# Paleomagnetism of the Moenave Formation: Implications for the Mesozoic North American apparent polar wander path

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## ABSTRACT

**Previous syntheses of the Mesozoic North American apparent polar wander (APW) path have suggested the presence of a sharp corner or cusp (the J-1 cusp) in the Late Triassic to Early Jurassic. Paleomagnetic data from the Lower Jurassic (Sinemurian) Moenave Formation clarify details of this important feature in the APW path. A total of 220 oriented cores were collected from 31 levels in four stratigraphic sections of the Moenave Formation in northern Arizona and southern Utah. Thermal demagnetization in multiple steps, generally between 600 and 660 °C, was successful in revealing the characteristic component of natural remanent magnetization at 23 sites. The paleomagnetic pole is lat = 58.2°N, long = 51.9°E; radius of 95% confidence ($\alpha_{95}$) = 4.5°. The Moenave pole position verifies the existence of the J-1 cusp, and thus supports the use of paleomagnetic Euler pole analysis in modeling the pattern of APW.**

## INTRODUCTION

Apparent polar wander (APW) paths provide important constraints for plate reconstructions, plate kinematics, and suspect terrane displacements. Interpretations can be diverse, however, depending on the method and selection criteria used to construct the APW path. Recent revisions of the North American Mesozoic APW path (Gordon et al., 1984; May and Butler, 1986) have provided greater detail in path geometry than in previous syntheses employing sliding-time-window averaging (Irving and Irving, 1982). Such details support the use of paleomagnetic Euler pole (PEP) analysis in modeling APW paths as small-circle tracks separated by cusps, or distinct changes in the direction of APW (Gordon et al., 1984; May and Butler, 1986). One of these cusps, J-1 of May and Butler (1986), occurs in the Late Triassic–Early Jurassic and is defined by paleomagnetic poles from the Chinle, Wingate, and Kayenta Formations. The J-1 cusp has been associated with changes in North American absolute plate motion during the breakup of Pangea. However, due to the paucity of well-determined paleomagnetic poles of this age interval, and the relatively large confidence limits associated with the available poles, details of the J-1 cusp are unclear.

The apex of the J-1 cusp is currently defined by the Wingate pole (Gordon et al., 1984, *from* Reeve, 1975) which is probably early Sinemurian in age (Peterson and Pipiringos, 1979). This paleomagnetic pole determination is problematical for several reasons. The Lukachukai Member of the Wingate sandstone is a fine- to coarse-grained eolian sandstone (Harshbarger et al., 1957) that has a complex magnetization history (Reeve, 1975). Severe data selection had to be applied in order to derive the set of "best" cleaned directions of magnetization for use in the pole determination. For these and other reasons, the Wingate pole has not been included in some APW path syntheses (Irving and Irving, 1982; Steiner, 1983a).

Paleomagnetic study of the Moenave Formation was undertaken to clarify details of the North American APW path in the Late Triassic–Early Jurassic. A thorough description of the stratigraphy and sedimentology of the Moenave Formation is in Wilson (1958). The Moenave Formation is composed of fine-grained, generally red to purple-red sandstones and siltstones that were deposited in a fluvial environment and are exposed in the Vermilion Cliffs of northern Arizona and southern Utah (Wilson, 1958) (Fig. 1). The Moenave Formation has been dated on the basis of occurrences of Early Jurassic palynomorphs in the Whitmore Point Member (Peterson et al., 1977; Peterson and Pipiringos, 1979). Recent palynomorphic studies in the Moenave and Chinle Formations support previous age assignments and were summarized by Litwin (1986). The Dinosaur Canyon Member is probably late (?) Hettangian to Sinemurian, and the Whitmore Point Member is Sinemurian to early Pliensbachian in age. On the time scale of Harland et al. (1982), absolute age limits for the Moenave would be approximately 200 to 210 Ma.

