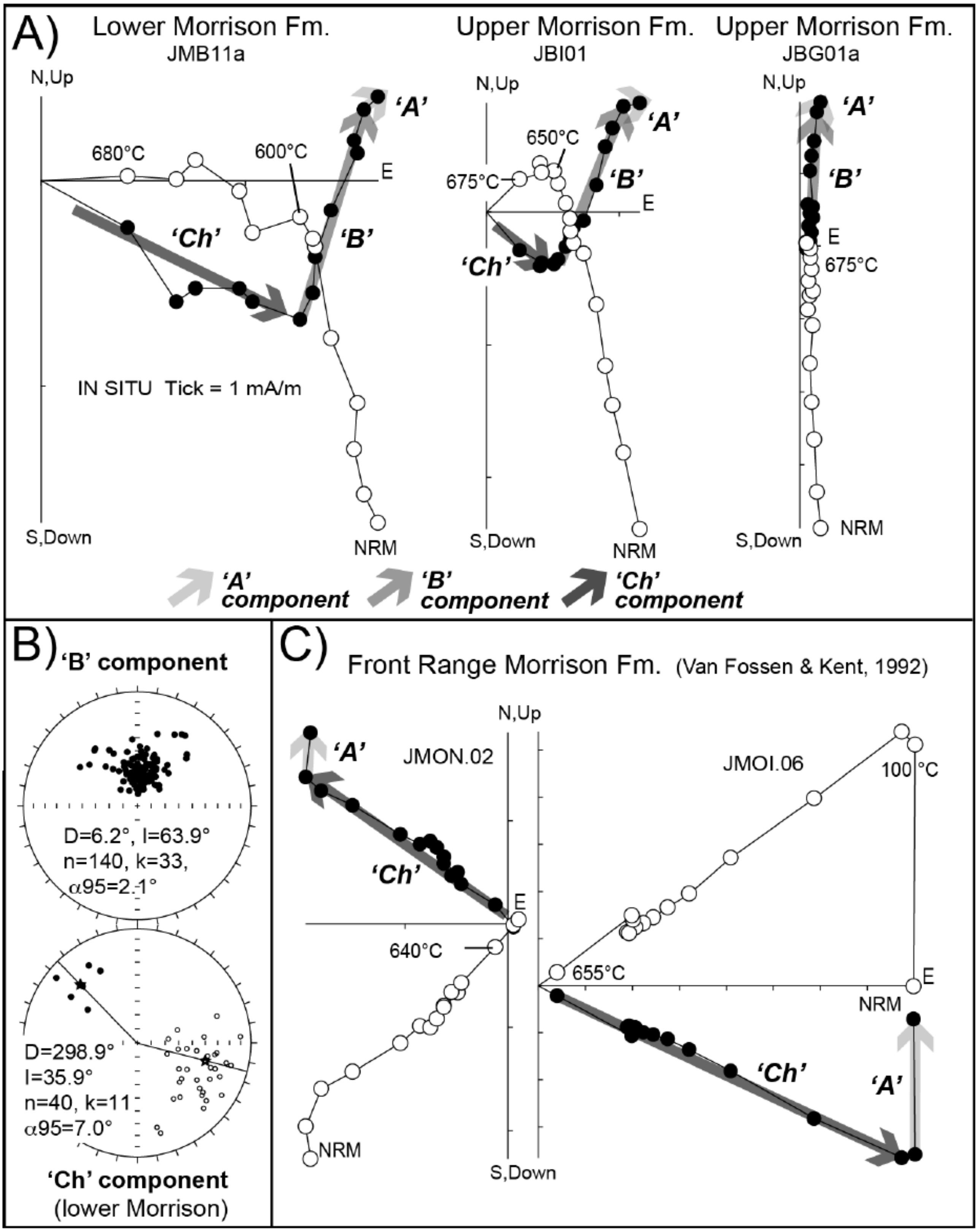

Figure 4. Paleomagnetic data of this study from the Morrison Fm. near Norwood on the Colorado Plateau (A,B) and of *Van Fossen and Kent* [1992] from the Front

