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New magnetostratigraphy and paleopole from the Whitmore Point Member of the Moenave Formation at Kanab, Utah

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Key words: Hettangian magnetostratigraphy, Moenave Formation, normal polarity, paleopole, J-1 cusp, North America apparent polar wander curve.

Abstract. The entire Whitmore Point Member of the Moenave Formation was sampled in close stratigraphic sequence (±0.3 m) from a vertical exposure in southwestern Utah. The polarity sequence in the Whitmore Point Member is essentially normal polarity, with five or more very short reversed intervals interspersed and a <1 m reversed interval at the top of the sequence. This polarity pattern dates the Whitmore Point Member as Hettangian. In the earliest Jurassic, the North American plate rotated even further westward from its Late Triassic position, and the movement appears to have been accompanied by an abrupt increase in plate motion because of the similarity in position of many Late Triassic paleopoles. The Moenave pole forms the 'J-1 cusp' of the North American apparent polar wander curve. The paleopole obtained by this study is somewhat further westward than those of previous studies. Within the 27 m of a mostly normal polarity sequence, the data show multiple, exceedingly short polarity intervals. The magnetization carrier is a maghemite-magnetite mineral, with the magnetization of an additional hematite carrier superposed. The lithostratigraphic sequence of the Moenave Formation is terminated by an unconformable surface, overlain by the Springdale Sandstone. Paleomagnetic directions of the Whitmore Point Member are exceedingly similar to those of the overlying Springdale Sandstone. Even though the two lithologic bodies are separated by a clear disconformity, the similarity in pole positions suggests that the two are closely related in time. It is possible that this disconformity represents the termination of the westward excursion of North America in earliest Jurassic time.

INTRODUCTION

The Whitmore Point Member of the Moenave Formation is part of the Glen Canyon Group of Triassic and Jurassic ages (Harshbarger *et al*., 1957; Lucas, Tanner, 2014). The Glen Canyon Group consists of a series of superposed formations: the rose-red to red brown Moenave Formation, of two members, the Dinosaur Canyon and superjacent Whitmore Point. The Springdale Sandstone, a sequence of rose-red to red brown thick sandstones and intervening mudstones, overlies the Moenave Formation, and in the past has been thought to be a member of the Moenave. Sequentially overlying the Springdale Sandstone is the red-brown Kayenta Formation. Higher, the thick Navajo Sandstone overlies and intertongues with the upper strata of the Kayenta Formation. The Navajo can be either red-brown or a bleached white color in this area.

A number of earlier studies have investigated the paleomagnetism of the Moenave Formation; Ekstrand and Butler (1989) first observed that the Moenave paleomagnetic data form a paleopole appreciably further westward relative to the paleopoles of the underlying Late Triassic Chinle Group. The Moenave directions represented the most eastward paleopole for North America in the early Mesozoic. When viewed in the context of other Mesozoic paleopoles, the apparent polar wander (APW) path for North America appeared to have a sharp bend (cusp) formed by the Moenave

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pole; that is to say that the apparent polar motion relative to North America during the Early Jurassic appears go east and then to reverse itself after Moenave time. This bend is known as the J-1 Cusp.

Molina-Garza *et al*. (2003) and Donohoo-Hurley *et al*. (2010) recollected the Moenave Formation and found directions similar to those of Ekstrand and Butler (1989). Sample collection for the present study of the Moenave Formation was carried out in 2001, prior to those of Molina Garza and Donahoo-Hurley. The study was conducted as part of a University of Wyoming Master's thesis, but never published. The objective of the study was to observe the 'J-1' cusp and the subsequent paleopole positions held in formations overlying the Moenave Formation. Hence, as part of the study, the Moenave Formation, the Springdale Sandstone, the main body of the Kayenta Formation, plus a stratigraphically higher "tongue" of the Kayenta Formation within the Navajo Formation, and a small portion of the Navajo Formation above the "tongue" all were sampled. Therefore, the Whitmore Point investigation is the stratigraphically lowest in a series of studies of the paleomagnetism of the Glen Canyon Group. Since some investigators do not believe the J-1 Cusp of the North American Apparent Polar Wander (APW) Curve reflects North American plate motion (*e.g*., Gordon, pers. comm., 2001), it would be instructive to determine what paleomagnetic pole positions are held in the sedimentary strata overlying the "J-1-cusp-bearing" Moenave Formation.