## PALEOMAGNETIC TECHNIQUES AND RESULTS

A total of 220 oriented cores (samples) were collected from 31 sites (individual beds of a few centimetres to about 1 m thick) in the Dinosaur Canyon and Whitmore Point Members of the Moenave Formation at four localities within the Vermilion Cliffs, where it is virtually flat-lying (Fig. 1). An average of 7 to 8 separately oriented cores per site were obtained from the finest-grained, least-permeable lithologies by using standard paleomagnetic coring techniques. Samples were oriented by using both magnetic and sun compasses. Initial natural remanent magnetization (NRM) intensities ranged from $10^{-2}$ to $10^{-3}$ A/m, and directions generally formed well-grouped clusters away from the present geomagnetic field direction at the sampling localities. Progressive thermal demagnetization experiments, in 14 steps between 200 and 700 °C, were performed on two pilot specimens from each site. Typical results are shown in Figure 2 (a and b). Minor secondary components of magnetization are generally removed by the 400 °C heating, followed by a very well defined linear decay of NRM directions toward the origin. Such stable demagnetization behavior suggests that a single-component, characteristic NRM was isolated in most of the samples. NRM was completely unblocked between temperatures of 640 and 680 °C, suggesting that hematite carries most of the NRM.

All remaining samples were subjected to progressive thermal demagnetization in eight steps to 680 °C by using the optimum temperature steps

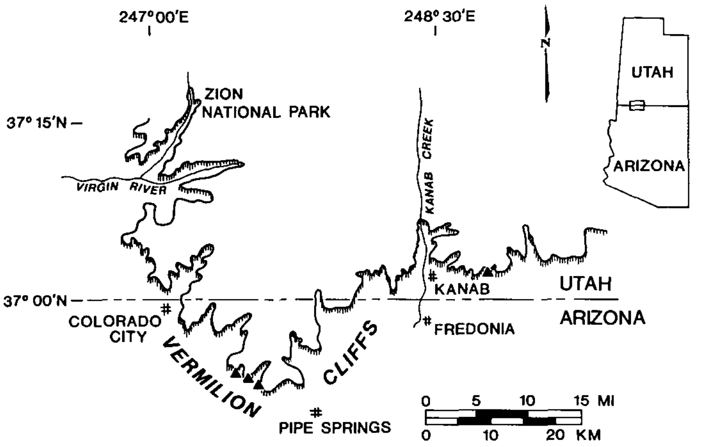


**Figure 1. Index map of Vermilion Cliffs region of northern Arizona and southern Utah. Triangles show four sampling locations (modified from Wilson, 1958).**

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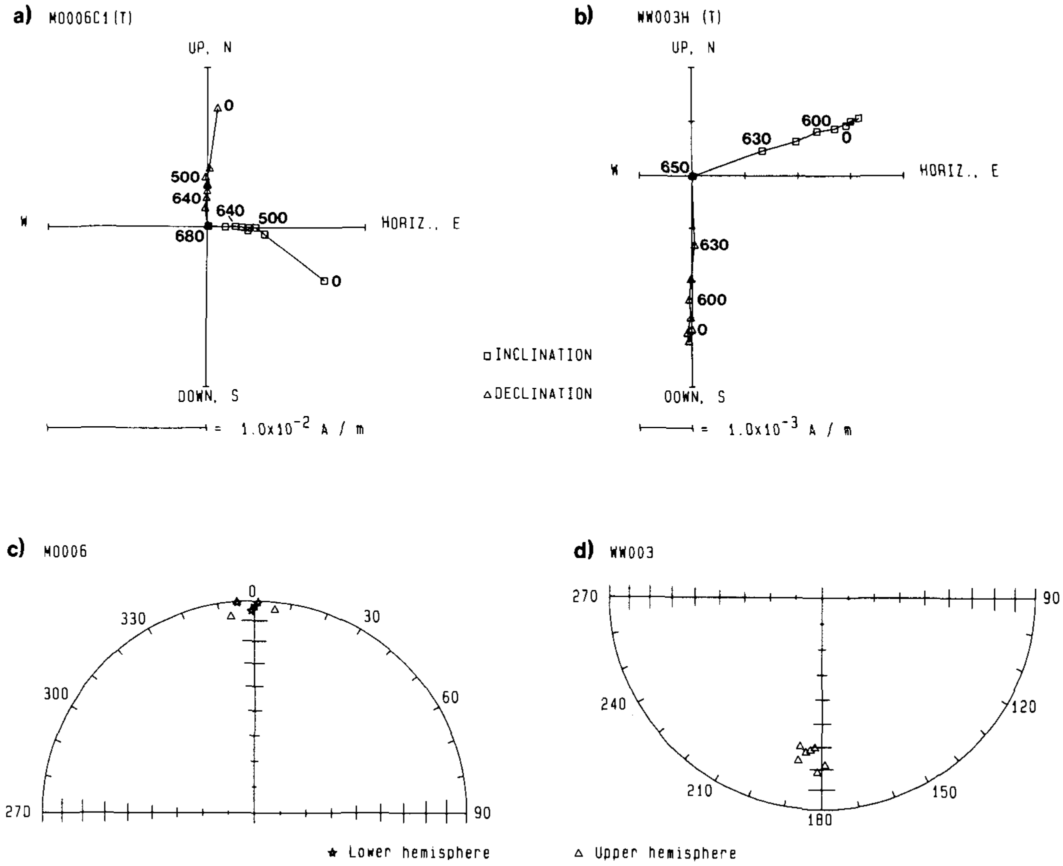


