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Anisotropy-based inclination correction for the Moenave Formation and Wingate Sandstone: implications for Colorado Plateau rotation

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The ~201 Ma paleopole for North America (NA) at the Triassic-Jurassic boundary (TJB) is observed in two widely different locations; one paleopole is determined from the Mesozoic rift basins in eastern NA and the other from the Colorado Plateau (CP) in the southwestern United States. A large discrepancy in paleopole positions from these two localities has been attributed to large amounts of clockwise vertical axis rotation of the CP (>10°) combined with inclination shallowing of the paleomagnetism. The sedimentary inclinations of the eastern North American basins have been corrected for shallowing, but the CP inclinations have not. Simple vertical axis rotation of the CP is not enough to bring the two paleopoles into agreement. This study of the Moenave and Wingate Formations was conducted to correct CP inclinations using their high field isothermal remanent anisotropy. The Moenave Formation and laterally equivalent Wingate Sandstone, which span the TJB, were sampled in southern Utah and northern Arizona. Thermal demagnetization isolated a characteristic remanence carried by hematite from 20 sites. High field (5 T) isothermal remanent anisotropy indicated shallowing of the characteristic remanence with an average flattening factor of $f = 0.69$. An inclination-corrected paleopole for the Moenave and Wingate Formations is located at 62.5°N 69.9°E ($\alpha_{95} = 5.5°$) and is shifted northward by 2.9° with respect to the uncorrected paleopole. When the inclination corrected paleopole is rotated counterclockwise 9.7° about an Euler pole local to the CP, it is statistically indistinguishable from the inclination-corrected paleopole from the eastern North American rift basins. Rotation of the uncorrected paleopole does not bring it into statistical agreement with rift basin paleopole, therefore an inclination shallowing correction is necessary to support rotation of the CP and bring the Moenave and Wingate paleopoles into agreement with the eastern North American basin paleopole.

Keywords: inclination correction, Moenave Formation, Colorado Plateau rotation, Wingate Sandstone, magnetic anisotropy

INTRODUCTION

The apparent polar wander path (APWP) for North America (NA) during the early Mesozoic has been observed from two widely different locations; in the sedimentary and volcanic rocks of the rift basins in the northeastern United States, and in strata in the American Southwest, on the Colorado Plateau (CP). The APWPs produced are significantly different, with a westward track of the paleopoles derived from the CP that requires a large (>10°) amount of CP rotation to reconcile the differences. The largest difference occurs at a cusp (J1) in the CP APWP, at the Triassic-Jurassic boundary (TJB), ~201 Ma (Gordon et al., 1984; Ekstrand and Butler, 1989; Molina-Garza et al., 2003; Kent and Olsen, 2008; Walker and Geissman, 2009). The 201 Ma paleopole from the sedimentary units and the Central Atlantic Magmatic Province (CAMP) volcanics in the Newark and Hartford Basins in eastern NA is 67°N, 93.8°E ($N = 3$, $\alpha_{95} = 3.2°$) (Kent and Olsen, 2008). The coeval paleopole from the latest Triassic and earliest Jurassic, including the Moenave Formation and Wingate Sandstone, on the CP is 58.8°N, 60.9°E ($N = 6$, $\alpha_{95} = 3.3°$) (Molina-Garza et al., 2003). Large amounts (>10°) of vertical axis clockwise rotation of the CP about an Euler pole local to the CP (Steiner and Lucas, 2000), combined with inclination shallowing of the paleomagnetism is suggested to be the reason for the difference between the pole paths (Kent and Olsen, 2008), but structural, geologic, and some paleomagnetic data suggest that the rotation is limited to less than 5° (Hamilton, 1981, 1988; Gordon et al., 1984; Bryan and Gordon, 1986, 1990; Cather, 1999; Molina-Garza et al., 2003). Inclination shallowing corrections have been shown to be important for geologically realistic interpretations of paleomagnetic data by many workers, using two different techniques that yield the same result when compared; the anisotropy technique (Kodama and Davi, 1995; Kodama, 1997; Tan and Kodama, 1998, 2002; Vaughn et al., 2005; Bilardello and Kodama, 2009, 2010) and the E/I technique (Tauxe and Kent, 2004; Kent and Tauxe, 2005; Kent and Olsen, 2008; Tauxe et al., 2008). Inclination shallowing has been corrected using the E/I technique (Tauxe and Kent, 2004; Kent and Tauxe, 2005; Kent and Olsen, 2008) for the paleopole from the sedimentary units in the eastern NA rift basins, but has not been corrected for the CP paleopole. When Molina-Garza et al.'s (2003) paleopole is rotated counter-clockwise 17° about a CP-local Euler pole to bring the longitude into agreement with the inclination corrected coeval eastern NA pole, there is still a difference in latitude of ∼9°. Simple vertical axis rotation alone cannot reconcile the differences between the paleopoles.

Determination of an accurate APW path for NA is necessary for reliable paleogeographic reconstructions and better understanding of North American plate motions. The shape of APW path can indicate whether there were abrupt or gradual changes in North American plate motion. If there is truly a cusp in the North American APW path, it would indicate that there were major changes in plate boundaries of NA over a relatively short period of time, the few million years that span the TJB (Lucas and Tanner, 2007a; Kent and Olsen, 2008). If the cusp observed in CP rocks is instead due to CP rotation, an inclination shallowing correction of CP rocks can help better constrain the amount of rotation, important to understanding western NA tectonics and better resolution of the NA APW path. A recent North American APW path that is based on igneous paleopoles and inclination-corrected sedimentary paleopoles (Kent and Irving, 2010) assumes 13° of clockwise rotation and inclination shallowing in the Morrison Formation, in the construction of the APW path. Direct measurement of the inclination shallowing in CP rocks would test the accuracy of this assumption.

