10-10-1986

North American Jurassic Apparent Polar Wander: Implications for Plate Motion, Paleogeography, and Cordilleran Tectonics

Steven R. May

Robert F. Butler
University of Portland, butler@up.edu

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 91, NO. B11, PAGES 11,519-11,544, OCTOBER 10, 1986

NORTH AMERICAN JURASSIC APPARENT POLAR WANDER: IMPLICATIONS FOR PLATE MOTION, PALEOGEOGRAPHY AND CORDILLERAN TECTONICS

Steven R. May[1] and Robert F. Butler

Department of Geosciences, University of Arizona, Tucson

Abstract. Eight paleomagnetic poles are considered to be reliable Jurassic reference poles for cratonic North America. These poles form a consistent chronological progression defining two arcuate tracks of apparent polar wander (APW) from Sinemurian through Tithonian time (203-145 Ma). Combined with reliable Triassic and Cretaceous reference poles, the resulting path is well modeled by paleomagnetic Euler pole (PEP) analysis and is significantly different from previous APW compilations. These differences reflect differences in original data sets, modes of analysis, and geologic time scales and translate into substantial and important differences in paleolatitude estimates for cratonic North America. PEP analysis reveals two cusps, or changes in the direction of APW: one in the Late Triassic to Early Jurassic (J1) and one in the Late Jurassic (J2). The J1 cusp represents the change in North American absolute plate motion associated with rifting of the central Atlantic and Gulf of Mexico, while the J2 cusp correlates temporally with the marine magnetic anomaly M21 plate reorganization and to various North American intraplate tectonomagmatic events (e.g., Nevadan Orogeny). Analysis of pole progression along the J1 to J2 and J2 to Cretaceous APW tracks indicates constant angular plate velocity of 0.6°-0.7°/m.y. from 203 to 150 Ma followed by significantly higher velocity from 150 to 130? Ma. Late Triassic-Jurassic reference poles indicate more southerly paleolatitudes for cratonic North America than have previous compilations requiring modification of displacement scenarios for suspect terranes along the western Cordillera.

Introduction

An apparent polar wander (APW) path is a time sequence of paleomagnetic poles that records the paleolatitude and azimuthal orientation of a plate within the dipolar geomagnetic field [Irving, 1977, 1979]. Invocation of the axial geocentric dipole hypothesis permits sequential palaeogeographies to be constructed within a reference frame tied to the rotation axis. APW paths contain information regarding both the direction and velocity of plate motion and therefore are fundamental to analyses of plate kinematics, terrane displacements, and paleogeography. For this reason, APW paths require constant revision and reinterpretation as new paleomagnetic, geochronologic, and tectonic data become available.

[1]Now at Exxon Production Research Company, Houston, Texas.

Paper number 6B5934.
0148-0227/86/006B-5934$05.00

Paleomagnetic studies for cratonic North America have been overshadowed in recent years by the popularity of using paleomagnetism to constrain the motion histories of suspect terranes within the western Cordillera [Beck, 1976, 1980; Hillhouse, 1977; Hillhouse and Gromme, 1980; Irving et al., 1985]. Unfortunately, our understanding of the North American APW path is not so advanced as to warrant this neglect especially for certain time intervals like the Jurassic. Reliable estimates of relative latitudinal displacements of suspect terranes are ultimately constrained by the accuracy of cratonic reference poles, yet perusal of recent compilations such as Irving and Irving [1982] and Harrison and Lindh [1982] reveals intervals of geologic time for which confidence parameters associated with reference poles are very large. Such uncertainties translate directly into imprecise and potentially inaccurate estimations of the paleolatitudinal history of North America. The Jurassic has been a particularly blatant example of this problem because of the paucity of well dated, reliable paleopoles, coupled with an unusually large amount of apparent polar wander.

The Late Triassic-Jurassic North American APW path records the opening and early plate motion evolution of the central Atlantic Ocean basin [Steiner, 1975, 1983]. Geometric analysis of the path can be directly related to plate reorganization and North American absolute motion within the geologically-geophysically constrained rift and drift history. The timing of first-order changes in the shape of the APW path as deduced by paleomagnetic Euler pole (PEP) analysis [Gordon et al., 1984] corresponds remarkably well with various global and regional plate and intraplate tectonic events suggesting causal relationships. The time scale used is that of Harland et al. [1982].

North American Jurassic APW

Historical Development of the Jurassic APW Path

The first Jurassic paleomagnetic results from North America were described by Collinson and Runcorn [1960]. Poles from the Kayenta and Carmel formations on the Colorado Plateau were used to construct the APW path shown in Figure 1a. As was common during this time, the calculated poles were based solely on directions of natural remanent magnetism (NRM) without aid of current demagnetization techniques. In the case of the Kayenta and Carmel Formations, NRM data provided very poor estimates of true pole positions. Subsequent work has shown that these units have significant Cenozoic or present field secondary overprints which have been successfully removed from Kayenta samples but not from the Carmel Formation [Steiner and Helsley, 1974; Steiner, 1983]. The Mesozoic APW path constructed by Collinson and Runcorn [1960] shows a gle track of polar motion from Early Triassic

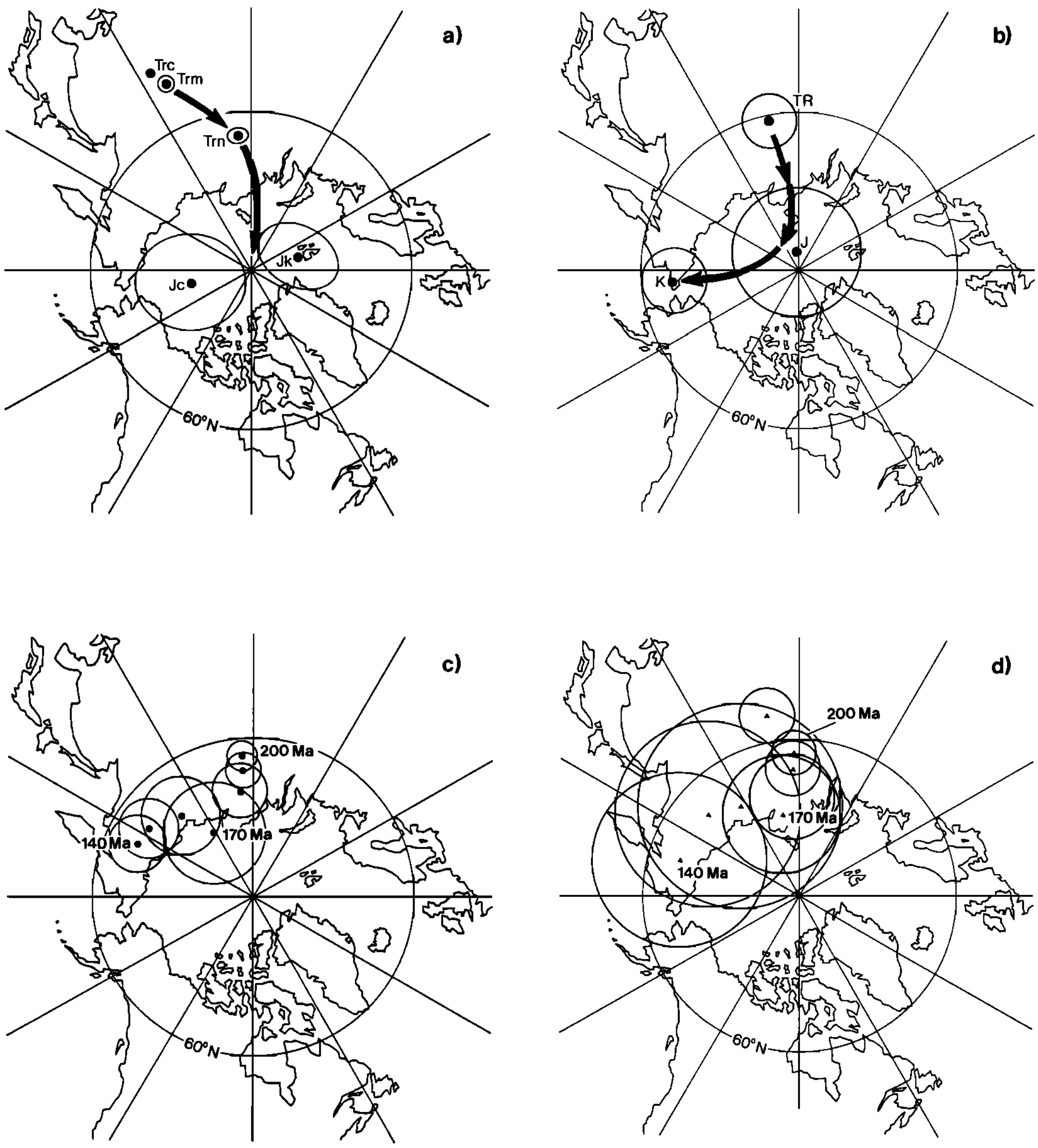


Fig. 1. "Late Triassic" through Jurassic North American APW paths. (a) Collinson and Runcorn [1960]; Trc, Triassic Chugwater Formation; Trm, Triassic Moenkopi Formation; Trn, "Triassic" Newark Group rocks; Jk, Jurassic Kayenta Formation; Jc, Jurassic Carmel Formation. (b) Irving and Park [1972]; TR, Triassic; J, Jurassic; and K, Cretaceous mean poles with associated A_{95} confidence circles. (c) Harrison and Lindh [1982]. (d) Irving and Irving [1982], Figures 1c and 1d were constructed with a "sliding-window" technique and show mean pole locations with A_{95} confidence circles. Mean ages of selected reference poles are shown in millions of years.

