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Absolute velocity of North America during the Mesozoic from paleomagnetic data

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Abstract

We use paleomagnetic data to map Mesozoic absolute motion of North America, using paleomagnetic Euler poles (PEP). First, we address two important questions: (1) How much clockwise rotation has been experienced by crustal blocks within and adjacent to the Colorado Plateau? (2) Why is there disagreement between the apparent polar wander (APW) path constructed using poles from southwestern North America and the alternative path based on poles from eastern North America? Regarding (1), a 10.5° clockwise rotation of the Colorado Plateau about a pole located near 35°N, 102°W seems to fit the evidence best. Regarding (2), it appears that some rock units from the Appalachian region retain a hard overprint acquired during the mid-Cretaceous, when the geomagnetic field had constant normal polarity and APW was negligible.

We found three well-defined small-circle APW tracks: 245–200 Ma (PEP at 39.2°N, 245.2°E, R = 81.1°, root mean square error (RMS) = 1.82°), 200–160 Ma (38.5°N, 270.1°E, R = 80.4°, RMS = 1.06°), 160 to ~125 Ma (45.1°N, 48.5°E, R = 60.7°, RMS = 1.84°). Intersections of these tracks (the "cusps" of Gordon et al. [Tectonics 3 (1984) 499]) are located at 59.6°N, 69.5°E (the 200 Ma or "J1" cusp) and 48.9°N, 144.0°E (the 160 Ma or "J2" cusp). At these times, the absolute velocity of North America appears to have changed abruptly.

North America absolute motion also changed abruptly at the beginning and end of the Cretaceous APW stillstand, currently dated at about 125 and 88 Ma (J. Geophys. Res. 97 (1992b) 19651). During this interval, the APW path degenerates into a single point, implying rotation about an Euler pole coincident with the spin axis.

Using our PEP and cusp locations, we calculate the absolute motion of seven points on the North American continent. Our intention is to provide a chronological framework for the analysis of Mesozoic tectonics. Clearly, if APW is caused by plate motion, abrupt changes in absolute motion should correlate with major tectonic events. This follows because large accelerations reflect important changes in the balance of forces acting on the plate, the most important of which are edge effects (subduction, terrane accretion, etc.). Some tectonic interpretations: (1) The J1 cusp may be associated with the inception of rifting of North America away from land masses to the east; the J2 cusp seems to mark the beginning of rapid spreading in the North Atlantic. (2) The J2 cusp signals the beginning of a period of rapid northwestward absolute motion of western North America; motion of tectonostratigraphic terranes in the westernmost Cordillera seems likely to have been directed toward the south during this interval. (3) The interval ~88 to ~80 Ma saw a rapid decrease in the paleolatitude of North America; unless this represents a period of true polar wander, terrane motion during this time should have been relatively northward.
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1. Introduction

How motion of a plate, continent or continental fragment is described depends on the reference frame. Most commonly, motion is measured with respect to another element of Earth's surface; for instance, North America's motion with respect to the mid-Atlantic ridge. Techniques for obtaining this kind of (relative) motion are well established (e.g., Morgan, 1968). Morgan (1971), following Wilson (1965), also introduced the concept of "absolute" motion, defined as motion with respect to the deep interior of the earth. His reference frame was the galaxy of hotspots, assumed to be fixed with respect to one another (and reasonably fixed with respect to Earth's spin axis).

The paleomagnetic Euler pole (PEP) concept of Gordon et al. (1984) offers another way to measure absolute motion. These authors reasoned that, if apparent polar wander (APW) is caused by motion of a crustal block with respect to the pole, the APW path should define a small circle centered on the Euler pole describing motion of the block with respect to the spin axis. Thus, PEP tracks (small-circle segments of the APW path) should permit direct measurement of motion of a continent or continental fragment with respect to Earth's axis of rotation. If hotspots are fixed with respect to the spin axis, the two methods (hotspot and PEP analysis) should yield identical motions.

In this paper, we use a set of published paleomagnetic poles to formulate a description of absolute motion of Mesozoic North America. One obvious value of such a formulation is tectonic; abrupt changes in plate motion (the "cusps" of Gordon et al., 1984) should correlate with important changes in the balance of forces driving and resisting plate motion, e.g., the physical processes controlling plate margin tectonics. However, in this paper, we do not attempt to suggest tectonic correlations, except superficially. Instead, we hope that regional geologists will examine our chronology of changes in plate motion in light of their independent reading of North American Mesozoic tectonics. If good correlations exist, the nature of the change in absolute motion may provide a valuable clue to the cause of specific tectonic events. On the other hand, lack of correlation between major tectonic and APW events may point to unsuspected problems, with the geology, with the PEP concept or even with some of the fundamental assumptions of paleomagnetism.

Data sets used in this analysis were assembled using the IAGA paleomagnetic database, eliminating all poles derived from rocks on the western edge of the continent where terrane displacements are pervasive. Poles about which there were significant doubts concerning age and/or tectonic history also were eliminated. Many entries were recalculated, to eliminate poorly determined site-mean directions (defined for our purposes as $\alpha_{95}>15°$ and/or $N<3$).

2. A fundamental assumption and some questions

The principal assumption underlying this research is that paleomagnetism can determine ancient positions of the geographic pole. This is the well-known "geocentric axial dipole" (GAD) hypothesis of paleomagnetism (e.g., Butler, 1992). Evidence supporting the GAD hypothesis is strong, but exceptions have been proposed (e.g., Westphal, 1993; Van der Voo and Torsvik, 2001). It remains possible—although in our opinion extremely unlikely—that peculiarities of geomagnetic behavior could produce a pattern of paleomagnetic poles that mimic a PEP track.

Several important questions need to be answered before attempting to use PEP analysis to determine North American absolute motion.

(1) Does the PEP method provide a robust description of APW? This can be tested directly, using abundant new data acquired since the previous PEP analyses of Gordon et al. (1984) and May and Butler (1986).

(2) Much of the data used to define North American APW comes from the southwestern U.S. (Arizona, Colorado, Utah and New Mexico). Many paleomagnetic poles from that region are derived from rocks on the Colorado Plateau. Based on regional structural patterns, Livaccari (1979) and Hamilton (1981) proposed that the Plateau rotated clockwise with respect to the craton during the Laramide orogeny. Most investigators apparently accept this view, but the amount of rotation is disputed (e.g., Steiner, 1986; Bryan and Gordon, 1990; Molina-Garza et al., 1998a; Kent and Witte, 1993). In addition, areas adjacent to, but not on,

the Plateau also may have undergone clockwise rotation (e.g., Molina-Garza et al., 1991; Hagstrum et al., 1994). Thus, we must answer several questions: How much has the area rotated? What is the best pole to use to "unrotate" the southwestern results?

(3) For most of Jurassic time, there are important differences in the North American APW path as constructed using poles from the southwest and the path determined from poles in the Appalachian area. Hagstrum (1993) provides a summary; see also Bazard and Butler (1994), Van Fossen and Kent (1990), Van der Voo (1992) and Courtillot et al. (1994). Briefly, poles from rocks from the southwest lie along a well-defined small circle at comparatively low latitudes for most of Jurassic time, whereas Appalachian poles of the same age lie at higher latitudes and do not fall on an obvious small circle. Which is correct and what causes the difference?

3. Triassic APW and a test of the PEP concept

The best way to refute a geologic hypothesis is with new data; if the hypothesis fails to explain the new data, it should be abandoned. The PEP hypothesis unmistakably survives the test of new Triassic paleomagnetic data (Fig. 1). The Gordon et al. (1984) Triassic PEP (Fig. 1a) was based on 12 individual pole positions. Our newer calculation (Fig. 1b) uses 19 poles (Table 1), only 2 of which were available in 1984. Despite this almost total difference in input data, a visual comparison shows that the two paths are very similar. In Fig. 1c, we show our new data set plotted against a small circle centered on the Gordon et al. (1984) PEP. The RMS misfit for Fig. 1c is 3.24°, only marginally larger than the minimum misfit (3.09°). It is clear that the PEP method provides a useful description

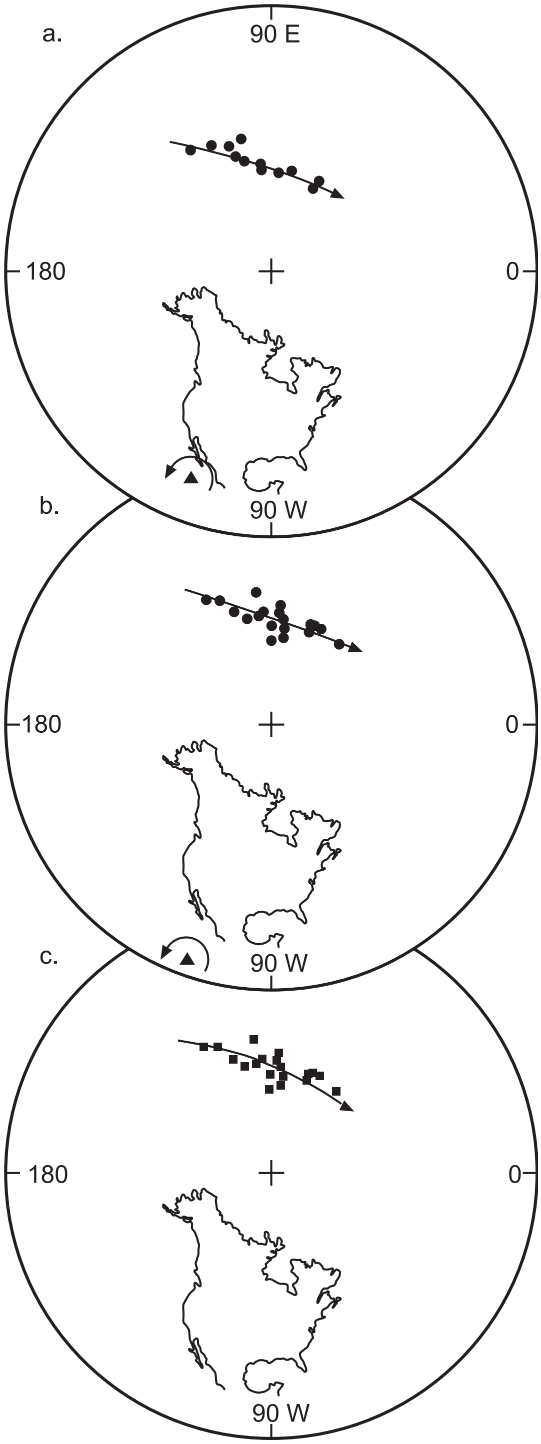

Fig. 1. APW with respect to North America for the Triassic and early Jurassic. Circles are paleomagnetic poles; triangles are PEP. Arrow partly surrounding the PEP gives the sense of rotation; arrows on small circle show the resulting direction of APW. (a) Triassic–early Jurassic data set, PEP and small circle of Gordon et al. (1984). (b) Pre-200 Ma data set, PEP and small circle from this paper. (c) Data from this paper (squares) plotted against the PEP of Gordon et al. (1984).