Here, we present new paleomagnetic results from the Moenave Formation and Wingate Sandstone for the 201 Ma paleopole from northern Arizona and southern Utah on the CP that have been corrected for inclination shallowing. These data allow us to make a better comparison of the two different paleopoles for the TJB for NA and to see if there can be a reconciliation of the latitude difference between the CP paleopole when unrotated and the coeval corrected eastern NA paleopole.

GEOLOGIC SETTING AND PREVIOUS WORK

The strata and CAMP volcanics from the Newark, Dan River-Danville, and Hartford rift basins in eastern NA were thoroughly studied paleomagnetically (Kent et al., 1995; Kent and Olsen, 1997, 1999, 2008; Tauxe and Kent, 2004; Kent and Tauxe, 2005). The rocks in these basins were dated by paleomagnetics and chronostratigraphy and span the TJB (Olsen and Kent, 1996; Olsen et al., 1996; Kent and Olsen, 1999, 2008; Hames et al., 2000), as well as biostratigraphy (Olsen et al., 2002; Lucas and Tanner, 2007b), ranging in age from ∼203 to ∼199.5 Ma (Kent and Olsen, 1999, 2008). Kent and Olsen (2008) conclude that these basins did not rotate with respect to each other based on the agreement of their inclination-corrected paleopoles, suggesting that they have not experienced significant vertical axis rotations with respect to cratonic NA. Also, a positive fold test that resulted from comparison of results from the Newark and Hartford basins (Kent and Olsen, 2008) indicates that the basins have remained coherent. Kent and Olsen (2008) combined inclination shallowing-corrected sedimentary results using the E/I technique (Tauxe and Kent, 2004) in the Newark and Hartford basins with the CAMP volcanic data from these basins, allowing the calculation of a 201 Ma paleopole for NA. Finally, they averaged several workers' paleopoles from the CP at 201 Ma, and rotated the uncorrected average paleopole counterclockwise 13.5° about a CP local Euler pole (Hamilton, 1981, 1988; Kent and Witte, 1993). They found that the uncorrected mean CP paleopole does not overlap the coeval eastern NA inclination-corrected paleopole; a disagreement in latitude of ∼7° remained, which could be reconciled by an inclination correction for the CP paleopole.

The CP is a coherent tectonic province in the American Southwest that rotated clockwise with respect to cratonic NA during Laramide tectonism and the opening of the Rio Grande Rift system, (Hamilton, 1981, 1988; Gordon et al., 1984; Steiner, 1986, 1988; Bird, 1998; Molina-Garza et al., 1998; Cather, 1999; Wawrzyniec et al., 2002). The amount of rotation has been debated by researchers for nearly 30 years and ranges from 1 to 17° (Hamilton, 1981, 1988; Kent and Witte, 1993; Cather, 1999; Steiner and Lucas, 2000; Molina-Garza et al., 2003; Kent and Olsen, 2008).

Previous studies have observed paleomagnetic directions consistent with the TJB-age J1 cusp paleopole in the Moenave Formation and the laterally equivalent Wingate Sandstone (Gordon et al., 1984; Ekstrand and Butler, 1989; Molina-Garza et al., 2003; Donohoo-Hurley et al., 2010). The Moenave Formation is a series of red beds comprised of fluvial and lacustrine mudstone and siltstone, as well as eolian sandstone of near equatorial continental origin (**Figures 1A,B**)

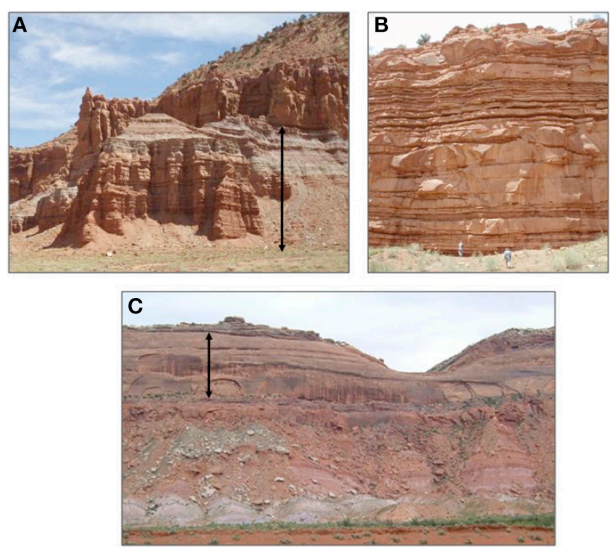

FIGURE 1 | (A) Moenave Formation at Potter Canyon, AZ, indicated by the arrow; **(B)** Moenave Formation at Tom's Canyon, Kanab, UT; **(C)** Wingate Sandstone at Comb Ridge, UT, indicated by arrow [photo credits: **(A,B)** A. McCall; **(C)** S. Daman].