Chugwater and Moenkopi Formation poles through a "Late Triassic Newark Formation" pole to the Jurassic Carmel and Kayenta poles, the average of which was indistinguishable from the geographic north pole.

Irving [1964] concluded that there were no reliable Jurassic paleopoles for North America and pointed out that the Kayenta and Carmel Formation results of Collinson and Runcorn [1960] were biased by present field overprint and were not representative of the Jurassic paleofield. However, Irving and Park [1972] published a mean Jurassic pole which, like the earlier Collinson and Runcorn result, was statistically coincident with the geographic pole (Figure 1b). This pole was based on an average of poles from the White Mountain Magma Series [Opdyke and Wensink, 1966], the Anticosti Island diabase dike [Larochelle, 1971], the Island Intrusions [Symons, 1970], and the Kayenta Formation pole of Collinson and Runcorn [1960].

Ironically, we now recognize that much of the early paleomagnetic work by DuBois et al. [1957], Opdyke [1961], deBoer [1967, 1968], and Beck [1972] on Newark Supergroup and related rocks of the northeastern United States was applicable to Jurassic APW. However, until the late 1970s, these rocks were considered to be Late Triassic rather than Early Jurassic.

McElhinny [1973] included only two paleopoles within his Jurassic mean pole, those being the White Mountain Magma Series pole [Opdyke and Wensink, 1966] and the "Appalachian Mesozoic dikes" pole of deBoer [1967]. The resultant mean Jurassic pole at 76°N, 142°E lacked an associated confidence oval but was used to define a track of APW connecting Triassic and Cretaceous poles exclusive of the north pole.

At about this time, a second generation of Mesozoic paleomagnetic data from Triassic and Jurassic sediments on the Colorado Plateau and from the eastern United States became available. The work of Steiner and Helsley [1972, 1974, 1975], Smith [1976], Steiner [1978], and Smith and Noltimier [1979] greatly improved our understanding of Jurassic APW and demonstrated unquestionably that the path did not pass through the geographic pole but tracked from Triassic to Cretaceous poles along a band of latitude between 60° and 70°N (present coordinates) [Steiner, 1975]. The second generation of APW paths [Irving, 1977, 1979; Van Alstine, 1979; Harrison and Lindh, 1982; Irving and Irving, 1982] have more or less approximated this latitudinal track of APW (Figures 1c and 1d). However, many of these compilations include less reliable paleopoles which tend to bias average reference poles toward high latitudes.

Constructing APW Paths: Techniques and Critiques

As more paleomagnetic data became available for all the major continents, the accepted procedure for calculating APW paths changed. From 1956 to 1977, the standard technique was to group all paleomagnetic poles according to geologic period and calculate mean reference poles of period duration. Van Alstine and deBoer [1978] suggested a technique for constructing APW paths that included demarcation of equal time intervals within which poles would be averaged. They pointed out that using geologic periods is unattractive because such periods are both long and of unequal duration. This tends to decrease the precision and usefulness of APW paths because details are overly smoothed and because rates of APW cannot be readily estimated by the relative separation between reference poles.

Irving [1977] also used a nonperiod standard time window averaging technique to generate post-Devonian reference poles for North America. Unlike Van Alstine and deBoer's 22-m.y. window, Irving used a sliding window average of 40-m.y. duration that was incremented at 10 m.y. steps. Irving [1979] and Irving and Irving [1982] have subsequently used the same technique but with a 30-m.y. duration window. Although useful for illustrating the first-order changes in APW, the sliding window technique masks some of the detailed structure present in the raw paleopole data set. Hairpins or cusps (sharp changes in the direction of APW) are heavily smoothed, and boundaries between episodes of rapid and slow APW become blurred. Also, previous Jurassic reference poles generated with the sliding window technique have been strongly biased into inaccurately high latitudes by the inclusion of several unreliable high-latitude poles.

Various weighting schemes have been discussed recently by Harrison and Lindh [1982] and Gordon et al. [1984]. Unfortunately, there does not appear to be any satisfactory scheme free of subjectivity. Although basically employing a 30-m.y. sliding window, Harrison and Lindh [1982] discuss a modification for constructing APW paths based on weighting individual paleopoles according to their "information content." Part of this technique involves weighting poles depending on the amount of overlap between the age range associated with the pole and the window being calculated. Harrison and Lindh [1982] show that age weighting and other somewhat more subjective weighting parameters can cause significant differences between alternative APW paths especially during intervals with low pole density, rapid APW, and poor age control. The Jurassic interval of North American APW has suffered from all of these problems. The most important conclusion of Harrison and Lindh [1982] is that the fundamental factor producing variation in APW paths is selection of an original data base.

Gordon et al. [1984] have suggested that APW paths can be generated by "paleomagnetic Euler pole" (PEP) analysis. Their methodology assumes that APW paths are composed of small circle segments and that deviation of any pole from a best fit small circle reflects inherent inaccuracy of paleomagnetic techniques not apparent polar wander. Upon calculating the best fit small circle approximation to a track of APW, Gordon et al. [1984] collapse the data onto a line describing constant angular pole displacement as a function of age. Moving back into pole space, they convert the PEP-APW model into a series of time incremented "reference poles" whose geometry and age progression are constrained by the original set of paleopoles but whose actual positions need not correspond to any of the original data.

PEP analysis is a very useful tool for modeling APW and associated plate motion, but synthetic reference poles thus derived should not be used as the sole basis for constraining absolute paleogeographies. PEP reference poles are based on a forced fit of paleopole data to a plate tectonic model. Any inaccuracy in the model will generate inaccurate reference poles and information inherent in the original data will be lost. Reference poles for paleotectonic-paleogeographic calculations should be based on actual paleomagnetic data and not on synthetic, model dependent approximations. A detailed and defensible application of paleomagnetic data requires calculation of the most appropriate reference pole compatible with the age of the desired reconstruction.

Although age weighting may be useful in conjunction with the sliding-window technique of APW path construction, weighting schemes in general are usually subjective and do not necessarily yield increased accuracy. The most important factor controlling the accuracy of, and variability between, APW paths is the reliability of the selected data base. Use of the terms "reliable" and "unreliable" in this paper reflects our judgement as to whether or not a particular study meets the designated minimum acceptance criteria. These criteria include demagnetization behavior, the number of sites, Fisher statistical parameters of the data set, age uncertainty, and geologic setting and are discussed in detail in the appendix. "Unreli-

TABLE 1. North American Jurassic Reference Poles.

Pole	Symbol on Figures	Age	Age, Ma	Pole Latitude °N	Pole Longitude °E	A_{95},* deg.	Reference
Upper Morrison Formation	UM	late Tithonian	145	67.6	161.9	3.9	1
Lower Morrison Formation	LM	early Tithonian	149	61.4	142.3	4.2	1
Glance Conglomerate	G	Rb/Sr	151±2	62.7	131.5	6.3	2
Corral Canyon Rocks	CC	Rb/Sr	172±5.8	61.8	116.0	6.2	3
Newark Trend Group II	NTII	Ar/Ar	179±3	65.3	103.2	1.4	4
Newark Trend Group I	NTI	Ar/Ar	195±4	63.0	83.2	2.3	4
Kayenta Formation	K	Pliensbachian	194-200	62.1	70.2	6.3	5
Wingate Formation	W	Sinemurian	200-206	59.0	63.0	8.0	6

*95% confidence angle about pole.