AGE

The Whitmore Point Member of the Moenave Formation comprises the deposits of a lake, consisting mainly of siltstone with periodic influxes of sand. It is not well dated. It contains palynomorphs, conchostracans (Lucas, Milner, 2006; Lucas *et al*., 2011), and vertebrate fossils (Lucas, Heckert, 2001). The most precise faunal age is provided by conchostracans, which suggest the base of the Jurassic is somewhere in the middle of the Whitmore Point Member (Lucas *et al*., 2011). However, only two/three conchostracan horizons establish this age determination. Comparison of the Whitmore Point magnetostratigraphy to the most recent timescale (Gradstein *et al*., 2012) reveals a very similar pattern in the Hettangian.

SAMPLING

The Whitmore Point Member was sampled on the northern edge of the Kanab (Utah) city limits (site 1 in Fig. 1). It was sampled from the cliffs that border the town's recreational area (37.0ºN, 247.5ºE). The sampled exposure is a sheer cliff face of more than 30 m height; Figure 2 shows about 4.2 m of the exposure. The sheerness of the exposure was expected to yield as fresh a magnetic signature as is possible from an outcrop section, that is, minimal secondary magnetizations overprinted upon the primary, than would be found in sloping topographic exposures. Secondary magnetizations from recent and Neogene geomagnetic fields were indeed minimal.

Sampling began one-half meter below the top of the Dinosaur Canyon Member of the Moenave Formation, and continued upward through the entire Whitmore Point Member to the contact with the massive sandstone forming the base of the overlying Springdale Sandstone at this locality. Approximately 26.8 m of Whitmore Pt. strata were sampled at an average spacing of 0.3 m.

All samples were obtained by coring with a hand-help gasoline-powered coring engine. Cores were oriented with a Brunton Compass attached to a core sleeve on the orientation device. One hundred and sixty eight samples were taken from the Whitmore Point (and uppermost half-meter of the Dinosaur Canyon Member). The stratigraphic sequence was measured in detail and sample numbers reflect their position in meters in the stratigraphic section relative to the base of the collection.

MAGNETIC CHARACTERISTICS

Subsequent to Ekstrand and Butler's (1989) study, Donohoo-Hurley *et al*. (2010) studied the Whitmore Point Member of the Moenave Formation. Donohoo-Hurley *et al*. (2010) found that hematite was the remanence carrier in the Whitmore Point Member. She performed numerous rock magnetic experiments, such as isothermal remanence determinations, 3-directional magnetization and demagnetization, hysteresis cycling, opaque petrographic examination, etc. All pointed to a hematite remanence carrier. However, the present study found that the primary remanence carrying element had unblocking temperatures of <580°C, strongly suggesting that the magnetization carrier is magnetite or its alteration product, maghemite. A sedimentary rock remanence in magnetite implies that the remanence of the Whitmore Point is a detrital remanent magnetization, *i.e*., a remanence acquired during deposition and dewatering of the sediment, because magnetite cannot form in the oxidizing conditions present on the Earth's surface; conditions for magnetite/maghemite formation are only met beneath the Earth's surface, in the igneous or metamorphic rock realms.

In addition to the magnetite-maghemite remanence, another magnetization, not uncommonly of the opposite polarity to the lower temperature magnetization, is held at higher unblocking temperatures, between 600° to 640°C. These re-