(Harshbarger et al., 1957; Wilson, 1967; Clemmensen et al., 1989; Olsen, 1989; Irby, 1996; Lucas and Heckert, 2001; Tanner et al., 2002; Molina-Garza et al., 2003; Tanner and Lucas, 2007). The age of the Moenave Formation is Late Triassic (Rhaetian) at its base and Early Jurassic at its top (Hettangian), as constrained by biostratigraphy (Morales, 1996; Lucas et al., 1997; Lucas and Heckert, 2001; Molina-Garza et al., 2003; Lucas and Tanner, 2007a). The laterally equivalent Wingate Sandstone (**Figure 1C**) is an eolian sandstone which is also dated through biostratigraphy as spanning the TJB (Lockley et al., 1992, 2004; Lucas et al., 1997; Molina-Garza et al., 2003; Lucas and Tanner, 2007a). Based on the biostratigraphy and magnetostratigraphy correlated with the Newark Basin, the Moenave and Wingate Formations were deposited over a period between 2 and 7 myr, (Molina-Garza et al., 2003; Lucas and Tanner, 2007a; Walker and Geissman, 2009). The geographic extent of these strata is restricted to the CP, and they are exposed in southern Utah and northern Arizona (Tanner and Lucas, 2007). Donohoo-Hurley et al. (2010) successfully completed a detailed magnetostratigraphic correlation between the TJB in the Moenave Formation and the TJB in marine and non-marine successions in the United Kingdom, Turkey, the Southern Alps, Morocco, and the Newark Basin in eastern NA.

The Moenave and Wingate Formations were studied paleomagnetically by several workers to verify the presence of a cusp in the APW path for NA from the CP at 201 Ma or to resolve the amount of rotation of the CP with respect to the stable craton. Paleopoles from the Mesozoic strata on the CP from previous workers (Steiner, 1986, 1988; Ekstrand and Butler, 1989; Kent and Witte, 1993; Molina-Garza et al., 1995, 1998, 2003; Steiner and Lucas, 2000) are all displaced west of the paleopoles determined from the rift basins of eastern NA. The most recent TJB paleopole from the CP is from Molina-Garza et al. (2003), who also conducted a detailed rock magnetic study of these strata, determining that their paleomagnetism is carried primarily by hematite. Molina-Garza et al.'s (2003) microscopic examination of their samples suggests that the hematite is mostly authigenic rather than of detrital origin, and therefore Molina-Garza et al. conclude that inclination shallowing during deposition was likely not present in the Moenave and Wingate Formations.

Molina-Garza et al.'s paleopole for 201 Ma included samples from the Springdale Sandstone Member of Kayenta Formation overlying the Moenave Formation and the Rock Point Member of the Chinle Formation below the Wingate Sandstone, which were not sampled in this study because the cusp in the North American APWP has been constrained to lie within the Moenave and Wingate Formations (Ekstrand and Butler, 1989; Molina-Garza et al., 1998, 2003).

METHODS

The Moenave Formation was sampled at natural outcrops and road cuts across southern Utah and northern Arizona, from 35 sites at six localities; Washington Dome and Warner Valley near St. George, UT; Leeds/Historic Babylon, UT; Potter Canyon, AZ; Echo Cliffs; AZ; and the area directly surrounding Kanab, UT (**Figure 2**). The Wingate Sandstone was sampled in southeastern Utah at five sites in the road cut that bisects Comb Ridge near the city of Bluff (**Figure 2**). Samples were collected from different stratigraphic levels within the sites and within the formations, so that secular variation could be averaged. Six to nine samples were collected from each site using a portable gasoline-powered chain saw that had been modified to be a rock drill with a 25 mm diameter diamond-core bit. Each drill-core sample yielded one or more individual specimens, one for thermal demagnetization and additional samples for inclination shallowing studies. Samples were collected from fine sandstone to coarse siltstone horizons. Samples were trimmed to 25 mm lengths for thermal demagnetization and eventually trimmed to be 9 mm diameter by 8 mm length cores for high-field IRM anisotropy measurements (Bilardello and Kodama, 2009).

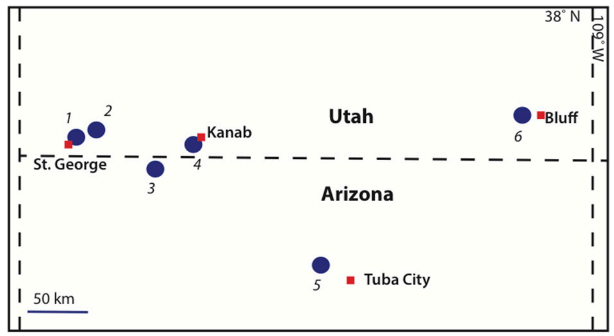

FIGURE 2 | Location map showing sampling locations. The east-west dashed line is the boundary between Utah and Arizona. Blue circles indicate sampling locations. 1. Washington Dome & Warner Valley, near St. George, UT; 2. Leeds/Historic Babylon, UT; 3. Potter Canyon, AZ; 4. Kanab, UT; 5. Echo Cliffs, AZ; 6. Comb Ridge, near Bluff, UT.

The samples were analyzed at Lehigh University's paleomagnetism laboratory. All measurements were made on a 2G Enterprises 755 superconducting magnetometer. Thermal demagnetization was used to isolate the characteristic remanent magnetization (ChRM) directions using an ASC Scientific Thermal Specimen Demagnetizer (Model TD-48 SC). Heating steps for demagnetization started at 125°C to determine if goethite was present in the samples and whether it needed to be demagnetized in the high-field anisotropy measurements. The progressive thermal demagnetization used 12–13 steps up to 685°C. Principal component analysis (Kirschvink, 1980) was used to determine the ChRM. Characteristic magnetizations with a maximum angular deviation (MAD) of more than 12° were excluded from the final site mean, and if all of the specimens for a site had MADs >12°, that site was excluded from the formation mean. Site and formation means were calculated using Fisher statistics (Fisher, 1953).

