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Paleomagnetism of the Brushy Basin Member of the Morrison Formation: Implications for Jurassic apparent polar wander

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Abstract. The paleomagnetism of the ~147 Ma (Tithonian) Brushy Basin Member of the Morrison Formation was analyzed to obtain a Late Jurassic paleomagnetic pole for North America. A total of 200 samples were collected from 25 sedimentary horizons (sites) at Norwood Hill in southwest Colorado. At Montezuma Creek in southeast Utah, 184 samples were collected from 26 sites. Detailed thermal demagnetization (up to nine temperature steps between 600°C and 680°C) and principal component analysis were required to confidently isolate characteristic remanent magnetization (ChRM) directions carried by hematite. Demagnetization behavior for many horizons is erratic and does not allow isolation of a high unblocking-temperature ChRM. Data selection criteria required sample ChRM directions to be defined by three or more thermal demagnetization steps and maximum angular deviations of sample ChRM directions to be ≤20°. Eight sites from the Norwood Hill location and 10 sites from the Montezuma Creek location passed these criteria. The 18 site-mean virtual geomagnetic poles yield a paleomagnetic pole position from the Brushy Basin Member of 68.3°N, 156.2°E ($A_{95} = 4.8°$, $K = 53$). This pole position is within 2° of the paleomagnetic pole which Steiner and Helsley (1975a) reported for the "upper" Morrison Formation at Norwood Hill, Colorado. A second paleomagnetic pole was calculated after excluding sites with site-mean $\alpha_{95} > 20°$ and sites with fewer than three samples that passed the above selection criteria. This additional editing did not significantly change the paleomagnetic pole position at the 95% confidence level. Along with other paleomagnetic poles from the continental interior the paleomagnetic data from the Brushy Basin Member of the Morrison Formation are interpreted to indicate that the Late Jurassic part of the North American apparent polar wander path progresses from a late Middle Jurassic (~160 Ma) position at ~60°N, 135°E toward the mid-Cretaceous pole position at 72°N, 191°E.

Introduction

Separate paleomagnetic poles calculated from the lower and upper parts of the Morrison Formation [*Steiner and Helsley*, 1975a] have been used to define the latest Jurassic apparent polar wander (APW) path for North America. These poles imply rapid APW during the latest Jurassic and provide the only link between older Jurassic (>151 Ma) and younger Cretaceous (<126 Ma) paleomagnetic poles. Consequently, the analysis of Morrison Formation paleomagnetism by *Steiner and Helsley* [1975a] has significantly influenced analyses of North American APW, including time-window averaging [e.g., *Irving and Irving*, 1982], paleomagnetic Euler pole (PEP) analyses [*Gordon et al.*, 1984; *May and Butler*, 1986], and interpretations of rapid northward motion of North America in the Late Jurassic [*May et al.*, 1989]. The samples for the initial study were collected from a single locality (Norwood Hill, Colorado), relatively few samples were collected from individual strata (generally less than two), and the magnetization of many samples was complex. Recently, *Van Fossen and Kent* [1992a] have suggested that steep inclination data may have been preferentially rejected from calculation of the Morrison paleomagnetic poles, causing the poles to be biased toward lower latitudes. Furthermore, *Van Fossen and Kent* [1993] have interpreted data from 143 Ma kimberlite dikes in central New York State to indicate an earliest Cretaceous (Berriasian?) paleopole ~23° east of the latest Jurassic (Tithonian?) upper Morrison paleopole of *Steiner and Helsley* [1975a].

To evaluate these concerns we have reexamined the magnetization of the Morrison Formation at Norwood Hill, Colorado (both the Brushy Basin and Salt Wash members), as well as at a new location near Montezuma Creek, Utah (Figures 1a and 1b, respectively). We collected multiple samples within each of several stratigraphic layers and analyzed specimens using thorough thermal demagnetization and principal component analysis. This procedure allowed identification of complexly magnetized strata and provided objective criteria for excluding strata which are unsuitable for paleomagnetic pole determination. In addition, we have considered recent studies of

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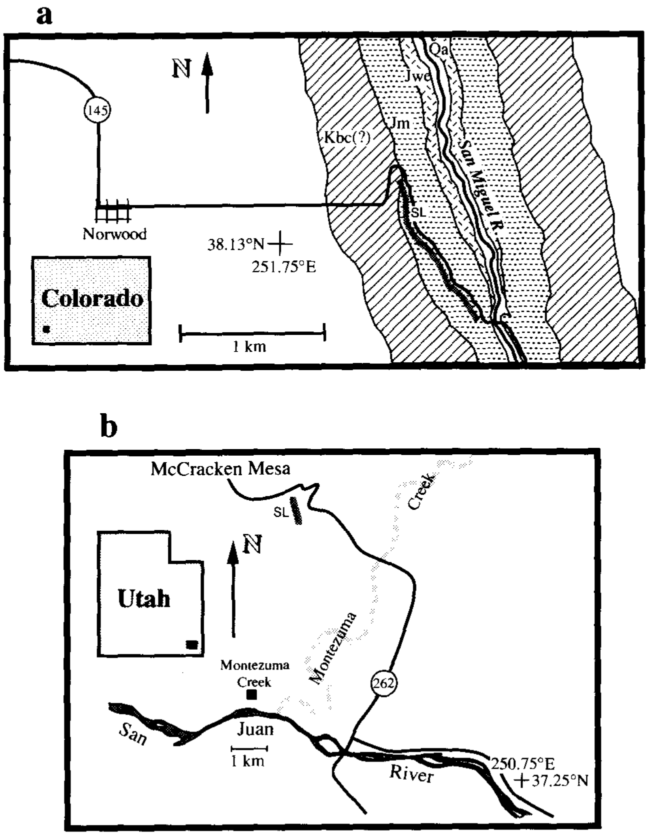

Figure 1. Maps showing sampling locations. (a) Norwood Hill, Colorado, location (38.13°N, 251.78°E). Sites MR001-MR030 were sampled within the dotted area labeled SL, sampling location. Abbreviations are Jwe, Jurassic Wanakah and Entrada Formations; Jm, Jurassic Morrison Formation; Kbc, Cretaceous Burro Canyon Formation; and Qa, Quaternary Alluvium. (b) Montezuma Creek, Utah (Navajo Nation), location (37.33°N, 250.67°E). Sites MR040-MR065 were sampled within the dotted area labeled SL, sampling location.

Morrison Formation stratigraphy, authigenesis, and age in our interpretation.

Our more recent analysis improves the reliability of the Morrison Formation paleomagnetic pole. Nonetheless, a fundamental conclusion is that the pole position we calculate from the Tithonian Brushy Basin Member of the Morrison Formation is indistinguishable from the paleomagnetic pole determined from the upper part of the Morrison Formation by *Steiner and Helsley* [1975a]. However, we found the lower member of the Morrison Formation at Norwood Hill (Salt Wash Member) to be complexly magnetized and impossible to interpret. Therefore we were not able to duplicate results from the lower Morrison paleomagnetic study of *Steiner and Helsley* [1975a].

Geology

The Morrison Formation at both the Norwood Hill and Montezuma Creek localities is composed of flat lying sandstone, tuff, and mudstone. The Morrison Formation unconformably overlies the San Rafael Group and is unconformably(?) overlain by the lower Cretaceous Burro Canyon Formation (Figure 2).

At the Norwood Hill locality the Brushy Basin Member has been subdivided into a lower part composed of interbedded sandstone and mudstone and an upper part composed of tuff and mudstone [*Turner and Fishman*, 1991]. The lower part of the Brushy Basin Member is equivalent to the Recapture Member of the Morrison Formation. It lies conformably above fluvial sandstones of the Salt Wash Member at the Norwood Hill location. At the Montezuma Creek location the entire Brushy Basin Member is equivalent to the upper part of the Brushy Basin Member at Norwood Hill (Figures 2 and 3), and it rests conformably above fluvial sandstone of the Westwater Canyon Member of the Morrison Formation.

The age of the Morrison Formation in this region has been determined by recent isotopic dating. *Kowallis et al.* [1991] obtained five single-crystal, laser fusion $^{40}Ar/^{39}Ar$ dates from plagioclases within tuff beds of the Brushy Basin Member at the Montezuma Creek location. These dates range from 145 ± 1.2 Ma to 149 ± 0.7 Ma; thus the Brushy Basin Member is Tithonian and/or earliest Berriasian in age according to the timescale of *Harland et al.* [1990].

In a recent analysis of the Morrison Formation of southeastern Utah, southwestern Colorado, and northwestern New Mexico, *Turner and Fishman* [1991] interpreted the tuffs of the upper portion of the Brushy Basin Member as volcanic ash deposits from a source located to the southwest. This ash is thought to have been deposited in a large alkaline, saline lake (Lake T'oo'dichi') where the shallow water environment and frequent evaporation to dryness produced a hydrogeochemical gradient which resulted in a basinward progression of diagenetic mineral zones. The Norwood Hill location is in the interior zone characterized by authigenic albite; the Montezuma Creek location is in the intermediate to outer zone characterized by the zeolite clinoptilolite. The albitic zone of the Norwood Hill location consists of both well-indurated albitic tuffs and less indurated red, brown, and green mudstones. The clinoptilolite zone of Montezuma Creek includes orange-pink tuffs, brown mudstones, and light-colored sandstones. The orange-pink color is due to the presence of finely crystalline hematite which occurs along crystallographic planes of clinoptilolite [*Bell*, 1983; *Turner and Fishman*, 1991]. Of importance in the interpretation of our paleomagnetic data is *Turner and Fishman's* [1991] argument that these authigenic minerals formed within 500,000 years after deposition in the alkaline,

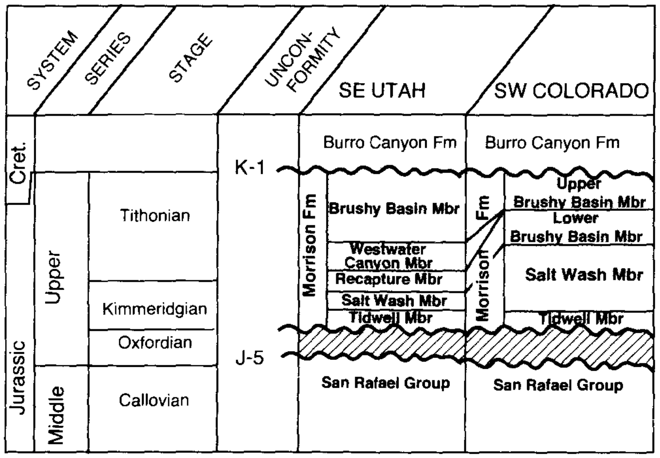

Figure 2. Regional Middle and Late Jurassic stratigraphy of southeastern Utah and southwestern Colorado (modified from *Baars et al.* [1988] and *Turner and Fishman* [1991]).

