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The red bed controversy revisited: shape analysis of Colorado Plateau units suggests long magnetization times

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Abstract

Several Triassic and earliest Jurassic sedimentary units from the Colorado Plateau region have distributions of virtual geomagnetic poles (VGPs) that are highly elongate along the path of apparent polar wander (APW). This suggests that the remanent magnetizations measured in these units were acquired over an extended period of time, possibly approaching 35 m.y., and are not precisely coeval with the stratigraphic age of the rock. Comparison with other paleomagnetic studies shows that the observed elongation is not a general attribute of the age of the rock, nor is it related to paleolatitude. The rocks that yield elongate VGP distributions are dominantly red to brown mudstones, and it is possible that their remanence is dominated by a slowly acquired chemical remanent magnetization, as suggested by Larson et al. [J. Geophys. Res. 87 (1982) 1081] and other authors. However, several superficially similar units from the Colorado Plateau have nearly circular VGP distributions. The process by which remanence is acquired in clastic sedimentary rocks merits further study.

Keywords: Red bed controversy; Shape analysis; Colorado Plateau

1. Introduction

During the late 1970s and 1980s, there occurred an important and, at times, acrimonious debate about process(es) of acquisition of remanent magnetization in sedimentary rocks, particularly red beds (for examples of opposing schools of thought, see Larson et al., 1982 and Tauxe and Opdyke, 1982; for a summary, see Butler, 1992, pp. 197–203). Briefly, some authors found evidence suggesting that the acquisition of remanence in the sedimentary rocks they studied was a relatively rapid detrital process, and thus that remanence was essentially contemporaneous with stratigraphic age. Such units are valuable for magnetostratigraphy and provide reliable data for the construction of paths of apparent polar wander (APW). However, other investigators encountered superficially similar rock units that seemed to have acquired their remanence over extended intervals of time, largely by chemical processes involving deposition of hematite cement between the detrital grains. Such rocks are of little or no value for magnetostratigraphy, and paleomagnetic poles derived from them are less useful in studies of APW. It now seems clear that both kinds of sedimentary rocks exist, as well as intermediate cases in which several modes of acquisition of remanence contribute to the characteristic direction of remanent magnetization (ChRM).

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Table 1
Elongations, paleolatitudes and scatter statistics for Triassic and Jurassic sedimentary rocks from the Colorado Plateau area

#	Unit	N	E_p	E_d	λ	K
1	Anton Chico M, Moenkopi Fm	38	8.05	2.12	0.2°	41.5
2	Bluewater Creek Fm	8	11.96	4.15	1.5	49.8
3	Church Rock M, Chinle Fm	8	1.50	2.69	5.8	44.8
4	Garita Creek Fm	12	1.49	4.63	− 0.9	97.7
5	Kayenta Fm	30	2.51	1.80	8.4	129.9
5n	Kayenta Fm, N polarity	17	7.12	2.09	9.3	113.5
5r	Kayenta Fm, R polarity	13	2.16	6.16	7.1	156.5
6	Moenave Fm	22	2.53	2.19	5.6	25.2
7	Moenkopi Fm	32	3.57	1.16	5.2	83.2
8	Owl Rock M, Chinle Fm	13	2.64	1.40	3.4	181.3
9	Redonda M, Chinle Fm	13	1.84	2.87	4.8	131.8
10	Red Peak M, Chugwater Fm	13	7.86	2.10	7.5	141.5
11	U Shale M, Chinle Fm	16	9.55	2.59	2.5	46.5

N, number of sites. E_p and E_d are elongations of sets of poles (VGPs) and directions, respectively. λ is paleolatitude. K is the Fisher (1953) precision parameter for VGPs. References: (1) Steiner and Lucas (1992); Molina-Garza et al. (1996); (2) Molina-Garza et al. (1998); (3) Kent and Witte (1993); (4) Molina-Garza et al. (1996); (5) Bazard and Butler (1991), Steiner and Helsley (1974); (6) Ekstrand and Butler (1989); (7) Helsley and Steiner (1974), Molina-Garza et al. (1991); (8) Bazard and Butler (1991); (9) Reeve and Helsley (1972), Molina-Garza et al. (1996); (10) Van der Voo and Grubbs (1977), Shive et al. (1984); (11) Bazard and Butler (1991).

It is important to know whether the remanence direction in a rock unit represents a brief (10^3–10^5 years) or extended (10^6–10^8) interval. Beck (1999) suggested that the shape of the distribution of virtual geomagnetic poles (VGP) might provide an important clue; units magnetized over a period of time that was long relative to the rate of apparent polar motion should form a distribution that is elongate in the direction of APW. This would be equally true if the magnetization process was continuous (involving extremely prolonged acquisition of a primary magnetization), or intermittent (involving several discrete intervals of magnetization and/or remagnetization). In this paper, we show that the shapes of VGP data sets from several sedimentary rock units from the Colorado Plateau region suggest that they were magnetized over a very long interval, perhaps several tens of millions of years. A similar study involving paleomagnetic directions (not VGP) was performed by Cederquist et al. (1997), who also found a general tendency for paleomagnetic data sets to be elongate parallel to the direction of APW.