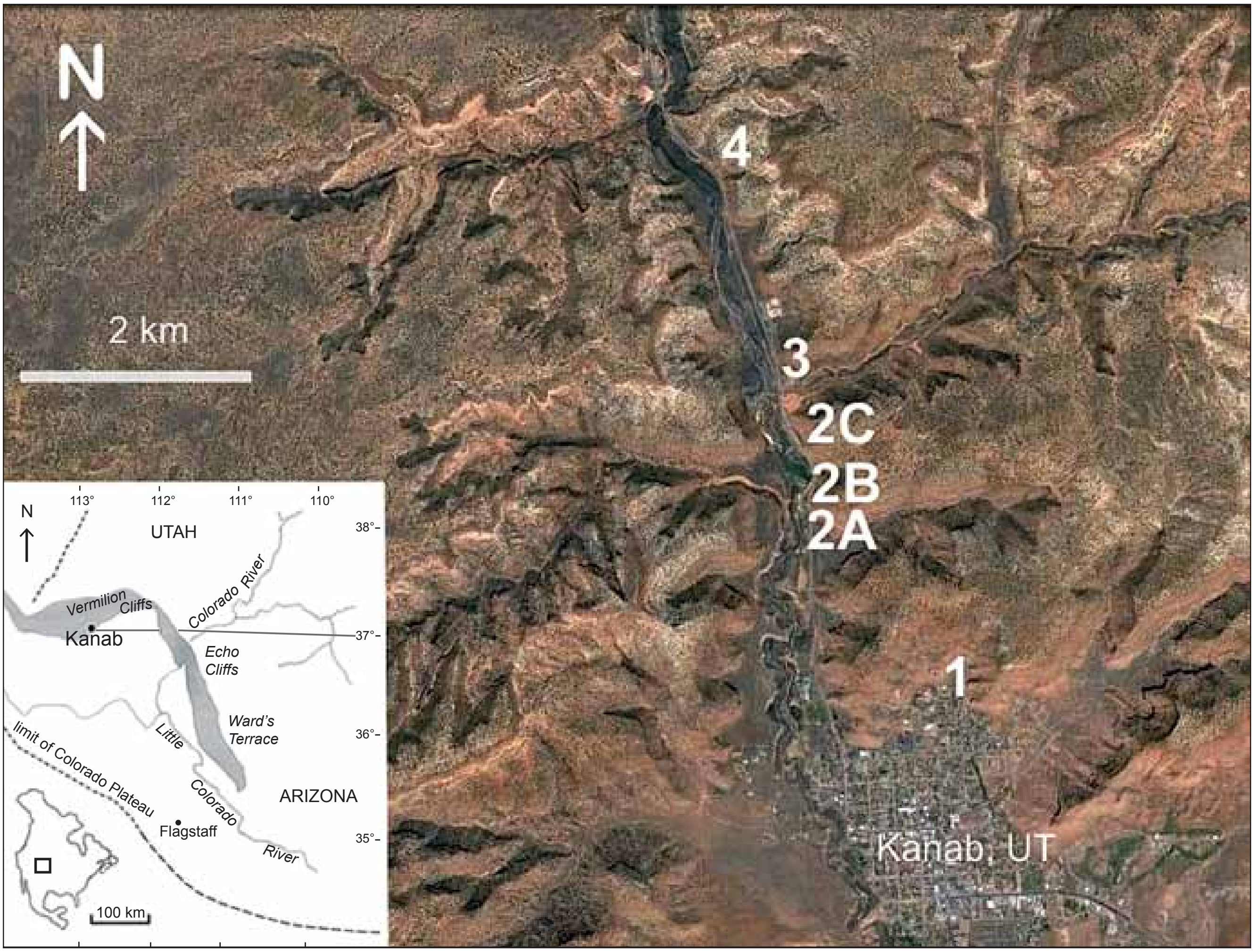

Fig. 1. Location map, showing the sampling sites near Kanab

1 – Whitmore Point. Other sites used in the series of studies of the Glen Canyon Group are: 2A, 2B, 2C – Springdale SS; 3 – Kayenta; 4 – Tenney Canyon Tongue of the Kayenta Formation. Grey shading on inset map is outcrop area of Moenave Formation

manence-carrying characteristics are common to both the Whitmore Point strata and the overlying Springdale Sandstone; that is, one remanence held below 580°C and another remanence, commonly of opposite polarity, between 600° and 640°C. Heating above 640°C destroys any remaining magnetization in the samples, and little or no original remanence remains.

In the present study, AF demagnetization up to 50 mT was performed on some of the Whitmore Point samples. The lower portion of the sampled section showed little response to AF demagnetization. The samples in the upper portion of the sequence showed small responses to AF treatment. At 17.4 m, of the 26.8 m section, an AF demagnetized sample showed slightly more directional change than the lower samples. Samples from 20 and 26 m exhibited notable directional change as compared to the lower samples, albeit still only small changes. The difference may reflect fresher mineralogy and less alteration in the uppermost portion of the cliff exposure.