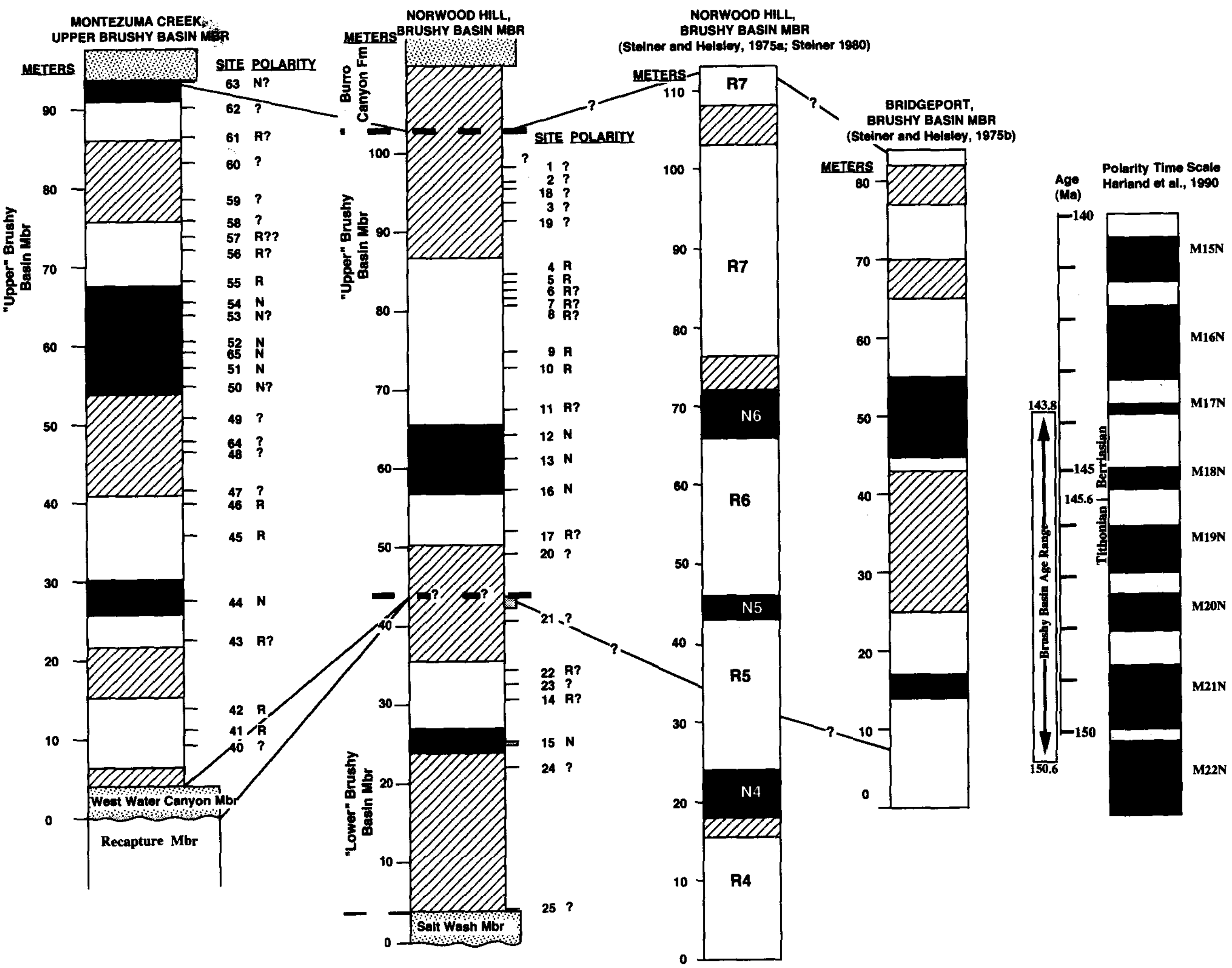

Figure 3. Relative stratigraphic positions of sites and interpretations of the magnetic polarity of their characteristic remanent magnetization (ChRM). Each number corresponds to a paleomagnetic site. Interpretation of the polarity of each site is shown by either an N (normal polarity) or R (reverse polarity) next to the site numbers and by the black (normal) and white (reverse) regions of the polarity columns. The diagonal lines represent sections where the polarity is unknown. Question marks adjacent to site numbers indicate sites rejected from pole calculations (see text). Sites with a polarity designation and a question mark are sites that were rejected from pole calculation, but the polarity of the ChRM from these sites was evident. An additional Norwood Hill, Colorado, polarity column [*Steiner and Helsley*, 1975a; *Steiner*, 1980] and a Bridgeport, Colorado, polarity column [*Steiner and Helsley*, 1975b] are shown for comparison with the polarity columns from this study. Also shown is the polarity timescale of *Harland et al.* [1990] and the age range of the Brushy Basin [from *Kowallis et al.*, 1991].

saline lake. Support for early diagenesis includes tuff rip-up clasts incorporated into overlying sandstone as well as the uncompacted nature of delicate shard textures in the tuff, which suggest cementation by authigenic minerals prior to compaction.

Sampling and Analysis

We collected 5 to 10 samples from 34 stratigraphic layers (sites) at the Norwood Hill locality. The stratigraphic distributions of these and other sites are shown in Figure 3. Nine sites are either pale red sandstone or red mudstone of the Salt Wash Member (not shown in Figure 3), eight sites are either red or green mudstone or pale red sandstone of the lower portion of the Brushy Basin Member, and 17 sites are either red, green, or brown albitic tuff or red mudstone of the upper portion of the Brushy Basin Member.

All samples collected at Norwood Hill are cores oriented in place using both a magnetic and sun compass. We also collected samples from 26 sites in the Brushy Basin Member at the Montezuma Creek locality (with the written permission of the Navajo Nation). These sites include red-orange, pink, chocolate brown, and gray-green tuff and mudstone. These samples are block samples oriented in place using a magnetic compass and spirit level and later cut into cubic specimens.

All samples were stored in a magnetically shielded room for the duration of analysis. Measurements were made using a two-axis cryogenic magnetometer and demagnetized using one of two vertical furnaces equipped with 8 to 10 thermocouples and magnetic shielding. The furnace design allows samples to be

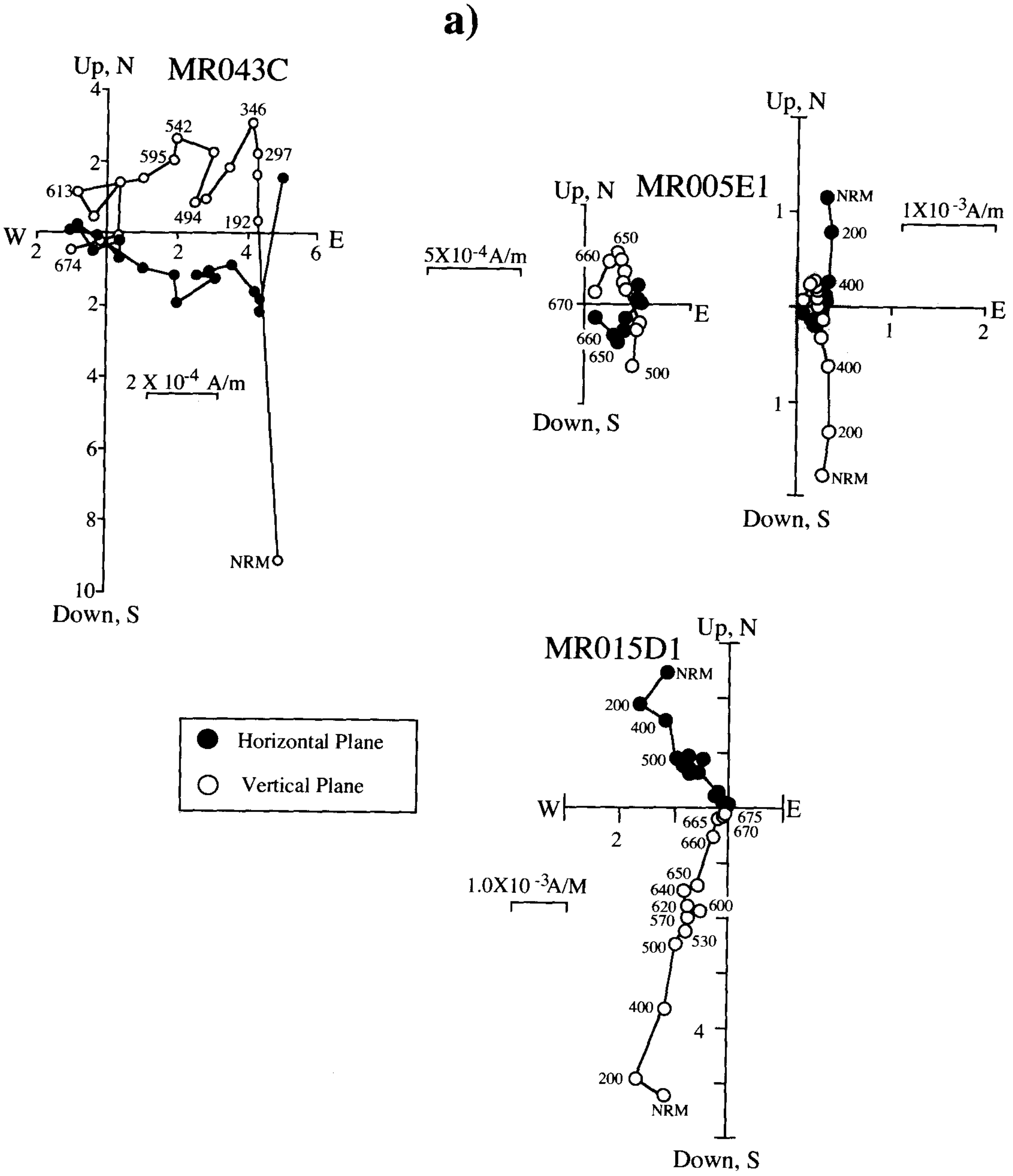

Figure 4. Vector endpoint diagrams for individual Brushy Basin Member specimens (a) MR043C, MR005E1, and MR015D1 and (b) MR051A, MR005A1, and MR045F showing representative thermal demagnetization behavior. Specimens MR005 and MR015 are from Norwood Hill; specimens MR043, MR045, and MR051 are from Montezuma Creek. Numbers next to data points of the vector endpoint diagrams indicate thermal demagnetization temperatures in °C. Open circles represent the projection of the vector into the vertical plane, and the closed circles represent projection of the vector into the horizontal plane.

demagnetized in steps as small as 5°C and cooled in a field of <10 nT.