2. Shapes of VGP distributions for some sedimentary units from the Colorado Plateau

Table 1 summarizes shape data for Colorado Plateau sedimentary units of Triassic and Jurassic age. Some of these data sets have been recalculated to eliminate unusually scattered site-mean directions (α_{95}>15°), and/or to combine two or more studies of the same unit. The method of shape analysis employed and details of data selection are described in Beck (1999).

Fig. 1 is a plot of the elongations of site-mean directions (E_d) vs. elongations of VGP (E_p). The boxed area near the origin would contain the elongations of all 13 cratonal paleomagnetic data sets analyzed in Beck (1999). About half of the data sets summarized in Table 1 fall within the same area, indicating that there is nothing particularly unusual about their shapes. However, five studies have distributions with strikingly elongate distributions of VGP. Moreover, as shown in Fig. 2, the direction of elongation in each case is parallel to the path of APW.

The APW path shown in Fig. 2 is a segment of a small circle centered on the Triassic–Early Jurassic paleomagnetic Euler pole (PEP) for stable North Amer-

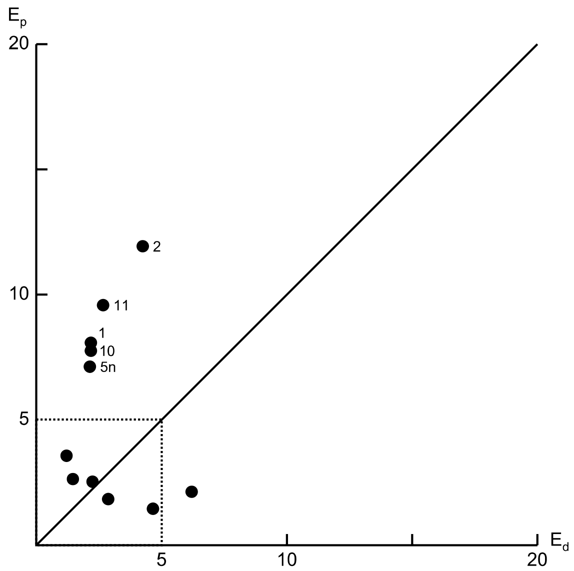

Fig. 1. Elongation (E_p) of sets of site-mean virtual geomagnetic poles (VGP) plotted against the elongation of sets of equivalent field directions (E_d). Data from Table 1.