Thermal demagnetization induced directional changes in all samples, as is common for red sedimentary rocks. It was successful in removing magnetic components of recent geomagnetic field directions, usually resulting in a well-defined normal polarity direction. The Whitmore Point samples exhibit linear decay of the remanence between 450° and 580°C. This unblocking temperature range was surprising because Donohoo-Hurley *et al*. (2010) found the hematite to be the principal remanence carrier. In the underlying Dinosaur

Fig. 2. Whitmore Point cliff exposure, showing about 4.2 m

Canyon Member, Molina-Garza *et al*. (2003) also found the principal carrier to be hematite. However, the main carrier in the Whitmore Point strata of this study is a mineral with unblocking temperatures below 580°C, therefore magnetite or maghemite. Again, this may signify that the sampling site for this study is a fresher exposure of these strata.

DATA

The natural remanent magnetization (NRM) of all samples is shown in Figure 3. Eighty-three independently oriented core samples were demagnetized using thermal demagnetization. The imprint of the present-day field and recent to Neogene fields was removed at low temperatures (200–250°C). At temperatures above 350–400°C, sample responses fell into a number of different categories.

First, 23% of the samples exhibited tightly clustered, normal polarity directions in response to thermal demagnetization between 450° and 580°C. Another 25% percent responded with normal polarity clusters of directions up through 580°C and then slight directional deviations from the cluster at temperatures above 580°C. An additional 26% showed normal polarity up to 580°C and displayed reversed polarity at higher temperatures by appreciable directional change towards, but not to, a reversed polarity direction. Fourteen percent display a reversed polarity direction at 630°C and generally return towards or to normal polarity. Those reversed components visible between 600° and 630°C (or occasionally 640°C) are antipodal to the lower temperature normal polarity component. Finally, 11% of the samples exhibited only a reversed polarity direction upon demagnetization to 580°C; above 580°C, these trend towards normal polarity and then back to reversed polarity.

In summary, a pervasive overprint of reversed polarity seems to be present in about 80% of the samples which exhibit normal polarity below ~580°C, and the samples that exhibit primary reversed polarity, display a normal polarity overprint at or above 600°C. The observation of high temperature reverse polarity above 580°C is observed from the lowest normal polarity sample (Dinosaur Canyon sample: –0.25 m) throughout most of the Whitmore Point sequence. This behavior is a classic case of the deposition of the mag-

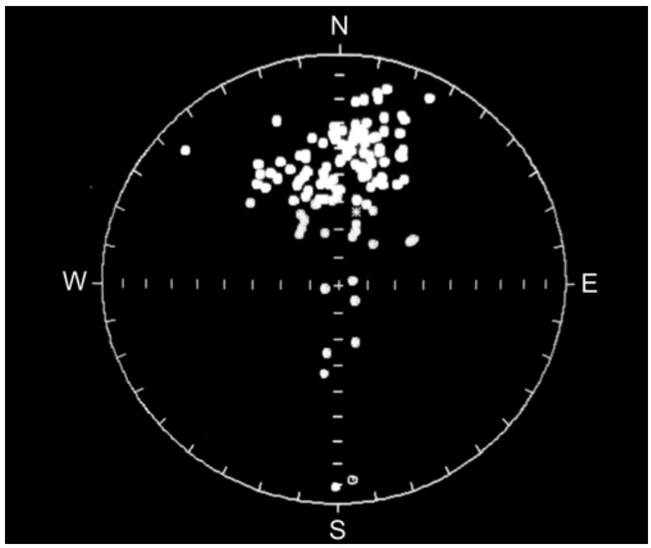

Fig. 3. Directions of natural remanent magnetization, equal-area projection

Open circles are upper hemisphere; solid circles are lower hemisphere. Asterisks indicate the present–day field and the axial dipole field (0°, 58°)