**Figure 2. Vector demagnetization diagrams (a, b) for two representative specimens, and equal-area projections (c, d) of within-site characteristic natural remanent magnetization directions from two paleomagnetic sites.**

based on pilot demagnetization results. Principal component analysis (Kirschvink, 1980) was applied to these demagnetization results between temperature steps of approximately 600 and 660 °C, including the origin as an equally weighted data point. (In some cases, lines were fit between approximately 550 and 630 °C when NRM was completely unblocked below 680 °C.) Characteristic NRM directions from two sites are illustrated in Figure 2 (c and d). Site mean directions and associated statistical parameters were calculated by using the method of Fisher (1953). Five sites were considered unreliable because of anomalous demagnetization behavior, yielding maximum angular-deviation angles from component analysis of >15°. Three other sites were also rejected on the basis of within-site $\alpha_{95}$ values that exceeded 15°. This selection procedure left 23 sites that we consider reliable recordings of the Early Jurassic geomagnetic field. The site mean data are presented in Table 1.

Polarities are dominantly normal; there were only four reversed polarity sites from the uppermost 2 m of the Whitmore Point Member. A reversals test (McFadden and Lowes, 1981) is passed at the 95% confidence level, suggesting that secondary components of magnetization have been effectively removed from the sample population. Chi-square tests (McFadden, 1980a) of both the radial and azimuthal distributions of the virtual geomagnetic poles (VGP) about the mean pole indicate that the distributions can be considered Fisherian.

Another important aspect of the VGP distribution is whether the dispersion of the site mean VGP indicates sufficient temporal averaging of geomagnetic secular variation. This was tested by comparing the calculated estimate, $k$, of Fisher's precision parameter for the between-site dispersion with that expected from a data set that has sufficiently averaged secular variation by using the chi-square tests of McFadden (1980b). The expected angular dispersion was calculated by using the 0–5 Ma geomagnetic field (McFadden and McElhinny, 1984). At the paleolatitude of the Moenave Formation sampling site, McFadden's test statistics, $k_l$ and $k_u$, are 27.0 and 45.0, respectively. The between-site VGP dispersion for the Moenave Formation yields $k$ = 45.3, with 95% confidence limits (Cox,