Pilot specimens were measured to determine the optimal thermal demagnetization steps required to reveal a characteristic component for each site. The natural remanent magnetization (NRM) of samples from many sites was found to consist principally of a steep, north-seeking, positive-inclination magnetization. In many cases, the demagnetization behavior was erratic. Specimen MR043C (Figure 4a) shows an example of this erratic behavior. In this case a high unblocking-temperature component could not be confidently isolated. Specimen MR005E1 (Figure 4a) shows an example for which detailed thermal demagnetization was required to isolate a high unblocking-temperature, characteristic remanent magnetization (ChRM). The ChRM is not revealed until the specimen has been demagnetized to >650°C. Because of this overprinting, specimens were typically demagnetized at 12–18 steps with a minimum of 5 steps between 600°C and 680°C.

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NRMs of Brushy Basin Member samples range in intensity from 2×10^{-2} A/m to 6×10^{-5} A/m. The well-indurated albitic tuffs of the Norwood Hill location were weakly magnetized; the orange-pink and chocolate brown mudstones of the Montezuma

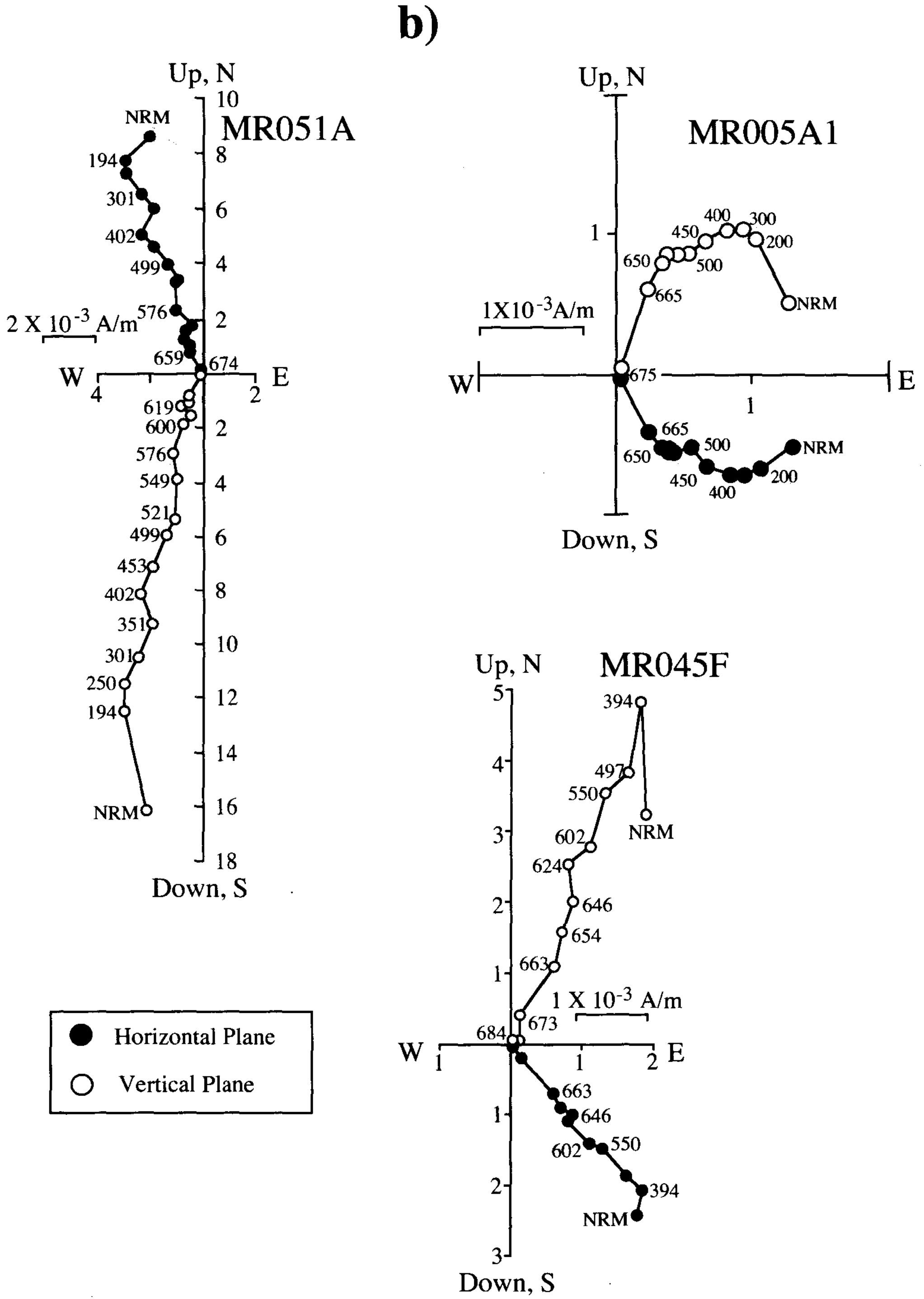

Figure 4. (continued)

Creek location had the strongest magnetizations. Most NRMs were inclined down to the northeast, north, or northwest, but a few were southeast directed and/or inclined upward (Figure 4).

A north and down-directed magnetization was removed during thermal demagnetization. This component was unblocked by 400°C in some samples (e.g., MR043C in Figure 4a) but persisted as a coherent component of magnetization up to 650°C in other samples (e.g., MR005E1 in Figure 4a). In no instance was a steep, negatively inclined magnetization (antipodal to the former direction) observed as an intermediate component. Furthermore, this intermediate component is indistinguishable from intermediate components unblocked at lower temperatures in other samples (e.g., MR043C and MR045F in Figures 4a and 4b, respectively). Thus we interpret the above described north and down component as a normal polarity, late Cenozoic (most likely present geomagnetic field) magnetization. Progressive thermal demagnetization of specimens revealed several sites with weak or erratic magnetizations. Because we could not confidently isolate a ChRM, we regard these sites as unsuitable for virtual geomagnetic pole calculations. Rejected sites fall into three general categories. The first category includes six weakly magnetized ($<4 \times 10^{-4}$ A/m) sites (MR001-003, MR011, and MR018-019), five of which are from well-indurated albitic tuffs of the uppermost portion of the Brushy Basin Member at Norwood Hill. The second category includes 14 sites which are more strongly magnetized but yield either erratic magnetizations or the ChRMs of samples (from the same site) are poorly grouped. These sites are identified in Figure 3 with a question mark symbol in the polarity column adjacent to the site number. The third category includes 13 sites with magnetization directions that changed systematically toward either a northwest and moderate down direction or southeast and moderate up direction during progressive thermal demagnetization; but with further demagnetization the specimen directions became scattered and a ChRM could not be confidently isolated. An example of this behavior is shown by specimen MR043C (Figure 4a). Although these latter sites are unsuitable for calculating a paleomagnetic pole, many were used for estimating magnetic polarity. These sites are identified in Figure 3 by a question mark symbol adjacent to their polarity designation. In no case was a specimen or site rejected from pole calculation because a ChRM was steeply inclined in a direction similar to the late Cenozoic direction expected for North America.

Other than the weak magnetizations of the well-indurated albitic tuffs, there is no obvious correlation between the lithology of sites and success or failure in recovering adequately defined ChRM directions. In general, our "best" results are from red mudstones of Norwood Hill and orange-pink clinoptolitic tuffs of Montezuma Creek, but well-determined ChRMs were also isolated in gray-green mudstones (MR044) and fine-grained sandstones (MR015).

A high unblocking-temperature magnetization was isolated in two or more specimens from the remaining 18 sites. We interpret the high unblocking-temperature spectra of these magnetizations to indicate hematite as the dominant carrier of the ChRM. This is consistent with the lithologic descriptions of hematite occurring along crystallographic planes of clinoptolite [*Bell*, 1983], the red to orange color of most samples, and the high blocking temperature of the ChRM. Principal component analysis [*Kirschvink*, 1980] was used to determine these magnetization directions. For most specimens, lines were fit to three or more measurement steps between 620°C and 680°C and the origin of vector endpoint diagrams. However, specimens from sites MR012 and MR013 had to be evaluated between 525°C and 650°C because the magnetization ceased to be systematic at higher demagnetization temperatures. Specimen ChRMs were excluded from further analysis if line fits resulted in a maximum angular deviation of >20°. In addition, one specimen from site MR009 was excluded because its