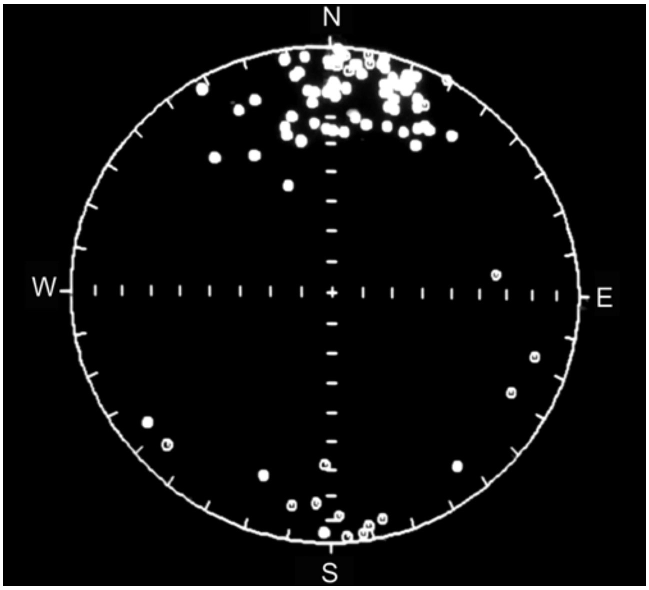

Fig. 4. All thermally demagnetized data from the Whitmore Point Member

netic minerals magnetite or maghemite, and alteration after deposition in a geomagnetic field of the opposite polarity. The alteration of the magnetite-maghemite mineral sequence to hematite records the magnetic field polarity during the time of alteration.

All sample measurements were analyzed by lines fit to the demagnetization paths generated by the successive thermal demagnetization heatings. Sample measurements were analyzed by the least squares method of Kirschvink (1980). Figure 4 shows all demagnetized directions of the Whitmore Point Member.

MAGNETOSTRATIGRAPHY

In summary of the above discussion, 89% of the Whitmore Point samples exhibited a normal polarity magnetization below 580–600°C, and 11% exhibited reversed polarity. The reversed polarity samples are largely in the upper half of the sequence, and the top meter of the Whitmore Point Member is entirely of reversed polarity. Samples from 26.1 through 26.8 m exhibited solely reversed polarity below 580ºC demagnetization.

The magnetostratigraphy recorded in the Whitmore Point is shown in Figure 5. Primarily, the Whitmore Point strata display normal geomagnetic field polarity. Some very short reversed intervals are present in the upper half, terminating in one meter of reversed polarity. This magnetostratigraphy strongly resembles that of strata of the Hettangian Stage in the Paris Basin (Yang *et al*., 1996). Figure 5 displays the Whitmore Point magnetostratigraphy adjacent to that of the Hettangian of the Paris Basin and the Ogg (2012) timescale. Although the match is imperfect, it indicates a period of dominantly normal polarity with brief interludes of reversed polarity. The fauna of the Paris Basin demonstrate a Hettangian age; therefore this comparison indicates that the Whitmore Point strata are Hettangian in age.

PALEOPOLE POSITIONS

The pole position from this study of the Whitmore Point lies at 55.7°E longitude and 60.4°N latitude. This pole was derived from 81 samples, only those that trended to the origin of orthogonal axes plots during demagnetization. Table 1 lists the associated statistics for this paleopole ("clean") along with the other Whitmore Point poles from the literature and poles of stratigraphically equivalent formations from the Colorado Plateau, such as the Wingate Sandstone (see Lucas, Tanner, 2014).

A second paleopole was calculated from the samples of this study that had the very least secondary magnetization, *i.e*., those samples that had the smallest errors on lines fit to the origin of orthogonal axes plots. This category involved about half of the samples from the previous calculation. This second calculation gave a more easterly paleopole: 47.9°E, 58.3º N ("cleanest", Table 1). The difference in the "cleanest" and the "clean" data of this study is probably a difference in the degree of outcrop weathering.

Although confidence limits of all three poles overlap, thus indicating that all three poles are statistically identical, both Whitmore Point poles of this study are slightly farther east than Ekstrand and Butler's (1989) Moenave paleopole (Table 1, Fig. 6). The two Whitmore Point poles of this study are younger than the Moenave pole of Ekstrand and Butler, because this study is only of the Whitmore Point Member, whereas Ekstrand and Butler's pole mixed sites in the Dinosaur Canyon Member and the Whitmore Point Member. Absent the confidence limits, Ekstrand and Butler's pole and the "clean" and "cleanest" poles of this study form a small progression to the east (Fig. 6A), possibly suggesting that the more easterly pole of this study (~48°E) may be the best representation of the true pole for Whitmore Point time and for the J-1 Cusp.