The inclination shallowing correction is based on Jackson et al. (1991) and assumes that magnetic anisotropy of a sample increases linearly with inclination flattening as a sample is compacted. The flattening follows the equation:

$$\tan I_m = f \tan I_o$$

from King (1955) where I_m is the measured inclination, I_o is the initial, pre-flattening inclination, and f is flattening factor (0 < f

< 1). Jackson et al. (1991) have established a relationship between remanence anisotropy and the f factor for magnetite particles. Tan and Kodama (2002) have modified this relationship for hematite particles (see below).

A flattening factor was determined for each site using the site's mean direction and the site's mean high field anisotropy. The flattening factors were used to correct for inclination shallowing following the high field anisotropy method (Bilardello and Kodama, 2009; Kodama, 2012). Small subsamples (9 mm diameter by 8 mm long) were drilled from the standard paleomagnetic cores. High field isothermal remanent magnetizations (hf-IRMs) were applied to the small subsamples in an ASC Scientific Impulse Magnetizer (Model IM-10-30). The subsamples were given the IRM in a field of 5 T in 9 different orientations, heated to 125°C to remove goethite magnetizations, then remeasured after each hf-IRM and heating. To be sure that the 5 T IRM had totally saturated the magnetization, IRM acquisition measurements were made in 15 steps up to 5 T to determine if the specimens' magnetizations were saturated.

The anisotropy data were fitted by least squares to a second rank anisotropy tensor following the method of McCabe et al. (1985). The eigenvalues from the specimens from each of the sites were averaged; then the flattening factor (f) could be calculated for that site, following the method of Tan and Kodama (2002):

$$f = [k_{\min}(2a + 1) - 1]/[k_{\max}(2a + 1) - 1)]$$

where $k_{\min}$ and $k_{\max}$ are the site average minimum and maximum eigenvalues of the remanence anisotropy and a is individual particle anisotropy of the magnetic grains carrying the remanence. The value of individual particle anisotropy, a, for hematite used in this study was 1.45, as determined by Kodama (2009). The equation used to correct the measured inclination (I_m) to the corrected inclination (I_c) with the calculated flattening factor (f) is:

$$\tan I_c = \tan I_m/f$$

from King (1955) where I_c is the corrected inclination and I_m is the measured inclination. The high-field anisotropy measurements were made for 3–6 specimens from each site, and the average flattening factor for each site was used to correct each site's mean direction. From the corrected site means, an inclination-corrected VGP for each site was calculated. The site VGP's were then averaged using Fisher statistics to determine a CP paleopole for 201 Ma. The inclination shallowing corrected CP paleopole was rotated about a CP-local Euler pole from Hamilton (1988) (34.6°N, 105.5°W) to determine how much rotation of the CP was necessary to bring the inclination-corrected TJB paleopole into agreement with the corrected eastern North American basins' paleopole, and to check if a vertical axis rotation of the CP will bring the corrected CP paleopole into agreement with the coeval eastern NA paleopole.

RESULTS

DEMAGNETIZATION RESULTS

The Moenave and Wingate Formation strata have remanent magnetizations that commonly show two or more unblocking temperature magnetization components (**Figures 3A–C**). Lower unblocking temperature components were typically removed after heating to 400 or 500°C, but for some specimens, heating to 600°C was necessary to remove the lower unblocking temperature overprints. The characteristic remanence (ChRM) could only be isolated by unblocking temperatures between about

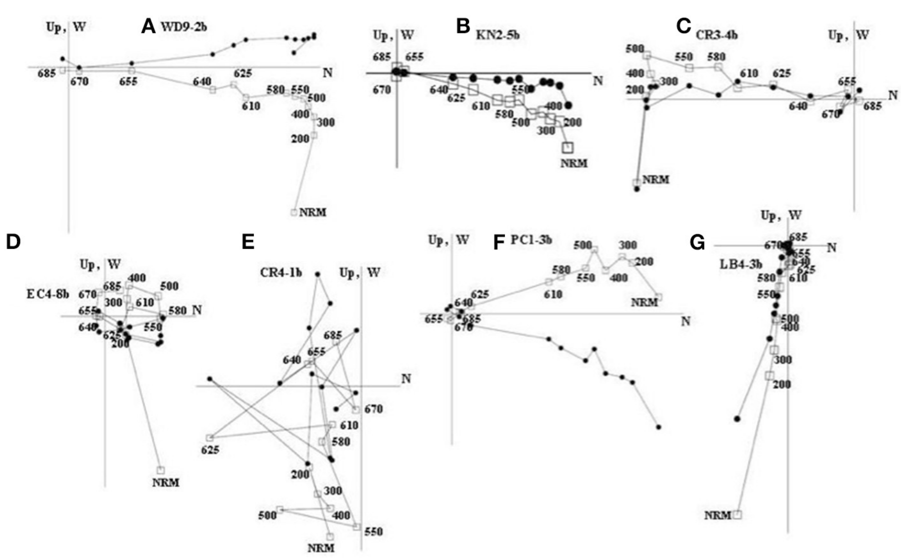

FIGURE 3 | Examples of demagnetization results; (A,B) are examples of northerly, shallow directions typical of the Moenave Formation; (C) is reversed polarity from the Wingate Formation; (D) (Moenave) and (E) (Wingate) did not yield clear directions from demagnetization; (F,G) are examples of sites possibly remagnetized or recording an excursion in the Moenave Formation. Solid circle trends are the declination and square open trends are inclinations.