TABLE 1. MOENAVE FORMATION SITE MEAN PALEOMAGNETIC DATA

| Site | $N/N_o$ | Demag range | $N'$ | Dec (°) | Inc (°) | $\alpha_{95}$ (°) | $k$ | $R$ | $J$ ($10^{-3}$ A/m) |
|---|---|---|---|---|---|---|---|---|---|
| DW01 | 6/7 | 600-670 | 5 | 21.89 | 4.82 | 5.0 | 182.36 | 5.97 | 4.71 |
| DW02 | 6/7 | 600-660 | 4 | 16.99 | -3.37 | 11.6 | 34.44 | 5.85 | 2.24 |
| DW03 | 4/7 | 600-660 | 4 | 0.25 | 14.51 | 15.3 | 36.94 | 3.92 | 1.21 |
| MO01 | 5/5 | 600-650 | 4 | 355.04 | -2.47 | 8.8 | 77.30 | 4.95 | 4.87 |
| MO02 | 5/7 | 600-660 | 4 | 20.64 | 22.30 | 11.9 | 42.50 | 4.91 | 4.91 |
| MO03 | 4/6 | 600-660 | 5 | 4.19 | 25.24 | 8.1 | 129.48 | 3.98 | 2.49 |
| MO04 | 7/7 | 600-660 | 5 | 6.26 | 16.38 | 4.1 | 216.05 | 6.97 | 2.37 |
| MO06 | 7/7 | 600-660 | 5 | 358.53 | -0.33 | 4.6 | 174.78 | 6.97 | 2.47 |
| MO08 | 4/6 | 600-660 | 4 | 25.63 | 28.21 | 9.2 | 101.38 | 3.97 | 0.67 |
| MO09 | 6/6 | 600-650 | 4 | 355.60 | 0.29 | 6.6 | 104.42 | 5.95 | 2.67 |
| MO13 | 3/4 | 525-640 | 6 | 188.01 | -21.93 | 5.1 | 595.36 | 3.00 | 0.65 |
| MO14 | 5/5 | 550-630 | 4 | 183.94 | -20.43 | 2.2 | 1243.68 | 5.00 | 0.96 |
| MO15 | 6/6 | 600-660 | 4 | 354.23 | 3.24 | 10.7 | 39.89 | 5.87 | 5.72 |
| MO16 | 6/6 | 600-650 | 4 | 14.25 | -3.18 | 4.8 | 192.83 | 5.97 | 4.22 |
| MO17 | 6/6 | 600-660 | 4 | 13.38 | -4.97 | 8.2 | 67.35 | 5.93 | 3.34 |
| MO18 | 6/6 | 600-650 | 4 | 4.29 | 7.61 | 12.9 | 28.09 | 5.82 | 3.67 |
| MO19 | 6/6 | 600-650 | 4 | 9.46 | -3.41 | 5.0 | 179.91 | 5.97 | 3.89 |
| MO21 | 6/6 | 600-660 | 4 | 30.72 | 21.14 | 11.4 | 35.55 | 5.86 | 7.82 |
| MO22 | 6/6 | 600-660 | 4 | 7.06 | 7.72 | 10.1 | 45.00 | 5.89 | 4.55 |
| MO24 | 6/6 | 600-650 | 3 | 354.74 | 3.99 | 8.9 | 57.25 | 5.91 | 1.16 |
| MO25 | 6/6 | 550-650 | 4 | 8.26 | 39.41 | 12.5 | 29.46 | 5.83 | 2.56 |
| WW02 | 4/5 | 525-630 | 4 | 188.49 | -15.59 | 9.5 | 93.69 | 3.97 | 0.38 |
| WW03 | 7/7 | 550-630 | 4 | 184.25 | -25.68 | 4.0 | 223.33 | 6.97 | 1.67 |

Note: $N$, number of samples used to determine site mean direction; $N_o$, number of samples thermally demagnetized; Demag range, thermal demagnetization temperature range (in °C) over which principal component analysis was applied; $N'$, number of demagnetization steps within Demag range; Dec, site mean declination; Inc, site mean inclination; $\alpha_{95}$, radius of the cone of 95% confidence about the mean direction; $k$, estimate of Fisher precision parameter; $R$, length of resultant of $N$ unit vectors; $J$, average site mean intensity of magnetization at the low temperature limit of the thermal demagnetization range.