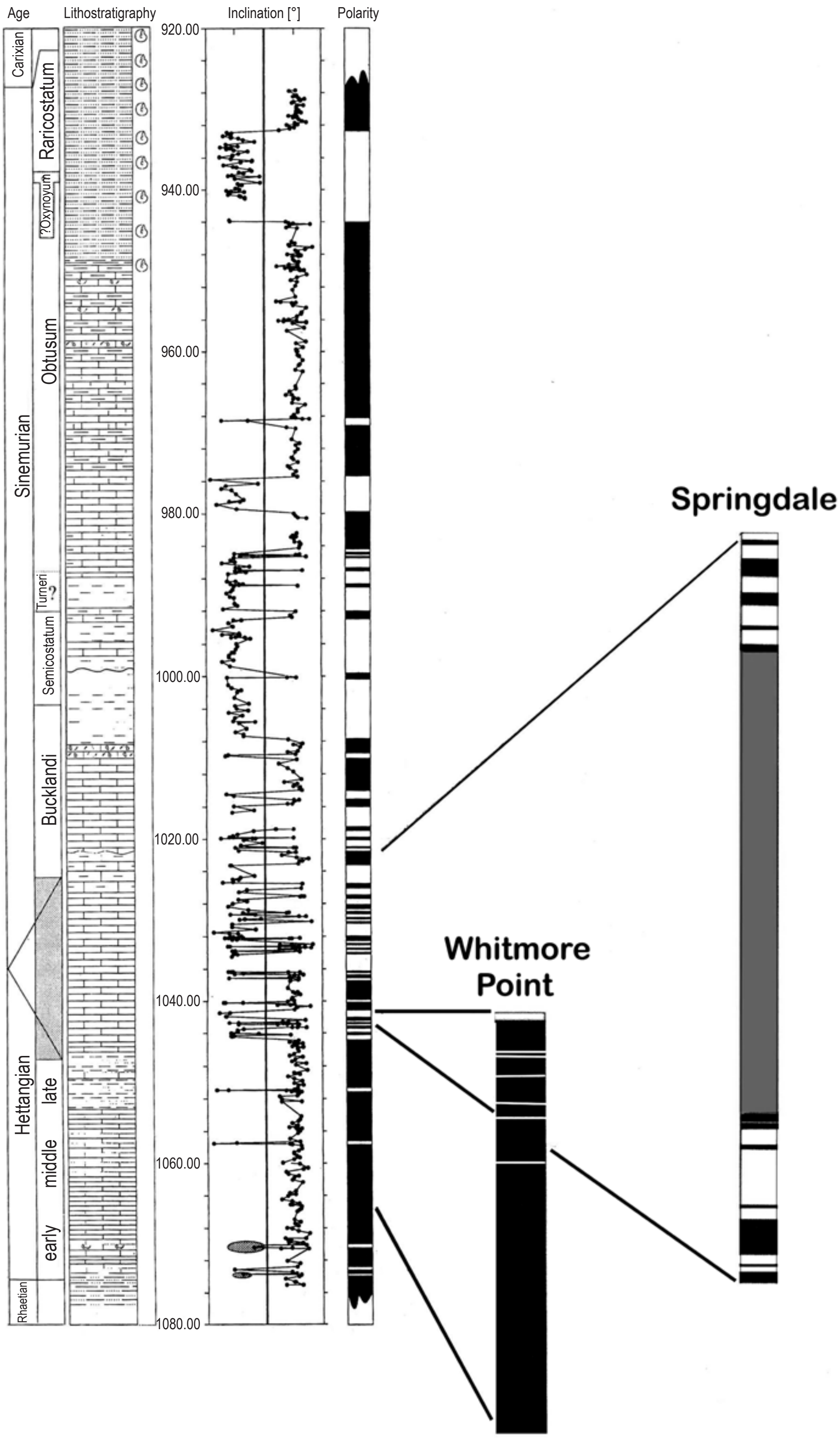

Fig. 5. Comparison between the paleomagnetic polarity from the Hettangian and Sinemurian of the Paris Basin (after Young *et al.*, 1996) and the Whitmore Point and Springdale magnetostratigraphy

Lithology and stratigraphy after Young *et al.* (1996) and earlier papers cited therein. Black is normal polarity; white is reversed polarity. Gray in polarity column indicates unsampled strata; gray in age column indicates unknown age