References: 1, Steiner and Helsley [1975]; 2, Kluth et al. [1982]; 3, May et al. [this issue]; 4, Smith and Noltimier [1979]; 5, Steiner and Helsley [1975]; 6, Reeve [1975] from Gordon et al. [1984].

able" does not necessarily mean that the original science was "wrong" or "sloppy" but commonly reflects complexity or uncertainty associated with critical parameters of a paleomagnetic data set which detract from its usefulness as a reference pole.

Our philosophy in constructing an APW path has been to select only high-quality paleomagnetic poles and to evaluate the time sequence of these original data. We acknowledge the contribution which has been made by the sliding-window-type analysis but object to the smoothing of useful details which will result. Smoothing techniques can be effective at filtering random errors but will reinforce the unwanted bias of systematic errors. In the case of Jurassic APW, paleopoles have commonly been polluted by unremoved late Mesozoic, Cenozoic, and present field overprints. Inclusion of such poles has resulted in inaccurately high latitudes for reference poles generated through sliding-window techniques.

Geologic Time Scales

Because APW paths are commonly based on a data set including paleopoles from paleontologically dated sedimentary rocks as well as radiometrically dated igneous rocks, the choice of a geologic time scale can influence spatiotemporal interpretations. Time scales are especially critical to the interpretation of Jurassic APW because the "absolute" ages associated with Jurassic period, epoch, and age boundaries have undergone significant revision in the past 20 years.

For example, the Chinle Formation of Late Triassic (Carnian-Norian) age was assigned an absolute age of 199 Ma by Irving and Irving [1982] using a time scale similar to Van Eysinga [1975]. The Chinle pole was therefore considered nearly correlative with a 195±5 Ma radiometrically calibrated pole from the Newark Trend igneous rocks and both were included in an average 200 Ma reference pole. Using the preferred time scale of Harland et al. [1982], the best pick for the absolute age of the Chinle is 220-230 Ma or approximately 25-30 m.y. older than the Early Jurassic (Pliensbachian) Newark trend rocks. Such examples are common within compilations of Late Triassic and Jurassic reference poles for North America and have led to imprecision and inaccuracy. Although the Harland et al. [1982] time scale will almost certainly experience revision, the consistency observed between predicted ages, radiometric ages, and relative pole positions is encouraging. The primary conclusions of this analysis would be the same had we used the Decade of North American Geology (DNAG) time scale [Palmer, 1983].

As our knowledge of both APW and geologic time scales becomes more sophisticated, it is important that any time sequence analyses be accompanied by a statement of the time scale used. Furthermore, as interdisciplinary synthesis of global and regional tectonics depends largely on recognizing temporal coincidence, it is imperative that all relevant data be analyzed with the same time scale. As discussed later, part of the apparent paleomagnetic discordancy for certain Cordilleran terranes can be traced directly to inaccurate reference poles generated with "outdated" geologic time scales.

Jurassic Paleomagnetic Poles

There are eight reliable paleomagnetic poles from Jurassic age rocks of cratonic North America (Table 1). These include Early Jurassic poles from the Wingate Formation [Reeve, 1975], the Kayenta Formation [Steiner and Helsley, 1974], and the Newark Trend Group I intrusive rocks [Smith and Noltimier, 1979]; Middle Jurassic poles from the Newark Trend Group II intrusive

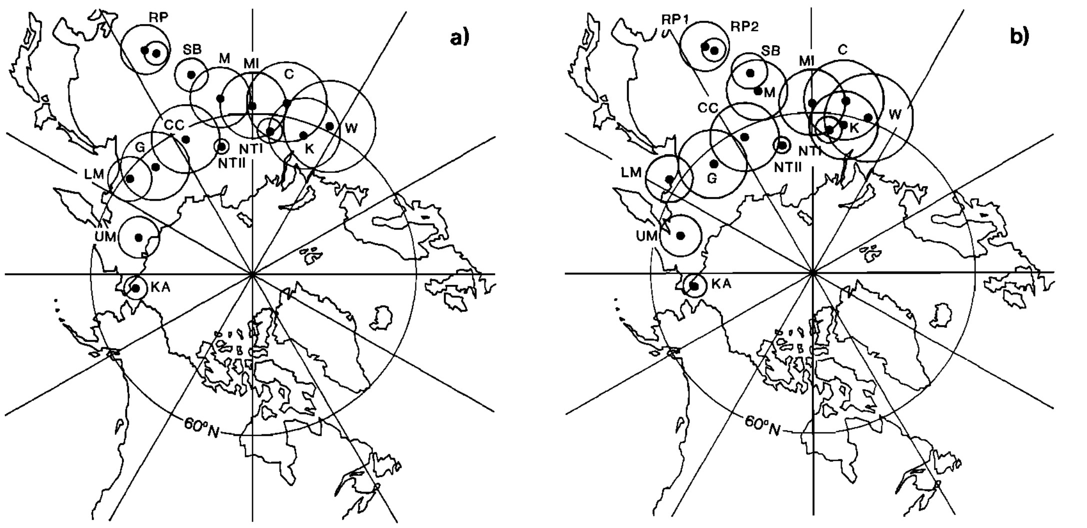


Fig. 2. Revised Triassic-Early Cretaceous North American APW path. (a) Stereographic north polar projection showing reliable reference poles as listed in Tables 1 and 2. Symbols for Jurassic poles are W, Wingate Formation; K, Kayenta Formation; NTI, Newark Trend Group I; NTII, Newark Trend Group II; CC, Corral Canyon; G, Glance Conglomerate (Canelo Hills); LM, lower Morrison Formation; UM, upper Morrison Formation. Other poles include RP, Red Peak Formation of Chugwater Group (two poles); SB, State Bridge Formation; M, Moenkopi Formation; MI, Manicouagan Impact Structure; C, Chinle Formation; and KA, Cretaceous average pole of Mankinen [1978]. Mean pole locations are shown by solid circles and associated A_{95} confidence regions. (b) Same as Figure 2a, but with poles from the Colorado Plateau corrected for 3.8° clockwise rotation as in Table 3. Modified poles include UM, LM, K, W, and M.

rocks [Smith and Noltimier, 1979], and the Corral Canyon sequence [May et al., this issue]; and Late Jurassic poles from the Glance Conglomerate [Kluth et al., 1982] and the lower and upper Morrison Formation [Steiner and Helsley, 1975].

The spatiotemporal distribution of these poles defines a consistent eastward progression of APW from Sinemurian to late Tithonian time (Figure 2). Detailed discussions of each of these poles as well as poles used in previous analyses but here considered unreliable are presented in the appendix. We wish to emphasize that our purpose in relegating these discussions to an appendix is to facilitate the coherent flow of our main ideas and conclusions and not to deemphasize the importance of that information. To the contrary, the appendix represents the basis of our analysis and contains numerous discussions of data interpretation which, to varying degrees, guide our conclusions.

Triassic and Cretaceous Poles

Similar analysis of Triassic and Early Cretaceous paleomagnetic poles provides a context of reliable pre- and post-Jurassic APW. These poles are not discussed in detail but are listed in Table 2 and shown in Figure 2. Early Triassic poles from the Chugwater Group and the Moenkopi and State Bridge formations illustrate the trend of the pre-Jurassic APW track, although the only reliable Late Triassic poles for North America are the Chinle Formation pole [Reeve and Helsley, 1972] of Carnian-Norian age and the Manicouagan pole [Robertson, 1967; Larochelle and Currie, 1967].

The single Cretaceous pole shown in various figures and Table 2 is an average Early-Middle Cretaceous pole calculated by Mankinen [1978]. Although certain of the eight poles used in this average are of questionable reliability, their consistency and tight clustering suggest that the mean pole is a good approximation of the paleofield during the Cretaceous stillstand ("stillstand" as used here refers to an interval of essentially no APW). The oldest of the reliable poles in this group is the Monteregian Hills intrusive pole which has been assigned a mean K/Ar age of 126±6 Ma, while the youngest pole is from the Niobrara Formation at approximately 85-90 Ma [Shive and Frerichs, 1974]. Recently reported fission track and Rb/Sr dates from the Monteregian Hills intrusives show two clusters of ages at about 118 Ma and 136 Ma [Eby, 1984]. Paleomagnetic results from this intrusive series need reevaluation, but the new geochronology suggests that the Cretaceous standstill may have begun as early as 136 Ma. The lack of significant APW during the interval from ?130 to 85 Ma justifies our use of a single mean pole in later PEP analysis of the Late Jurassic APW track. It is important to realize that the episode of rapid Late Jurassic APW ended by at least 126±6 Ma, and probably somewhat earlier, although there are no reliable poles of certain Berriasian age.