Table 1
Triassic and early Jurassic reference poles for North America

#	Unit	Age	N	A_{95}	Lat./Long.	Lat./Long.-R
1	Moenave Fm	Sinemurian	22	4.7	58.1/51.3	60.6/71.3
2[a]	Newark 1	200 Ma	10	2.3	63.0/83.2	
3	Baked Newark seds	200	23	4.7	59.7/68.8	
4[a]	Watchung basalts	200	17	4.7	64.2/91.1	
5	U. Newark Fm.	Hettangian	9	6.6	54.8/94.4	
6	Church Rock Fm.	U. Norian	8	8.4	56.7/63.3	57.5/82.6
7	Redonda Fm.	U. Norian	5	7.1	60.1/82.9	57.9/102.8
8	Owl Rock Fm.	M. Norian	13	3.1	56.8/66.8	57.0/86.1
9	M. Newark Fm.	Norian	9	6.2	56.0/97.5	
10	Petrified Forest Fm.	Norian/Carnian	65	3.0	57.2/68.3	57.2/87.7
11	Manicouagan str.	215	10	6.1	59.6/90.2	
12	U. Shale Fm.	L. Norian	16	5.5	57.2/84.9	54.8/103.2
13	Garita Creek Fm.	U. Carnian	12	4.4	52.9/86.3	50.4/102.8
14	Bluewater Creek Fm.	U. Carnian	8	7.9	55.2/87.0	52.6/104.3
15	L. Newark Fm.	U. Carnian	8	6.1	53.1/108.5	
16[a]	Maine plugs	225	12	2.3	48.3/97.1	
17	Moenkopi Fm.	L. Triassic	32	2.8	56.2/103.5	51.4/119.4
18	Anton Chico Mbr.	L. Anisian	38	3.6	45.8/117.8	39.6/129.4
19	Red Peak Mbr.	L. Triassic	13	3.5	47.9/112.9	

Lat./long. = north latitude/east longitude of paleomagnetic pole, lat./long.-R = pole rotated 10.5° about 35°N, 102°W (SW group only), N = number of sites, A_{95} = circle of 95% confidence. References: (1) Ekstrand and Butler (1989); (2) Smith and Noltimier (1979); (3) Kodama et al. (1994); (4) McIntosh et al. (1985); (5) Witte and Kent (1990); (6) Kent and Witte (1993); (7) Reeve and Helsley (1972); (8) Bazard and Butler (1991); (9) Witte et al. (1991); (10) Steiner and Lucas (2000); (11) Larochelle and Currie (1967), Robertson (1967); (12) Bazard and Butler (1991); (13) Molina-Garza et al. (1996); (14) Molina-Garza et al. (1998b); (15) Witte and Kent (1989); (16) Fang and Van der Voo (1988); (17) Helsley and Steiner (1974), Molina-Garza et al. (1991); (18) Steiner and Lucas (1992), Molina-Garza et al. (1996); (19) Van der Voo and Grubbs (1977), Shive et al. (1984).

CG, Chinle Group; MF, Moenkopi Formation; CF, Chugwater Formation.

[a] Not used in PEP calculations.

of North American APW, at least for the early Mesozoic.

4. Western and eastern subsets, and the problem of plateau rotation

Our Triassic–early Jurassic data set (Table 1) contains 8 poles from eastern North America and 11 from the southwest. Fig. 2 shows these subsets; the small circle and PEP shown are those of Fig. 1b. The western subset (Fig. 2a) gives a good visual fit to the small circle, but the eastern subset (Fig. 2b) does not. (RMS misfit is 2.3° for Fig. 2a and 4.1° for Fig. 2b.) However, much of the eastern-subgroup misfit is caused by three poles (2, 4, 16; Table 1). These poles represent igneous rocks that may retain a hard secondary overprint, as argued below. Also, between-site scatter for pole 16 is extremely small, suggesting that geomagnetic secular variation may not have been completely averaged. Eliminating these three entries reduces the RMS misfit to 1.6° (Fig. 2c). In subsequent calculations, we omit poles 2, 4 and 16, although the effect of retaining them is small. Without these three poles, the best-fit pre-200 Ma small circle is: 18.9°N, 252.5°E, R = 102.8°, RMS misfit = 1.96°. For all practical purposes, this is identical to the Gordon et al. (1984) 200–300 Ma PEP.

The five remaining eastern poles (Fig. 2c) represent an interval of ~ 25 m.y. (late Carnian to early Sinemurian). Eight southwestern poles represent this same time span. A plot of the means of these two groups (Fig. 2d) clearly demonstrates that the southwestern subgroup is displaced with respect to the eastern subgroup.

On the basis of regional geology, Hamilton (1981) proposed that the entire Colorado Plateau rotated clockwise as a rigid block during the Laramide orogeny. He suggested that the pole of rotation lay somewhere immediately east of the rotating block.

The amount of relative rotation of the Plateau is disputed. Hamilton (1981) favored a rotation of

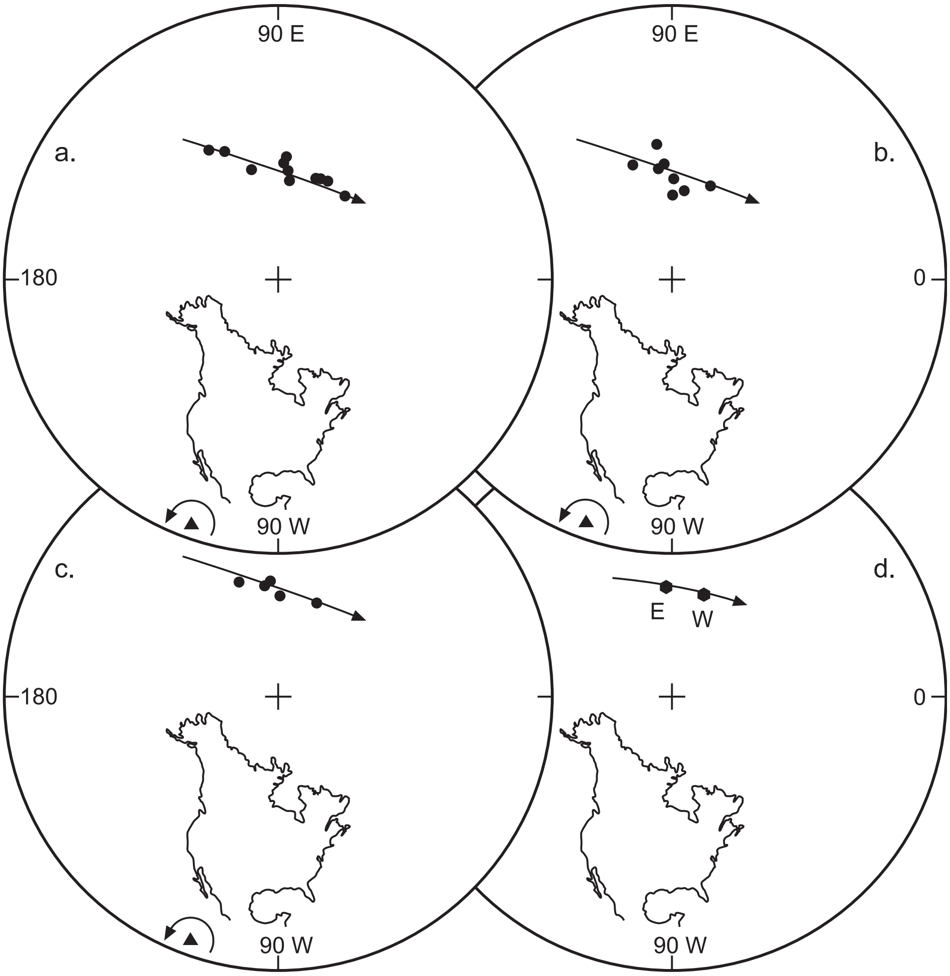

Fig. 2. Pre-200 Ma poles from the southwest (a), from eastern North America (b) and from eastern North America with three poles rejected (c). (d) shows means of southwestern and eastern groups. Hexagons are means of groups of poles; other symbols as in Fig. 1.

about 4°, based on the orientation and displacement of Laramide structures nearby. Bryan and Gordon (1990) obtained a similar result, using a method that minimized misfit to their PEP tracks. On the other hand, Steiner (1986) and Kent and Witte (1993) used direct pole-to-pole comparisons and obtained estimates of roughly 10°. Molina-Garza et al. (1998a) also compared Plateau and cratonal poles, using a method that did not rely on the choice of PEP track, but that was sensitive to the location of the rotation pole; their preferred estimate of rotation was about 7°. In a later study, Hamilton (1988) increased his (geological) estimate of total rotation to 8°.

Paleomagnetic estimates of Plateau rotation are complicated by the fact that there also have been rotations off the Plateau. For instance, Hagstrum et al. (1994) found clockwise rotations ranging up to several tens of degrees throughout a large area south of the Plateau, and Molina-Garza et al. (1991) proposed a small clockwise rotation of portions of central New Mexico. For the purposes of this paper, it is necessary to "correct" (unrotate) poles from the southwest. Lacking the information needed to treat each pole individually, we will treat the entire southwestern subset as if it came from a single block. To avoid problems with precise stratigraphic correlation and to allow errors in individual pole locations to "average out", we base our estimate of rotation on the mean values of eastern and southwestern poles for the interval 225–200 Ma (Fig. 2d). These means are 57.3°N, 93.8°E for the eastern subset and 57.4°N, 74.1°E for the southwestern subset. The amount of Plateau rotation thus is equal to the angle subtended by these two points at the pole of relative rotation between the SW area and the craton. However, the precise location of this pole is unknown.

We tested three rotation poles: (1) 35°N, 102°W, near the preferred location of Hamilton (1981); (2) 38°N, 115°W, a point within the Plateau itself; (3) 55°N, 136°W, calculated by Molina-Garza et al. (1998a) in the study mentioned earlier. Rotation angles vary little between these three choices (Table 2) and are all about 10–11°.

It should also be possible to search for the best PEP by finding the spot that minimizes misfit to a small circle. We tested the three options of the preceding paragraph in this way, by rotating the southwest set of poles counterclockwise by the angles given in Table 2, then combining these restored poles with the eastern subset and calculating a best-fit small circle. RMS errors for the three cases are similar (Table 2).

On several grounds, it appears that a rotation of 10.5° about 35°N, 102°W is the best choice (Fig. 3). Not only does it minimize misfit, it fits the geology best. Hamilton (1981) proposed that the Colorado Plateau had rotated clockwise because Laramide structures are contractional east and northeast of the Plateau and extensional to the south. For clockwise rotations, this requires a pole located somewhere east of the Plateau. For the remainder of this paper, we will use the rotation of line 1, Table 2 to "restore" poles from the southwest. An exhaustive computer search might turn up a slightly better choice, but any difference would be insignificant.

Table 2
Alternative paleomagnetic Euler poles for pre-J1 time

Rotation	λ	ϕ	R	RMS
1	39.2°N	245.2°E	81.1°	1.82°
2	38.4	245.8	83.1	2.00
3	41.9	248.5	81.1	2.40

Testing Colorado Plateau rotations.
λ, ϕ are latitude and longitude of paleomagnetic Euler pole. R is radius of best-fit small circle. RMS is root mean square misfit. Rotations: (1) 10.5° about 35N, 102W; (2) 10.3° about 38N, 115W; (3) 11.2° about 57.4N, 136W.

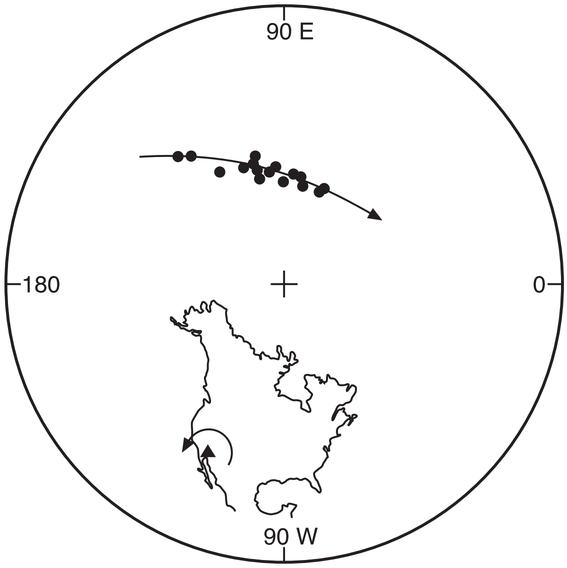

Fig. 3. North American APW, 250–200 Ma. Symbols as in Fig. 1. Southwestern poles corrected for 10.5° of clockwise rotation, about 35°N, 102°W. Three eastern poles eliminated (see Table 1).

5. Mid-Jurassic APW and Cretaceous remagnetization

There is a clear difference between patterns of mid-Jurassic (Hettangian–early Callovian) APW defined by poles from the southwest and their coeval eastern equivalents (Table 3, Fig. 4). As shown, the southwestern subset gives an excellent fit to a small circle, whereas the eastern does not. From Fig. 4, the eastern subset appears to be streaked toward the present spin axis, suggesting that a recent overprint has survived magnetic cleaning.

However, survival of a recent overprint in these rocks is unlikely. For instance, the Moat Volcanics were cleaned thermally to over 600°, and the Newark B pole, although interpreted as secondary, represents results after thermal demagnetization in the range 300–680°. The case for the remaining two eastern poles (5, 6; Table 3) is weaker, because these rocks were cleaned using the alternating field method.