Table 1

Paleomagnetic mean directions for the Whitmore Point and equivalent strata

Study	Formation	N Lat	E Long	α_{95}	N
THIS STUDY all "clean" samples	Whitmore Pt	60.4	55.7	3.1	81s
THIS STUDY "cleanest" samples	Whitmore Pt	58.3	47.9	3.6	44s
Ekstrand and Butler	Moenave (D&W)	58.2	51.9	4.5	23S
Molina-Garza *et al*., 2003	Moenave (D)	63.7	59.7	5.8	28S
Molina-Garza *et al*., 2003	Wingate	57.4	56.6	6.4	17S
Kent and Witte	Church Rock	57.5	67.0	10.7	9S
Reeve	Church Rock	59.0	63.0	2.5	28s

"clean" means that most or all secondary magnetization was removed; "cleanest" means that all secondary magnetization was removed; D&W – Dinosaur Canyon and Whitmore Point Members of the Moenave Formation; S – number sites; s – number samples

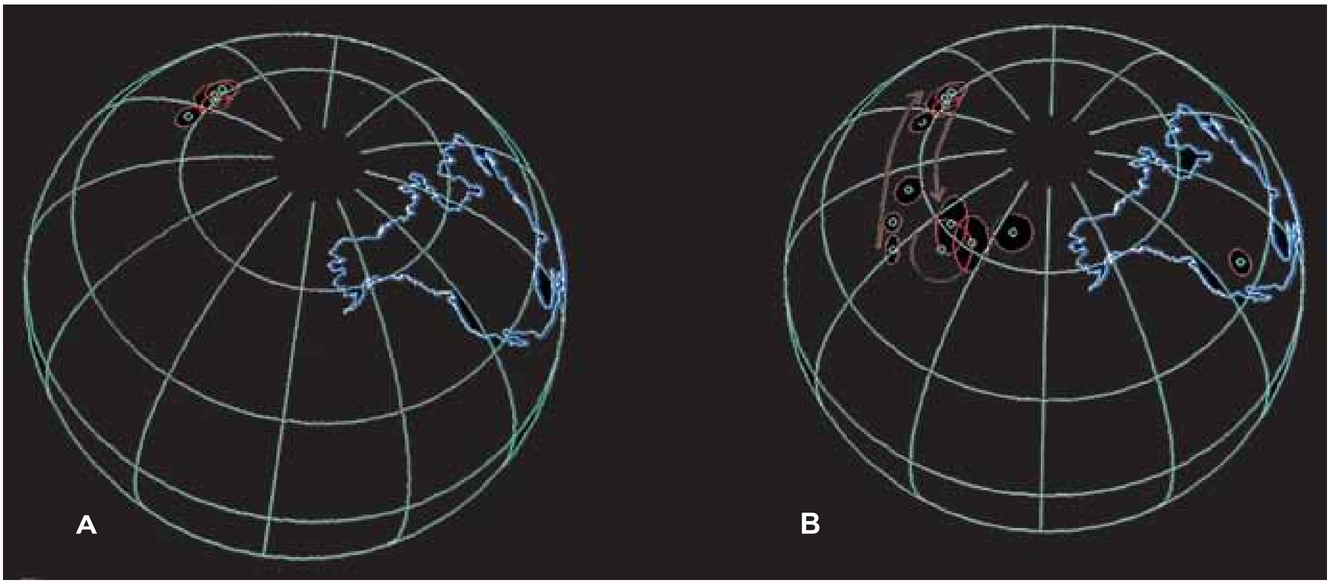

Fig. 6. Whitmore Point paleopoles and Mesozoic APW

A – Two determinations (all samples and selected samples) of the paleopoles from this study of the Whitmore Point Member and the paleopole of Ekstrand and Butler (1989). The mean Late Triassic Chinle pole (the most westerly pole) of Steiner and Lucas (2000) also is shown for a point of reference. **B** – Mesozoic North American apparent polar wander curve for the Colorado Plateau with the three J-1 cusp poles

DISCUSSION AND CONCLUSIONS

AGE IMPLICATIONS

The Whitmore Point exhibits almost entirely normal polarity, with a few very short (commonly one sample) reversed polarity intervals. This magnetostratigraphy is extremely similar to that of the fossiliferous Hettangian strata of the Paris Basin (Yang *et al*., 1996), shown in Figure 5. The Whitmore Point magnetostratigraphy also resembles and that of the Liassic of Hounslow *et al*. (2004), as well as that of two of the Whitmore Point localities of Donohoo-Hurley *et al*. (2010). Figure 5 also shows the latest the geologic time scale for the Rhaetian (Ogg, 2012, p. 716) and the Hettangian and Sinemurian (Ogg, Hinnov, 2012, p. 766).