Table 1. Site-Mean Directions and Poles for the Morrison Formation

Site	N/N_0	Temperature, °C	N_s	D, deg	I, deg	R	k	α_{95}, deg	Plat, °N	Plon, °E
				Brushy Basin Member of the Morrison Formation						
MR004*	4/6	600-670	7	146.6	–46.7	3.78	14	25.5	–60.4	331.6
MR005	6/6	600-679	7	143.3	–49.1	5.96	136	5.8	–58.7	337.9
MR009	3/7	570-670	8	149.9	–46.4	2.99	382	6.3	–62.8	328.1
MR010*	2/6	630-678	7	142.6	–36.0	1.90	–	–	–52.9	323.1
MR012	6/7	525-650	8	347.5	53.8	5.89	46	10.0	79.2	145.2
MR013	5/7	530-650	8	325.4	58.2	4.94	72	9.1	63.1	174.4
MR015	5/7	560-670	8	323.1	52.7	4.95	75	8.9	59.9	164.0
MR016	5/5	600-660	5	341.1	57.9	4.98	210	5.3	75.2	169.2
MR041	5/7	600-675	7	153.9	–48.9	4.95	73	9.0	–67.1	329.3
MR042	4/7	605-680	8	149.8	–49.5	3.94	47	13.5	–64.1	334.0
MR044	3/7	600-675	7	337.5	65.3	2.96	52	17.3	70.1	199.4
MR045	7/7	600-675	7	141.2	–56.9	6.97	186	4.4	–59.4	353.0
MR046	3/7	600-675	7	141.3	–40.1	2.99	202	8.7	–53.9	328.1
MR051	7/7	600-675	7	337.6	54.9	6.95	122	5.5	71.9	161.5
MR052	5/7	600-670	6	351.0	50.9	4.97	123	6.9	80.6	125.4
MR054*	3/7	576-660	6	347.0	47.0	2.94	35	21.2	75.4	124.4
MR055*	2/3	575-660	6	165.6	–54.7	1.99	–	–	–78.2	334.8
MR065	6/7	600-660	5	351.9	54.4	5.93	69	8.1	82.7	138.1
				Salt Wash Member of the Morrison Formation						
MR029	5/8	600-675	8	328.8	52.4	4.88	32	13.7	64.3	159.9
MR030	5/7	600-675	8	300.6	31.7	4.54	9	27.4	34.7	157.7

N, number of specimens used to determine site-mean direction, virtual geomagnetic pole (VGP), and associated statistics; N_0, number of specimens thermally demagnetized (one specimen per sample); temperature, maximum thermal demagnetization temperature range over which principal component analysis was applied; N_s, number of demagnetization steps within demagnetization temperature range; D, site-mean declination; I, site-mean inclination; R, length of resultant of N unit vectors; k, estimate of Fisher precision parameter; α_{95}, radius of the cone of 95% confidence about the mean direction; Plat, latitude of site-mean pole (virtual geomagnetic pole, VGP); Plon, longitude of site-mean pole (VGP). Refer to Figure 3 for site location and stratigraphic position.

*Sites excluded from determination of pass B paleomagnetic pole (see text and Table 2).

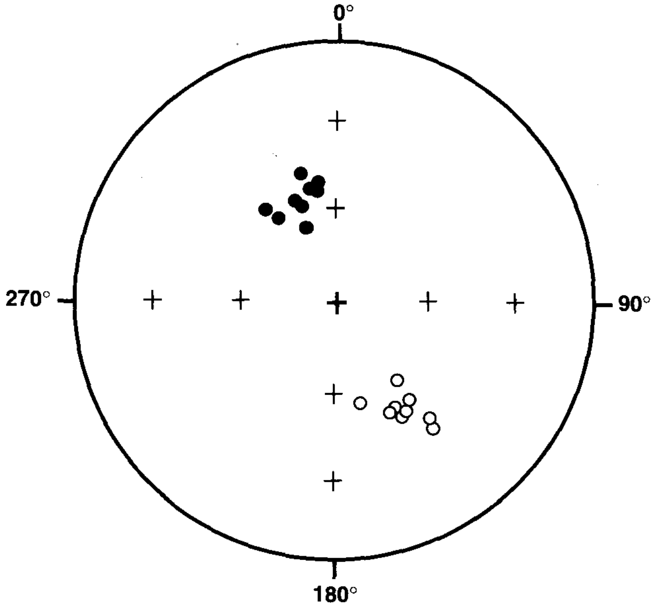

Figure 5. Equal-area projection showing site-mean directions calculated from line-fit directions. Open circles of equal-area projections are upper hemisphere; solid circles are lower hemisphere.

ChRM direction was more than two angular standard deviations from all ChRM directions of that site. Orientations of line fits were used to calculate the site-mean directions listed in Table 1 and shown in Figure 5.

We interpret magnetizations directed northwest and down (e.g., specimens MR015D1 in Figure 4a and MR051A in Figure 4b) as normal polarity magnetizations, and we interpret magnetizations directed southeast and up (e.g., specimens MR005A1 and MR045F in Figure 4b) as reverse polarity magnetizations. The presence of multiple-polarity zones and geologic arguments for early authigenesis (including early formation of hematite) suggest these magnetizations were acquired within 10^4–10^5 years after deposition. However, the mean of the normal polarity group and mean of the inverted reverse polarity group listed in Table 1 are separated by ~11°. These means are distinguishable at the 95% confidence level but become indistinguishable if separated by <7° (the critical angle). Thus these data fail the reversal test of *McFadden and McElhinny* [1990]. We interpret this to indicate that a small, unremoved secondary component is still biasing the observed directions even after detailed thermal demagnetization. This is not surprising, given the high unblocking-temperature spectra of the secondary magnetizations removed from some samples (e.g., MR005E1 in Figure 4a). The suspected, unremoved secondary component appears to be inclined steeply down because the normal polarity data are biased toward a steeper inclination and the reverse polarity data are biased toward a shallower inclination. This is consistent with overprinting by a normal polarity, late Cenozoic magnetization. The paleomagnetic pole has been determined from roughly equal numbers of normal and reverse polarity sites, so the effect of this secondary component on the pole position should be minimized but not necessarily eliminated.

The polarities of the 18 sites listed in Table 1 and the polarities estimated from some of the rejected sites (discussed above) have been used to construct the polarity stratigraphies shown in Figure 3. Also shown in Figure 3 are polarity stratigraphies reported for Norwood Hill, Colorado, and Bridgeport, Colorado, by *Steiner and Helsley* [1975a, b]. We observe a similar polarity stratigraphy at Norwood Hill and Montezuma Creek as *Steiner and Helsley* [1975a, b] reported for the Brushy Basin Member at Norwood Hill and Bridgeport, Colorado. Our polarity zones for Norwood Hill do differ somewhat from those reported by *Steiner and Helsley* [1975a] and *Steiner* [1980] for the same section. The uppermost reverse polarity and normal polarity zones (R7 and N6 of *Steiner and Helsley* [1975a]) appear well established at all locations. However, the polarity stratigraphy we observed at Norwood Hill includes only one normal polarity interval in the lower 50 m of the Brushy Basin Member, whereas Steiner and Helsley observed two normal polarity intervals (N5 and N4 of *Steiner and Helsley* [1975a], our Figure 3). The N5 normal polarity interval observed by Steiner and Helsley may be recorded in the interval which we did not sample (e.g., between our sites 20 and 21, Figure 3). Furthermore, the Montezuma Creek section where we observe at least two normal polarity zones is equivalent to only the upper portion of the Brushy Basin Member at Norwood Hill [*Turner and Fishman*, 1991]. Thus if the N5 polarity zone is in the upper portion of the Brushy Basin Member, then it may be the same normal polarity zone as the lowest normal polarity zone in our Montezuma Creek section. In any case, the fundamental conclusion illustrated by Figure 3 is that the Brushy Basin Member was magnetized during an interval dominated by reverse polarity.

Figure 3 also shows a comparison of the age range for the upper portion of Brushy Basin Member at Montezuma Creek (143.8 Ma to 150.6 Ma, *Kowallis et al.* [1991]) to the magnetic polarity timescale of *Harland et al.* [1990]. Although a correlation to chrons M22 through M17 is allowable, the dominance of reverse polarity in the Brushy Basin Member suggests a correlation to chrons M17R through M19R. Alternatively, the section may correlate to chrons M16R through M18R if the Brushy Basin Member is considered to be a few million years younger than reported by *Kowallis et al.* [1991] or if these chrons are slightly older than reported by *Harland et al.* [1990]. This latter correlation is consistent with that of *May and Butler* [1986] who suggested that, based on a revised 145 Ma age for the Morrison Formation, the polarity zonation of *Steiner and Helsley* [1975a] and *Steiner* [1980] is best correlated with chrons M16 to M19, and this correlation is consistent with *Channell and Grandesso* [1987], who placed the Tithonian/Berriasian boundary (145.6 Ma according to *Harland et al.* [1990]) in either the lower part of chron M17 or near the base of chron M18.

Virtual geomagnetic poles (VGPs) calculated for each of the reliable 18 Brushy Basin Member sites are listed in Table 1. These VGPs were used to calculate the Brushy Basin paleomagnetic poles listed in Table 2. Separate poles have been calculated for Norwood Hill, for Montezuma Creek, and for the combined data set. An additional paleomagnetic pole was calculated after excluding site means with α_{95}s > 20° (MR004 and MR054) and site-mean directions determined from fewer than three specimen ChRM directions (MR010 and MR055). The pole determined from the remaining 14 VGPs is listed as "pass B" in Table 2. All four pole positions listed in Table 2 are indistinguishable from one another at the 95% confidence level (using the method of *McFadden and Lowes*, 1981). The additional editing used to calculate the pass B pole has little effect upon the pole position and does not decrease the angular dis-

Table 2. Mean Directions and Paleomagnetic Poles (Fisher Analysis) for the Brushy Basin Member of the Morrison Formation

	N	D, deg	I, deg	R	k	α_{95}, deg	Plat, °N	Plon, °E	R	K	A_{95}
Pass A, All Site Means											
All	18	333.7	51.8	17.76	70	4.1	68.3	156.2	17.68	53	4.8
							(65.1)	(159.8)			
Normal	9	340.7	55.4	8.92	104	5.1	74.4	161.8	8.88	65	6.5
Reverse	9	147.9	–47.8	8.92	97	5.3	–62.3	333.0	8.91	87	5.6
Pass B, Sites MR004, MR010, MR054, and MR055 Excluded											
All	14	333.5	53.3	13.84	82	4.4	68.5	159.8	13.77	56	5.3
							(65.3)	(162.9)			
Normal	8	339.7	56.5	7.94	112	5.2	73.8	165.7	7.89	65	6.9
Reverse	6	146.6	–48.6	5.97	157	5.4	–61.2	335.2	5.97	149	5.5
Brushy Basin Member, Norwood Hill, Colorado											
All	8	329.3	50.4	7.91	76	6.4	64.4	156.3	7.89	65	6.9
							(61.2)	(159.7)			
Normal	4	334.3	56.1	3.98	122	8.3	69.6	165.8	3.95	66	11.4
Reverse	4	145.5	–44.6	3.98	166	7.2	-58.8	329.9	3.99	229	6.1
Brushy Basin Member, Montezuma Creek, Utah											
All	10	337.4	52.8	9.87	70	5.8	71.4	156.1	9.82	49	6.9
							(68.2)	(159.9)			
Normal	5	345.6	54.6	4.96	105	7.5	78.1	156.3	4.95	77	8.8
Reverse	5	150.0	–50.4	4.95	80	8.6	–64.8	336.1	4.94	62	9.8

N, number of sites; D, mean declination; I, mean inclination; R, length of resultant of N unit vectors; k, best estimate of Fisher precision parameter of directional distribution; α_{95}, radius of cone of 95% confidence about direction; Plat, latitude of paleomagnetic pole; Plon, longitude of paleomagnetic pole; K, best estimate of Fisher precision parameter of VGP distribution; A_{95}, radius of cone of 95% confidence about paleomagnetic pole. Normal and reverse indicate polarity of subdivisions of data sets. Latitudes and longitudes in parentheses are paleomagnetic poles corrected for proposed 4° clockwise rotation of the Colorado Plateau.

tance between the mean of the normal polarity group and the antipode of the mean for the reverse polarity group.