Table 3
Selected Hettangian to lower Callovian reference poles for North America

No.	Unit	Age	*N*	A_{95}	Lat./Long.	Lat./Long.-R
1	Summerville Fm.	L. Callovian	10	7.4°	56.2/130.8	48.8/142.7
2	Moat Volc.	165 Ma	9	7.4	78.7/90.3	
3	Corral Canyon Volc.	172	11	6.9	61.8/116.1	55.6/132.0
4	Newark B	~175	24	3.2	72.0/90.0	
5	Newark ignrx 2	~175	156	1.4	65.3/103.2	
6	S. Carolina diabase	190	14	7.4	66.6/107.6	
7	Kayenta Fm	Pliensbachian	30	2.3	59.9/67.3	59.9/88.2
8	Moenave Fm.	Sinnemurian	22	4.7	58.1/51.3	60.6/71.3
9	Sugarloaf Fm.	Hettangian	30	9.1	57.7/81.3	

Lat./long. = N latitude and east longitude of pole, with no correction for rotation. Lat./long.-R = latitude and longitude of pole after correction for a rotation of 10.5° about an Euler pole at 35°N, 102°W. References: (1) Bazard and Butler (1992); (2) Van Fossen and Kent (1990), May et al. (1986); (4) Witte and Kent (1989, 1990); (5) Smith and Noltimier (1979); (6) Dooley and Smith (1982); (7) Steiner and Helsley (1974), Bazard and Butler (1991); (8) Ekstrand and Butler (1989); (9) McEnroe and Brown (2000).

We speculate that some Appalachian poles may retain an overprint, but one acquired during the Cretaceous rather than in the present field (Fig. 5). As shown, poles from late Triassic–early Jurassic igneous rocks of the northern and central Appalachians (Seguin et al., 1981) are distributed along a great circle connecting the J1 cusp (~ 200 Ma; see below) with the mid-Cretaceous pole of Van Fossen and Kent (1992a). In Fig. 5, curve A is a small-circle fit to the southwestern subset of Table 4 and curve B is a great circle connecting the J1 cusp and mid-Cretaceous pole. Rocks magnetized during the interval 200–160 Ma should have poles that fall along curve A, as several clearly do. Alternatively,

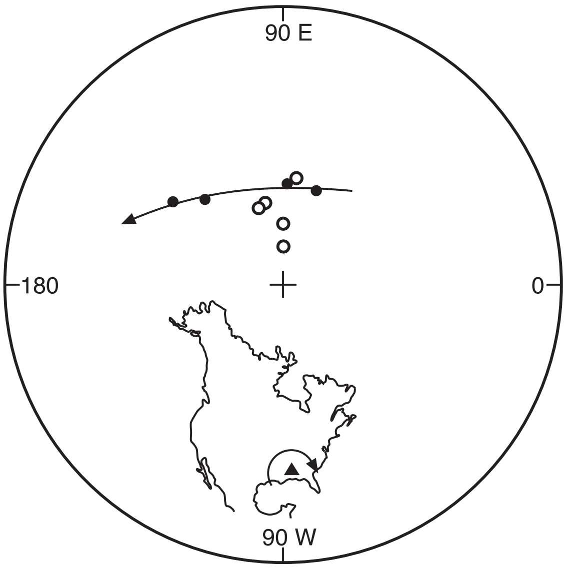

Fig. 4. North American APW, 200–160 Ma. Hollow symbols indicate eastern poles. Other symbols as in Fig. 1.

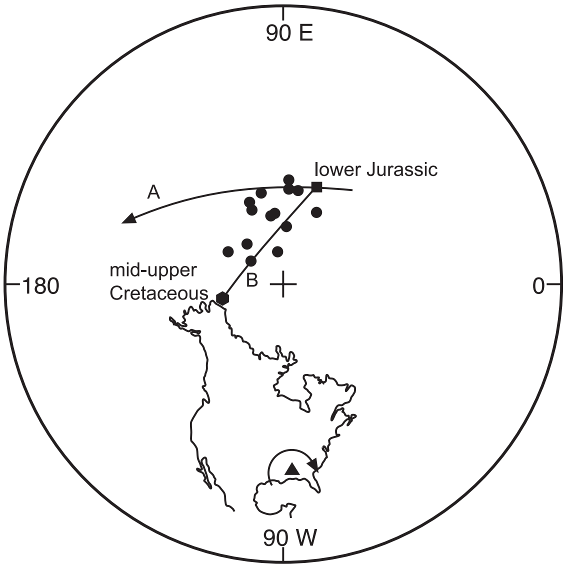

Fig. 5. Paleomagnetic poles from northern Appalachian igneous rocks (Table 1 of Seguin et al., 1981). Hexagon is mid-Cretaceous stillstand pole of Van Fossen and Kent (1992a,b). Curve A is 200–160 Ma North American APW; curve B is a great circle between the J1 cusp (square) and the mid-Cretaceous stillstand. Rocks formed at J1 time, then partially remagnetized during the Cretaceous, should have poles lying near curve B.

Table 4
Selected paleomagnetic poles from Appalachian igneous rocks

Ref. #	Unit	N Lat.	E Long.
1	Connecticut dikes	64.3	102.1
2	Maryland ig rxs	68.0	105.3
3	Md/Pa sills	62.0	104.5
4	Avalon ig rxs, N'flnd	73	88
5	New Brunswick ig rxs	74.1	98.3
6	Massachusetts lavas	59	88
7	Watchung basalts	63.0	90.1
8	N. Carolina, NW dikes	52.8	60.2
9	N. Carolina, N-S dikes	71.5	53.5
10	S. Carolina dikes	64.1	83.4
11	Georgia, N. Carolina dikes	64.9	80.1
12	Sassamansville diabase	71.8	136.5
13	Moat Volcanics	78.7	90.3
14	Holden diabase	60.1	80.5
15	Ware diabase	73.5	85.8
16	Pelham-Loudville diabase	65.3	95.6

References: (1) Smith (1976), Smith and Noltimier (1979); (2) Smith (1976); (3) Beck (1972); (4) Hodych and Hayatsu (1980); (5) Carmichael and Palmer (1968), Seguin et al. (1981); (6) Irving and Banks (1961); (7) McIntosh et al. (1985); (8, 9) Smith (1987); (10) Dooley and Smith (1982), Bell et al. (1979); (11) Watts, from Dooley and Smith (1982); (12) Kodama and Mowery (1994); (13) Van Fossen and Kent (1990); (14–16) McEnroe and Brown (2000).

poles from rocks that formed near J1 time but were partially remagnetized during the Cretaceous should fall along curve B. Seven poles fit this description. Poles that plot within the wedge-shaped area between curves A and B may have been magnetized (or remagnetized) during the early or middle Jurassic, then partially remagnetized during the Cretaceous.

Appalachian igneous rocks in general conform to this same pattern (Fig. 6; data in Table 4). Fig. 6 differs from Fig. 5 in that it includes newer data, as well as poles from the southern Appalachians. To minimize scatter, we excluded several older studies of single dikes or flows that are unlikely to average secular variation. Streaking toward the Cretaceous reference pole is clearly evident.

If there is a tendency for Appalachian rocks to retain a mid-Cretaceous partial remagnetization, it remains to consider why such a tenacious overprint might have been acquired by these rocks, but not by coeval rocks in the American southwest.

An important attribute of mid-Cretaceous time is that it was free from polarity transitions; the field had normal geomagnetic polarity for >30 m.y. Equally unusual is the fact that there was essentially no APW relative to North America during that time. Thus, any North American rocks already in existence experienced an unvarying field for 30 m.y. or more. This may help to account for acquisition of an extremely hard secondary magnetization.

All the rocks involved in Fig. 5 and most of those in Fig. 6 were magnetically cleaned by the alternating field (a.f.) method. According to Dunlop and Özdemir (1997), a.f. demagnetization may fail to eliminate a viscous overprint held in high coercivity, small volume grains. Magnetite-bearing rocks exposed to a unidirectional ambient field for over 30 m.y. might be expected to acquire a strong partial remagnetization, part of which would reside in such grains. Most studies of Appalachian igneous rocks shown in Figs. 5 and 6 were a.f. demagnetized at < 30 mT, hence may retain some Cretaceous overprint.

However, thermal demagnetization should remove even a very hard single-domain overprint. From Pullaiah et al. (1975), a magnetization acquired at surface temperature in 30 m.y. unblocks at approximately 275° if carried by magnetite or 400° if carried by hematite. Even if the rocks were at

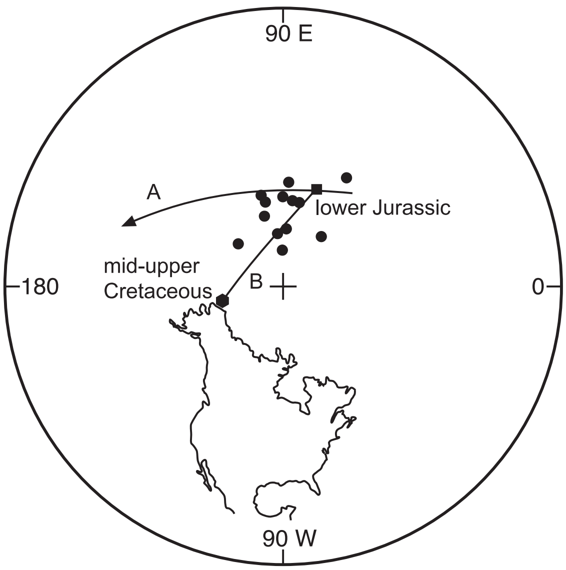

Fig. 6. Paleomagnetic poles from northern and central Appalachian igneous rocks, including newer data. Symbols as in Fig. 5. Data in Table 4.

100° C for 30 m.y., peak temperatures of 300° (magnetite) or 450° (hematite) should erase any overprint, provided that it resided in single-domain grains.

The Moat Volcanics and Newark B poles thus are difficult to explain in terms of Cretaceous partial remagnetization. The rocks from which these poles were derived were thermally demagnetized to over 600°; hence, any secondary magnetization residing in single-domain grains should have been eliminated. Perhaps, the answer lies in the nature of the magnetic carriers. Dunlop and Xu (1994) show that, in a multidomain assemblage, a partial thermal magnetization with peak temperature (T_0) below the Curie temperature (T_c) will unblock over a temperature range extending from T_0 nearly to T_c. Such overprints, when recognized by low-temperature demagnetization, have been shown to significantly affect the direction of characteristic remanence (Dunlop et al., 1997). In light of this, perhaps some partial thermal remagnetization associated with the emplacement of nearby 122 Ma Cretaceous intrusions (Van Fossen and Kent, 1992a) survived laboratory demagnetization in the case of the Moat Volcanics and some other Appalachian rocks. In contrast, rocks from the southwest are largely sedimentary, were thermally demagnetized, and no nearby source of heat to promote remagnetization is known.

A similar case of strong Cretaceous remagnetization is found in sedimentary and volcanic rocks near the Sierra Nevada (Mankinen, 1978; Russell et al., 1982).

6. The J1 cusp

Gordon et al. (1984) proposed the term "cusp" for the intersection of two APW "tracks". Thus, a cusp records an abrupt change in direction of APW.

Our choice of J1 cusp is defined by the intersection of small circles centered at 39.2°N, 245.2°W (R = 81.1°) for the Triassic and earliest Jurassic, and at 38.5°N, 270.1°E (R = 80.4°) for the middle and later Jurassic (Fig. 7). The pole to the Pre-J1 track is based on restored southwestern data combined with all eastern data except poles 3, 5 and 16 of Table 1. The post-J1 PEP represents only southwestern data.

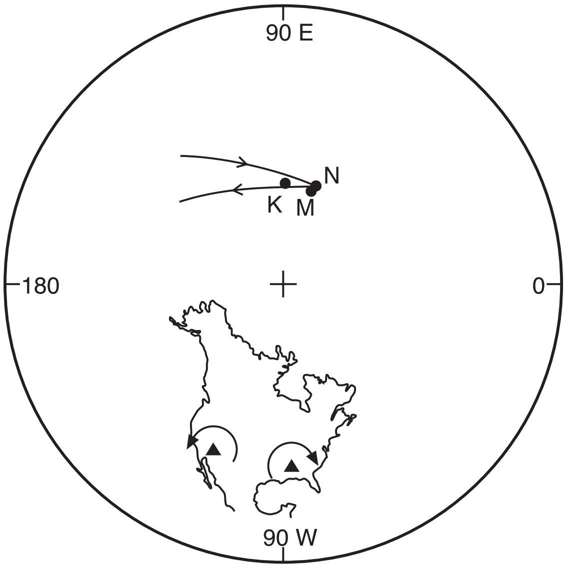

Fig. 7. The J1 cusp. At J1 cusp time, absolute motion of North America reversed abruptly. Nearby poles for the Kayenta (K), Newark baked sediments (N) and Moenave (M) plot near the J1 cusp and serve to date it (~ 200 Ma). Rotation poles (triangles) are 245–200 Ma (SW North America) and 2090–160 Ma (SE North America).