A Revised Jurassic APW Path

Using the time scale of Harland et al. [1982], Jurassic paleopoles form a consistent chronologic progression that defines a path of APW from the Sinemurian through the Tithonian (203-145 Ma). Combined with reliable Late Triassic and Early Cretaceous paleopoles, the resulting APW path is

TABLE 2. Triassic and Cretaceous North American Reference Poles.

Pole	Symbol on Figures	Age	Age, Ma	Pole Latitude °N	Pole Longitude °E	A_{95}, deg.	Reference†
Cretaceous Average	KA	mean	130-85	68.0	186.0	2.2	1
Manicouagan Structure	MI	K/Ar	215±5	58.8	89.9	5.8	2
Chinle Formation	C	Carnian-Norian	220-230	57.7	79.1	7.0	3
Moenkopi Formation	M	Early-Middle Triassic	231-248	57.0	100.3	5.3	4
State Bridge Formation	SB	Early Triassic	243-248	52.0	107.0	3.0	5
Red Peak Formation	RP	Early Triassic	243-248	46.6	113.5	1.9	6
Red Peak Formation	RP	Early Triassic	243-248	45.4	115.3	4.1	7

See footnote for Table 1.

†References: 1, Mankinen [1978]; 2, Robertson [1967] and Larochelle and Currie [1967]; 3, Reeve and Helsley [1972]; 4, Baag and Helsley [1974]; 5, Christensen [1974] from Gordon et al. [1984]; 6, Shive et al. [1984]; 7, Herrero-Brevera and Helsley [1983].

different from previously published compilations of Irving [1977], Van Alstine and deBoer [1978], Briden et al. [1981], Irving and Irving [1982], and Harrison and Lindh [1982]. These differences include a marked cusp in the Early Jurassic, as also recognized by Gordon et al. [1984], relatively low latitudes for Late Triassic through Late Jurassic reference poles (58°-63°N present coordinates), and a second cusp in the Late Jurassic. Each of these features has implications for North American plate motion and paleolatitudes and for Cordilleran paleogeography.

To illustrate the important characteristics of the revised Jurassic APW path, we compare it to the recent and popular path of Irving and Irving [1982] (Figure 1d). It is important to remember that these paths were constructed in fundamentally different ways and with quite different geological time scales. Our technique is to generate an APW path simply as a time sequence of high-quality paleopoles. This provides access to the maximum amount of information inherent in the raw data. Irving and Irving [1982], on the other hand, use a sliding-window averaging technique with less rigorous data selection to reveal first-order patterns of APW.

As discussed previously, differences in geologic time scales can profoundly influence the interpretation of APW especially when a sliding-window averaging technique is used. Although not cited, the time scale used by Irving and Irving [1982] was similar to that of Van Eysinga [1975] which places the Triassic-Jurassic boundary at approximately 195 Ma and the Jurassic-Cretaceous boundary at 141 Ma. The 200 Ma reference pole was therefore constructed as a Late Triassic pole at 63°N, 92°E, A_{95}=4°. The correlative pole in terms of absolute age in our revised path is the Sinemurian (200-206 Ma) Wingate Formation pole located at 59°N, 63°E, A_{95}=8°. Depending on which of these 200 Ma poles one chooses, estimated paleolatitudes for North America are significantly different. All of the "Late Triassic" and Jurassic reference poles in Irving and Irvings' compilation predict higher paleolatitudes for North America than does our revised APW path. The magnitude of this difference translates into differences in predicted mean paleolatitude at San Francisco of approximately 750 km at 200 Ma and 600 km at 170 Ma. Such differences obviously affect interpretations concerning the allochthoneity of Cordilleran suspect terranes.

In conjunction with differences in the absolute positions of reference poles, the basic geometries of the paths are dissimilar. The moving average technique of Irving and Irving (and others) has the effect of smoothing changes in direction of APW. Because abrupt changes in APW may be correlated with important plate reorganizations and intraplate tectonic events [e.g., Beck, 1984], this is an important difference. Numerous correlations can be hypothesized between the structure recognized in the revised APW path and North American tectonics.

Paleopoles From the Colorado Plateau

Until recently, much of our knowledge of Jurassic APW was based on paleomagnetic studies from sedimentary rocks on the Colorado Plateau [Steiner, 1983]. Plateau-derived poles still comprise 50% of the present list of reliable data and are critical for understanding Early and Late Jurassic features of the APW path. Recently, there has been some discussion that the Colorado Plateau may have experienced a small clockwise rotation with respect to the rest of the craton in post-Jurassic time. Before proceeding with a discussion of Jurassic APW analysis, we must first address the question of tectonic rotation of the Colorado Plateau.

On the basis of regional tectonic arguments, Hamilton [1981] and Cordell [1982] suggest that the Colorado Plateau experienced 3°-5° of clockwise rotation with respect to cratonic rocks

TABLE 3. Reference Poles From the Colorado Plateau After a 3.8° Clockwise Rotation is Removed

Pole	Latitude °N	Longitude °E	A_{95} deg.
Upper Morris Formation	64.6	164.2	3.9
Lower Morrison Formation	58.6	146.2	4.2
Kayenta Formation	61.9	78.1	6.3
Wingate Formation	59.6	70.4	8.0
Moenkopi Formation	55.4	106.5	5.3

east of the Rocky Mountains and the Rio Grande Rift during Laramide and Neogene time. Gordon et al. [1984] noted that paleopoles from rocks on the Colorado Plateau are displaced systematically clockwise from equivalent age reference poles from other parts of North America. This is especially evident with respect to the Triassic poles and can be interpreted either as a small clockwise rotation of the plateau or as the result of systematic errors in age assignments and correlation. Steiner [1984] has suggested that similar discrepencies are present between plateau and nonplateau poles of Pennsylvanian and Devonian age as well and argues for tectonic rotation. Also noted by Steiner, however, is the lack of discordance between Permian poles.

Bryan and Gordon [1985] quantitatively analyzed the magnitude of potential Colorado Plateau rotation using paleomagnetic poles and found a clockwise value of $3.8° \pm 2.9°$. Using this mean value, we have recalculated plateau poles (Table 3, Figure 2b). The basic morphology of the Triassic-Cretaceous APW path is unaffected by this recalculation, but differences in detail do alter our interpretations of PEP analysis.

Tracks and Cusps

As discussed originally by Francheteau and Sclater [1969] and more recently by Gordon et al. [1984], APW paths can be modeled as a series of small circle segments, each of which defines a paleomagnetic Euler pole (PEP) in the same way as do hot spot tracks or transform faults. The applicability of the PEP methodology is based upon the notion that large plates tend to rotate about one absolute motion pole for long periods of time (i.e., 10^7-10^8 years). Arguments in favor of plate motion stability include the long, continuous nature of fracture zones and the curvilinear nature of hot spot tracks [Gordon et al., 1984].

The generally accepted view of plate motion appeals to boundary conditions (i.e., ridges and trenches) as the primary control over both direction and velocity [Forsyth and Uyeda, 1975]. It follows that stable boundary conditions generate plate motions about single Euler poles at constant angular velocity for long intervals of time. An alternative hypothesis would be that frequently changing boundary conditions should preclude plate motion of constant direction and velocity. PEP analysis of the revised APW path allows us to test these two models for the Jurassic-Early Cretaceous history of North American motion.

In relation to paleomagnetic data, Francheteau and Sclater [1969] were perhaps the first to view APW paths in light of a punctuated equilibrium model for plate motion. Irving and Park [1972] similarly recognized that APW paths consist of long, arcuate "tracks" separated by relatively sharp "hairpins." Tracks were interpreted as periods of constant plate motion relative to the magnetic pole, and hairpins were interpreted as the record of periodic change in the direction of plate motion. Subsequently, the concept of hairpins received little attention in the late 1970s and early 1980s largely due to advent of the sliding-window technique for constructing APW paths that was popularized by Irving [1977]. The recent analysis of Gordon et al. [1984] has revived the concept of hairpins, called "cusps," and their recognition is potentially important to understanding the nature and implications of North American Jurassic APW.

Paleopole data selected for the present analysis reveal two cusps within the Jurassic APW path, an older cusp labeled "J1" and a younger cusp labeled "J2" (Figure 3). The apex of the J1 cusp is presently defined by the Wingate Formation pole and that of the J2 cusp by the lower Morrison Formation pole (see the appendix). Each of these cusps directly reflects a change in the direction and velocity of North American plate motion, which in turn may be expressed on a regional scale by episodes of intraplate deformation. Tracks separated by these cusps are labeled Tr-J1, J1-J2, and J2-K and represent intervals of North American plate motion describable by single poles of rotation.