A corrected set of pole positions (listed in parentheses in Table 2) was calculated assuming a 4° clockwise rotation of the Colorado Plateau during Laramide deformation and subsequent opening of the Rio Grande Rift (as described by *Bryan and Gordon* [1990]). The amount, timing, and geographic extent of this proposed deformation is controversial [*Bazard and Butler*, 1991; *Chase et al.*, 1992; *Kent and Witte*, 1993], so the significance of these pole positions corrected for rotation(?) of the Colorado Plateau is uncertain. However, it is noteworthy that the correction results in these poles being rotated toward lower latitudes rather than toward the higher-latitude position which *Van Fossen and Kent* [1992b] have proposed for the Late Jurassic.

Paleomagnetism of the Salt Wash Member of the Morrison Formation

Samples were also collected from nine sites in the upper 40 m of the Salt Wash Member of the Morrison Formation at Norwood Hill, Colorado. Eight of these sites are red-brown to pale red fluvial sandstone, and one is an interbedded red mudstone. Three of the pale red sandstone sites (MR027, MR028, MR033) include conspicuous planar, heavy mineral laminae; none of the sandstones sampled is conspicuously burrowed. NRM intensities ranged from 1×10^{-2} A/m for the mudstone to 2×10^{-4} A/m for one of the pale red sandstone sites. The NRMs were generally directed downward to the north or northwest.

We were not able to confidently isolate a ChRM in the pale red "channel" sandstones. During progressive thermal demagnetization, data never defined a stable endpoint direction (e.g., MR033H1 and MR027B1 in Figure 6a). Some samples (such as MR028B1 in Figure 6a) retain a lower unblocking-temperature component (presumably in titanomagnetite) as well as a poorly defined, high unblocking-temperature component (presumably in hematite). The poorly defined hematite direction was inconsistent between sites and between samples within a single site (e.g., samples MR028B1 and MR028H1 from site MR028, Figure 6a). It is noteworthy that the lower unblocking-temperature component in sample MR028B1 (Figure 6a) defines a magnetization direction (declination = 318°, inclination = 29°) similar to the direction *Steiner and Helsley* [1975a] reported as the primary magnetization (normal polarity) of the lower Morrison Formation (Salt Wash Member). Although some of these sites may be useful for polarity information, we do not consider them suitable for calculation of a paleomagnetic pole. A ChRM was isolated in only two specimens from the red mudstone site. Unfortunately, the ChRM directions determined from these specimens differ by ~25°. Because of the uncertain nature of this magnetization, we excluded this site from further analysis.

The best results obtained from the Salt Wash Member came from two red-brown, fine-grained sandstones (MR029 and MR030 in Figure 6b). Even some samples from these sites appear to be unreliable recorders of the geomagnetic field. Figure 6b shows a comparison of results for two samples (MR030C1 and MR030H1) from a single horizon of planar-bedded, fine-grained sandstone. The inclination of the ChRM

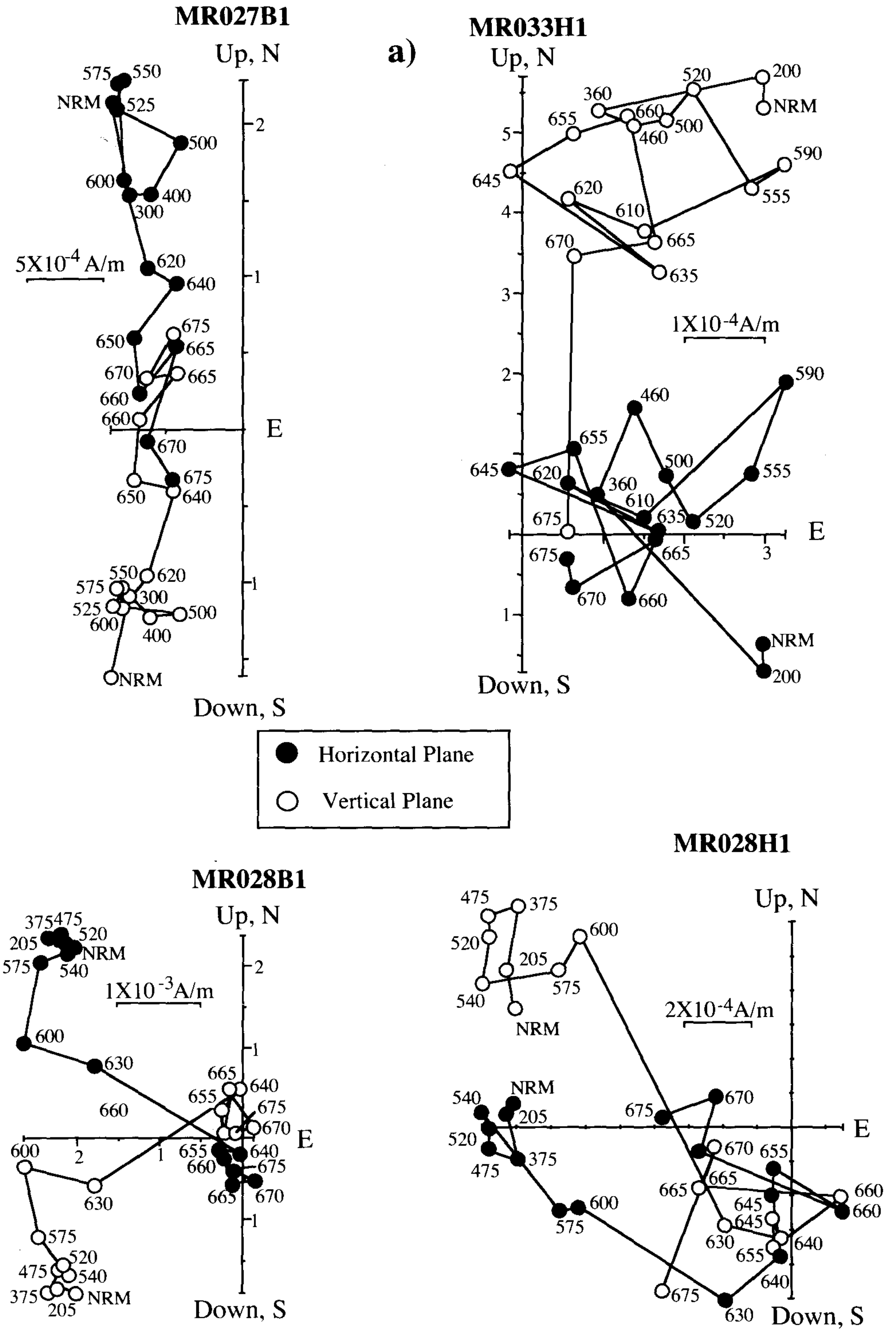

Figure 6. Vector endpoint diagrams for individual Salt Wash Member specimens (a) MR027B1, MR033H1, MR028B1, and MR028H1 and (b) MR029A1, MR030C1, and MR030H1 showing representative thermal demagnetization behavior. All specimens are from Norwood Hill, Colorado. Specimens in Figure 6a are from pale red channel sandstone (fine- to medium-grained); specimens in Figure 6b are from darker red, fine-grained sandstone. Numbers next to data points of the vector endpoint diagrams indicate thermal demagnetization temperatures in °C. Open circles represent the projection of the vector into the vertical plane; closed circles represent projection of the vector into the horizontal plane.

of sample MR030C1 is substantially shallower than the inclination of the ChRM of sample MR030H1. This suggests the magnetization of sample MR030C1 has undergone variable inclination shallowing, possibly due to compaction. The same analytical procedures described above for the Brushy Basin Member were used to evaluate the ChRMs of samples that did not display such obvious complications. The site-mean directions calculated for these sites are listed in Table 1.