600 to 685°C. When the ChRM could not be isolated and the MAD was greater than 12° (**Figures 3F,G**), the specimen was rejected, unfortunately leading to a high rejection percentage in some sites, often over 50%. Sites having less than three specimens meeting the MAD criteria had to be rejected because Fisher statistics could not be calculated. If the site mean had a 95% confidence radius (α_{95}) greater than 15°, it was also rejected. Some sites appear to be completely remagnetized or possibly record a magnetic field excursion, such as sites LB4 and PC1 (**Table 1**; **Figures 3D,E**), as they are outliers to the distribution of northerly, shallow directions; these were also omitted from the final uncorrected formation mean (**Figures 4A,B**). The mean direction for the Moenave and Wingate Formations, with stratigraphic tilt correction, but without inclination shallowing correction is $D = 358.8°$, $I = 12.8°$ ($N = 20$ sites, $k = 31.8$, $\alpha_{95} = 5.9°$; **Table 1**; **Figure 4**), which, when compared to Molina-Garza et al.'s (2003) direction for the Moenave and Wingate Formations only, is statistically the same using the discrimination of means method (McFadden and Lowes, 1981). This study's mean direction was also compared to Donohoo-Hurley et al.'s (2010) more recent results from the Moenave Formation and it is statistically indistinguishable from their mean direction ($D = 2.9°$; $I = 14.6°$; $N = 58$; $k = 13.7$; $\alpha_{95} = 5.2°$).

ANISOTROPY RESULTS

IRM acquisition measurements (**Figure 5**) show that the magnetizations of the specimens were nearly saturated by 5 T. The magnetizations of all three specimens started to saturate by about 3.5 T (**Figure 5**). Modeling of the IRM acquisition curves (Kruiver et al., 2001) indicates two coercivity components in the samples. Most of the magnetization (80–85%) has a mean coercivity of 795 mT while the remainder has a mean coercivity of 100 mT. Considered in light of the thermal demagnetization results would suggest the presence of hematite (795 mT coercivity component and 685°C unblocking temperatures) and perhaps some minor amounts of magnetite (100 mT coercivity component and 400–500°C unblocking temperatures).

Anisotropy measurements showed a bedding parallel fabric present in the high-field IRM (**Figure 6**); when plotted, the minimum, intermediate, and maximum axes of high field-IRM magnetizations show a preferred orientation, with the maximum and intermediate axes oriented nearly parallel to bedding and the minimum axes nearly perpendicular to bedding. A flattening factor for each site was calculated (**Table 1**), with values for f ranging from 0.58 to 0.84. An average flattening factor for the Moenave ($f = 0.69$) was not applied to the mean of the site means because of the differences in lithology between sites; instead, each site mean was corrected by the site's average anisotropy. The mean f factor for the Moenave Formation compares reasonably well with the tabulation by Kodama (2012) which indicates $f = 0.6$ for hematite-bearing rocks and $f = 0.7$ for magnetite-bearing rocks. The inclination-corrected stratigraphic coordinate mean direction for the Moenave and Wingate at ~201 Ma is $D = 358.7°$, $I' = 17.9°$ ($N = 20$ sites, $k = 25.9$, $\alpha_{95} = 6.5°$; **Table 1**), a steepening of the inclination by 5.1°, and a calculated paleolatitude for the Moenave and Wingate Formations at the time of deposition is ~9° N. Bilardello et al.'s (2011) study of error propagation in an anisotropy-based inclination shallowing correction indicates that for reasonable errors in the estimation of the f factor (<30%), the α_{95} cone of confidence is increased by less than a degree and the magnitude of the correction is affected by a similar amount. Therefore, error propagation was not conducted.

The elongation/inclination (E/I) technique (Tauxe and Kent, 2004) is an alternative way of correcting inclination shallowing; however, it needs a large number of samples (~100) for a well-constrained correction. Since the mean direction for the Moenave and Wingate Formations reported here is statistically indistinguishable from Donohoo-Hurley et al.'s (2010) mean direction for the same formations, the datasets were combined to yield $N = 78$ and allow an E/I inclination correction to compare to the anisotropy-based correction reported here. The E/I corrected inclination for the combined datasets was 17.2° and compares very favorably with the anisotropy-based corrected inclination (17.9°). The 95% confidence interval around the E/I corrected inclination ($I = 12°$ to $I = 24°$ or $-4.9°/+6.1°$) is comparable to the anisotropy-based 95% confidence limit of 6.5°.

DISCUSSION

The latitudes of the uncorrected and inclination shallowing corrected paleopoles calculated are not significantly different. The uncorrected, unrotated paleopole determined for the Moenave and Wingate Formations on the CP is 59.6°N, 69.6°E ($N = 20$ sites, $\alpha_{95} = 5.2°$) (**Figure 7**). When corrected for the measured inclination shallowing for each site, the corrected, unrotated mean paleopole for the Moenave and Wingate Formations on the CP is 62.5°N, 69.9°E ($N = 20$ sites, $\alpha_{95} = 5.5°$). The inclination corrected paleopole location shifted 2.9° northwards, less than the 95% confidence limit for each paleopole. In this case, the inclination shallowing effects did not significantly change the paleomagnetic pole location from the uncorrected CP paleopole. In their study to generate a magnetostratigraphy for the Late Triassic and Early Jurassic on the CP, Molina-Garza et al. (2003) determined that the weak magnetic remanence in the Moenave and Wingate Formations is carried by a hematite grain coating, which was sometimes irregular, rather than detrital hematite; therefore, they argued that the paleomagnetic inclinations were not shallowed during deposition. The shallowed inclinations that were measured in this study were probably flattened during burial compaction, suggesting an early chemical remanent magnetization (CRM) for the remanence, assuming Molina-Garza et al.'s (2003) interpretation of a CRM as the primary remanence carrier.