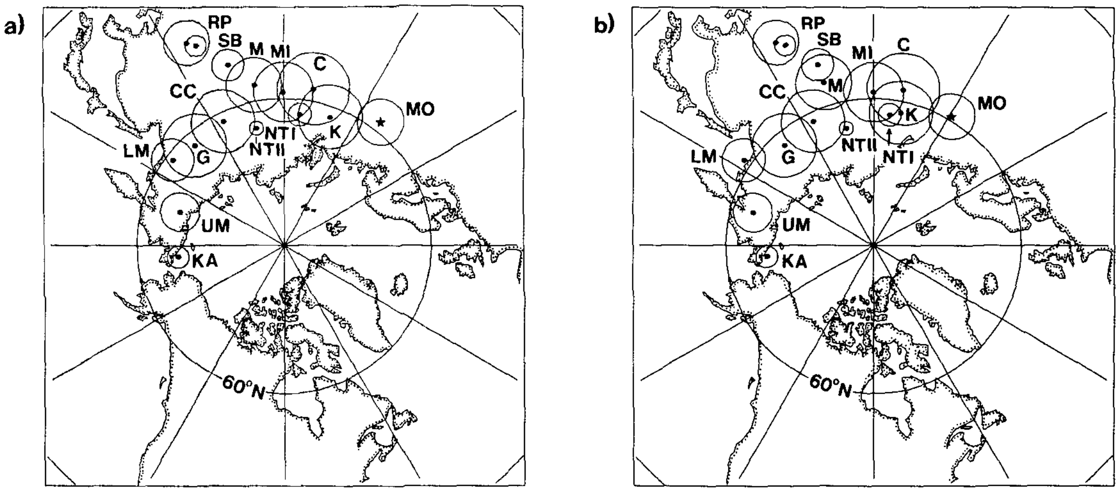


**Figure 3. a: Stereographic north polar projection of Triassic–Early Cretaceous North American apparent polar wander (APW) path of May and Butler (1986), including Moenave pole position (star, labeled MO). Symbols for Triassic poles: RP = Red Peak Formation of Chugwater Group (two poles; Shive et al., 1984; Herrero-Bervera and Helsley, 1983). SB = State Bridge Formation (Christensen, 1974, *from* Gordon et al., 1984). M = Moenkopi Formation (Helsley and Steiner, 1974, *from* May and Butler, 1986). MI = Manicouagan impact structure (Robertson, 1967; Larochelle and Currie, 1967). C = Chinle Formation (Reeve and Helsley, 1972). Symbols for Jurassic poles: K = Kayenta Formation (Steiner and Helsley, 1974, *from* May and Butler, 1986). NTI = Newark trend group I and NTII = Newark trend group II (Smith and Noltimier, 1979). CC = Corral Canyon (May et al., 1986). G = Glance Conglomerate (Kluth et al., 1982). LM = Lower Morrison Formation, UM = Upper Morrison Formation (Steiner and Helsley, 1975). KA corresponds to Cretaceous average pole of Mankinen (1978). Solid circles indicate pole positions, with associated $\alpha_{95}$ confidence areas. b: Mesozoic North American APW path, corrected for proposed 3.9° rotation of Colorado Plateau. Correction applied to poles M, MO, K, LM, and UM.**

1969) of 29.0 and 65.0. Therefore, the angular dispersion of the data set indicates adequate averaging of geomagnetic secular variation.

## DISCUSSION AND CONCLUSIONS

The use of red sediments in paleomagnetism (especially magnetostratigraphy) has been controversial with reference to the actual mode and timing of remanence acquisition (Larson et al., 1982; Steiner, 1983b). Liebes and Shive (1982) have examined the magnetization of soft-sediment deformational structures in the Moenkopi and Chugwater Formations and have concluded that the characteristic NRM was formed as a chemical remanent magnetization after deposition but prior to burial to a depth of about 1 m. In our sampling of the Moenave Formation, we did not encounter similar structures that would allow such field tests.

The comparison of between-site dispersion observed in the Moenave Formation with that expected for adequate averaging of geomagnetic secular variation provides evidence that the time lag between deposition and acquisition of the characteristic component of NRM is short in comparison with the time scales of secular variation. The observed between-site VGP dispersion is that predicted for a set of random spot-readings of the geomagnetic field. The clear implication is that the characteristic NRM within each site is acquired rapidly compared to the time scales of geomagnetic secular variation. These observations suggest that the characteristic NRM in the Moenave Formation was acquired within about 1 ka of deposition, as either a depositional or a chemical remanence.

The Moenave Formation pole position is located at 58.2°N, 51.9°E; $\alpha_{95}$ = 4.5° (Table 2) and is shown in Figure 3a with the Triassic–Early Cretaceous APW path of May and Butler (1986). This pole is at the end of the track of Triassic poles, which young toward westerly longitudes, and at the beginning of the track of Jurassic poles, which young toward easterly longitudes. Because of the extreme dispersion of directions observed and other problems mentioned above, the Wingate pole is not considered reliable and was not included in the revised APW path shown in Figure 3a.