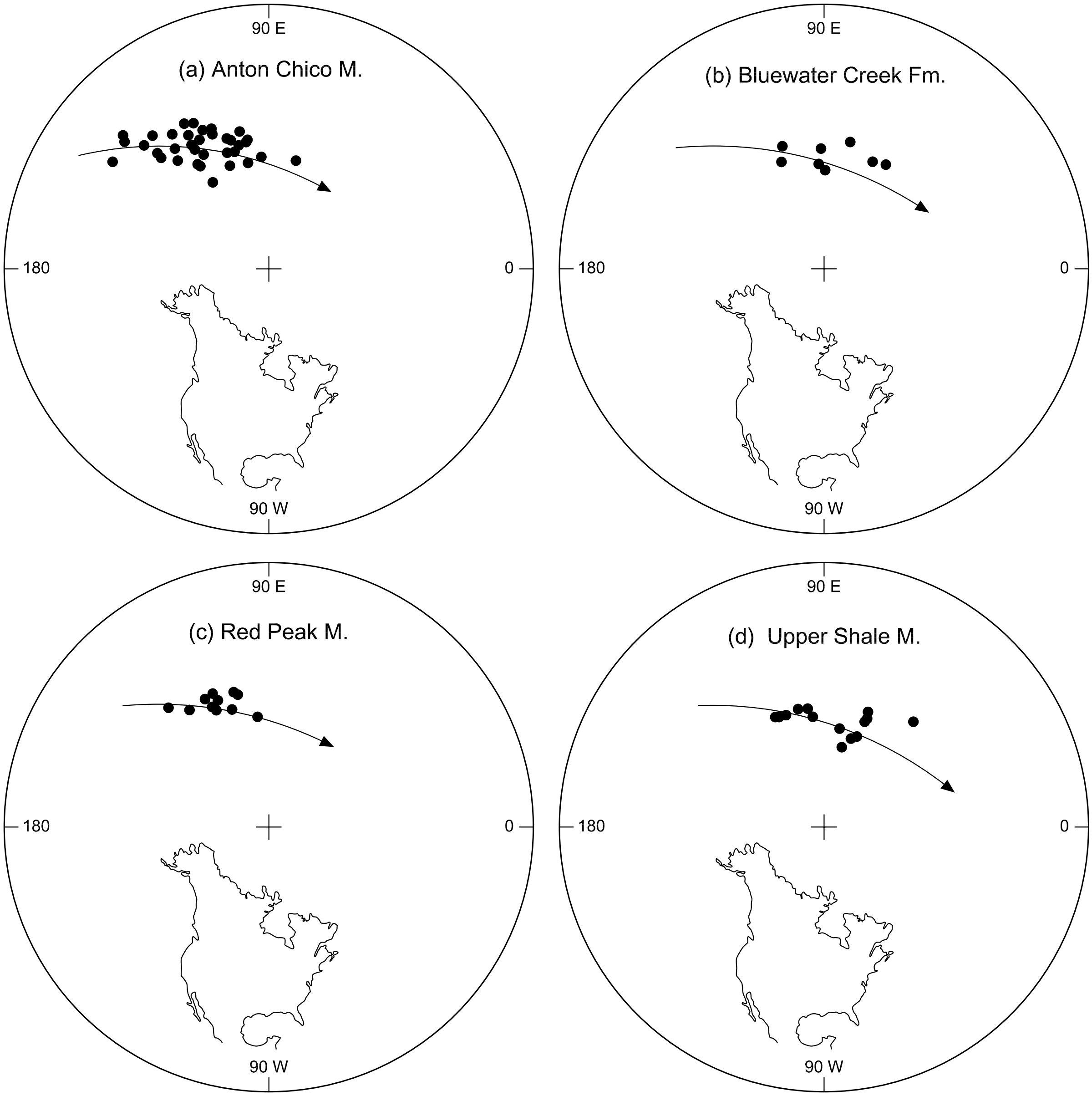

Fig. 2. Site-mean VGPs for various units from the Colorado Plateau region. Curve shown is the path of apparent polar wander (APW) for the Triassic and early Jurassic. (a) Anton Chico Member of the Moenkopi Formation; (b) Bluewater Creek Formation; (c) Red Peak Member of the Chugwater Formation; (d) Upper Shale Member of the Chinle Formation.

ica. The PEP used is from Beck and Housen (2000 and in preparation): 245 to 200 Ma; 35.1° N, 246.3° E, with a radius of 85.1°. Although based largely on new data, this PEP differs very little from the original 300 to 200 Ma PEP of Gordon et al. (1984).

From Fig. 2, it is clear that rocks sampled from the Anton Chico Member of the Moenkopi Formation, the Bluewater Creek Formation, the Upper Shale Member of the Chinle Formation, and the Red Peak Member of the Chugwater Formation have unusually large VGP elongations, and that the direction of elongation is closely parallel to the direction of APW. This suggests that these four units acquired their remanent magnetizations over a substantial period of time. However, as shown next, part of the elongation could be inherent in the direction-to-pole mapping relationship of the geomagnetic field.

To estimate how long an interval of remanence acquisition is indicated, we performed a numerical experiment. First we created a set of directions arrayed in a circle ($R = 10°$), centered on the expected direction for an arbitrary "reference locality" within the Colorado Plateau (38° N, 115° W). The mean direction of this set ($D = 356.1°$; $I = 15.3°$) is the geomagnetic axial dipole field direction at the reference locality, assuming that the paleomagnetic pole was coincident with the J1 cusp (Gordon et al., 1984), which from Beck and Housen (2000) was located at 59.6° N, 72.7° E. This circular distribution of field directions then was mapped into VGP at the reference locality, resulting in the oval distribution of poles shown in Fig. 3a.

The obvious elongation ($E_p = 3.73$) seen in Fig. 3a is caused by the direction-to-pole mapping relationship and the low paleolatitude of the site. As is well known, a circular distribution of directions maps into an oval distribution of VGP, oriented with its long axis normal to the paleomeridian; this effect varies with latitude and is greatest for paleolatitudes near the equator. The fact that, in the example illustrated in Fig. 3a, the distribution seems to be elongate along the APW path is a potentially misleading coincidence, resulting from the fact that the reference locality and the PEP are very nearly identical.

Next we "stretched" the distribution of Fig. 3a, using a modified Monte Carlo process. For each of several runs, each member of the set shown in Fig. 3a was rotated clockwise through an angle chosen randomly to lie between 0 and some arbitrary maximum value, R_{max}. The pole of rotation used was the pre-J1 PEP given earlier. This simulates acquisition of remanence over a long interval, during which the paleomagnetic pole traversed along its track. It was found that R_{max} of about 30° was needed to duplicate the elongation values found in the data sets illustrated in Fig. 2 (Fig. 3b shows an example).