The average flattening factor for the Moenave is 0.69, which is one standard deviation away from the average flattening factor calculated for redbeds (0.58 ± 0.11) by Bilardello and Kodama (2010) and consistent with Kodama's (2012) average of tabulated inclination shallowing ($f = 0.6$) studies for hematite-bearing rocks. These tabulations are based on values ranging from a low value of 0.4 measured in the Newark Supergroup redbeds of the Newark Basin (Kent and Tauxe, 2005) to a high value of 0.83 measured in Carboniferous redbeds from New Brunswick and Nova Scotia (Bilardello and Kodama, 2009, 2010; Kodama, 2012). This study's results fall within this range (**Table 1**). If a CRM has a flattening factor of ~0.7, the magnitude of shallowing would be greater for steeper inclinations than observed in

Table 1 | Paleomagnetic data and statistical parameters.

	Site	n/n_d	*D*, deg	*I*, deg	*I′*, deg	*k*	α_{95}	*f*	Strike, Dip
Moenave Formation	EC1*	4\7	209.5	77.8		10.8	29.4		
	EC2*	4\7	13.0	47.0		9.1	32.2		
36.2°N, 111.4°W	EC3	6\8	4.6	21.2	29.4	408.0	3.3	0.69	342, 29
	EC4*	0\5							
	EC5*	0\5							
37.1°N, 112.5°W	KN1	8\8	357.6	8.6	12.2	63.2	7.0	0.70	42, 4
37.1°N, 112.5°W	KN2	6\6	3.2	16.7	26.4	701.7	2.5	0.61	42, 4
37.1°N, 112.5°W	KN3	6\6	14.8	5.9	8.6	41.9	10.5	0.68	42, 4
37.1°N, 112.5°W	KN4	8\8	14.1	6.1	9.3	198.0	3.9	0.66	42, 4
37.1°N, 112.5°W	KT1	8\8	339.3	19.2	27.9	80.3	6.2	0.66	286, 4
37.1°N, 112.5°W	KW1	7\8	4.4	6.1	9.4	210.8	4.2	0.65	356, 4
37.1°N, 112.5°W	KW2	7\7	359.6	9.2	10.9	52.3	8.4	0.84	356, 4
	LB1*	0\5							
37.2°N, 113.4°W	LB2[R]	4\8	176.6	−22.7	−27.2	431.1	4.4	0.82	49,33
	LB3*	2\5							
	LB4*	4\7	98.9	58.1		221.7	6.2		
37.2°N, 113.4°W	LB5[R]	6\8	172.9	−37.0	−46.6	41.4	10.5	0.71	49,33
	PC1*	8\8	21.7	−15.2		197.1	4.0		
	PC2*	7\7	15.8	−10.2		40.8	9.6		
	PC3*	6\6	18.1	51.2		42.4	10.4		
36.9°N, 112.8°W	PC4	7\7	24.2	23.8	37.2	52.4	8.4	0.58	330, 2
	PC5*	0\5							
36.9°N, 112.8°W	PC6	6\7	337.4	7.9	10.8	33.2	11.8	0.73	330, 2
37.1°N, 113.4°W	WD1	7\8	346.0	9.0	13.4	68.1	7.4	0.66	46, 38
	WD2*	1\6							
37.1°N, 113.4°W	WD3	5\7	351.8	9.9	13.1	88.3	8.2	0.75	46, 38
37.1°N, 113.4°W	WD4	7\7	0.9	1.4	1.9	417.7	3.0	0.73	38, 40
37.1°N, 113.4°W	WD5	8\8	357.8	12.4	17.8	479.2	2.5	0.68	38, 40
37.1°N, 113.4°W	WD6	8\8	358.7	13.9	17.6	193.6	4.0	0.78	38, 40
	WD7*	8\8	93.6	43.4		288.5	3.3		
	WD8*	0\7							
37.1°N, 113.4°W	WD9	8\8	349.2	12.5	17.2	52.9	7.7	0.71	38, 40
37.0°N, 113.4°W	WV1	8\8	13.1	7.1	12.1	79.1	6.3	0.58	302, 7
	WV2*	3\6	180.8	−34.3		4.2	69.8		
	WV3*	4\6	169.5	8.9		7.2	36.9		
Wingate Sandstone	CR1*	2\5							
	CR2*	4\5	33.9	25.9		12.9	26.6		
37.3°N, 109.7°W	CR3[R]	8\9	170.0	−1.9	−3.1	35.5	9.4	0.62	31, 41
	CR4*	0\5							
	CR5*	0\5							
Selected sites, mean directions	Uncorr	20	358.8	12.8		31.8	5.9		
	Corrn	20	358.7	17.9		25.9	6.5		

n/n_d is the number of specimens used versus the number of specimens demagnetized; D is the declination in degrees, I is the uncorrected inclination, I′ is the corrected inclination, k is Fisher's precision parameter, α95 is the radius of the confidence interval around the mean.