The same tracks and cusps are recognizeable regardless of whether corrected or uncorrected plateau poles are used. The J1 cusp is somewhat modified because restoration of the Wingate and Kayenta Formation poles decreases the "sharpness" of the cusp. Although the Sinemurian age Wingate pole still forms the apex of the J1 cusp, it is no longer statistically significant from poles

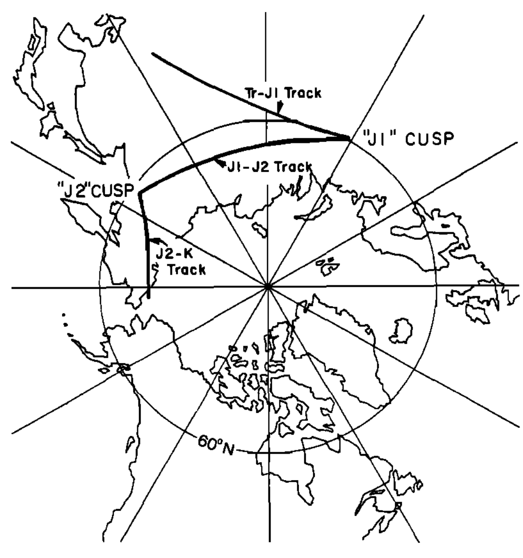


Fig. 3. PEP model and terminology applied to the revised North American Triassic-Early Cretaceous APW path.

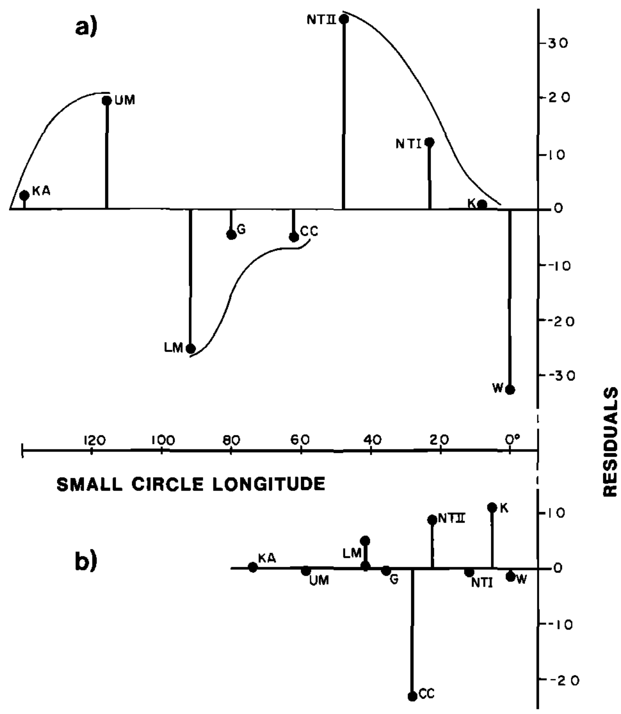


Fig. 4. Residual distribution for (a) single PEP fit, and (b) double PEP fit. "Small circle longitude" is the coordinate of a pole transformed into PEP space and then standardized so that the Wingate pole (W) is arbitrarily placed at 0° (uncorrected plateau pole data).

whose ages range from Carnian-Norian to Pliensbachian. The timing of the J1 cusp is therefore not as distinct after correction for Plateau rotation and may be viewed as a 25-30 m.y. APW standstill interval of North American plate motion reorganization.

Because both the Wingate Formation and lower Morrison Formation poles are from rocks on the plateau, the absolute arc length of the J1-J2 track is unaffected by rotation of the Colorado Plateau. The J2 cusp as defined by the lower Morrison pole moves slightly to the east and to a lower latitude. The J2-K track becomes arcuate with the opposite sense of concavity after rotation correction because two of the three poles defining this track are from the Morrison Formation on the plateau.

All of these modifications to the Jurassic APW path affect PEP analysis illustrating the sensitivity of the latter technique for small data sets. The following discussion addresses PEP parameters for two sets of Jurassic pole positions: one with uncorrected plateau poles (UPP) (i.e., no tectonic correction) and one with corrected plateau poles (CPP) (i.e., 3.8° clockwise rotation removed). Rotation of the Colorado Plateau is regarded with some suspicion because all of the poles from the plateau are from sedimentary rocks which for the Triassic and Jurassic have a history of exhibiting present field secondary overprints which tend to bias pole locations toward the geographic north pole. Because of the orientations of the Triassic and Jurassic APW paths, small unremoved overprints of this type provide the same general sense of discordance as would a small clockwise rotation of the plateau (see Summerville Formation pole in the appendix).

PEP Analysis

The PEP technique employed to analyze the distribution and geometry of the nine reliable Jurassic and Early Cretaceous reference poles was facilitated through use of a computer program that allows small circles to be fit to a sequence of poles. The technique involves an iterative minimization of the arc length from individual poles to the small circle plane used to fit the trend of the poles. This program calculates the best fit PEP, the latitude of the small circle about the PEP, a total residual (i.e., the sum of individual pole versus small circle misfits), coordinates of individual data transformed into PEP space (i.e., rotated so that Euler pole is coincident with north geographic pole), and individual residuals associated with each pole. Residual values are simply the angular misfit of a pole with respect to the best fit small circle.

Individual poles were not weighted according to their associated confidence parameters or to a "standard error" as done by Gordon et al. [1984]. Most A_{95} are between 4° and 8° except for the two Newark Trend poles (1.4° and 2.3°). It was not considered desirable to weight these latter two poles heavily as there is some question whether or not these values are artificially small due to overestimation of the actual number of independent sites (see the appendix).

In the present analysis, the Early Jurassic-Early Cretaceous APW path is fitted with two small circles rather than one, as was done by Gordon et al. [1984]. Because of their interpretation of paleopole absolute age and because of inclusion of certain poles considered here to be unreliable (i.e., Summerville and Twin Creek formations) (the appendix), they were unable to discriminate the two-track nature of the Jurassic-Cretaceous APW path. Our defense of a two-track fit is based on simple visual inspection of the revised APW path as well as analysis of the spatial distribution of residuals and a trend line analysis "F" test.

As shown in Figure 4, the distribution of residuals for a single PEP fit to the UPP data set is not random along the track. The distribution is symmetrical with positive values at both ends (with the exception of W) and negative values within the 116°-142°E longitude window (60°-100° longitude relative transformed coordinates). The largest negative residual for this fit is associated with the lower Morrison Formation pole, an observation we use to help define the J2 APW cusp. This systematic distribution implies failure of the single PEP model to resolve structure inherent in the raw data set. Our single-track PEP at 85°N, 90°E is not significantly different from the "B" pole of Gordon et al. [1984] at 84°N, 11°E.

The along-track distribution of residuals for the single PEP fit of the CPP data set is somewhat less obviously systematic, but again the largest negative residual is associated with the lower Morrison pole and positive residuals are generated for both younger (Cretaceous average) and older (Kayenta through Glance) poles (Table

TABLE 4a. Paleomagnetic Euler Pole Data: Uncorrected Plateau Poles

Pole	Transformed Latitude °N	Transformed Longitude °E	Residual
J-K "Single Fit" PEP: 85.0°N, 90.0°E, small circle latitude = 66.7°, total residual = 13.8°			
W	63.37	328.56	-3.346
K	66.75	336.33	0.033
NTI	67.96	351.77	1.243
NTII	70.14	16.31	3.423
CC	66.20	30.89	-.0513
G	66.23	48.94	-0.484
LM	64.18	60.41	-2.536
UM	68.65	84.11	1.932
KA	66.96	107.83	0.247
J1-J2 Track PEP: 52.0°N, 286.0°E, small circle latitude = 26.5°, total residual = 5.1°			
W	26.33	156.93	-0.119
K	27.57	162.01	1.115
NTI	26.39	168.67	-0.062
NTII	27.32	178.68	0.870
CC	24.08	185.16	-2.373
G	26.45	192.74	-0.003
LM	27.02	198.55	0.572
J2-K Track PEP: 31.0°N, 176.0°E, small circle latitude = 52.5°, total residual = 0.09°			
LM	52.52	205.88	0.012
UM	52.46	188.76	-0.043
KA	52.54	173.86	0.031

4). The total residual for a single PEP fit to the CPP APW data is even larger than for the UPP data (15.0° versus 13.8°). The location of the PEP is unchanged by use of the corrected plateau poles.