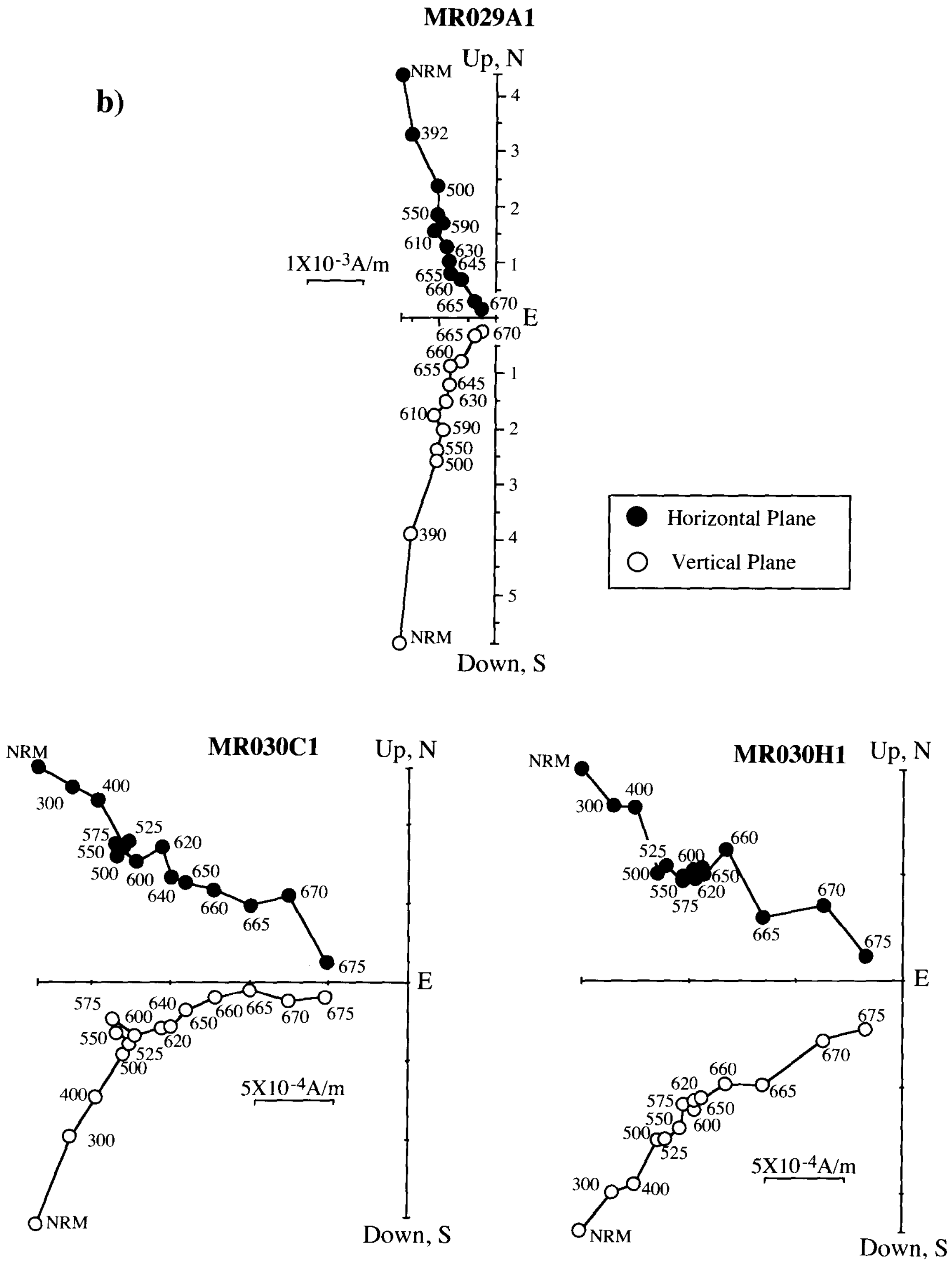

Figure 6. (continued)

Unfortunately, with acceptable(?) results from only two sites, we were unable to adequately evaluate the age of the magnetization.

Our experience indicates that the magnetizations of the fine- to medium-grained sandstones that compose the bulk of the Salt Wash Member generally do not define stable endpoint directions upon demagnetization. Additionally, directional results are inconsistent between sites, display inconsistency within some sites, and appear, in some cases, to have suffered inclination shallowing. Thus the Salt Wash Member appears unsuitable for determination of a paleomagnetic pole. This conclusion conflicts with the study of *Steiner and Helsley* [1975a], who reported well-clustered directions upon demagnetization and identified the pale red channel sandstone as carrying a stable remanent magnetization. However, *Steiner* [1980] later reported that a hard secondary magnetization and intervals of uncertain polarity are prevalent in the lower half of the Norwood section (including the Salt Wash Member). Also, *Steiner* [1983] presented a detailed study of Salt Wash channel sandstones where she demonstrated that depositional and post-depositional processes (deposition on sloping channel surfaces and burrowing) have adversely affected the magnetization direction of some of the channel sandstones. The ChRMs which *Steiner* [1983] isolated (at 560°C) in the unburrowed sandstone from Norwood Hill are poorly clustered ($k = 6.8$, $N = 8$, $\alpha_{95} = 21.2°$), and six of the horizons possess an inclination shallower than the mean inclination that *Steiner and Helsley* [1975a] originally determined for the lower Morrison Formation. *Steiner* [1980] attributed this dispersion to undetected burrowing. Furthermore, *Steiner* [1992] recently reported lower and upper Morrison Formation paleomagnetic poles from the Morrison Formation in east-central New Mexico. The position of the upper Morrison pole from eastern New Mexico is similar (157.7°E, 72.5°N) to the upper Morrison pole from western Colorado [*Steiner and Helsley*, 1975a] (161.8°E, 67.5°N) and to the Brushy Basin pole we report here. In contrast, the position of the lower Morrison pole from New Mexico (154.8°E, 52.9°N) is different from the lower Morrison pole that *Steiner and Helsley* [1975a] determined from the Salt Wash Member in western Colorado (142.2°E, 61.4°N). *Steiner* [1992] suggests this discrepancy may be due to rotation of the Colorado Plateau between the time of deposition of the lower and upper Morrison Formation. Perhaps a simpler explanation is that the lower facies of the Morrison Formation did not accurately record the Jurassic paleomagnetic field. However, the agreement of the higher-quality data from the upper portion of the Morrison Formation does provide important evidence against large, post-147 Ma rotation of the Colorado Plateau.

We suspect that much of the Salt Wash Member (lower Morrison Formation) has undergone depositional and post-depositional processes (including, in some cases, inclination shallowing) which adversely affected the ChRM direction. It is not clear that a reliable Jurassic paleomagnetic pole can be determined from the lower Morrison Formation. Until a consistent, high unblocking-temperature ChRM is isolated from multiple samples within several horizons of the Salt Wash Member (i.e., data which pass the reliability criteria used for the Brushy Basin Member), we regard the reliability of the lower Morrison pole [*Steiner and Helsley*, 1975a] as questionable and exclude it from our analysis of North American Jurassic APW.

Discussion and Conclusions

ChRMs obtained from eight sites within the Brushy Basin Member of the Morrison Formation at the Norwood Hill location combined with results from 10 sites at the Montezuma Creek location define a paleomagnetic pole at 68.3°N, 156.2°E. This pole is within 2° of the paleomagnetic pole which *Steiner and Helsley* [1975a] reported for the upper Morrison Formation at Norwood Hill, Colorado (pole NH in Figure 7). Our pole is also statistically indistinguishable from the paleomagnetic pole which *Steiner* [1992] reported for the Morrison Formation of east-central New Mexico (NM in Figure 7). Furthermore, our paleomagnetic pole from the Brushy Basin Member lies within the locus of points reported by *Van Fossen and Kent* [1992] for the "inclination only" data that they obtained from the lower portion of the Morrison Formation in the Front Range of Colorado (Figure 6). It should be noted that the lower portion of the Morrison Formation in the Front Range of Colorado correlates with the Brushy Basin Member of the Morrison Formation (F. Peterson, written communication, 1993). Thus *Van Fossen and Kent's* [1992] Morrison pole should be compared with Steiner and Helsley's upper Morrison pole and the Brushy Basin Member pole from this paper.

The agreement of paleomagnetic poles obtained from age-equivalent Morrison Formation strata at three widely separated regions (including regions east of the Colorado Plateau in New Mexico) by researchers using different laboratories and different analytical techniques confirms the position of the upper Morrison paleomagnetic pole near 68°N, 156°E. Early formation of hematite, as well as other authigenic minerals [*Turner and Fishman*, 1991], and the presence of several near-antipodal polarity zones that are at least generally correlative between widely separated stratigraphic sections suggest that the age of magnetization is close to the well-determined depositional age of 147 ± 3 Ma [*Kowallis et al.*, 1991]. We find no evidence to indicate that preferential rejection of steep inclination data led *Steiner and Helsley* [1975a] to calculate an erroneously shallow inclination pole for the upper part of the Morrison Formation (as suggested by *Van Fossen and Kent*, 1992a). Thus we regard the Brushy Basin paleomagnetic pole as a well-defined Tithonian–Berriasian paleomagnetic pole for North America.

The Brushy Basin pole is also similar to some Late Jurassic paleomagnetic poles from other continents rotated into North American coordinates. The ~144 Ma paleomagnetic pole from dolerites of Svalbard [*Halvorsen*, 1989] and a 152 Ma pole inferred from an analysis of west Gondwana inclination data [*Van der Voo*, 1992] are located close to the Brushy Basin paleomagnetic pole when rotated into North American coordinates (67°N, 161°E and 70°N, 155°E, respectively). However, other Late Jurassic–earliest Cretaceous paleomagnetic poles are located at higher latitudes in North American coordinates [*Halvorsen*, 1989; *Van Fossen and Kent*, 1992a,b] or in different positions [*Van Fossen and Kent*, 1993]. Furthermore, the reconstruction parameters for the fit of North America and Europe are uncertain, and the paleomagnetic poles from Europe and Africa do not provide an internally consistent APW path [*Van der Voo*, 1992]. Also, the Jurassic–earliest Cretaceous paleomagnetic poles from other continents (such as those from South America) suffer similar structural and age ambiguities as many of the Jurassic paleomagnetic poles from North America. Thus, although the coincidence of the Svalbard and west Gondwana paleomagnetic poles with the Brushy Basin paleomagnetic pole is encouraging, it is not clear that these comparisons are an effective method for evaluating North American Jurassic APW.

Figure 8 shows the Brushy Basin paleomagnetic pole (pass B, Table 2) along with other Jurassic and Early Cretaceous paleomagnetic poles from interior North America. The coordinates, statistics, and references associated with these poles are listed in Table 3. The dark-shaded band shown in Figure 8 indicates our interpretation of North American APW during the Jurassic. However, no simple APW path can explain all the observations, and our choices of the paleomagnetic poles judged most representative of Jurassic APW require some explanation.