Range off the Colorado Plateau (C). (A) Representative vector endpoint diagrams for progressive thermal demagnetization of NRM of samples from the lower and upper Morrison Fm. (see Supporting Information 1, Tables S1 and S2) revealing the presence of an initial (low temperature) ‘A’ transient component direction followed by an intermediate ‘B’ component overprint (Supporting Information 1, Table S3), and an occasional high temperature ‘Ch’ component direction trending to the origin of the demagnetization axes (Supporting Information 1, Table S4). (B) The n=140 ‘B’ component directions from lower and upper Morrison samples, and the n=40 (sporadic) ‘Ch’ component directions from the lower Morrison samples, are plotted on equal area stereograms with associated standard Fisher statistics (the upper Morrison yielded only 6 ‘Ch’ component directions that are not figured but listed in Supporting Information 1, Table S4). (C) Representative thermal demagnetization diagrams for NRM of lower Morrison samples from the Front Range of Colorado (from *Van Fossen and Kent* [1992]) showing the absence of the pervasive ‘B’ component overprint that tends to dominate samples from Norwood on the Colorado Plateau (see panel A).

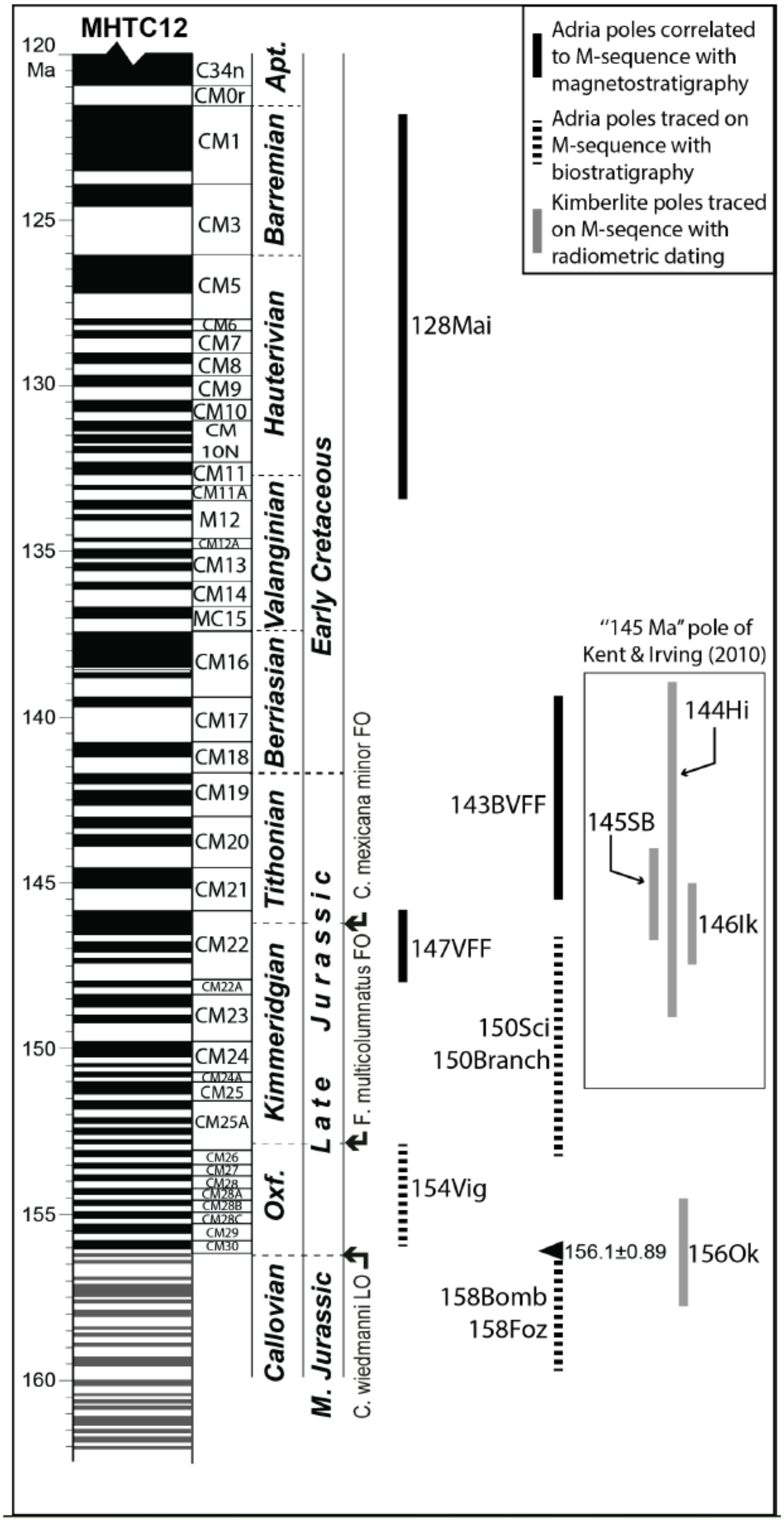

Figure 5. Chronology of Jurassic–Early Cretaceous poles from Adria (acronyms as in **Table 1**) derived from stratigraphic sections correlated to the M-sequence

marine magnetic anomalies of *Malinverno et al.* [2012] (MHTC12) by means of magnetostratigraphy (continuous solid lines) or correlated using key nannofossil events (dashed lines). These bioevents are the FO (= first occurrence) of *C. mexicana minor* and the FO of *F. multicolumnatus*, correlated to the MHTC12 sequence using magnetostratigraphy from the S'Adde section of Sardinia [*Muttoni et al.*, 2018], and the LO (= last occurrence) of *C. wiedmanni*, estimated at ~156 Ma based on an Ar/Ar date (156.1±0.89 Ma) on an ash layer at the top of the *Rosso Ammonitico Medio* at Kaberlaba [*Pellenard et al.*, 2013], which is indicated. Also shown by gray bars are the age ranges of the 146.4±1.4 Ma Ithaca kimberlite pole (146Ik) [*Van Fossen and Kent*, 1993], the 144±5 Ma Hinlopenstretet dikes pole (144Hi) [*Halvorsen*, 1989], the 145.4±1.4 Ma Swartruggens-Bumbeni kimberlites pole (145SB) [*Hargraves et al.*, 1997], and the 156.1±1.6 Ma Ontario kimberlites pole (156Ok) [*Kent et al.*, 2015]. See text for discussion and additional references.