The intersection of these two tracks is at 59.6°N, 69.5°E.

To date the J1 cusp, we must look to poles that lie nearby (Fig. 7). Of these, the Moenave and Newark baked sediments poles are closest to the cusp and serve to date it, at about 200 Ma. The coincidence of the Moenave with the J1 cusp was previously recognized by Ekstrand and Butler (1989).

7. Late Jurassic to mid-Cretaceous APW and the J2 cusp

In late Callovian–early Oxfordian time North American APW appears to have changed direction abruptly, defining another cusp. This interpretation is based on the fact that four late Jurassic reference poles from the southwest and the mid-Cretaceous reference pole (Van Fossen and Kent, 1992a; McEnroe, 1996) define a clear small-circle segment (Fig. 8) that intersects the mid-Jurassic small circle at a high

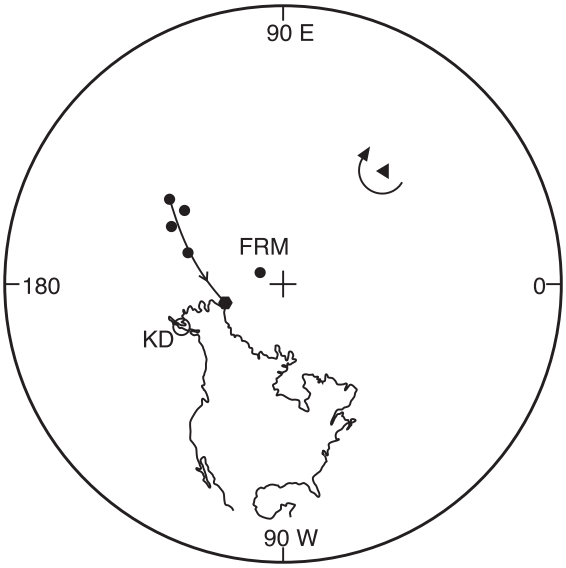

Fig. 8. North American APW, 160–125 Ma. Data in Table 6. Symbols as in Figs. 1 and 5. Hollow circle (KD) is kimberlite dike pole (Van Fossen and Kent, 1993). FRM is the Front Range Morrison pole of Van Fossen and Kent (1992b).

angle. The intersection—the J2 cusp—is at 48.9°N, 144.0°E (Fig. 9).

Paleomagnetic data for the late Jurassic through mid-Cretaceous are summarized in Table 5. The small circle shown (Fig. 8; 45.2°N, 48.3°E, $R = 60.6$, RMS = 1.82°) is fitted to poles 1, 3, 4, 5 and 7; the Cretaceous stillstand pole and four poles from the southwest. Two other poles of the correct age are omitted, as discussed below.

We have chosen to omit pole 6 (FRM, Fig. 8)—the Front Range Morrison pole of Van Fossen and Kent (1992b)—because we believe it represents a Tertiary remagnetization. New results from the Morrison Formation in the Black Hills (P. Gregoire et al., submitted; Fig. 9) yield a result that is virtually identical to the Front Range Morrison pole—and to the Eocene reference pole of Diehl et al. (1983). Gregoire et al. believe that the Black Hills rocks were remagnetized during Laramide regional uplift and igneous activity. Because of its similarity in pole position and its location in a zone of Laramide deformation, the same may be true of the Front Range Morrison pole. It is possible, of course, that the Front Range and Black Hills poles represent the true position of APW in the late Jurassic and the similarity of late Jurassic and Laramide pole positions is a coincidence, although this seems unlikely.

The remaining pole (KD; Fig. 8) presents a difficult problem. Pole KD is a result from seven kimberlite dikes near Ithaca, NY (Van Fossen and Kent, 1993). Van Fossen and Kent (1993) argue that this pole represents a valid point on the North American APW path. If so, it records an episode of APW that cannot easily be accounted for in terms of plate motion. Some alternative explanations that might help explain the anomalous position of the kimberlite pole follow:

(1) Between-site scatter for the kimberlite pole is extremely small. This might indicate that the geomagnetic secular variation has not been averaged, although Van Fossen and Kent (1993) argue otherwise.
(2) An 18° clockwise rotation of the sampling area would bring the kimberlite pole into agreement with the Cretaceous stillstand pole. Thus, from a purely geometric standpoint, this could indicate that the sampling area experienced a counterclockwise rotation sometime after the mid-Creta-

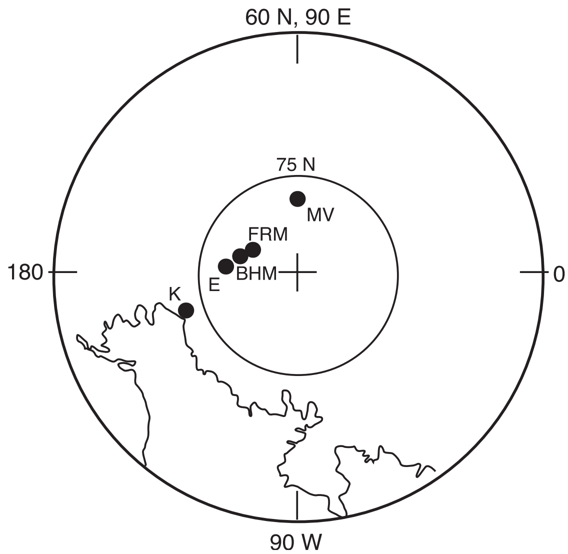

Fig. 9. The Front Range Morrison pole, the Black Hills Morrison pole (BHM) and the Eocene reference pole (E) are essentially identical, suggesting Laramide remagnetization. Also shown is the Moat Volcanics (MV) pole of Van Fossen and Kent (1990). Note change of scale.

Table 5
Selected Callovian to late Cretaceous reference poles for North America

No.	Unit	Age	N	A_{95}	Lat./Long.	Lat./Long.-R
1	K stillstand[a]	88–125	6	3.0	71.4/194.9	
2	kimberlite dikes	143	7	3.8	58.0/203.1	
3	U. Morrison Fm.	Tithonian	16	3.8	68.7/153.0	60.2/162.3
4	Canelo Hills Volcs.	151	14	7.6	60.9/130.3	53.5/143.3
5	L Morrison Fm.	Kimmeridgian	3	5.3	61.4/142.2	53.3/152.9
6	Morrison Fm., Colo.	L Oxfordian	8	[b]	83.7/150.4	
7	Summerville Fm.	L Callovian	10	7.4	56.2/130.8	48.8/142.7

Column headings as in Table 3. References: (1) Van Fossen and Kent (1992a), McEnroe (1996); (2) Van Fossen and Kent (1993); (3) Steiner and Helsley (1975), Bazard and Butler (1994); (4) Kluth et al. (1982); (5) Steiner and Helsley (1975); (6) Van Fossen and Kent (1992b); (7) Bazard and Butler (1992).

[a] For this study, N is the number of studied rock units, comprising 18 separate VGP.

[b] Inclination-only statistics.

ceous, and that the remanent magnetization carried by the dikes is younger than supposed. There appears to be no evidence supporting this alternative, which appears extremely unlikely.

(3) Van Fossen and Kent (1993) report that the dikes have a weakly defined, vertical, north–south trending plane of magnetic anisotropy. Strong magnetic anisotropy can deflect remanent magnetization away from the direction of the ambient field. However, in this case, anisotropy should produce an apparent clockwise rotation, opposite to what is observed.

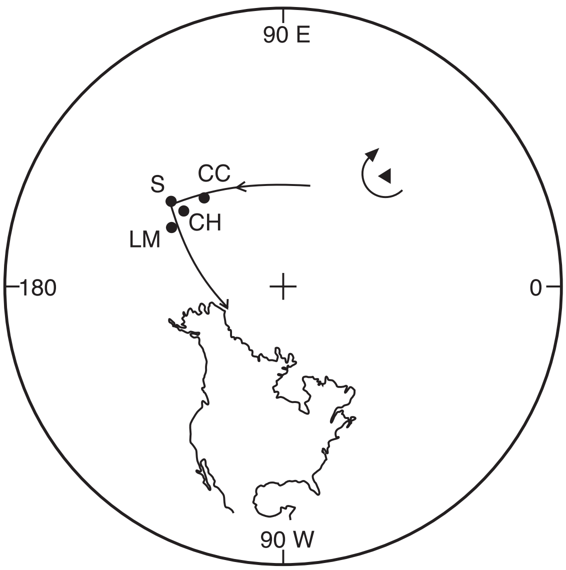

Fig. 10. The J2 cusp, dated at about 160 Ma by Corral Canyon (CC), Summerville (S), Canelo Hills (CH) and lower Morrison (LM) poles.

We do not know how to interpret the kimberlite pole. Van Fossen and Kent (1993) regard it as evidence of a separate episode of APW. If so, it may represent an event not associated with plate motion; perhaps a brief episode of unusually strong non-dipole activity (e.g., a prolonged "excursion"; Merrill et al., 1998). More data, especially for the latest Jurassic and earliest Cretaceous, are needed to investigate this interesting problem.

As before, the J2 cusp is dated by nearby poles (Fig. 10). The nearest is the Lower Callovian Summerville pole, which serves to date the J2 cusp at about 160 Ma. At this time, another abrupt change in the absolute motion of North America apparently took place.

8. The mid-Cretaceous stillstand and the K1 and K2 cusps

Another important change in North American absolute motion must have occurred at the inception of the mid-Cretaceous APW stillstand (Van Fossen and Kent, 1992a; McEnroe, 1996). The oldest pole known to be involved in the stillstand is about 125 Ma, and the youngest Jurassic pole known along the J2-K track is from the Upper Morrison Formation, which is Tithonian (145–150 Ma). We refer to the change in APW that took place at the beginning of the stillstand as the K1 cusp, which thus is bracketed loosely at 125–150 Ma.

Table 6
Selected latest Cretaceous through Tertiary reference poles for North America

Pole	Unit	Age	*N*	A_{95}	Lat./Long.
1	Columbia Plateau basalts	Miocene	59	4.8°	85.1/171.5
2	San Juan, CO, volc.; Montana intrusives	Oligocene	101	2.9	82.0/136.1
3	Absaroka volc.	Eocene	35	7.8	80.9/167.3
4	Montana intrusives	Paleocene	36	4.4	81.0/179.4
5	Adel Mtns. volc.	75 Ma	26	6.8	82.2/209.9
6	Elkhorn Mtns. volc.	80	15	9.6	80.3/189.5

Column headings as in Table 4. References: (1) Choiniere and Swanson (1979), Hooper et al. (1979); (2) Diehl et al. (1988) and Table 1 from Beck et al. (1977); (3) Sheriff and Shive (1980), Shive and Pruss (1977); (4) Moccasin–Judith Mountains and Little Rocky Mountains data from Diehl et al. (1983); (5) Gunderson and Sheriff (1991); (6) Diehl (1991).

From K1 time until about 88 Ma, North America rotated about the geographic pole (the spin axis). Rotation about the spin axis generates an APW "track" that consists of a single point. Relative to North America in its present position, the geographic pole was at 71.4°N, 194.9°E during this interval. This is our choice of PEP for the period 125–88 Ma.

Another abrupt change in the absolute velocity of North America occurred at the end of the Cretaceous stillstand—sometime between 88 and 80 Ma. This is the age of the K2 cusp.

Reference poles for 50 m.y. of late Cretaceous and Tertiary time form a tight cluster, with no obvious evidence of APW (Fig. 11a). Instead, there appears to be another stillstand: 82.5°N, 176.3°E, with $N=6$, $K=467$ and $A_{95}=3.1°$. Although it is possible to construct an APW path through this stillstand, total polar motion is <5°. Thus, we will treat APW at the end of the Cretaceous as an abrupt shift from one stillstand to another, occurring between about 88 and 80 Ma. We model this as a rotation of 12° about the pole to the great circle connecting the two stillstands, 3.5°N, 294.5°E (Fig. 11b).