The single PEP residual distribution can be rectified by partitioning the data and using multiple trend lines. The Jurassic APW path is best modeled as two tracks with an intervening cusp (J2) now recognized at approximately the 149 Ma lower Morrison pole. The distribution of residuals for the two PEP fit is nonsystematic, suggesting that this model better approximates the data distribution (Figure 4). We have also used a trend line analysis "F" test to evaluate the statistical significance in terms of total residual minimization afforded by the two PEP model over the one PEP model. This test is significant at the 95% confidence level. The F test is not significant at the 95% confidence level if we increase the degrees of freedom further by adding a third segment to the J1-K APW path. It is not clear from visual inspection or from residual distribution where a third track would be fitted.

PEPs for both UPP and CPP data sets are listed in Table 4 and shown in Figures 5 and 6. The UPP J1-J2 PEP falls within the North American plate in south-central Quebec while the CPP J1-J2 PEP is located east of Florida. Both are shown with contoured solution spaces which represent the distribution of total residual as a function of location within the region of fit. In Figures 5 and 6 we show two contoured residual classes as labeled.

Solution spaces have elliptical shapes with long axes oriented perpendicular to the trend of the APW small circle, caused by the fact that the azimuth of the APW track is better defined than the radius of curvature. The general shape of the solution space for our best fits is similar to that reported by Gordon et al. [1984]. However, because we made no assumptions about the predicted statistical description of the total residual distribution, we do not convert the contoured solution into a 95% confidence field as do Gordon et al. [1984].

Although the absolute location of the best fit PEPs for the J1-J2 track is quite different between the UPP and CPP cases, both poles lie

TABLE 4b. Paleomagnetic Euler Pole Data: Corrected Plateau Poles

Pole	Transformed Latitude °N	Transformed Longitude °E	Residual
J-K Track "Single Fit" PEP: 85.0°N, 90.0°E, small circle latitude = 66.1°, total residual = 15.0°			
W	64.26	336.99	-1.867
K	66.77	345.74	0.644
NTI	67.96	351.77	1.830
NTII	70.14	16.31	4.010
CC	66.20	30.89	0.074
G	66.23	48.94	0.103
LM	61.11	63.66	-5.016
UM	65.52	84.79	-0.612
KA	66.96	107.83	0.834
J1-J2 Track PEP: 30.0°N, 287.0°E, small circle latitude = 4.4°, total residual = 4.7°			
W	4.56	162.38	0.141
K	4.82	166.79	0.401
NTI	4.92	169.40	0.506
NTII	5.35	178.41	0.931
CC	2.09	184.24	-2.326
G	4.75	191.00	0.339
LM	4.42	199.29	0.008
J2-K Track PEP: 43.0°N, 22.0°E, small circle latitude = 21.6°, total residual = 0.07°			
LM	21.59	152.39	-0.027
UM	21.60	163.57	-0.011
KA	21.65	173.62	0.037

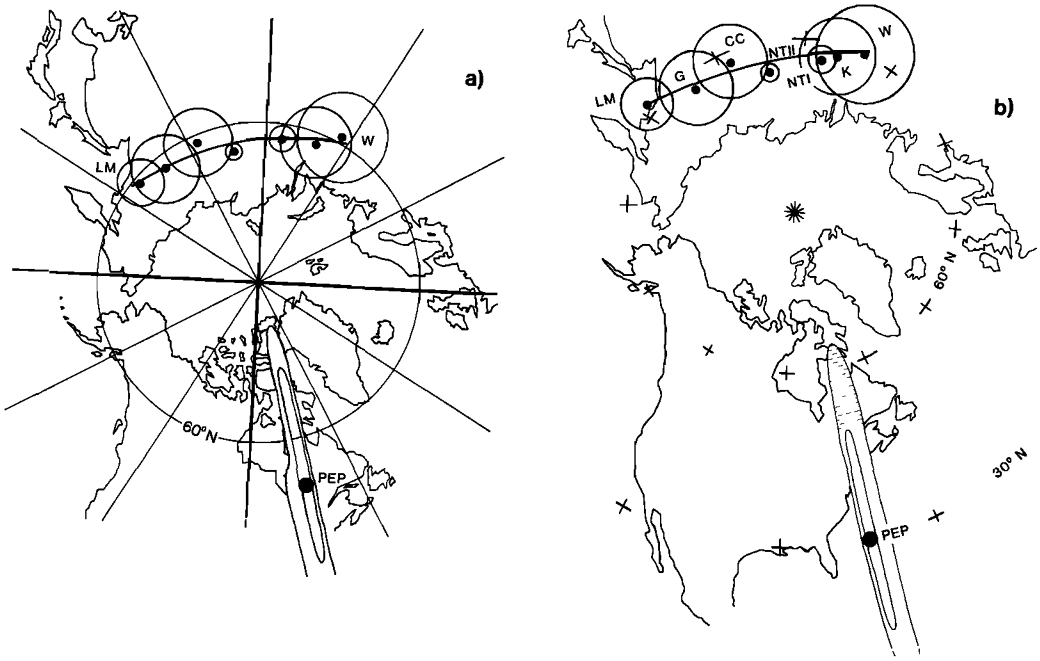


Fig. 5. J1-J2 track poles with best fit PEPs: (a) UPP data, (b) CPP data. Contoured solution space for total residuals: (a) 5.12°-6.13°, 6.13°-7.15°, (b) 4.65°-5.55°, 5.55°-6.46°. Shaded region of solution space in Figure 5b shows field of kinematically "reasonable" Euler poles.

along the same great circle and in fact fall within each others optimum solution spaces. This reflects the sensitivity of PEP analysis to slight changes in curvature of an APW track and emphasizes the difficulty in using PEPs to constrain location dependent parameters such as the linear velocity for any point within the North American plate. The best fit CPP PEP (Figure 5b) is unreasonable in that it does not describe the North American rotation required to open the central Atlantic basin. Given the lack of significant APW for Africa during the Early-Middle Jurassic [Irving and Irving, 1982] and the hot spot model of Morgan [1983], any Euler pole for North American absolute motion must be located north of Jurassic age Atlantic oceanic crust. The shaded region of the PEP solution space in Figure 5b, or the UPP PEP (Figure 5a) are better estimates of a kinematically reasonable J1-J2 track Euler pole. Again, this emphasizes the poorly constrained distance of the PEP from the J1-J2 track along the relatively well-constrained PEP great circle.

The effect of Colorado Plateau rotation is even more dramatic for the J2-K PEPs. The UPP J2-K PEP (Figure 6a) is located in the north central Pacific, whereas the CPP PEP (Figure 6b) is located in Yugoslavia. Again, both PEPs fall

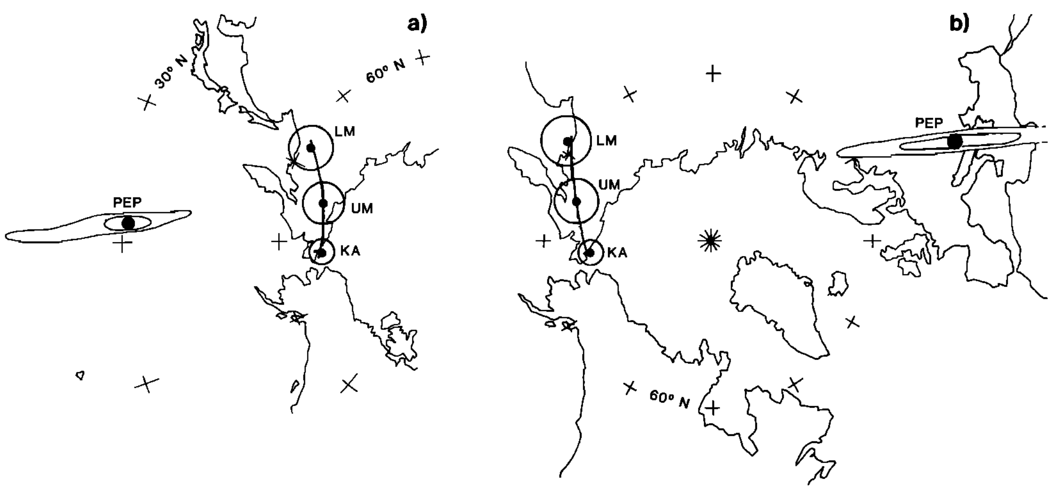
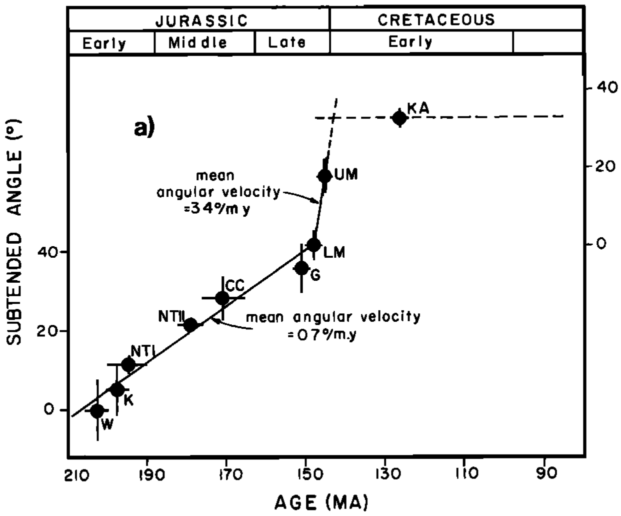


Fig. 6. J2-K track poles with best fit PEPs and small circle trends: (a) UPP, (b) CPP. Contoured solution space for total residuals: (a) 0.09°-0.48°, 0.48°-0.88°, (b) 0.08°-0.34°, 0.34°-0.61°.