The Rhaetian magnetostratigraphy is shown to be alternating normal polarity and reversed polarity intervals, with polarity intervals of appreciable length, ending with a normal polarity interval at the top (Fig. 5). As this figure demonstrates, the Whitmore Point could only be latest Rhaetian at best, because nearly all reversed polarity intervals in the Whitmore Point (this study and Donohoo-Hurley *et al*., 2010) consist of single samples. Samples from this study of the generally were separated by 15–20 cm. The only lengthy (multi-sample) reversed polarity interval in the Whitmore Point was the one at the top.

The comparison of the Whitmore Point magnetostratigraphy to the fossiliferous Paris Basin strata and Ogg and Hinov's (2012, p. 766) Hettangian magnetostratigraphic compilation is striking in its similarity. This comparison yields a very good match to the magnetostratigraphy displayed by the Whitmore Point Member. The Whitmore Point magnetostratigraphy does not match the Rhaetian (Ogg, 2012, p. 716) except the uppermost Rhaetian normal polarity interval.

The Whitmore point polarity signature also does not match the Sinemurian which has frequent polarity changes in the lowest part (Yang *et al*., 1996) and large amounts of reversed polarity following. The Sinemurian as a whole is shown to be multiple polarity changes, clearly not the polarity pattern held by the Whitmore Point Member, but the type of polarity pattern found in the overlying Springdale Sandstone (see companion paper, Steiner, this volume).

The latest geologic time scale leads to no other conclusion than that the Whitmore Point is Hettangian in age. The Whitmore Point may be either Hettangian in its entirety or it may be Middle–Late Hettangian. The one-meter reversed interval at the top of the Whitmore Point conceivably could correspond to the first reversed interval of the Sinemurian (Fig. 5).

TECTONICS

The paleopoles calculated in this study of the Whitmore Point Member are statistically the same as that of Ekstrand and Butler (1989), but very slightly farther east. The pole from the samples of this study with the least secondary magnetization remaining after demagnetization is slightly more easterly than the complete data set, even though none of these poles are statistically distinguishable at the 95% confidence limit.

The Dinosaur Canyon Member (Ekstrand, Butler, 1989; Donohoo-Hurley *et al*., 2010) and the Whitmore Point Member (Ekstrand, Butler, 1989; Donohoo-Hurley *et al*., 2010; this study) display the J-1 Cusp paleopole of the North American APW path. Therefore, the age of the J-1 Cusp appears to be Hettangian (and Sinemurian: see accompanying paper on the Kayenta Formation by Steiner, 2014 – this volume). It probably does not extend into the Rhaetian, as it was not observed in the Newark Supergroup (Witte *et al*., 1991).

The easterly longitude poles from this study of the Whitmore Point and of the Moenave Formation by Ekstrand and Butler (1989) and Donohoo-Hurley *et al*. (2010) indicate a relatively eastward motion of the North American paleopole during Hettangian time. This may either represent a westward motion of the NA continent, or true polar wander. However, the J-1 Cusp pole forms a continuation of the arc of polar motion defined by the Pennsylvanian, Permian, and Triassic poles. Moreover, the NA apparent polar wander path (APW), including the J-1 Cusp, closely resembles the arcuate APW modeled by Gordon *et al.* (1984), suggesting that the cusp is part of the plate motion trace for North America.

The timing of this apparent polar motion approximately coincides with the extrusion of the CAMP Large Igneous Province in eastern North America. North America is the outermost plate of Pangea in the northern hemisphere. The copious CAMP intrusion/extrusion seemingly must have caused some plate motion of North America away from Pangea. Alternatively the entire Pangea supercontinent might have moved westward and then eastward to cause the J-1 Cusp trace, but there is no evidence of this in the APW paths of other continents.

The apparent polar motion of the J-1 Cusp could have been either True Polar Wander or plate motion. Even though sea floor spreading had not yet begun, the plate boundaries are the sites of the extrusion and intrusion of the very large volumes of CAMP magma. The occurrence of CAMP and the J-1 Cusp in the same time interval suggests a cause and effect, and that some motion of the outermost plate (North America) may have occurred to accommodate the voluminous material emplaced.

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