**Indicates sites excluded from the final calculations, as explained in the text. [R]Indicates sites which are reversed.*

EC, = Echo Cliffs, AZ; KN = Northern Kanab, UT; KT = Tom's Canyon, Kanab, UT; KW = Western Kanab, UT; LB = Leeds/Historic Babylon, UT; PC = Potter Canyon, AZ; WD = Washington Dome, St. George, UT; WV = Warner Valley, St. George, UT; CR = Comb Ridge, near Bluff, UT.

Strike, dip follows the convention that strike is to the left when looking down dip.

the Moenave Formation. The Moenave and Wingate Formation sites that were sampled typically have lithologies of fine sandstones and coarse siltstones, but medium sand was present in a few sites. These coarser specimens would have experienced less compaction and therefore less shallowing of the inclinations. The small amount of inclination shallowing is consistent with Molina-Garza et al.'s (2003) observation of pigmentary chemically precipitated hematite rather than detrital hematite being the dominant magnetic mineral carrying the remanence.

With the inclination shallowing corrected, the amount of rotation of the CP necessary to bring the coeval paleopoles into agreement can be calculated using Demarest's (1983) approach as reported in Butler (1992). When the inclination corrected CP mean paleopole for the TJB is rotated about an Euler pole local to the CP, (34.6°N, 105.5°W; Hamilton, 1988), the amount of rotation needed to align the longitude of the CP paleopole with the coeval paleopole from the northeastern US is 9.7°, yielding a rotated, corrected paleopole for the CP at 61.7°N, 90.5°E ($N = 20$, $\alpha_{95} = 5.5°$), with a calculated error on the rotation of $\pm$ 5°. The corrected, rotated CP paleopole is statistically indistinguishable from the eastern NA basin corrected paleopole (Kent and Olsen, 2008) using the discrimination of means (McFadden and Lowes, 1981). If the uncorrected paleopole is rotated 10.1° about the CP Euler pole the uncorrected, rotated CP paleopole is statistically different from the eastern NA basins' paleopole. This result suggests that the CP rotated on the order of 10° clockwise since the deposition of the Moenave Formation and Wingate Sandstone and that the westward displacement in the APW path for NA from the CP is likely an artifact of this rotation as suggested previously by many workers (e.g., Kent and Witte, 1993; Kent and Olsen, 2008).

With the amount of rotation of the CP calculated, the amount of translation along an arc around the Euler pole can be calculated. This amount varies with distance from the Euler pole, but was calculated for the approximate location of the eastern edge of the piercing point on the CP from Cather (1999). The ~10° of rotation at a point to close to the CP Euler pole in eastern New Mexico yields only ~20 km of northeastern translation. This is less than the displacement Cather (1999) calculated for the eastern edge of the CP in New Mexico using stratigraphic pinchouts as piercing points, with amounts range from 33 to 110 km. The

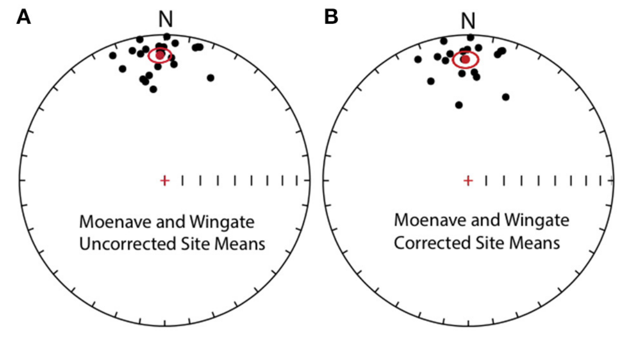

FIGURE 4 | (A, Left**)** Equal area net showing Moenave and Wingate Formations uncorrected site means and mean of the site means with 95% confidence cone in red. **(B**, Right**)** Moenave and Wingate Formations corrected site means and mean of site means (red).

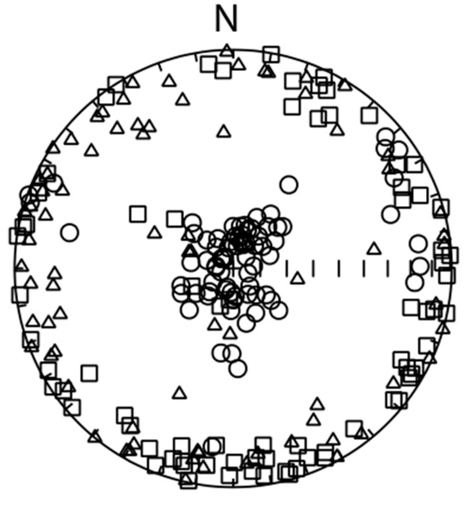

FIGURE 6 | Equal area net showing Moenave Formation high field anisotropy results in stratigraphic coordinates. Open circles are minimum axes, squares are maximum axes, and triangles are intermediate axes, all points lower hemisphere. Minimum axes are perpendicular to bedding, with maximum (and intermediate) axes lying in the bedding plane indicating a bedding parallel fabric typical of deposition and compaction in sedimentary rocks.