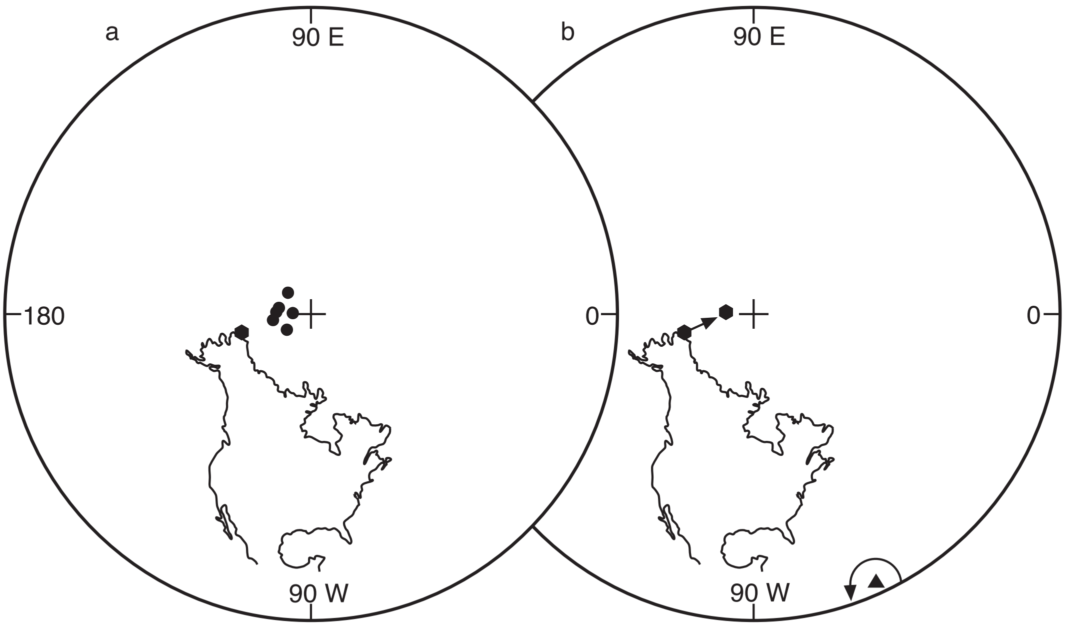

Fig. 11. (a) Latest Cretaceous through Miocene reference poles for North America (Table 6), defining a second APW stillstand; (b) 88–80 Ma APW modeled as a finite rotation about the pole to the great circle connecting two APW stillstands.

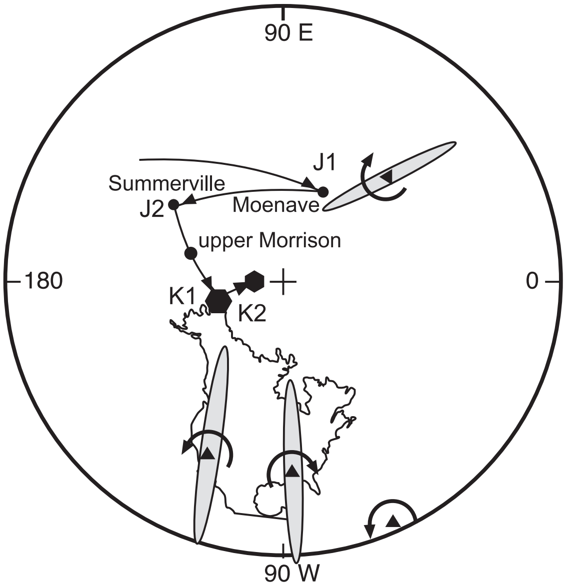

Fig. 12. North American APW, 250–30 Ma. 95% confidence regions about mean PEPs indicated.

Fig. 12 summarizes North American APW for the Mesozoic.

9. Angular velocities

As discussed by Gordon et al. (1984), it is more difficult to measure angular motion along an APW track than to define the track itself. In this paper, we have assumed constant angular velocity over the length of each track; angular velocity along the track thus is equal to the total angle subtended at the PEP by the ends of the track, divided by the duration of the track. This implies that changes in velocity occur only at cusps. Because the existence of a track implies no important changes in driving forces for the duration of the track, an assumption of constant angular velocity is reasonable. Errors in angular

Table 7
Paleomagnetic Euler poles and angular velocities

Period (Ma)	λ °N	ϕ °E	R (°)	a (°)	b (°)	ω (°/m.y.)
245–200	39.2	245.2	81.1	34	2.5	0.9
200–160	38.5	270.1	80.4	26	2.0	1.0
160–125	45.1	48.5	60.7	22.5	2.0	0.9
125–88	71.2	194.1	0	[a]		0.4
88–80	3.6	294.7	90	[a]		1.5

λ?, ϕ?, ω are latitude, longitude of paleomagnetic Euler pole, and angular velocity, respectively. R is radius of best-fit small circle. a, b are major and minor axes of the ellipse of 95% confidence.

[a] Not possible to compute confidence limits.

Table 8
Absolute velocity of selected points on North America during the Mesozoic, determined from paleomagnetic data

Place	Before J1		After J1		Difference vector	
	Azimuth	Speed	Azimuth	Speed	Azimuth	Speed
Cordova	234	48	27	72	218	117
Seattle	240	17	15	47	207	60
Los Angeles	120	10	347	44	336	52
Rapid City	331	17	21	22	71	17
St. John's	345	71	147	53	157	123
Philadelphia	6	51	160	22	178	71
Jacksonville	13	48	218	21	201	68
	Before J2		After J2		Difference vector	
Cordova	80	72	333	96	301	136
Seattle	59	47	327	100.0	302	112
Los Angeles	24	44	323	99	297	87
Rapid City	64	22	330	100	318	104
St. John's	187	53	331	90.2	344	136
Philadelphia	158	22	331	99	322	121
Jacksonville	278	21	331	100.0	341	89
	Before K1		After K1		Difference vector	
Cordova	289	96	270	10	111	86
Seattle	302	100	270	23	131	81
Los Angeles	299	99	270	31	131	73
Rapid City	316	100	270	29	150	83
St. John's	342	90	270	35	185	86
Philadelphia	330	99	270	35	185	86
Jacksonville	325	100.0	270	38	167	84
	Before K2		After K2		Difference vector	
Cordova	270	11	216	165	217	155
Seattle	270	23	229	152	223	135
Los Angeles	270	31	219	141	208	124
Rapid City	270	29	246	132	240	107
St. John's	270	35	230	118	216	94
Philadelphia	270	35	262	101	258	67
Jacksonville	270	38	259	85	250	48

Motion of seven points on the North American continent with respect to the geographic pole (spin axis), from Euler poles given in Table 7. Velocities given as azimuth and speed (in km/m.y.). Velocities calculated for four times or abrupt change: J1, about 200 Ma; J2, about 160 Ma; K1, somewhere in the interval 125–150 Ma; K2, about 88 Ma. Between cusps velocities changed very little. Difference vectors are $\boldsymbol{D} = \boldsymbol{B} - \boldsymbol{A}$, where $\boldsymbol{B}$ and $\boldsymbol{A}$ are the vectors of absolute motion before and after the cusp, respectively.

velocity have no effect on the timing or location of cusps.

Between K1 and K2 no track is defined (or, more correctly, the track defined has zero length), so—for lack of a better method—for the period 125–88 Ma, we use North America's angular velocity relative to the hotspot framework from Engebretson et al. (1985).

Angular velocities, PEP locations and confidence limits are summarized in Table 7.

10. Absolute motion of North America

Using the cusps, PEP locations and angular velocities determined earlier, we next calculated absolute velocities for six points on the margin of North America and one near its center (Figs. 14–16, Table 8). For each cusp, we computed a velocity immediately before (***B***) and after (***A***) by the cusp. We also calculated a difference vector (***D*** = ***A*** − ***B***). The magnitude of ***D*** indicates the kinematic importance of the

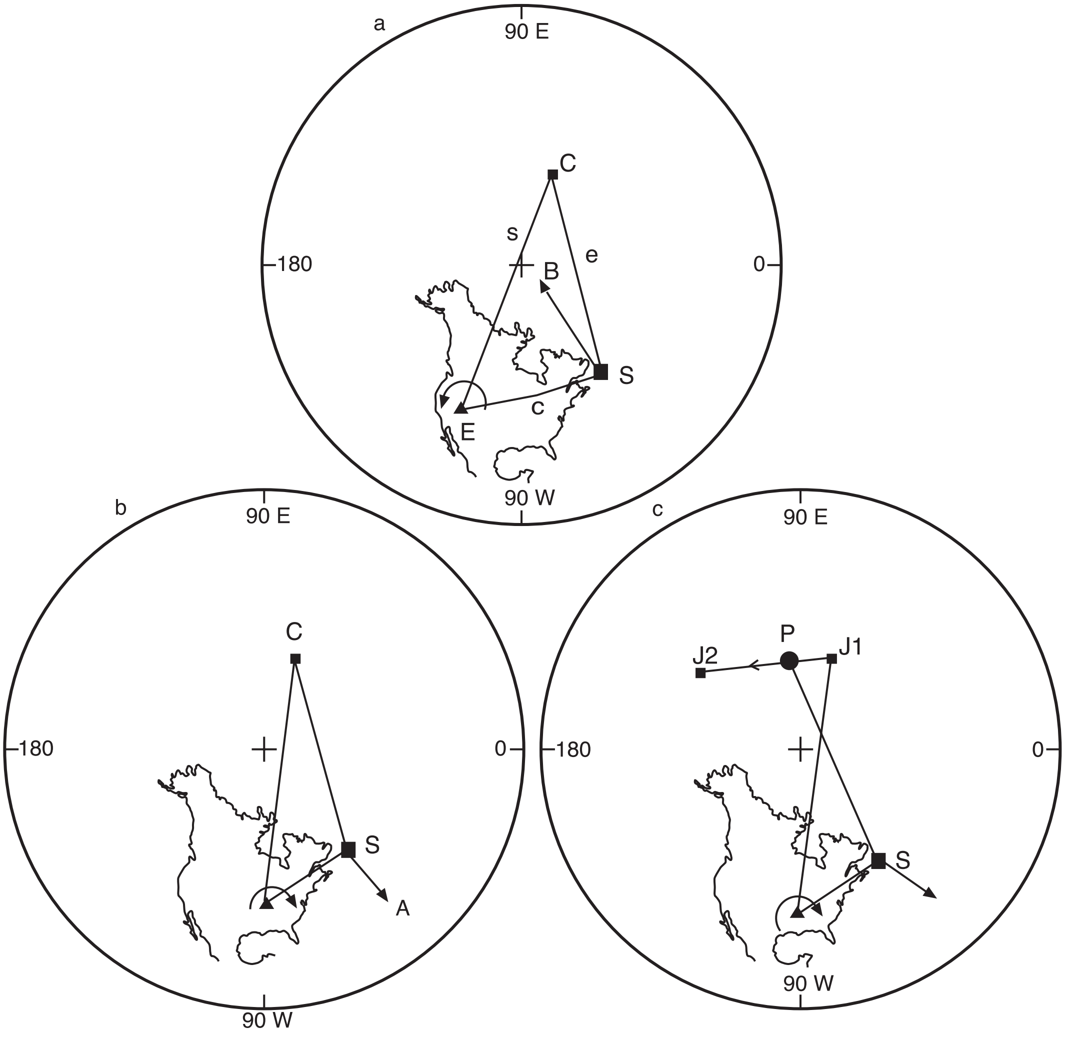

Fig. 13. Calculation of the absolute velocity of St. John's, Newfoundland before (a) and after (b) J1 time. (c) Between cusps (e.g., at point *P*) the direction of motion changes slowly and smoothly and the speed is constant. Points *C*, *E* and *S* define a spherical triangle (angles *S*, *C*, *E*; sides *s*, *c*, *e*). Side *e* is the paleomeridian; *c* is the great-circle distance between PEP and site (St. John's, in the example). Vectors ***B*** and ***A*** show the absolute motion of St. John's before and after J1 time, respectively.

velocity change, and the magnitude and direction together may suggest something about the nature of the change. A representative calculation is shown in Fig. 13, using St. John's, Newfoundland, as an example.