Beck and Housen (2000) found that a steady rotation of 0.9°/m.y. could account for APW during the interval 245 to 200 Ma; Gordon et al. (1984) calculated

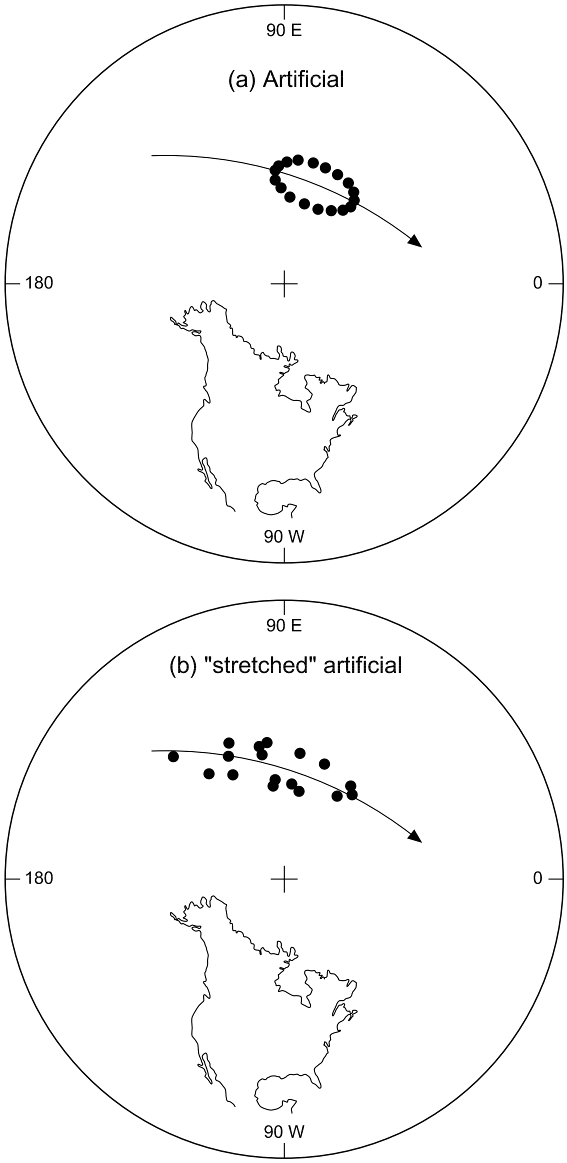

Fig. 3. Artificial data. (a) Artificial, perfectly circular set of directions mapped to VGP; (b) VGP of a, "stretched" along the path of APW, simulating remanence acquisition over an extended period of time. Compare Fig. 2a. See text.

0.78°/m.y. Thus, if the elongate data sets shown in Fig. 2 are on average stretched about 30°, the total magnetization intervals indicated are of the order of 35 m.y.

The estimate just given assumes a constant rate of APW. If, instead, APW during the Triassic and Late Jurassic consisted of alternating intervals of rapid and slow polar motion, and if the units of Fig. 2 were deposited when APW was particularly rapid, their magnetization intervals might be significantly shorter. We regard this as highly unlikely.

Note also that this estimate of "stretching" should be considered a minimum. The initial assumption underlying the numerical experiment described above was that the collection of field directions was circular. However, as shown in Beck (1999), this is rarely the case; as an often-violated rule, VGP data sets tend to be slightly less elongate (more nearly circular) than the corresponding sets of directions. A circular distribution of VGP would require even more than 30° of stretching to distort into the shapes shown in Fig. 2.