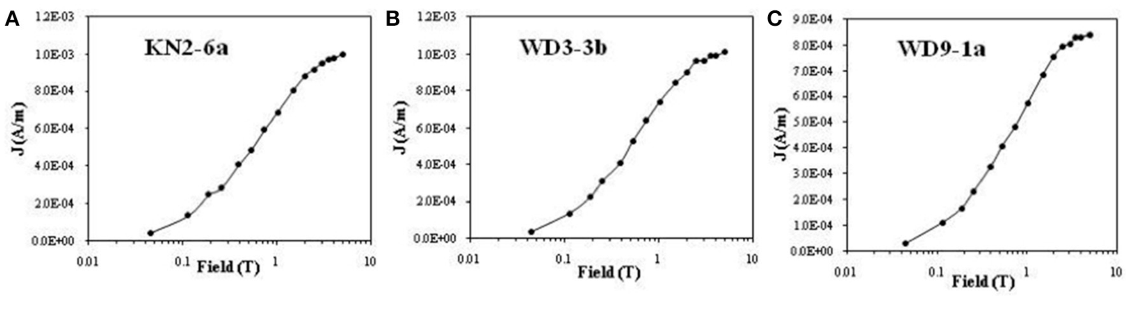

FIGURE 5 | IRM acquisition of Moenave Formation samples. All three samples (**A**, Northern Kanab; **B,C**, Washington Dome) have nearly reached saturation by 5 T.

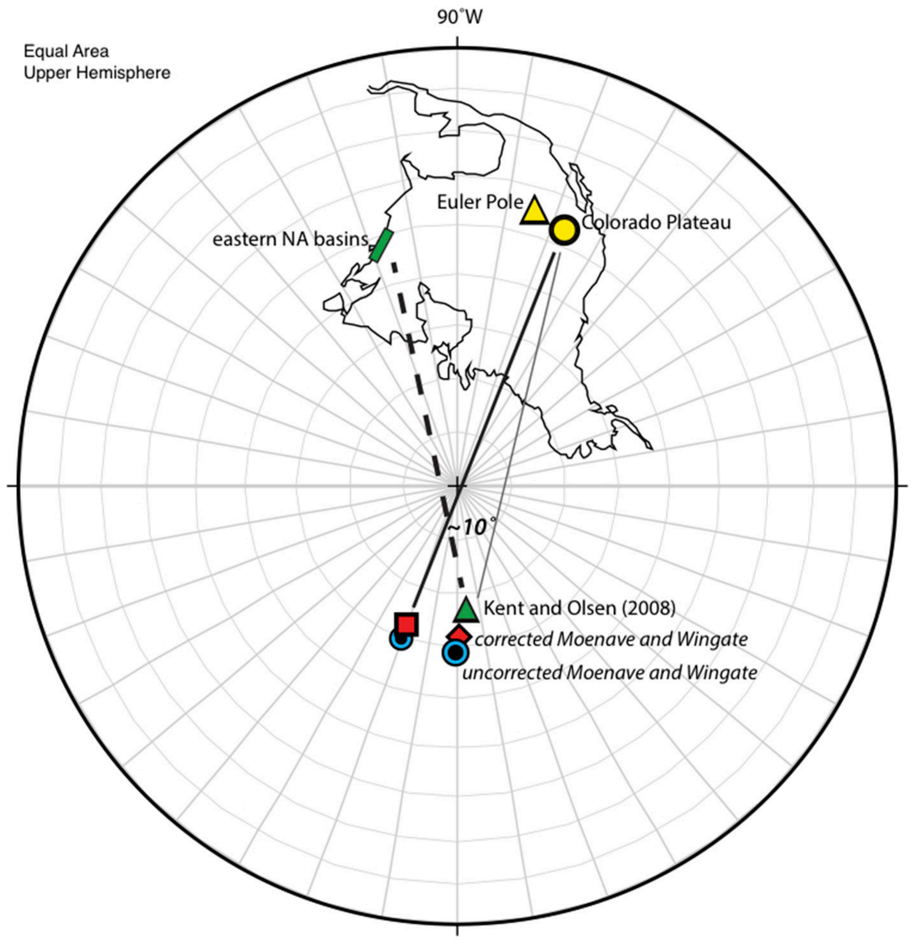

FIGURE 7 | Corrected (red) and uncorrected (blue) paleopoles from the Moenave and Wingate Formations shown in their *in situ* position (solid black line connects them to the Colorado Plateau locality) and with CP rotation removed (light gray line connects to the Colorado Plateau locality). The Kent and Olsen (2008) paleopole (green triangle) is the reference pole from the eastern NA basins (dashed line connects to its locality). A rotation of ∼10° will bring the CP Moenave and Wingate paleopole into agreement with the eastern North American basin paleopole.

discrepancy could suggest that the Euler pole for CP rotation is further from the CP as suggested by Cather (1999) or that the geological observations overestimate the amount of displacement along the fault systems.

CONCLUSIONS

Inclination shallowing corrections for the Moenave Formation and the Wingate Sandstone on the CP have significant implications for the amount of CP rotation and translation, as well as the paleomagnetic remanence in red beds. Even though the remanence in these red beds is a CRM, both the anisotropy-based inclination correction reported here and an E/I correction confirm inclination shallowing with $f = 0.7$. The shallowing was probably caused by burial compaction, if the CRM was acquired shortly after deposition and before significant amounts of burial. When corrected for inclination shallowing, the paleopole for the CP at the Triassic/Jurassic boundary, ∼201 Ma, shifts 2.9° northwards in latitude. The inclination-corrected paleopole, when rotated about a CP local Euler pole 9.7 ± 5° to account for clockwise rotation of the plateau, matches the coeval corrected eastern NA paleopole, at the 95% confidence level. The amount of translation of the CP calculated from the rotation is smaller than geological estimates of fault displacement along the eastern edge of the CP.

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