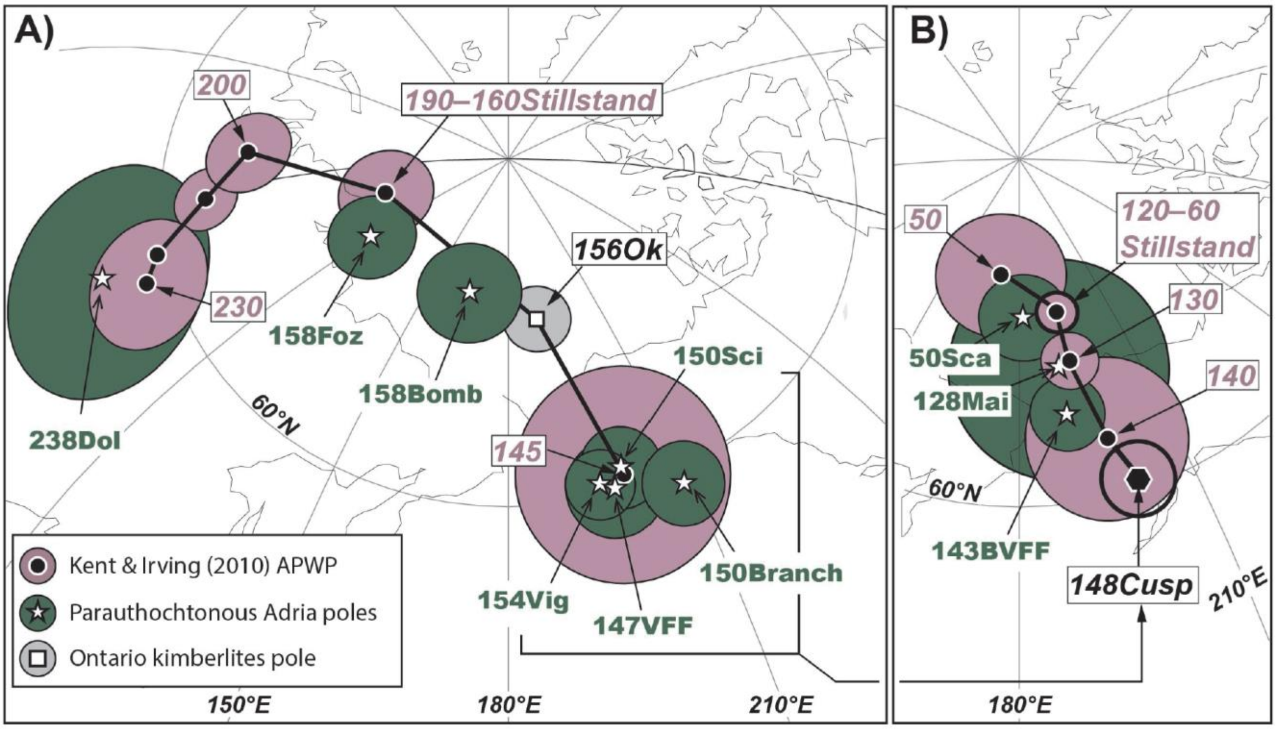

Figure 6. Sedimentary paleopoles from Adria corrected for *I*-error using the E/I method compared to the *Kent and Irving* [2010] reference APWP for (A) Late Triassic–Jurassic (230 Ma to 145 Ma) that includes the Jurassic monster polar shift from 160 to 145 Ma, and (B) Cretaceous–Paleogene (145 Ma to 50 Ma). Poles in both panels are plotted in North American coordinates. Acronyms of Adria poles have a numerical prefix that refers to the central age of the pole (e.g., 238Dol has central age of 238 Ma; see **Table 1** and text for further information). The 156 Ma Ontario kimberlites pole (156Ok) [*Kent et al.*, 2015] is also shown.