For reasons given above, we excluded the paleomagnetic pole from the lower Morrison. We also exclude paleomagnetic poles determined from Newark trend intrusions [*Smith and Noltimier*, 1979] and North Carolina dikes [*Smith*, 1987]. The magnetization age, structural orientation during magnetization, and the degree to which paleosecular variation has been averaged are questionable for these data [*Prevot and*

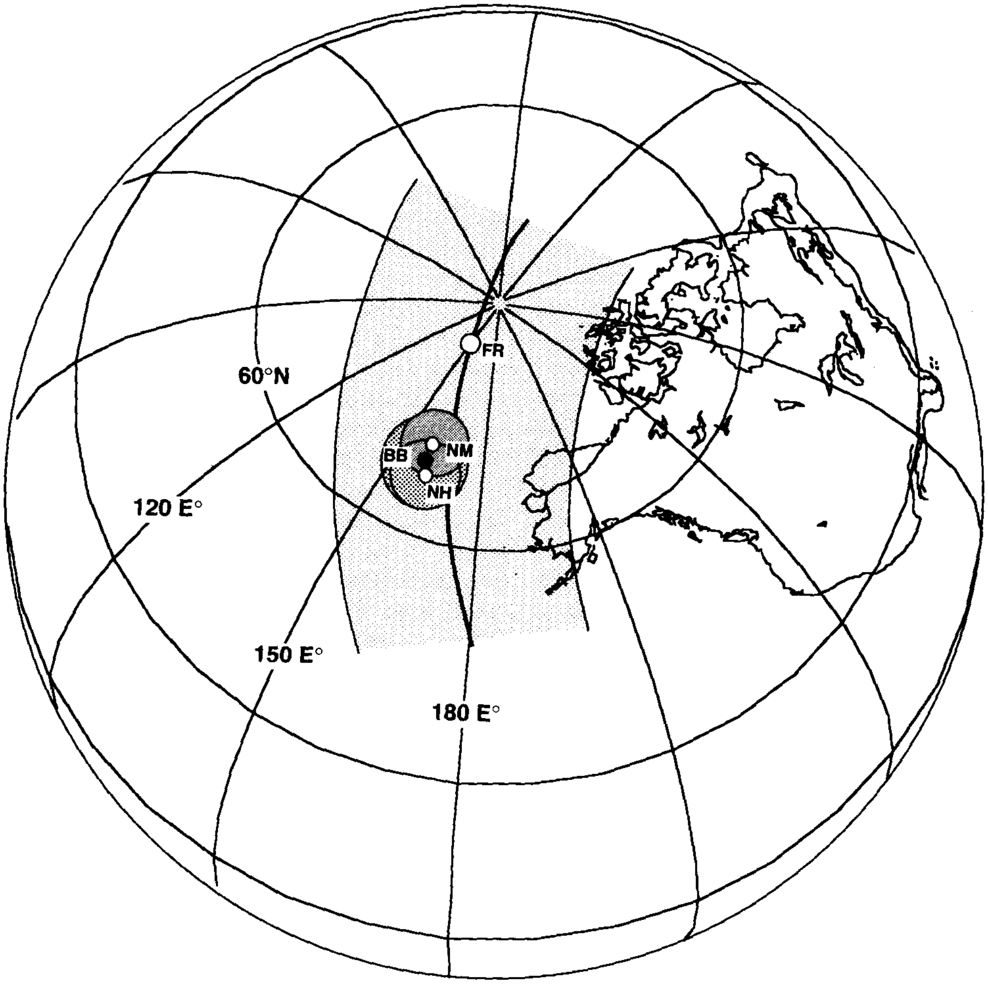

Figure 7. Comparison of Brushy Basin Member paleomagnetic pole (BB) with other paleomagnetic poles calculated from the Morrison Formation. NH is the paleomagnetic pole determined from the upper portion (Brushy Basin Member) of the Morrison Formation at Norwood Hill, Colorado, by *Steiner and Helsley* [1975a]. NM is the paleomagnetic pole calculated from the Morrison Formation of New Mexico (including regions off the Colorado Plateau) by *Steiner* [1992]. FR is the paleomagnetic pole from the Morrison Formation of the Front Range region, Colorado, by *Van Fossen and Kent* [1992a]. Solid arcuate line and dotted region represent the locus of points and 95% confidence region which Van Fossen and Kent reported from an "inclination only" analysis of their Front Range data.

McWilliams, 1989; *Witte and Kent*, 1990, 1991; *Bazard and Butler*, 1991]. In the same manner, we question the utility of the paleomagnetic poles from the Moat Volcanics (MV of Figure 8) and the Newark B component (NB of Figure 8) in constraining Jurassic APW. In contrast to the other paleomagnetic poles shown in Figure 8, the Newark B component and Moat Volcanics paleomagnetic poles were determined from secondary magnetizations. Any secondary magnetization carries a fundamental uncertainty regarding paleohorizontal at the time of magnetization, in addition to uncertainties in the age of acquisition. Because the paleomagnetic directions from the Moat Volcanics and Newark B component are steeply inclined and divergent from other North American Jurassic magnetizations, we suspect that these secondary magnetizations may have been acquired between periods of deformation (similar to the process described by *Burmester et al.* [1990]) and/or they are contaminated by unremoved components of late Cenozoic age (see discussion by *Butler, et al.* [1992] and reply by *Van Fossen and Kent* [1992b]).

We do not include the paleomagnetic pole from the Glance Conglomerate in Figure 8, despite the positive reversal test (class C of *McFadden and McElhinny* [1990]) and conglomerate test [*Kluth et al.* 1982]. At the time of the paleomagnetic analysis by *Kluth et al.* [1982], the upper portion of the volcanic units in the Canelo Hills region were grouped within the Mount Hughes Formation by *Kluth* [1982]. The units sampled for paleomagnetic analysis included rocks within the Canelo Ridge and Canelo Pass members of the Mount Hughes Formation and were thought to record a single volcanic sequence, with no age difference between these members. Subsequent mapping by *Vedder* [1984] indicates correlation of the Canelo Pass Member of the Mount Hughes Formation with the Glance Conglomerate (hence the name change of this unit). It is the volcanic units of the Glance Conglomerate which yielded the Rb/Sr isochron age of 151±2 Ma reported by *Kluth et al.* [1982]. More importantly, the stratigraphic revisions and geochemical studies of *Vedder* [1984] and *Krebs and Ruiz* [1987] suggest that the Canelo Ridge Member of the Mount Hughes Formation may be

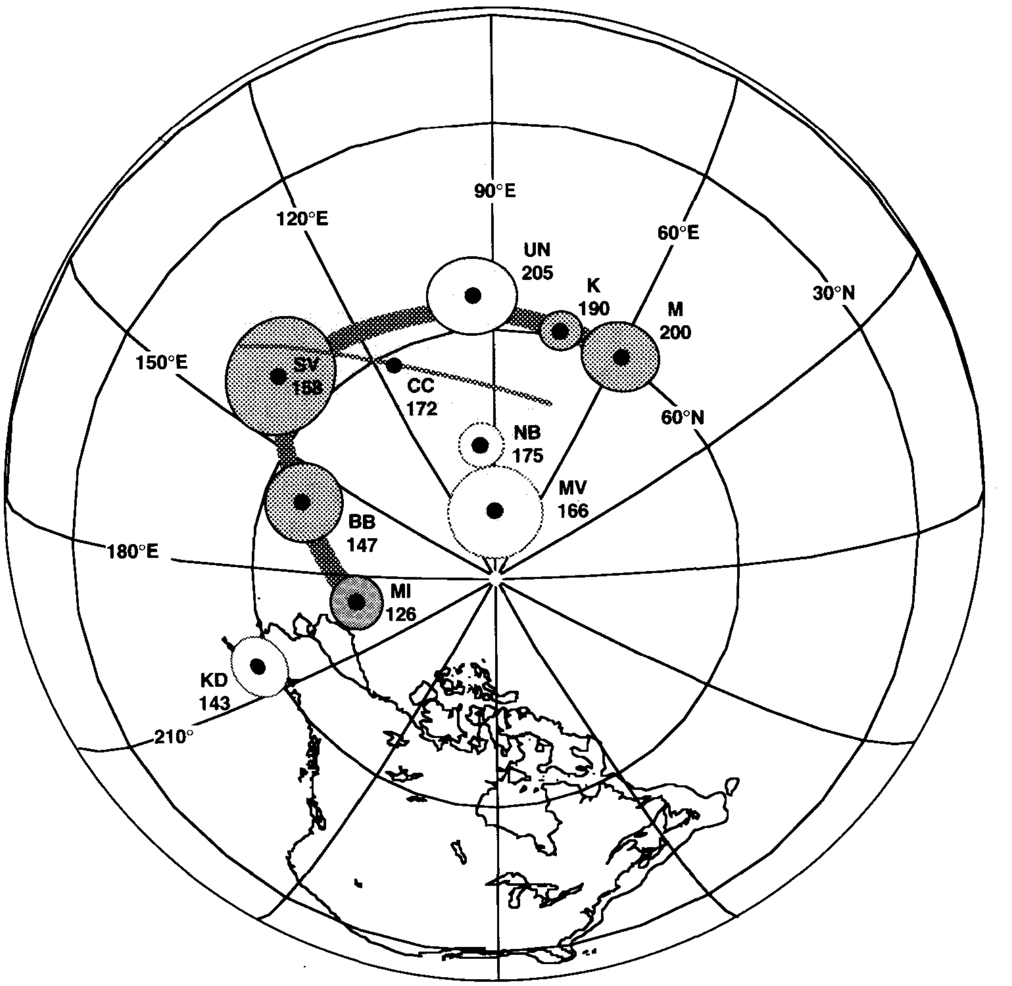

Figure 8. Jurassic and oldest Cretaceous paleomagnetic poles for North America; UN, Upper Newark paleomagnetic pole; M, Moenave paleomagnetic pole; K, Kayenta paleomagnetic pole; NB, Newark B component paleomagnetic pole; CC, Corral Canyon paleomagnetic pole; MV, Moat Volcanics paleomagnetic pole; SV, Summerville paleomagnetic pole; BB, Brushy Basin paleomagnetic pole; KD, New York Kimberlite Dikes paleomagnetic pole; and MI, Monteregian Hill intrusives paleomagnetic pole. The dotted ovals represent 95% confidence of the pole position. Numbers below each pole designation are pole ages as reported in Table 3. The poles from the Colorado Plateau (M, K, SV, BB) have each been corrected for a 4° clockwise rotation of the Colorado Plateau (using the Euler pole of *Bryan and Gordon* [1990]). The dark, dotted band passing through M, K, UN, SV, BB, and MI represents our interpretation of Jurassic APW for North America. The thin colatitude band represents vertical axis rotation (20° clockwise and 20° counterclockwise) of the paleomagnetic poles about an Euler pole at 31.5°N, 249.3°E . The lighter, wider band is the 95% confidence region for the Corral Canyon colatitudes. Paleomagnetic pole positions, ages, and references are listed in Table 3.

correlative with the Welded Tuff Member of the Canelo Hills Volcanics of *Hayes and Raup* [1968]. This latter unit is poorly dated but could be ~20 m.y. older than the Glance Conglomerate, raising the possibility that the paleomagnetic samples analyzed by *Kluth et al.* [1982] are split between two volcanic sequences of significantly different age. In addition, *Krebs and Ruiz* [1987] have shown that at least some Jurassic volcanic units in the Canelo Hills were affected by post-emplacement potassium metasomatism, and this chemical alteration may have affected the Rb/Sr systematics. Until these issues of volcanic stratigraphy and geochronology of the Jurassic volcanic rocks in the Canelo Hills region are clarified, the paleomagnetic pole from the Glance Conglomerate should not be used for determination of North American Jurassic APW.