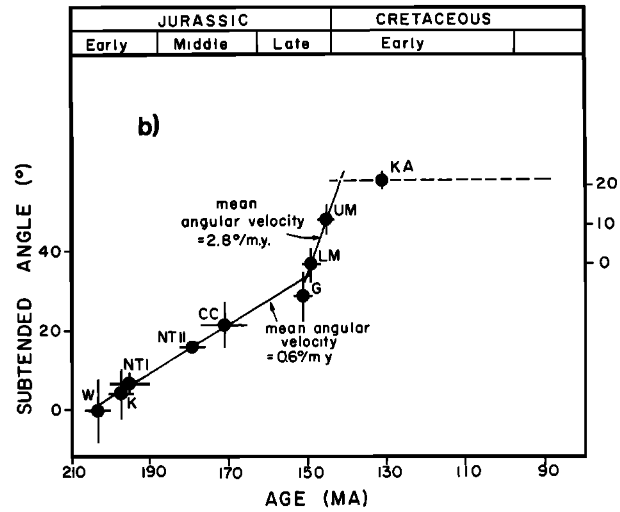


Fig. 7. Angular velocity diagrams for (a) UPP and (b) CPP Jurassic APW path. Subtended angles and best fit regression lines were calculated separately for the J1-J2 and J2-K tracks and then composited. Values along right margin show subtended angles for the J2-K track poles using the lower Morrison pole as a reference.

approximately along a great circle perpendicular to the J2-K track but rotation of the lower and upper Morrison poles causes the CPP J2-K track to be concave northward as opposed to southward for the UPP J2-K track.

Angular Velocity Analysis

The transformed coordinate data in Table 4 can be used directly to evaluate the angular progression of poles along each of the two Jurassic APW tracks. This is done by plotting the angular distance of successive poles (i.e., longitude along best fit circle) away from the Wingate Formation pole as a function of age. To the extent that angular progression values approximate linear trends, we may conclude constant angular plate velocity about a particular PEP. This is an expected corollary of PEP plate motion philosophy: that is plates that experience approximately constant boundary conditions will not only rotate about fixed Euler poles but should do so with constant angular velocities. It is important to remember, however, that plate velocities calculated in this way are minimum estimates because of the longitude ambiguity inherent in paleomagnetic data.

Trend lines to the angular displacement data in Figure 7 are generated using unconstrained, unweighted linear regression. Correlation coefficients of 0.98 and 0.99 for the UPP and CPP J1-J2 regression lines, respectively, indicate that these data are well described by a linear fit and therefore by the PEP model. The passage of the UPP J1-J2 velocity line through the lower Morrison data point in Figure 7a is solely a coincidence of the linear regression fit (i.e., we did not constrain the line to necessarily include this point). The J2-K track was constrained to pass through both Morrison poles because (1) this is the true regression through a data field of N=2, and (2) the fit is very poor if we include the oldest reliable Early Cretaceous pole (Moteregian Hills 126$\pm$6 Ma) on this track (correlation coefficient = 0.90). Lacking other Tithonian-Berriasian age poles, the PEP model predicts a transition from J2-K rapid APW to the Cretaceous stillstand at approximately 140-142 Ma regardless of whether UPP or CPP poles are used. The absolute age of this transition is, however, very dependent on the time scale we use to assign ages to the Morrison poles. If we determine a best fit CPP J1-J2 line excluding the lower Morrison pole and then map the lower Morrison pole subtended angle onto this line, an absolute age of 140 Ma is predicted. While not consistent with the Harland et al. [1982] time scale, this estimate is consistent with the Van Hinte [1976] time scale.

Our application of the angular velocity diagram differs from Gordon et al. [1984], who do not use linear regression but constrain their lines to pass through data points corresponding to poles they interpret as track end points. But there is no reason why the position of the Wingate pole should be considered any better determined than any other pole on the "J-K" track. Neither is there any reason why the Monteregian Hills pole should represent the beginning of the Cretaceous stillstand. Therefore the linear regression method is probably a better approach to the angular velocity problem.

The slopes of the J1-J2 lines define angular velocities of 0.7°/m.y. and 0.6°/m.y. for UPP and CPP data sets, respectively. The J2-K lines, constrained only by the two Morrison Formation angular displacements, suggest dramatically higher angular velocities of 3.4°/m.y. and 2.8°/m.y. during the Tithonian. We believe that the increased plate velocity indicated by the Morrison poles is real but that the absolute values suggested by PEP angular displacement analysis are approximate at best.

Angular velocities associated with each of the PEPs yield linear velocities calculated at San Francisco, California, of about 5 cm/yr for the UPP J1-J2 pole and for a pole in the shaded region of the CPP J1-J2 solution space (Figure 5b). The UPP J2-K pole yields a linear velocity of about 30 cm/yr, and the CPP J2-K pole of 50 cm/yr. These latter values can be somewhat reduced by selecting PEPs closer to San Francisco, but still within the calculated solution space. However, even after selecting alternative pole locations, linear velocities seem unreasonably high. Perhaps this reflects problems with the age progression of poles along the J2-K track or inadequate constraint on the location of J2-K PEPs because of the small (N=3) data set.

Implications for North American Plate Motions and Tectonics

One of the goals of APW analysis is to understand the kinematic history of plate motion in relation to global tectonic and intraplate deformational events. It is therefore instructive to investigate the potential correlation between such events and the J1 and J2 cusps of the Jurassic APW path. The following discussions of North American tectonics and Jurassic APW are based on the CPP path shown in Figure 2b. This is considered a more conservative and defensible approach because both J1 and J2 cusps are defined by plateau poles. Uncorrected, the J1 cusp is more pronounced, and one is enticed into more elaborate tectonic scenarios than the true uncertainties probably warrant.

J1-J2 APW Track and Opening of the Atlantic Ocean

Correlations and relationships between the Jurassic APW path and the origin and evolution of the central Atlantic Ocean have been discussed for over a decade [Steiner, 1975; Dalrymple et al., 1975; Smith and Noltimier, 1979]. We can now compare the timing of the J1 and J2 cusps and the direction of J1-J2 and J2-K North American motion with the Atlantic rift and drift history.

The Sinemurian Wingate Formation pole is used to define the J1 cusp, but at the 95% confidence level it is not distinct from poles whose ages range from Carnian-Norian (Chinle Formation) to Pliensbachian (Kayenta Formation and Newark Group I, 195±4 Ma) (Figure 5). This Late Triassic to Early Jurassic timing of plate reorganization corresponds temporally with the breakup of Pangea and the separation of North America from Africa and South America. The syn-rift phase of this event is recorded by various Late Triassic-Early Jurassic red bed sedimentary sequences along the North American Atlantic and Gulf coasts.

The Chinle, Wingate, and Kayenta formations are correlative with rocks in the Newark Supergroup of the eastern United States [Olsen et al., 1982]. These sediments and interbedded lavas were deposited in fault-bounded basins interpreted as pull-apart structures and half grabens formed during early rifting between North America and Gondwana [Manspizer, 1981; Klitgord et al., 1984]. The oldest rocks in these basins are considered to be Carnian in age [Olsen et al., 1982] indicating that some degree of basin development had begun by Late Triassic time. The timing of actual plate separation and emplacement of oceanic crust is not well constrained and has been estimated at anywhere from Pliensbachian to Bathonian in age [Gradstein and Sheridan, 1983]. Klitgord et al. [1984] equate the initiation of seafloor spreading with the last major pulse of mafic igneous intrusions into the onshore rift basins at 179±3 Ma [Sutter and Smith, 1979]. The J1 cusp therefore correlates well with the syn-rift phase of Atlantic spreading history. Both the age range of rift sediments and the apparent duration of plate motion reorganization as recognized by the J1 cusp suggest a period of crustal stretching of at least 25-30 m.y.