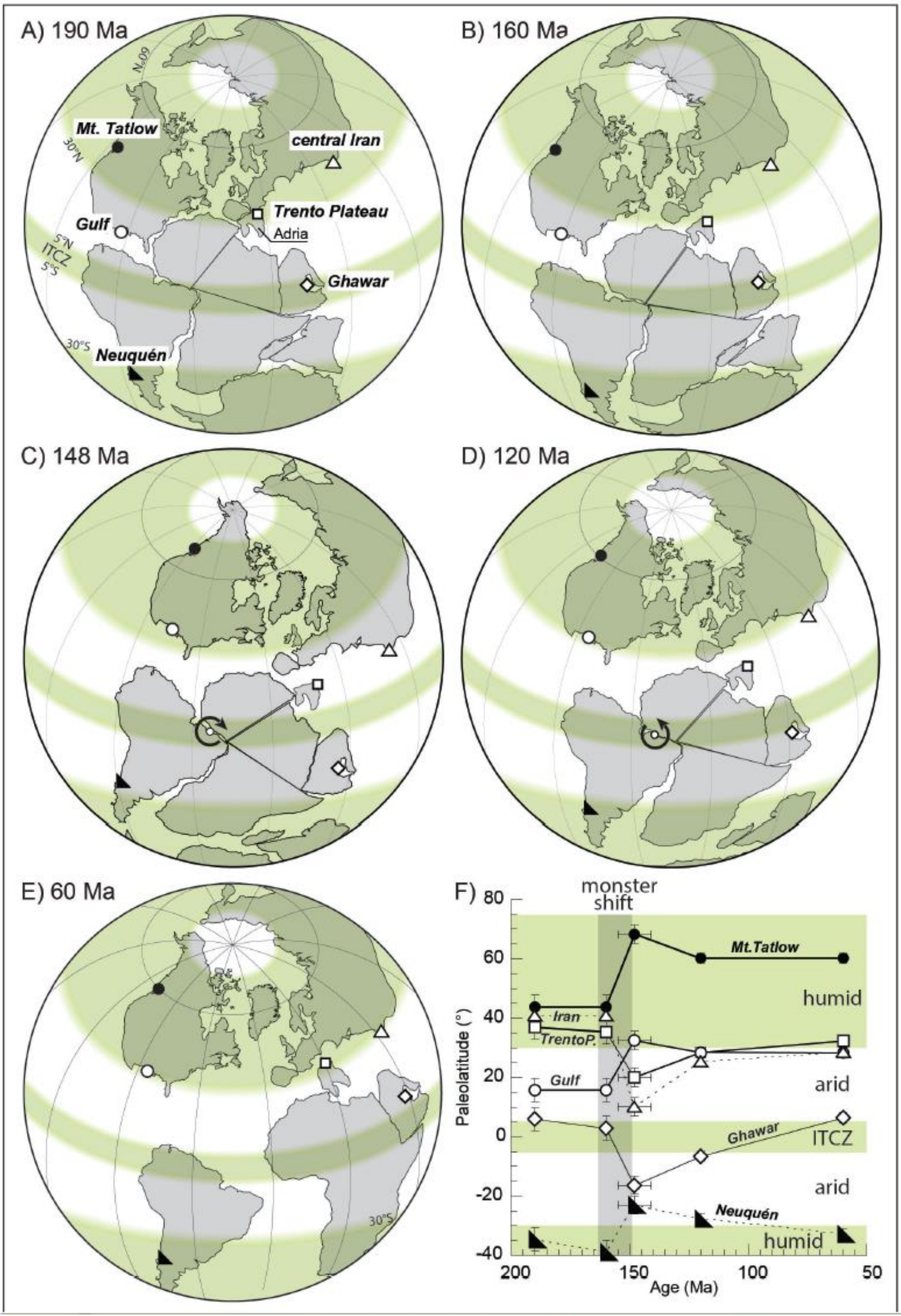

Figure 7. Paleocontinental reconstructions from 190 to 60 Ma bracketing the Late Jurassic monster polar shift. In panels (A) at 190 Ma and (B) at 160 Ma, North America has been reconstructed using the Early Jurassic 190–160 Ma stillstand

pole, in panel (C) (148 Ma) using the Late Jurassic 148Cusp pole, and in panels (D) at 120 Ma and (E) at 60 Ma using the 120–60 Ma stillstand pole (**Table 1**). Europe has been rotated to North America using reconstruction poles in *Srivastava and Tapscott* [1986] (panels A–C) and *Muller et al.* [1993] interpolated (panels D–E). Greenland has been rotated to North America using *Srivastava and Tapscott* [1986]. Northwest Africa has been rotated to North America using *Klitgord and Schouten* [1986] at maximum fit (panel A), an interpolated pole between *Klitgord and Schouten* [1986] at Blake Spur and *Roest et al.* [1992] at M25 (panel B), *Roest et al.* [1992] at M25 (panel C), and *Muller et al.* [1993] interpolated at 120 and 60 Ma (panels D–E). South America has been rotated to northwest Africa using *Royer et al.* [1992] (panels A–C), and to North America using *Muller et al.* [1993] interpolated (panels D–E). India, Antarctica, Arabia, and Australia have been rotated to northwest Africa using *Besse and Courtillot* [2002] interpolated (panels A–C), and to North America using *Muller et al.* [1993] interpolated (panels D–E). Rotation of continents during the monster shift seems to have occurred about an Euler pole centered on the equator in the Bight of Benin (circle with clockwise rotation symbol in panel C), followed by a slower counterclockwise rebound attained at 120 Ma (panel D). The variations of paleolatitude that selected sites (Mt. Tatlow in North America, Trento Plateau on Adria, Ghawar in Arabia) experienced from 190 to 60 Ma and across the Jurassic monster shift are indicated in panel F (for sites location, see panel A). The green belts in all diagrams represent zonal climate belts where precipitation exceeds evaporation (mid latitude and equatorial humid belts) as opposed to areas with excess evaporation and/or little precipitation (tropical and polar arid belts). ITCZ is the intertropical convergence zone. See text for discussion.