Fig. 13a shows the situation immediately before the J1 cusp. North America is rotating about an Euler pole located at 39.2°N, 245.2°E, at 0.9°/m.y. The angular distance between the Euler pole and St. John's is 44.9°; hence, St. John's is moving in the direction shown at a speed of $111.2 \times 0.9 \times \sin(44.9°) = 71$ km/m.y. Side *e* in spherical triangle SEC represents the paleomeridian of St. John's at J1 time. From spherical trigonometry, angle *S* is 105° and, because the motion of St. John's is normal to *c*, its absolute motion is 71 km/m.y., azimuth 345° (vector ***B***). Immediately after J1 (Fig. 13b), the velocity of St. John's is 53 km/m.y., with an azimuth of 147° (***A***). The difference vector (***D***) for this change is 123 km/m.y., azimuth 157°. ***A***, ***B*** and ***D*** are given with respect to the position of the spin axis at J1 time, indicated by point ***C*** (Fig. 13), because point ***C*** represents the pole at J1 time, in current North American coordinates.

Between cusps, difference vectors are small. This follows because, as the paleomagnetic pole traverses its track, the azimuth of motion of any point on the plate changes slowly, and—given our assumption of constant angular velocity—speed changes not at all. Thus, angle *S* (Fig. 13) will decrease slowly as the pole traverses its track from J1 toward J2, and the azimuth of motion will slowly increase, while speed remains constant.

11. Discussion

The chronology of changes in absolute velocity of North America provides important clues to help interpret Mesozoic tectonics. Major velocity changes should reflect important changes in the sum of forces acting on the plate and, if the change involves tractions on the edge of the plate, a tectonic signature should be evident. Tectonic events that might cause a change in plate velocity include "choking-up" of a subduction zone by collision with an exotic terrane, initiation of a new subduction zone, growth or decay of one previously active and the onset of continental rifting. In particular, because the western margin of North America was a convergent plate boundary during the Mesozoic, understanding the absolute motion of the overriding (continental) plate can provide insight into the underlying cause of Cordilleran deformational events, important changes in magmatic activity and changes in the direction of relative displacement of Cordilleran tectonostratigraphic terranes.

Important changes in North America's absolute velocity took place at the J1, J2, K1 and K2 cusps. The first two are fairly well dated at about 200 and 160 Ma, respectively. The K1 cusp is loosely bracketed between 125 and 150 Ma. The K2 cusp occurred no earlier than about 88 Ma or later than about 80 Ma.

From the standpoint of western North America, two periods appear to be particularly significant.

At the J2 cusp, or about 160 Ma, the western edge of the continent abruptly changed direction and speed. Immediately prior to 160 Ma, the western edge of the continent was moving slowly to the east (Fig. 15), but after 160 Ma it moved toward the Pacific basin, with a strong northward component (Fig. 16). It follows that, unless plates of the Pacific basin had an even larger northward component, plate interaction from 160 to perhaps 125 Ma was sinistral. As proposed in Beck (1989), terrane motion relative to North America at this time was probably toward the south. Geological evidence of southward relative displacement of pieces of western North America is well documented (e.g., Oldow, 1983).

A second important change took place at the K2 cusp, about 88 Ma. As modeled (Fig. 17), the absolute velocity of western North America changed from about 20 km/m.y. to the west to about 150 km/m.y. to the southwest. This abrupt velocity change should be reflected in the tectonic and/or magmatic history of the Cordillera. Also, if North America's rapid southwestward drift was not shared by plates of the Pacific basin, plate interaction at that time should have been strongly north-oblique, and terrane motions rapidly northward. Evidence of late Cretaceous and Tertiary right-lateral faulting (an expected consequence of right-oblique subduction) also is abundant throughout the western North American Cordillera.

The abrupt nature of the 88–80 Ma transition suggests the alternative possibility of true polar wander (TPW); motion of the entire earth or its outer shell with respect to the spin axis (e.g., Goldreich and Toomre, 1969; Prévot et al., 2000). TPW can be triggered by redistribution of mass within the earth; its speed should depend in part on mantle viscosity and is currently a subject of debate. The period 88–80 Ma falls near the end of an interval of TPW suggested by Prévot et al. (2000) from the global distribution of paleomagnetic poles for igneous rocks. However, Prévot et al. (2000) argue that most of the TPW took place at about 110 Ma, which appears unlikely (Tarduno and Smirnov, 2000). A more relevant comparison is Sager and Koppers (1999), who found evidence for an abrupt shift of the Pacific plate at about 84 Ma, using paleomagnetic data from seamounts (but see also Cottrell and Tarduno, 2000). However, the sense of polar displacement proposed by Sager and Koppers (1999) is opposite that found in the North American record of APW.

Whether the result of TPW or plate motion, the period 88–80 Ma represents an abrupt transition between two periods of negligible North American APW. As shown in Fig. 11, this can be modeled as a ccw rotation of North America about a point in the western Pacific. Beck (1999) shows that South American APW during the Mesozoic also can be described as two periods of stillstand (165–115 and 80–70 Ma). The transition between these two stillstands, which involved a clockwise rotation of about 9°, is poorly dated (ca. 115–80 Ma). Acknowledging this imprecision, we nevertheless speculate that these antithetical rotations may be synchronous, represent relative plate motions, not TPW, and reflect a common cause, the onset of interaction of both continental blocks with the Caribbean plate.

With regard to eastern North America, the most significant velocity change took place at about 160 Ma. The absolute velocity of eastern North America prior to about 160 Ma was small and directed outward, toward the Atlantic basin (Fig. 15). After J2 time, the direction was inward—away from the Atlantic—and rapid (Fig. 16). Without knowing the absolute motion of Africa and Europe, it is not possible to infer anything reliable about the opening of the Atlantic from this observation. However, from the paleomagnetic evidence, it seems likely that active spreading in the central Atlantic started at about J2 time.

The J1 cusp also is associated with a change in velocity along the eastern edge of North America. Prior to J1 time, eastern North America had a moderate absolute velocity toward the NW (Fig. 14), whereas after J1 it began to move slowly SE. Again, without independent knowledge of the motion of

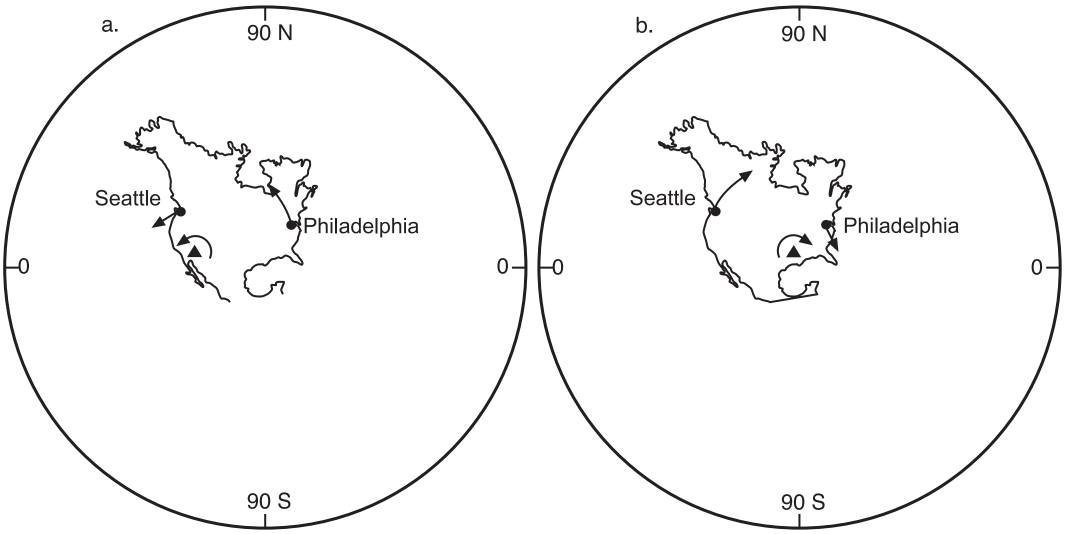

Fig. 14. Absolute motion of Seattle (S) and Philadelphia (P) before (a) and after (b) J1 time. Arrows scaled to indicate relative velocity. Note change of projection. Longitudes are arbitrary.

Europe and Africa, it is dangerous to interpret North American absolute motion in terms of tectonics. However, an early episode of Triassic extension is suggested, perhaps followed by compression in the early Jurassic.

Fig. 16 suggests another possible consequence of the absolute motion of North America. Between J2 and K1 time, the pole of absolute rotation of North America was far away to the southwest, indicating rapid northward motion of the entire continent. For example, Seattle and Philadelphia gained, respectively, about 25° and 30° of latitude during this period. Such a large increase in latitude should be recognizable in the paleoclimatic record, unless somehow masked by global climatic changes. Possible evidence of this rapid northward motion is preserved in fossil flora from Albian–Cenomanian rocks from the North Slope of Alaska, which indicate a relatively cool climate (Spicer and Parrish, 1986). After K2 time, these areas would move rapidly to the south.

12. Caveats and questions

One potentially vulnerable aspect of this study is our choice of a large rotation for all poles from the southwest, whether or not they were derived from rocks actually on the Colorado Plateau. How much rotation has taken place is hotly debated and we acknowledge that we have not ended the argument.

To test how sensitive the analysis is to the value of Plateau rotation, we recalculated the position of the J1 cusp assuming 4° of clockwise rotation for the Colorado Plateau and nearby areas. With the smaller rotation, the J1 cusp moves to 60.7°N, 69.4°E, 1.1° from our preferred location, and the shapes of the pre-J1 and J1–J2 tracks are essentially unchanged. There is a more significant contrast in the location of the J2 cusp (55.7°N, 131.9°E, about 10° from our preferred position). The shape of the J2–K1 track also changes (new PEP at 22.7°N, 31.0°E, $R = 77.2°$). However, this makes surprisingly little difference in the calculated absolute velocity of North America. For example, the velocity of Seattle immediately after J2 time assuming 4° of rotation is 96 km/m.y., azimuth 334°, whereas with the original assumption of 10.5° rotation these values are 100 km/m.y., azimuth 327°. In general, choice of rotation for the SW data had no significant effect on the tectonic conclusions of this analysis.

A second question concerns the significance of the large confidence limits on PEP location (Fig. 12). As Gordon et al. (1984) found, the 95% confidence region is elongate normal to the trend of the track. To estimate the effect of this uncertainty, we calculated the absolute velocity of several points on North America using the ends of the confidence ellipses. In all cases, the differences were small; speeds changed by < 10% and azimuths by < 20°. In no case did we find a change that would negate any tectonic interpretations given earlier.

Finally, it is curious that the motion of North America derived from APW data agrees so poorly with calculations based on the fixed-hotspot framework. For instance, Fig. 10 of Engebretson et al. (1985) depicts the location of San Francisco tracking steadily westward (at varying speeds) during the interval 180 Ma to present. In contrast, our research (Figs. 14–17) indicates that westward motion of North America did not begin until about 160 Ma.

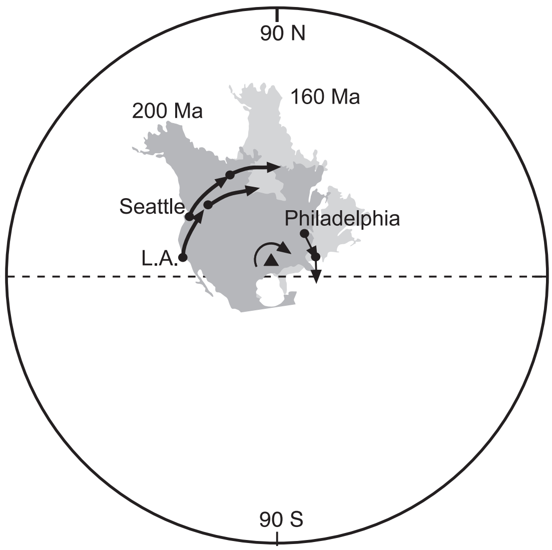

Fig. 15. Dark/light shading shows North America at J1/J2 time. Arrows scaled to indicate relative velocity. For change in velocity at J1 time, compare with Fig. 14b. Longitudes are arbitrary.