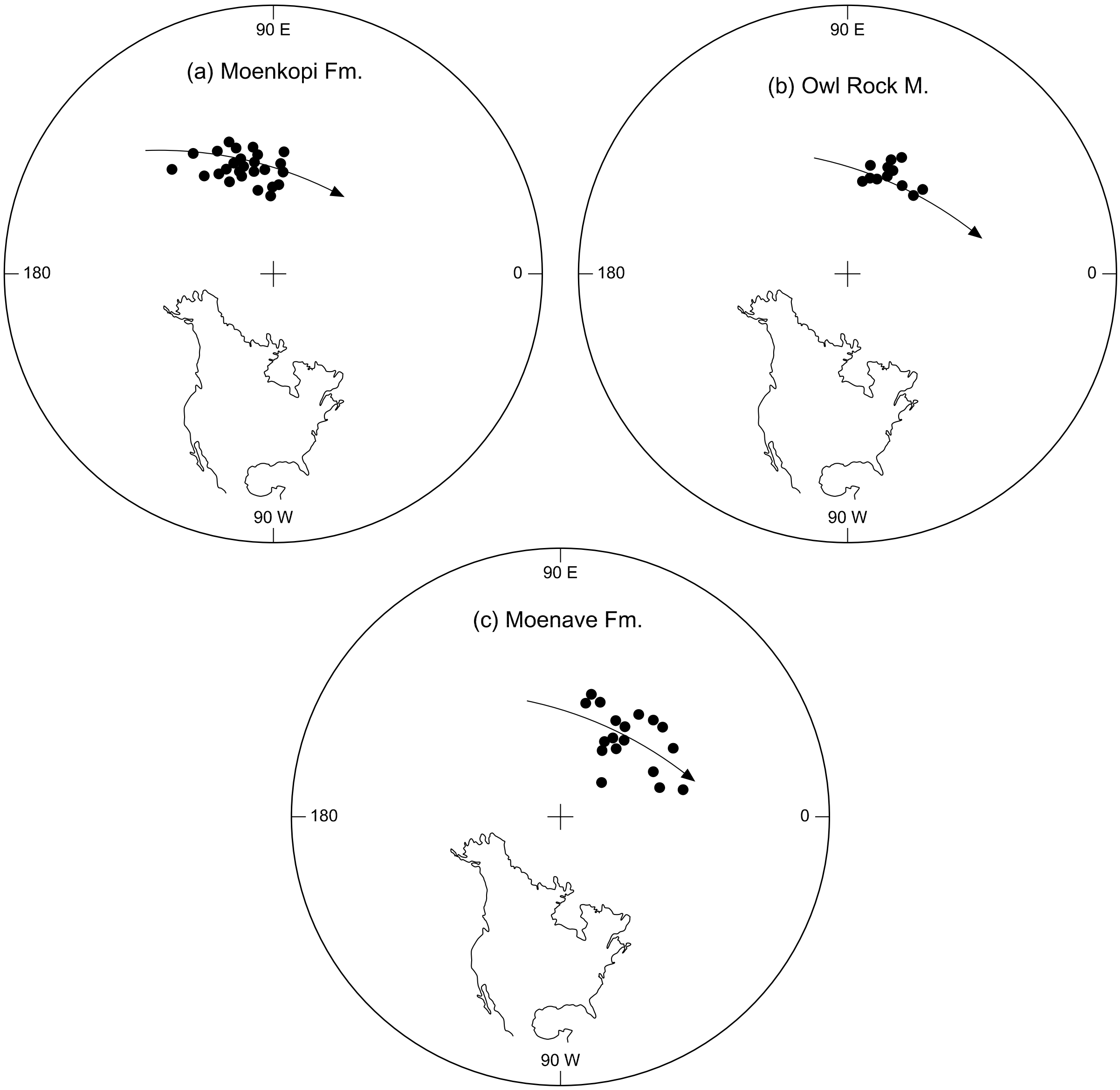

Fig. 4. Several other nearly circular data sets are slightly elongate along the path of APW. (a) Moenkopi Formation (Helsley and Steiner, 1974; Molina-Garza et al., 1991); (b) Owl Rock Member of the Chinle Formation (Bazard and Butler, 1991); (c) Moenave Formation (Ekstrand and Butler, 1989).

Several other Plateau paleomagnetic data sets, although not highly elongate, nevertheless appear to be stretched parallel to the direction of APW; Fig. 4 shows examples. These somewhat elongate distributions may point to a slightly extended period of remanence acquisition. However, because the sampling locations for these units are close to the PEP, the direction-to-pole mapping relationship also may be responsible (compare Fig. 3a). Larson et al. (1982) first noted that Moenkopi directions were elongate parallel to the expected direction of APW.

To summarize, the distributions of some Triassic–Jurassic paleomagnetic data sets from the Colorado Plateau region strongly suggest that remanent magnetization was acquired over periods of up to several tens of millions of years. It remains to examine other alternatives.

3. Other explanations

If it is accepted that the VGP data sets shown in Fig. 2 are elongate along the path of APW, then one or more of several things must be true:

(1) All these units have low paleolatitudes (< 10°; Table 1) and are elongate normal to the paleomeridian. Perhaps some unsuspected attribute of the geomagnetic field at low paleolatitude is responsible.
(2) The elongate units are all Triassic or Jurassic in age. Perhaps elongate sets of VGP are somehow an attribute of that particular time interval.
(3) Perhaps the elongate distributions are the result of geomagnetic secular variation (SV).
(4) If none of these explanations are true, then it seems that conditions of deposition and lithification of these particular rock units must somehow have caused them to acquire their remanent magnetization over a long interval of time.

3.1. Paleolatitude

Table 1 lists three low-latitude Plateau units (Garita Creek Formation, reverse-polarity subgroup of the Kayenta Formation, Redonda member of the Chinle Formation) that have VGP distributions that are nearly circular. Moreover, as shown in Table 2 and Fig. 5, low-latitude units from other regions and other time-periods do not have highly elongate distributions of VGP. Thus, low paleolatitude probably is not responsible.

3.2. Age of rock

The three Plateau units mentioned in the preceding paragraph are Triassic or Early Jurassic in age and are not elongate. Furthermore, rock units of Triassic or Jurassic age from the general Appalachian area (Beck and Housen, 2000) and the South American craton (Beck, 1999) have VGP distributions that are usually elongate. Thus, the age of the rock also cannot explain the distributions seen in Fig. 2.