Paleomagnetic data from the Corral Canyon Jurassic volcanic arc rocks in southeastern Arizona are included in Figure 8. Paleomagnetic evidence for a primary origin of the magnetization in the Corral Canyon section include: (1) the presence of normal and reverse polarity sites within the continuous stratigraphic sequence, (2) the data pass the fold test of *McFadden* [1990] (definition 2) at the 99% confidence level (test statistic, 0.033; 95% critical value, 4.036), although improvement in directional grouping of structurally corrected site-mean ChRM directions is statistically significant only at the 75% level of confidence using the fold test of *McElhinny* [1964], and (3) the dispersion of site-mean VGPs (S = 11.5°) is consistent with random sampling of geomagnetic secular variation. The Corral Canyon paleomagnetic data and isotopic age information are interpreted to indicate a primary magnetization at 172.2 ± 5.8 Ma.

A serious question about the reliability of the paleomagnetic pole from the Corral Canyon sequence involves the structural

Table 3. North American Jurassic–Earliest Cretaceous Paleomagnetic Poles

Unit	Age	Plat, °N	Plon, °E	A_{95}, deg	K	N	Ref
Upper Newark Basin (extrusive zone red beds)	Hettangian (~208–203 Ma)	55.5	94.6	5.4	72	11	1
Moenave Formation	Hettangian–Sinemurian (~205–195 Ma)	58.2 (59.4	51.9 59.2)	4.5	45	23	2
Kayenta Formation	Pliensbachian (~195-187 Ma)	59.0 (59.1	66.6 74.2)	2.4	155	23	3
Newark B Component*	175 Ma (remagnetization)	74	96	2.6	63	50	4
Corral Canyon†	172 ± 5.8 Ma	61.8	116.0	6.2	50	12	5
Moat Volcanics*	166 Ma (remagnetization)	81.6	89.7	5.6	56	16	6
Summerville Formation	late Callovian–earliest Oxfordian (~158 Ma)	56.3 (53.6	133.4 138.2)	7.2	42	11	7
Brushy Basin Member	147 ± 3 Ma	68.3 (65.1	156.2 159.8)	4.8	53	18	8
New York Kimberlites	143 Ma	58.0	203.1	3.8	550	7	9
Monteregian Intrusives	126 Ma	72	191	3.1	50	70	10

Plat, latitude of paleomagnetic poles; Plon, longitude of paleomagnetic poles; A_{95}, radius of cone of 95% confidence about paleomagnetic pole; K, best estimate of Fisher precision parameter of VGP distribution; N, number of sites used to calculate paleomagnetic pole; References: 1, *Witte and Kent* [1990]; 2, *Ekstrand and Butler* [1989]; 3, *Bazard and Butler* [1991]; 4, *Witte and Kent* [1991]; 5, *May et al.* [1986]; 6,*Van Fossen and Kent* [1990]; 7, *Bazard and Butler* [1992]; 8, this study; 9, *Van Fossen and Kent* [1993]; 10, *Foster and Symons* [1979]. Latitudes and longitudes in parentheses are paleomagnetic poles corrected for proposed 4° clockwise rotation of the Colorado Plateau.

*Paleomagnetic poles determined from secondary magnetizations.

†Paleomagnetic pole determined from rocks of southeastern Arizona (ambiguous structural setting).

setting of these rocks. *Hagstrum and Lipman* [1991] demonstrated that some Jurassic volcanic rocks from southeastern Arizona have experienced post-Jurassic, vertical axis, clockwise rotations. They have suggested that because of the ambiguous structural coherence of this region, the absolute positions of these paleomagnetic poles should probably not be used as constraints in interpreting the pattern of North American Jurassic APW. We think it unwise to completely discard the Corral Canyon paleomagnetic pole from analysis of Jurassic APW as this is the only Jurassic paleomagnetic pole determined from volcanic rocks of the continental interior which have likely retained a primary magnetization.

We can allow for the uncertainty introduced by possible vertical axis rotation of the sampled areas by using only the mean paleomagnetic inclination from the Corral Canyon sequence. The resulting colatitude circle (centered on the sampling location) along which the Corral Canyon paleomagnetic pole could lie is shown in Figure 8. It is noteworthy that a correction for clockwise rotation of the Corral Canyon sampling area would cause this pole to move closer to the preferred APW path of Figure 8, and the age of this pole is consistent with the systematic age progression along this path. Because of the structural ambiguity associated with the Corral Canyon paleomagnetic pole, we regard the colatitude band obtained from this paleomagnetic pole (Figure 8) as a secondary means of evaluating Jurassic APW.

Therefore we believe the distribution of paleomagnetic poles from the regional stratigraphic succession on the Colorado Plateau (Moenave, Kayenta, Summerville, and Morrison formations) provides the most useful information for determining the pattern of North American Jurassic APW. These paleomagnetic poles have all been determined by recent and detailed laboratory analyses of large paleomagnetic sample collections from structurally uncomplicated areas of the Colorado Plateau. We emphasize that the preferred APW path shown in Figure 8 is only an estimate of Jurassic APW based on an admittedly small data set. Certainly the large time gaps in this path and the dependence of the APW path geometry on the position of the

Summerville pole are points of concern. Nevertheless, we feel it best to use these few "reliable" data rather than to construct a circuitous path through all available data.

As discussed above, the amount and exact geometry of clockwise rotation of the Colorado Plateau during Laramide deformation and Cenozoic opening of the Rio Grande Rift are uncertain. Thus there is attendant uncertainty in the exact position of the Jurassic APW path shown in Figure 8 with respect to cratonic North America. However, because the plateau is structurally stable internally, any Colorado Plateau rotation will coherently adjust these paleomagnetic poles with respect to the craton without changing the geometric relationships among the paleomagnetic poles.

Another complication with the Jurassic paleomagnetic poles is the inconsistency of the paleomagnetic poles from the Colorado Plateau with the position of the paleomagnetic pole *Witte and Kent* [1990] determined from Hettangian sedimentary rocks of the Newark Basin (UN in Figure 8). The position of this pole may indicate extremely rapid Early Jurassic APW (~4.5°/m.y, assuming no Colorado Plateau rotation and a duration of ~5 m.y. from the middle Hettangian to middle Sinemurian), or it may be a consequence of large Colorado Plateau rotation [*Kent and Witte*, 1993]. The Newark Hettangian pole was determined exclusively from normal polarity data that did not afford a fold test nor other tests of the magnetization age, so, alternatively, it may represent a younger remagnetization, consistent with its position on the APW path band shown in Figure 8. A detailed discussion of Late Triassic–Early Jurassic North American APW is beyond the scope of this paper, but clearly, additional studies are required to resolve this portion of the North American APW path. The reader is referred to discussions by *Witte et al.* [1991], *Bazard and Butler* [1991], and *Molina-Garza et al.* [1991] for additional analysis.

A paleomagnetic pole recently determined from ~143 Ma kimberlite dikes in central New York State [*Van Fossen and Kent*, 1993] presents a complication for the Jurassic–Early Cretaceous portion of the North American APW path shown in Figure 8. The kimberlite dikes pole (KD) is ~23° from the Brushy Basin pole (BB), yet the ages of the rocks from which these poles have been determined are indistinguishable (within the error limits of the dating methods). The kimberlite age has been determined from K-Ar age data that varies from 113 ± 11 Ma to 146 ± 8 Ma, although most of the age determinations are consistent with the 143 Ma age [*Van Fossen and Kent*, 1993]. If the ages and pole positions are correct, they imply extremely rapid APW during the 150 to 140 Ma interval. Although the kimberlite data pass a reversal test, the angular dispersion of these data is low (estimated angular standard deviation of 3.5°), and only seven sites define the pole. Thus it is not clear whether paleosecular variation has been averaged. We agree with *Van Fossen and Kent* [1993] that new studies are needed to substantiate this kimberlite pole. Therefore, at this time we regard the paleomagnetic pole determined from the 126 Ma Monteregian intrusives as the oldest reliable Cretaceous paleomagnetic pole for North America. A paleomagnetic pole determined from lamprophyre dikes of Newfoundland [*LaPointe*, 1979, *Prasad*, 1981] may be slightly older (129 Ma) but its position (207°E, 71°N, recalculated by *Globerman and Irving* [1988]) is similar to the Monteregian pole.

The positions of the Summerville, Brushy Basin, and Monteregian paleomagnetic poles indicate that a change in direction of APW occurred during the late Middle Jurassic to Late Jurassic. *May and Butler* [1986] noted this change in the direction of APW and designated this corner or cusp in the APW path the "J2 cusp" Although a change in APW direction is still required, the age of the J2 cusp and the rate of Late Jurassic APW are probably different than concluded by *May and Butler* [1986]. Whereas May and Butler concluded an age of ~151 Ma (age of the Glance Conglomerate) for the J2 cusp, our current best estimate is that the trend of APW defined by the Summerville, Brushy Basin, and Monteregian paleomagnetic poles began by at least ~158 Ma (the age of the Summerville Formation). Exactly when this track of APW began is uncertain due to the lack of high-quality, 190 Ma to 160 Ma paleomagnetic poles, and our interpretation is based exclusively on the position of the Summerville pole. Approximately 16° separates the Summerville Formation pole from the Brushy Basin Member pole, and ~12° separates the Brushy Basin and Monteregian paleomagnetic poles. The age differences between these pairs of rocks (9 m.y. and 21 m.y., respectively) suggest rates of Late Jurassic APW of 1.8°/m.y. to 0.6°/m.y. Contrary to the previous conclusions by *May and Butler* [1986] and *May et al.* [1989], the rate of APW during the Late Jurassic does not appear to be substantially higher than the APW rate during the Early and Middle Jurassic.

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