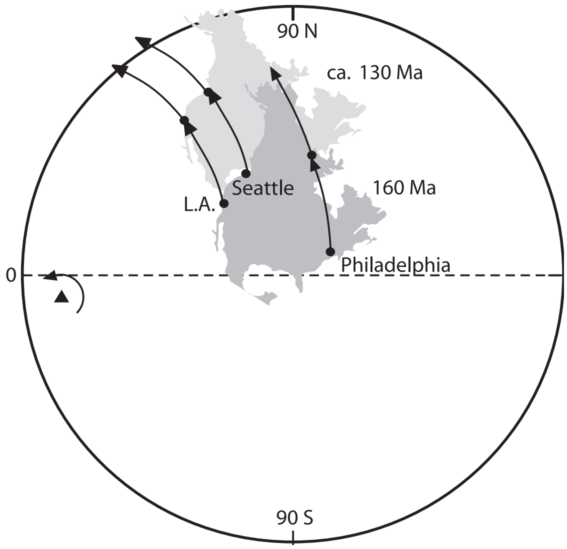

Fig. 16. Dark/light shading shows North America at J2/K1 time. For velocity change at J2, compare with Fig. 14. Longitudes are arbitrary.

Furthermore, from Fig. 10 of Engebretson et al. (1985), the latitude of San Francisco increased steadily from 180 to about 60 Ma, then began to slowly decrease. Our results are quite different. For instance, we show moderate northward movement of western North America during the interval 200–160 Ma, followed by rapid NW motion of western North America during the interval 160 to perhaps 125 Ma. From 125 to 88 Ma, we calculate that no latitudinal change took place. Most problematic of all is the interval 88–80 Ma, during which the APW record indicates that western North America had a high velocity toward the SW, whereas the hotspot record apparently calls for steady movement toward the WNW. Van Fossen and Kent (1992a,b) also discuss the lack of agreement between the APW and hotspot tracks for this interval.

The smooth path of North America deduced from the hotspot record is difficult to reconcile with the abrupt changes in absolute motion implied by North American APW. Seafloor-spreading data are sparse or nonexistent for Jurassic and earlier time, and a lack of magnetic anomalies during the interval 125–85 Ma also makes reconstruction difficult. However, the rapid change in paleolatitude between 88 and 80 Ma should be readily identifiable in the hotspot record, but apparently is not recognized.

We do not know where the problem lies. Two possibilities follow:

(1) The prime suspect must be motion of the hotspot framework with respect to the spin axis, especially for the interval 88–80 Ma. Recent investigations of the Emperor seamount chain (Tarduno and Cottrell, 1997) and various Pacific hotspot chains (Koppers et al., 2001) appear to establish that individual hotspots do at times move with respect to one another, with velocities comparable to the velocities of lithospheric plates. If individual hotspots move with respect to one another, it appears reasonable that the hotspot framework itself also can move with respect to Earth's spin axis.

(2) A second alternative is less likely, in our view, and easier to test. Perhaps the smooth motion of North America in the hotspot framework represents the true absolute motion of North America, and the abrupt changes seen in the APW path are actually long-term episodes of non-axial behav-

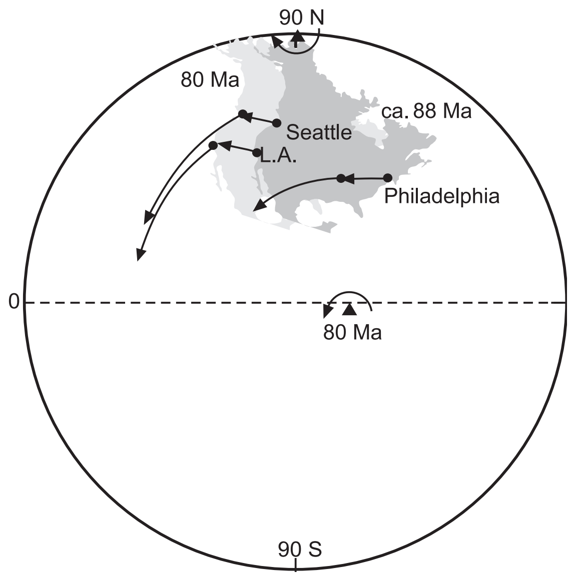

Fig. 17. Dark/light shading shows North America at 88 and 80 Ma. For change in velocity at K2 time, compare with Fig. 15. (No change in velocity occurred between K1 and K2 times.) Longitudes are arbitrary.

ior of the geomagnetic field. The long-term dipolar nature of the field is well established, and the supposition that the dipole is axial if averaged over a geologically short period of time is strongly supported (e.g., Merrill et al., 1998). If, nevertheless, there were long-term episodes of non-axial dipole orientation during the Mesozoic, evidence should be found in both the tectonic and paleoclimatological record. Cusps then would be purely geomagnetic events, and there would be no correlation between tectonics and APW. Also, rapid shifts in paleolatitude (e.g., Figs. 16 and 17) would be purely geomagnetic, with no paleoclimatological consequences. As implied above, there appear to be strong lines of evidence to refute this alternative.

13. Summary

Paleomagnetic Euler pole analysis indicates that there were five abrupt changes in the absolute motion of North America during the Mesozoic. The first two are fairly well dated at about 200 and 160 Ma, whereas the latter three are less well constrained (~ 125, 88 and 80 Ma). It seems likely that the first two are associated with the initial rifting of North America away from Europe and Africa and the onset of spreading in the North Atlantic, respectively. The 160 Ma change (the J2 cusp) also should correlate with the initiation of sinistral convergence along the western edge of the continent. During the somewhat poorly defined period of 88–80 Ma, North America appears to have moved rapidly toward the SSW; convergence during this interval should have been strongly north-oblique. Rotation of the Colorado Plateau (and at least some neighboring areas) appears to have been about 10.5° clockwise, about a rotation pole located somewhere immediately east of the Plateau.

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Appendix A

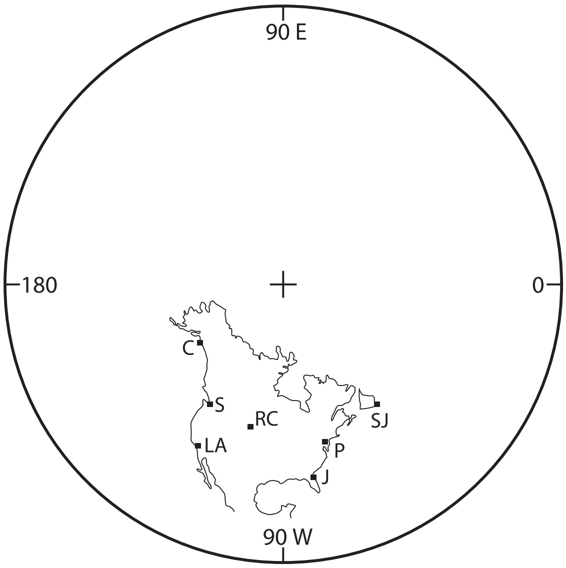

Fig. A1. Locations for which absolute velocities tabulated in Table 8. C, Cordova, AK (60.3°N, 145.4°W); J, Jacksonville, FL (30.2°N, 81.4°W); LA, Los Angeles, CA (34.0°N, 118.2°W); P, Philadelphia, PA (40.0°N, 75.1°W); RC, Rapid City, SD (44.1°N, 103.1°W); S, Seattle, WA (47.4°N, 122.2°W); SJ, St. John's, Newfoundland (47.3°N, 52.4°W).

References

Bazard, D., Butler, R., 1991. Paleomagnetism of the Chinle and Kayenta Formations, New Mexico and Arizona. J. Geophys. Res. 96, 9847–9872.
Bazard, D., Butler, R., 1992. Paleomagnetism of the middle Jurassic Summerville formation, East Central Utah. J. Geophys. Res. 97, 4377–4386.
Bazard, D., Butler, R., 1994. Paleomagnetism of the brushy basin member of the Morrison formation: implications for Jurassic apparent polar wander. J. Geophys. Res. 99, 6695–6710.
Beck, M., 1972. Paleomagnetism of upper Triassic diabase from southeastern Pennsylvania: further results. J. Geophys. Res. 77, 5673–5687.
Beck, M., 1989. Paleomagnetism of continental North America: implications for displacement of crustal blocks within the Western Cordillera, Baja California to British Columbia. In: Pakiser, L., Mooney, W. (Ed.), Geophysical Framework of Continental United States, vol. 172. Geol. Soc. Am. Mem., Boulder, CO, pp. 471–492.
Beck, M., 1999. Jurassic and cretaceous apparent polar wander relative to South America: some tectonic implications. J. Geophys. Res. 104, 5063–5068.

Beck, M., Sheriff, S., Diehl, J., Hailwood, E., Lipman, P., 1977. Further paleomagnetic results from the San Juan volcanic field of southern Colorado. Earth Planet. Sci. Lett. 37, 124–130.

Bell, H., Books, K., Daniels, D., Huff, W., Popenoe, P., 1979. Diabase dikes in the Haile–Brewer area, South Carolina, and their magnetic properties: shorter contributions to geophysics. U.S. Geol. Surv. Prof. Pap. 1123, C1–C18.

Bryan, P., Gordon, R., 1990. Rotation of the Colorado Plateau: an updated analysis of paleomagnetic poles. Geophys. Res. Lett. 17, 1501–1504.

Butler, R., 1992. Paleomagnetism. Blackwell Scientific Publications, Boston. 319 pp.

Carmichael, C., Palmer, H., 1968. Paleomagnetism of the late Triassic North Mountain Basalt of Nova Scotia. J. Geophys. Res. 73, 2811–2822.

Choiniere, S., Swanson, D., 1979. Magnetostratigraphy and correlation of Miocene basalts of the northern Oregon Coast Range and Columbia Plateau, southeast Washington. Am. J. Sci. 279, 755–777.

Cottrell, R., Tarduno, J., 2000. Late Cretaceous true polar wander: not so fast. Science 288, 2283.

Courtillot, V., Besse, J., Theveniaut, H., 1994. North American Jurassic apparent polar wander: the answer from other continents. Phys. Earth Planet. Inter. 82, 87–104.

Diehl, J., 1991. The Elkhorn mountains revisited: new data for the late Cretaceous paleomagnetic field of North America. J. Geophys. Res. 96, 9887–9894.

Diehl, J., Beck, M., Beske-Diehl, S., Jacobson, D., Hearn, B., 1983. Paleomagnetism of the late Cretaceous–early Tertiary north–central Montana alkalic province. J. Geophys. Res. 88, 10503–10609.

Diehl, J., McClannahan, K., Bornhorst, T., 1988. Paleomagnetic results from the Mogollon–Datil volcanic field, southwestern New Mexico, and a refined mid-Tertiary reference pole for North America. J. Geophys. Res. 93, 4869–4879.

Dooley, R., Smith, W., 1982. Age and magnetism of diabase dykes and tilting of the Piedmont. Tectonophysics 90, 283–307.

Dunlop, D., Özdemir, Ö., 1997. Rock Magnetism: Fundamentals and Frontiers. Cambridge Univ. Press, Cambridge. 573 pp.

Dunlop, D., Xu, S., 1994. Theory of partial thermoremanent magnetization in multidomain grains: 1. Repeated identical barriers to wall motion (single microcoercivity). J. Geophys. Res. 99, 9005–9023.

Dunlop, D.J., Özdemir, Ö., Schmidt, P.W., 1997. Paleomagnetism and paleothermometry of the Sydney basin: 2. Origin of anomalously high unblocking temperatures. J. Geophys. Res. 102, 27285–27295.

Ekstrand, E., Butler, R., 1989. Paleomagnetism of the Moenave Formation: implications for the Mesozoic North American apparent polar wander path. Geology 17, 245–248.

Engebretson, D., Cox, A., Gordon, R., 1985. Relative motions between oceanic and continental plates in the Pacific Basin. Geol. Soc. Am., Spec. Pap. 206. 59 pp.

Fang, W., Van der Voo, R., 1988. Paleomagnetism of middle–late Triassic plutons in southern Maine. Tectonophysics 156, 51–58.

Goldreich, S., Toomre, A., 1969. Some remarks on polar wandering. J. Geophys. Res. 74, 2555–2567.