3.3. Secular variation

This is an extremely unlikely culprit. For SV to account for the shapes seen in Fig. 2 requires it to have been unusually intense, noncircular, and oriented along the APW path. However, SV is a geomagnetic phenomenon arising from causes in the core, whereas APW is mainly the result of the motion of lithospheric plates on the surface. There seems to be no reason why these two processes should be linked.

We conclude that some sedimentary units from the Colorado Plateau area acquired their remanent magnetization over an interval of several tens of millions of years. The elongate units tend to be reddish to brownish mudstones, siltstones and fine-

Table 2
Other low-latitude sites

#	Site	E_p	E_d	λ
1	Dewey Lake Permian red beds, Texas	2.43	2.99	6.4°
2	Gamarri lavas, Pliocene, Ethiopia	2.38	4.81	5.1
3	Gettysberg–Newark Jurassic diabase sills	1.45	3.05	9.3
4	Diabase sills, Jurassic, Liberia	2.38	2.54	0.6
5	Lima-Limo volcanics, Oligocene, Ethiopia	1.37	3.68	0.1
6	Porto Franco volcanics, Jurassic, Brazil	3.20	4.55	8.3
7	Fernando de Noronha basalts, Pliocene, Brazil	1.41	4.25	8.9
8	Wegel Tena volcanics, Oligocene, Ethiopia	1.11	2.84	2.4

E_p , E_d and λ as in Table 1. References: (1) Molina-Garza et al. (1989); (2) Kidane et al. (1999); (3) Beck (1972); (4) Dalrymple et al. (1975); (5) Rochette et al. (1998); (6) Schult and Guerreiro (1974); (7) Schult et al. (1986); (8) Rochette et al. (1998).

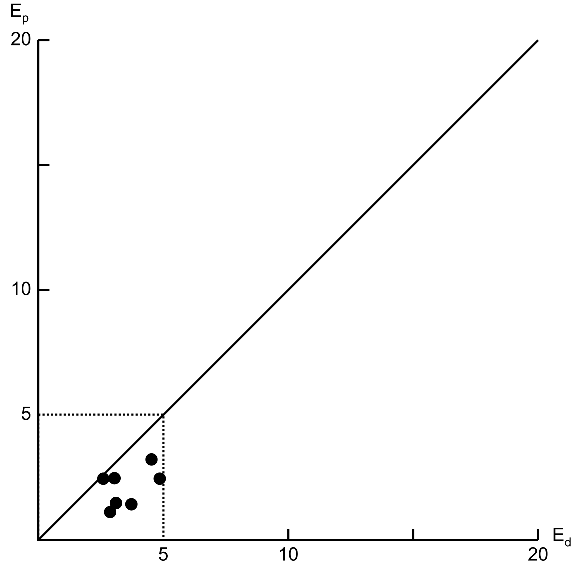

Fig. 5. VGP elongation (E_p) plotted against directional elongation (E_d). Data in Table 2. Compare Fig. 1.

grained sandstones; perhaps the dominant component of their magnetizations is a slowly acquired chemical remanent magnetization. However, the Garita Creek Formation where sampled by Molina-Garza et al. (1996) also is described as a fine-grained reddish to brownish siltstone and sandstone, yet the Garita Creek Formation has a VGP distribution that is nearly circular. The Redonda Member of the Chinle Formation is similar, as is, apparently, the Moenave Formation. These two units are negligibly elongate. Furthermore, the Bluewater Creek Formation where sampled by Molina-Garza et al. (1998) is not a red bed (Molina-Garza, personal communication, 2001). Close petrological and mineralogical examination, accompanied by field tests where it is feasible (e.g., Molina-Garza and Geissman, 1999), will be needed to determine whether there is some lithological record of extended diagenesis that can explain the elongate distributions.

4. Can APW be determined from a single paleomagnetic study?

If a unit acquires its remanent magnetism over a long interval of time during which significant APW occurs (and thus exhibits and unusually elongate VGP distribution), in principal it should be possible to estimate APW from a single study. (This assumes that no other causes of elongation are present; Beck, 1999.) Table 3 provides an illustration.

Table 3 gives best-fit small circles to the data sets indicated. Each set has been rotated counterclockwise by 10.5°, to reverse Laramide rotation of the Colorado Plateau and surrounding areas (Beck and Housen, 2000 and in preparation). The last column gives the angle between the Triassic–Early Jurassic PEP (35.1° N, 246.3° E) and the best-fit small circle given in columns 4 and 5. Clearly, the Anton Chico and Upper Shale Member sets give a reasonably accurate estimate of APW, whereas the Kayenta N and Red Peak sets do not; the Bluewater Creek is intermediate.

From Table 3, whether or not a data set properly defines APW may depend to a great extent on E_p and N. The normal-polarity Kayenta subset and the Red Peak set yield poor estimates of APW; for these sets, N is reasonably large but elongations are small (<8). At the other extreme, N for the Anton Chico and Upper Shale Member VGP sets are large and each has $E_p>8$, although barely so. The remaining study (Bluewater Creek) has a very large elongation but small N; a small circle fitted to these data provides at best a rough estimate of APW.