Steiner (1986) and Bryan and Gordon (1986) have discussed possible relative rotation of the Colorado Plateau with reference to cratonic North America either during the Laramide orogeny or during extension of the Rio Grande rift. Steiner (1986) compared paleomagnetic poles from formations on the Colorado Plateau with poles from age-equivalent formations on the craton. This analysis led to the conclusion that the Colorado Plateau has rotated 11° clockwise with reference to the craton since Jurassic time. Unfortunately, age equivalence of the relevant formations is very difficult to establish, given that most of the formations are red beds with sparse fossil age control.

TABLE 2. MOENAVE FORMATION MEAN DIRECTION AND AVERAGE PALEOMAGNETIC POLE

| | Formation mean direction | | | | | Paleomagnetic pole | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *N* | Inc (°) | Dec (°) | *R* | *k* | $\alpha_{95}$ (°) | Lat (°N) | Long (°E) | *R* | *k* | $\alpha_{95}$ (°) |
| 23 | 11.5 | 7.9 | 22.19 | 26.07 | 6.0 | 58.2 | 51.9 | 22.51 | 45.26 | 4.5 |

Note: *N*, number of sites; Inc = formation mean inclination; Dec = formation mean declination; *R* = length of resultant of *N* unit vectors; *k* = estimate of Fisher precision parameter; $\alpha_{95}$, radius of cone of 95% confidence about mean direction or pole.

Bryan and Gordon (1986) analyzed available Carboniferous through Mesozoic paleomagnetic poles from on and off the Colorado Plateau by using a maximum likelihood estimate technique to determine the rotation of the set of Colorado Plateau poles that would minimize the space-time dispersion of the entire set of poles. This approach has the advantage of providing rigorously determinable estimates of the error limits in the rotation and is more robust in the sense that the results are less sensitive to errors in the age assignments of particular formations. Bryan and Gordon (1986) concluded that the Colorado Plateau had rotated clockwise by 3.9° with 95% confidence limits of 1.4° and 6.6°. We believe that their result provides the best current estimate of Colorado Plateau rotation. Accordingly, in Figure 3b we present the Mesozoic APW path for North America with the poles from the Colorado Plateau corrected for 3.9° of clockwise rotation.

The revised APW paths in Figure 3 clarify the details of the J-1 cusp in the Late Triassic–Early Jurassic. In the APW path of May and Butler (1986), the J-1 cusp was not well resolved because of the large confidence circles associated with the Late Triassic Chinle and Early Jurassic Wingate and Kayenta poles. However, on the basis of the statistical test of McFadden and Lowes (1981), the Moenave pole is distinguishable from the Chinle and Kayenta poles with 99% confidence, even after correction for Colorado Plateau rotation. Therefore, the geometry of the J-1 cusp is now more clearly defined. The best estimate of the age of the J-1 cusp is virtually the age of the Moenave Formation, or approximately 200 to 210 Ma. In this 10 m.y. time interval, the plate motion responsible for the Triassic arc of APW must have been replaced by a different system of plate motion responsible for the Early through Middle Jurassic arc of APW.

The position, age, and duration of the J-1 cusp also has major implications for North American paleogeography and the proposed motion history of Cordilleran suspect terranes. Because the Moenave pole verifies the low latitude and far western longitude of the Late Triassic–Early Jurassic part of the APW paths of Gordon et al. (1984) and May and Butler (1986), attendant predictions of more southerly North American paleolatitudes than suggested from previous APW compilations are supported. Although no specific interpretation of terrane displacements has been done based on the Moenave pole, verification of the J-1 cusp supports the conclusion that paleolatitudes of Upper Triassic and Lower Jurassic rocks of the Intermontane superterrane (Terrane 1) of the Canadian Cordillera are concordant with those of the North American craton (May and Butler, 1986).

By providing a better definition of the J-1 cusp in the North American APW path, the Moenave pole also lends considerable support to the use of paleomagnetic Euler pole analysis in modeling APW paths. With this clarification of the pattern of APW in the Late Triassic–Early Jurassic, the track and cusp geometry of Mesozoic APW suggested by Gordon et al. (1984) and May and Butler (1986) is more clearly established.

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*Reviewer's comment*

The result of this study is clearly significant; it will be an oft-cited paleomagnetic pole.

John W. Geissman