Gordon, R., Cox, A., O'Hare, S., 1984. Paleomagnetic Euler poles and apparent polar wander and absolute motion of North America since the carboniferous. Tectonics 3, 499–537.

Gunderson, M., Sheriff, S., 1991. A new Late Cretaceous paleomagnetic pole from the Adel Mountains, west–central Montana. J. Geophys. Res. 96, 317–326.

Hagstrum, J., 1993. North American Jurassic APW: the current dilemma. EOS Trans. Am. Geophys. Union 74, 65–72.

Hagstrum, J., Lipman, P., Moore, R., 1994. Late Cretaceous paleomagnetism of the Tombstone district and vicinity: evidence for a rotational domain boundary in southeastern Arizona. Tectonics 13, 1295–1308.

Hamilton, W., 1981. Plate-tectonic mechanism of Laramide deformation. Contrib. Geol. 19, 87–92.

Hamilton, W., 1988. Laramide crustal shortening. In: Schmidt, C., Perry, W. (Eds.), Interaction of the Rocky Mountain Foreland and the Cordilleran Thrust Belt, vol. 171. Geol. Soc. Am. Mem., Boulder, CO, pp. 27–40.

Helsley, C., Steiner, M., 1974. Paleomagnetism of the lower Triassic Moenkopi formation. Geol. Soc. Amer. Bull. 85, 457–464.

Hodych, J., Hayatsu, A., 1980. K–Ar isochron age and paleomagnetism of diabase along the trans-Avalon aeromagnetic lineament—evidence of late Triassic rifting in Newfoundland. Can. J. Earth Sci. 17, 491–499.

Hooper, P., Knowles, C., Watkins, N., 1979. Magnetostratigraphy of the Imnaha and Grande Ronde basalts in the southeast part of the Columbia Plateau. Am. J. Sci. 279, 737–754.

Irving, E., Banks, M., 1961. Paleomagnetic results from the upper Triassic lavas of Massachusetts. J. Geophys. Res. 66, 1935–1939.

Kent, D., Witte, W., 1993. Slow apparent polar wander for North America in the late Triassic and large Colorado Plateau rotation. Tectonics 12, 291–300.

Kluth, C., Butler, R., Harding, L., Shafiqullah, M., Damon, P., 1982. Paleomagnetism of late Jurassic rocks in the northern Canelo Hills, southeastern Arizona. J. Geophys. Res. 87, 7079–7086.

Kodama, K., Mowery, A., 1994. Paleomagnetism of the Sassamansville diabase, Newark Basin, southeastern Pennsylvania: support for middle Jurassic high-latitude paleopoles for North America. Geol. Soc. Amer. Bull. 106, 952–961.

Kodama, K., Hedlund, C., Gosse, J., Strasser, J., 1994. Rotated paleomagnetic poles from the Sassamansville syncline, Newark basin, southeastern Pennsylvania. J. Geophys. Res. 99, 4643–4653.

Koppers, A., Morgan, J.P., Morgan, J.W., Staudigel, H., 2001. Testing the fixed hotspot hypothesis using 40Ar/39Ar age progressions along seamount trails. Earth Planet. Sci. Lett. 185, 237–252.

Larochelle, A., Currie, K., 1967. Paleomagnetic study of igneous rocks from the Manicouagan structure, Quebec. J. Geophys. Res. 72, 4163–4169.

Livaccari, R., 1979. Late Cenozoic tectonic evolution of the western United States. Geology 7, 72–75.

Mankinen, E., 1978. Paleomagnetic evidence for a Late Cretaceous

deformation of the Great Valley sequence, Sacramento Valley, California. J. Res. U.S. Geol. Surv. 6, 383–390.
May, S., Butler, R., 1986. North American Jurassic polar wander: implications for plate motion, paleogeography, and Cordilleran tectonics. J. Geophys. Res. 91, 11519–11544.
May, S., Butler, R., Shafiqullah, M., Damon, P., 1986. Paleomagnetism of Jurassic volcanic rocks in the Patagonia Mountains, southeastern Arizona: implications for the North American 170 Ma reference pole. J. Geophys. Res. 91, 11545–11556.
McEnroe, S., 1996. A Barremian–Aptian (early Cretaceous) North American paleomagnetic reference pole. J. Geophys. Res. 101, 15835–15891.
McEnroe, S., Brown, L., 2000. Palaeomagnetism, rock magnetism and geochemistry of Jurassic dykes and correlative redbeds, Massachusetts, USA. Geophys. J. Int. 143, 22–38.
McIntosh, W., Hargraves, R., West, C., 1985. Paleomagnetism and oxide mineralogy of upper Triassic to lower Jurassic red beds and basalts in the Newark Basin. Geol. Soc. Amer. Bull. 96, 463–480.
Merrill, R., McElhinny, P.M., McFadden, P.M., 1998. The Magnetic Field of the Earth. Academic Press, London. 531 pp.
Molina-Garza, R., Geissman, J., Van der Voo, R., Lucas, S., Hayden, S., 1991. Paleomagnetism of the Moenkopi and Chinle formations in central New Mexico: implications for the North American apparent polar wander path and Triassic magnetostratigraphy. J. Geophys. Res. 96, 14239–14276.
Molina-Garza, R., Geissman, J., Lucas, S., Van der Voo, R., 1996. Paleomagnetism and magnetostratigraphy of Triassic strata in the Sangre de Cristo Mountains and Tucumcari Basin, New Mexico, USA. Geophys. J. Int. 124, 935–953.
Molina-Garza, R., Acton, G., Geissman, J., 1998a. Carboniferous through Jurassic paleomagnetic data and their bearing on rotation of the Colorado Plateau. J. Geophys. Res. 103, 24179–24188.
Molina-Garza, R., Geissman, J., Gomez, A., Horton, B., 1998b. Paleomagnetic data from Triassic strata, Zuni uplift, New Mexico: further evidence of large-magnitude Triassic apparent polar wander of North America. J. Geophys. Res. 103, 24189–24200.
Morgan, W., 1968. Rises, trenches, great faults, and crustal blocks. J. Geophys. Res. 73, 1959–1982.
Morgan, W., 1971. Convection plumes in the lower mantle. Nature 230, 43.
Oldow, J., 1983. Tectonic implications of a late Mesozoic fold and thrust belt in northwestern Nevada. Geology 11, 542–546.
Prévot, M., Mattern, E., Camps, P., Daignieres, M., 2000. Evidence for a 20° tilting of the Earth's rotation axis 110 million years ago. Earth Planet. Sci. Lett. 179, 517–528.
Pullaiah, G., Irving, E., Buchan, K., Dunlop, D., 1975. Magnetization changes caused by burial and uplift. Earth Planet. Sci. Lett. 28, 133–143.
Reeve, S., Helsley, C., 1972. Magnetic reversal sequence in the upper portion of the Chinle Formation, Montoya, New Mexico. Geol. Soc. Amer. Bull. 83, 3795–3812.
Robertson, W., 1967. Manicouagan, Quebec, paleomagnetic results. Can. J. Earth Sci. 4, 641–649.
Russell, B., Beck, M., Burmester, R., Speed, R., 1982. Cretaceous magnetizations in northwestern Nevada and tectonic implications. Geology 10, 423–428.
Sager, W., Koppers, A., 1999. Late Cretaceous polar wander of the pacific plate: evidence of a rapid true polar wander event. Science 287, 455–459.
Seguin, M., Rao, K., Venugopal, D., Gahe, E., 1981. Paleomagnetism of parts of the late Triassic diabase dike system associated with the trans-New Brunswick aeromagnetic lineament. Can. J. Earth Sci. 18, 1776–1787.
Sheriff, S., Shive, P., 1980. The Rattlesnake hills of central Wyoming revisited: further paleomagnetic results. Geophys. Res. Lett. 7, 589–592.
Shive, P., Pruss, E., 1977. A paleomagnetic study of basalt flows from the Absaroka Mountains, Wyoming. J. Geophys. Res. 82, 3039–3048.
Shive, P., Steiner, M., Huyke, D., 1984. Magnetostratigraphy, paleomagnetism and remanence acquisition in the Triassic Chugwater formation of Wyoming. J. Geophys. Res. 89, 1801–1815.
Smith, T., 1976. Paleomagnetic study of lower Mesozoic diabase dikes and sills of Connecticut and Maryland. Can. J. Earth Sci. 13, 597–609.
Smith, W., 1987. Paleomagnetic results from a crosscutting system of northwest and north–south trending diabase dikes in the North Carolina Piedmont. Tectonophysics 136, 137–150.
Smith, T., Noltimier, H., 1979. Paleomagnetism of the Newark Trend igneous rocks. Am. J. Sci. 279, 778–807.
Spicer, R., Parrish, J., 1986. Paleobotanical evidence for cool north polar climates in middle Cretaceous (Albian–Cenomanian) time. Geology 14, 703–706.
Steiner, M., 1986. Rotation of the Colorado Plateau. Tectonics 5, 649–660.
Steiner, M., Helsley, C., 1974. Magnetic polarity sequence of the upper Triassic Kayenta formation. Geology 2, 191–194.
Steiner, M., Helsley, C., 1975. Reversal pattern and apparent polar wander for the late Jurassic. Geol. Soc. Amer. Bull. 86, 1537–1543.
Steiner, M., Lucas, S., 1992. A middle Triassic paleomagnetic pole for North America. Geol. Soc. Amer. Bull. 104, 993–998.
Steiner, M., Lucas, S., 2000. Paleomagnetism of the late Triassic Petrified Forest Formation, Chinle Group, western United States: further evidence of "large" rotation of the Colorado Plateau. J. Geophys. Res. 105, 25791–25808.
Tarduno, J., Cottrell, R., 1997. Paleomagnetic evidence for motion of the Hawaiian hotspot during formation of the Emperor seamounts. Earth Planet. Sci. Lett. 153, 171–180.
Tarduno, J., Smirnov, A., 2000. Stability of the earth with respect to the spin axis for the last 130 million years. Earth Planet. Sci. Lett. 184, 549–553.
Van der Voo, R., 1992. Jurassic paleopole controversy: contributions from the Atlantic-bordering continents. Geology 20, 975–978.
Van der Voo, R., Grubbs, K., 1977. Paleomagnetism of the Triassic Chugwater redbeds revisited (Wyoming, USA). Tectonophysics 41, 27–33.
Van der Voo, R., Torsvik, T., 2001. Evidence for late Paleozoic and Mesozoic non-dipole fields provides an explanation for the Pangea reconstruction problems. Earth Planet. Sci. Lett. 187, 71–81.

Van Fossen, M., Kent, D., 1990. High-latitude paleomagnetic poles from middle Jurassic plutons and moat volcanics in New England and the controversy regarding Jurassic APW for North America. J. Geophys. Res. 95, 17503–17516.

Van Fossen, M., Kent, D., 1992a. Paleomagnetism of 122 Ma plutons in New England and mid-Cretaceous paleomagnetic field for North America: true polar wander or large-scale differential mantle motion? J. Geophys. Res. 97, 19651–19662.

Van Fossen, M., Kent, D., 1992b. Paleomagnetism of the Front Range (Colorado) Morrison formation and an alternative model of late Jurassic North American apparent polar wander. Geology 20, 223–226.

Van Fossen, M., Kent, D., 1993. A paleomagnetic study of 143 Ma kimberlite dikes in central New York State. Geophys. J. Int. 113, 175–185.

Westphal, M., 1993. Did a large departure from the geocentric axis dipole hypothesis occur during the Eocene? Evidence from the magnetic polar wander path of Eurasia. Earth Planet. Sci. Lett. 117, 15–28.

Wilson, J., 1965. Evidence from ocean islands suggesting movement in the earth. R. Soc. London, Phil. Trans. 258, 145–165.

Witte, W., Kent, D., 1989. A middle Carnian to early Norian (~ 225 Ma) paleopole from sediments of the Newark Basin, Pennsylvania. Geol. Soc. Amer. Bull. 101, 1118–1126.

Witte, W., Kent, D., 1990. The paleomagnetism of red beds and basalts of the Hettangian extrusive zone, Newark Basin, New Jersey. J. Geophys. Res. 95, 17533–17545.

Witte, W., Kent, D., Olsen, P., 1991. Magnetostratigraphy and paleomagnetic poles from late Triassic–earliest Jurassic strata of the Newark basin. Geol. Soc. Amer. Bull. 103, 1648–1662.