We performed another numerical experiment to determine under what circumstances one can safely estimate APW from a single data set. First, we created a Fisherian distribution of VGP, then rotated each member of the distribution about an arbitrary rotation pole, the amount of each rotation being chosen randomly to

Table 3
Best-fit small circles to VGP distributions of selected units from the Colorado Plateau area

Unit	N	E_p	N Lat	E Long	R	Δ
Anton Chico	38	8.05	31.3	243.8	90.0°	4.3°
Bluewater Creek	8	11.96	27.0	261.6	81.1	15.4
Kayenta N	17	7.12	− 6.6	248.6	123.7	41.8
Red Peak	13	7.86	59.9	157.3	29.6	59.7
Upper Shale Member	16	9.55	31.7	254.7	91.5	7.8

Unit, N, E_p as in Table 1. N Lat, E Long are north latitude and east longitude of center of best-fit small circle; R is radius. Δ is angular difference between center of best-fit small circle and the Triassic–earliest Jurassic (Pre J1) PEP of Beck and Housen (2000): 35.1° N, 246.3° E, $R=85.1°$.

lie between 0 and some maximum value. Next, we calculated the elongation of the resulting "smeared" data set, then fitted a small circle to it to estimate the position of the rotation pole. We repeated these calculations with different values of N, intrinsic initial scatter, and radius of rotation. To summarize the results: (1) About the best one can expect from this method is a pole that is within 5° or 10° of the true pole. (2) The minimum value of E_p for which a useful pole can be extracted is about 10. (3) The total length of arc is important, hence the larger R (the radius of the small circle), the better. (4) Unless the intrinsic scatter (of the original, "unsmeared" set) is very small, the method is useless.

The Anton Chico and Upper Shale Member sets define APW fairly well because each of these conditions is satisfied. R is nearly 90° for Triassic–Early Jurassic units from the Colorado Plateau area. Each unit is represented by a substantial number of sites; the numerical experiment described earlier suggests that $N \sim 20$ or more will describe APW reasonably well. Finally, the Anton Chico and Upper Shale Member units have values of Fisher's (1953) precision parameter of about 45, even though their VGP data sets are highly elongate; if they were not elongate, their scatter would be much less. The same numerical experiments indicate that the "unsmeared" (that is, nearly circular) value of K for the Anton Chico and Upper Shale Member lies between about 120 and 200. This is far less scattered than usually encountered and probably indicates that nonaxial short-term elements of the geomagnetic field were averaged within-site, because of very prolonged magnetization.

5. The Kayenta problem

The Kayenta Formation posses a difficult problem. As shown in Fig. 6a, normal-polarity VGPs from this unit form a highly elongate distribution that seems to lie along the APW path for pre-J1 time, but the reverse-polarity VGPs clearly do not (Fig. 6b). There are two difficulties with this observation:

(1) The age usually given for the Kayenta Formation is Pliensbachian, which makes it younger than the J1 cusp. Thus, if slow acquisition of magnetization caused the elongation, Kayenta normal-polarity VGPs should be elongate along the J1–J2 track, not the pre-J1 track shown in Fig. 6a. Fig. 6c shows the Kayenta normal subset superimposed on the J1–J2 track (from Beck and Housen, 2000). The pre-J1 track clearly provides the better fit. (Rms errors for Fig. 6a and c are 2.85° and 4.06°, respectively.) Thus, if slow acquisition of remanence is the cause of the elongate distribution of VGP, then the Kayenta Formation would appear to be older than the J1 cusp, implying that either the cusp or the rock unit is misdated.

(2) As shown, reverse-polarity VGPs for the Kayenta Formation are nearly circular but the normal-polarity subset is highly elongate. Data for the Kayenta Formation come from Bazard and Butler (1991) and Steiner and Helsley (1974), who sampled different areas. Both sets of authors reported interbedded normal- and reverse-polarity rocks, and neither mentioned any lithological differences between layers of different polarity. Although they used significantly different laboratory procedures, both sets of authors reported normal-polarity VGPs that are elongate, and reverse-polarity VGPs that are circular.

We do not know how to interpret this second observation; obvious possibilities seem unlikely. (1) Perhaps there is an undetected lithological/mineralogical difference between the normal- and reverse-polarity rocks, such that the ChRM of the normal-polarity rocks is a CRM acquired over a long period of time (during which the field was dominantly normal), whereas the reverse-polarity rocks retain a DRM or a CRM acquired fairly rapidly. (2) Perhaps there was a fundamental difference in characteristics of the different polarity states of the geomagnetic field while the Kayenta Formation was being magnetized. This difference would have to include markedly different secular variation behavior during the two polarity states, as well as alignment of the long-axis of normal-polarity VGP parallel to the path of APW. (3) Perhaps there was a failing in laboratory technique. For instance, it is possible (although not likely) that the normal-polarity samples retain a normal-polarity overprint that was eliminated in the

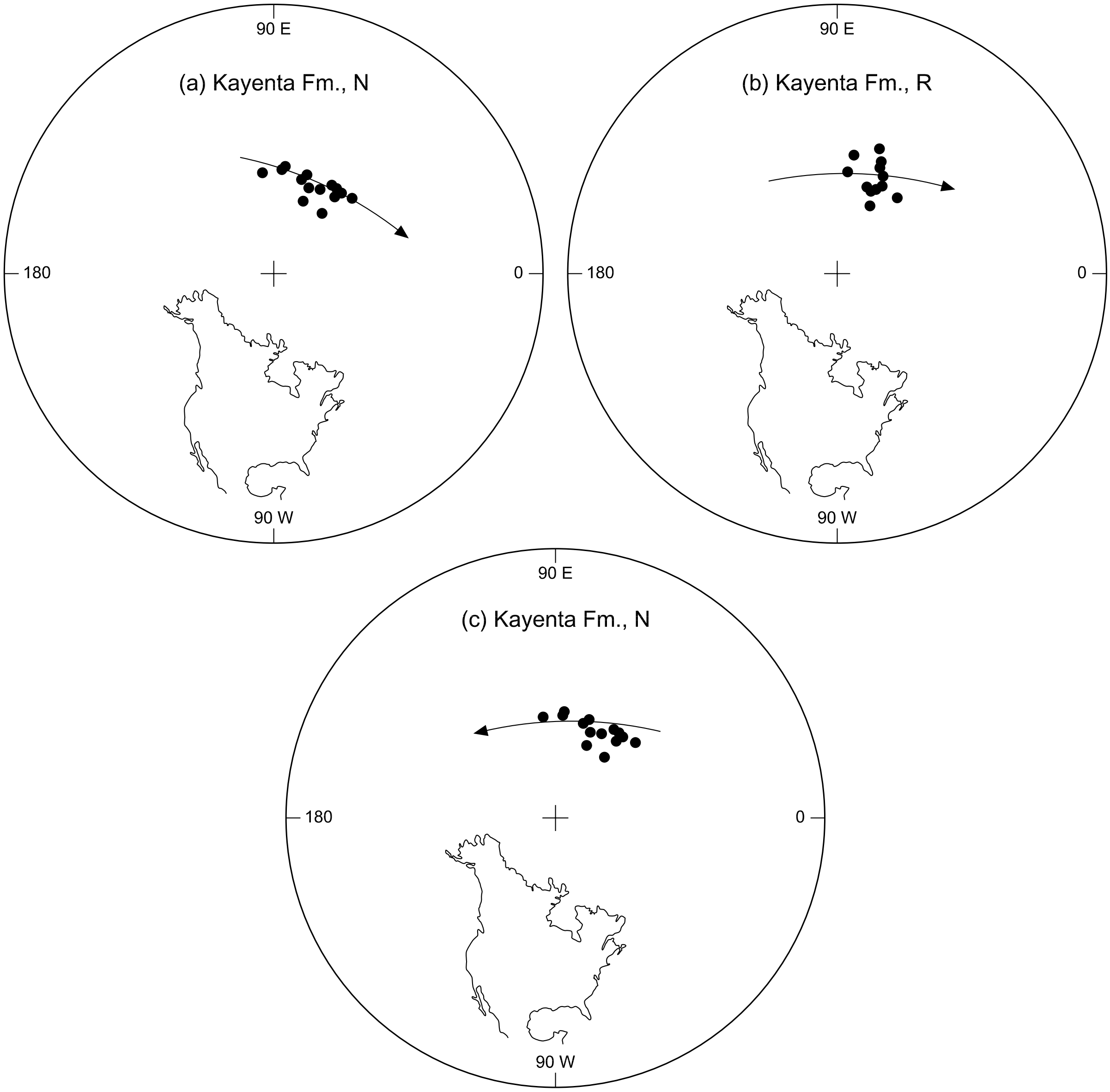

Fig. 6. Kayenta Formation. (a) VGP for sites of normal polarity; the pre-J1 APW path is shown. (b) VGP for sites of reverse polarity; same APW path. (c) *N* polarity sites shown with post-J1 APW path.

reverse-polarity samples. This might come about, for instance, because a normal-polarity overprint would be somewhat easier to be recognized in a sample with a reverse ChRM than in one with a normal ChRM. A thorough restudy of the Kayenta Formation seems indicated.

6. Conclusions

Shape analysis indicates that several sedimentary units of the Colorado Plateau area (mainly red to brown fine-grained clastics) acquired their remanent magnetizations over an extended period of time, perhaps ranging up to several tens of millions of years. However, other superficially identical rock units appear to have been magnetized much more quickly. The latter units furnish important data for the study of APW, whereas paleomagnetic poles from the former should be used with caution.

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