No significant APW is recorded by 210-180 Ma paleopoles from Africa and South America [Irving and Irving, 1982; Vilas, 1981], and the hot spot model of Morgan [1983] predicts relatively minor northwest motion of thes plates during the Early Jurassic. This requires that the opening of the central Atlantic was accommodated primarily by North American absolute plate motion [Steiner, 1983]. This NW absolute motion of North America during Jurassic opening of the central Atlantic is recorded by the J1-J2 and J2-K APW tracks. The transition from rift to drift along the central Atlantic likely occurred during the late Early to Middle Jurassic (i.e., during the J1-J2 track time). The linearity of the J1-J2 track segment on the angular velocity diagram (Figure 7) suggests that North American plate angular velocity was constant during this fundamental tectonic transition.

Cusp J2

Using the magnetic polarity time scale of Harland et al. [1982], the J2 cusp (late Kimmeridgian-early Tithonian) corresponds temporally with a change in orientation of central Atlantic marine magnetic anomalies at chron M21 time (Kimmeridgian) [Schouten and Klitgord, 1982]. Associated with this plate reorganization, seafloor spreading may have ceased in the Gulf of Mexico leaving the Yucatan block and the Gulf basin as part of the northwestward moving North American plate. Continued spreading between North America and South America occurred along a ridge system through the proto-Caribbean south of the Yucatan block [Pindell, 1985]. The oldest marine magnetic anomalies recognized in the Venezuelan Basin as possible remnants of proto-Carribean spreading are approximately 150 Ma [Ghosh et al., 1984].

The major change in central Atlantic marine magnetic anomalies at chron M21 time, which we correlate with the J2 APW cusp, includes not only the general orientation but also geometrical details. Between chron M21 and M11 time, Schouten and Klitgord [1982] note the relative absence of anomaly offsets, which implies to them that the Mid-Atlantic Ridge was relatively straight and offset only by a few large transform faults. This is consistent with rapid seafloor spreading, which we suggest may correlate with rapid North American absolute plate motion during J2-K time. Sundvik et al. [1984] suggest a primary seafloor spreading origin for the transition from smooth to rough oceanic basement between anomaly M13 and M11 time. This is believed by them to reflect a decrease in the rate of mid-Atlantic spreading which may correspond to the transition from the J2-K APW track to the Cretaceous stillstand.

Intraplate Deformation in Western North America

A number of tectonomagmatic events along the western edge of North America correspond temporally with the J1 and J2 cusps of the Jurassic APW path. In the southern Cordillera the continental magmatic arc active throughout the Early? and Middle Jurassic in southeastern Arizona and northern Sonora shuts off at approximately 150 Ma and sweeps quickly to the continental margin by about 145 Ma [Coney and Reynolds, 1977; Damon et al., 1981]. This may reflect a change in the angle of subduction of the downgoing Farallon plate associated with a change in the relative and/or absolute plate motion across the southern Cordilleran trench. This implied reorganization corresponds closely with our estimated age of the J2 cusp and the associated change in North American absolute motion. A similar westerly arc migration is recognized at about this time in northern California [Saleeby et al., 1982].

As had been previously discussed by Steiner [1978, 1983] and Kluth et al. [1982], Gordon et al. [1984] recognized a subinterval of rapid APW in "Middle and Late Jurassic time" documented by the Summerville and Morrison Formation poles. The latter authors note a possible correlation with the Nevadan Orogeny in the northern Sierra Nevada and Klamath Mountains, suggesting that this event may be more closely related to North American absolute motion than to relative plate motions. We agree in part with this interpretation. However, recognition of the J2 cusp makes the temporal coincidence significantly more appealing and the plate kinematic scenario more consistent with PEP philosophy.

The Nevadan Orogeny has been interpreted by Saleeby et al. [1982] as an event of crustal shortening associated with collapse of an interarc basin within which oceanic crust as young as 157 Ma was being generated. In their model, approximately E-W directed convergence caused thrusting of older Mesozoic arc rocks on the east over interarc basin rocks on the west, with associated incorporation of ophiolites and intrusion of peridotitic to dioritic igneous complexes. The timing of the Nevada Orogeny in the northern Sierra Nevada and Klamath Mountains is well constrained at about 145-150 Ma. The youngest strata affected by Nevadan deformation are Kimmeridgian and a Pb/U zircon date from the predeformation or syndeformation Bear Mountain pluton in the Klamaths is 149±2 Ma [Saleeby et al., 1982]. Published dates for the lower Coon Mountain intrusive complex which postdates the Nevadan cleavage range from 142 to 150 Ma. The apparent age of the Nevadan Orogeny therefore correlates very well with the J2 cusp and attendant change in North American absolute plate motion. Paleomagnetic data interpreted as a "Nevadan" remagnetization have been obtained from rocks in the northern Sierra Nevada [Bogen et al., 1985]. A paleomagnetic pole calculated from these results is indistinguishable at the 95% confidence level from either of the Morrison Formation poles.

Oldow et al. [1984] recognize three major episodes of structural deformation in Mesozoic arc rocks of the northern Sierra Nevada and northeastern Oregon. The oldest of these is a Triassic-Jurassic event expressed as isoclinal folds with steep N-NW striking axial plane cleavage, steep fold axes and steep lineations. Radiometric dates associated with these structures are approximately 200 Ma [Saleeby, 1981], suggesting temporal correspondence with the J1 cusp. The second episode recognized by Oldow et al. is the Late Jurassic Nevadan event, which produced a structural fabric coplanar with the older event and folding contemporaneous with west to southwest vergent thrust or reverse faults.

One implication of relating tectonic episodes observed in the western United States to cusps in the Jurassic APW path is that although the timing suggests a cause/effect relationship, the change in North American absolute plate motion is not reflected by different orientations of structures in the Sierran region. As discussed by Beck [1983] and Moore and Karig [1980], the axis of shortening in zones of oblique subduction represented by structures in the leading edge of an upper plate is not necessarily parallel to the vector of relative plate motion. Rather, the shortening axis probably reflects the normal component of convergence and is constrained by the shape and orientation of the plate boundary. In other words, although episodes of intraplate deformation may be the result of changes in plate motion and therefore correspond to APW cusps, the expression of accommodated strain as reflected within regional structural fabric may bear no relation to the direction of motion of either plate. The temporal correlations of the above outlined tectonomagmatic events in western North America with the J1 and J2 cusps are intriguing and should be noted in regional tectonic syntheses.

Terrane Displacement

The western Cordillera of North America is a collage of tectonostratigraphic terranes whose paleogeographic relationships during Paleozoic and Mesozoic time with respect to cratonic North America and to each other are uncertain [Coney et al., 1980; Coney, 1981]. Paleomagnetic data from these terranes have proven useful for quantifying latitudinal displacements and azimuthal rotations [Beck, 1976, 1980]. Tectonic translation/rotation is measured by comparing observed paleomagnetic directions with expected directions calculated from cratonic reference poles. For this reason, reliable cratonic reference poles are fundamental to accurate estimation of the displacement history of suspect terranes within orogenic belts. The Late Triassic through Jurassic APW path presented in this paper differs significantly from previous APW analyses and from various reference poles previously calculated for comparison with specific paleomagnetic studies of Cordilleran terranes.

Paleomagnetic data from Late Triassic and Jurassic rocks in a number of suspect terranes are discussed in light of the revised APW path. Cratonic reference poles appropriate for each study have been calculated with Fisher statistics assigning unit weight to each paleopole (Table 5). In cases where only two poles are averaged, the larger of the two confidence parameters is taken for the average pole. This may be a somewhat conservative approach, but recalculation of reference poles from individual weighted VGPs does not alter the conclusions. In many cases, recalculation of concordance/discordance values merely modifies the magnitude of apparent dis-

TABLE 5. Cratonic Reference Poles for Concordance/Discordance Calculations

No.	Pole	Age	Age, Ma	Latitude °N	Longitude °E	A_{95} deg.
1	Manicouagan + Chinle	Late Triassic	220	58.4	84.4	7.0
2	Chinle Formation	Carnian-Norian	220-230	57.7	79.1	7.0
3	Newark Group I	Ar/Ar	195	63.0	83.2	2.3
4	Wingate + Kayenta + Newark Group I	Sinemurian-Pliensbachian	200	61.6	77.0	5.4
5	Wingate Formation	Sinemurian	200-206	59.6	70.4	8.0
6	Kayenta Formation	Pliensbachian	194-200	61.9	78.1	6.3
7	Wingate + Kayenta	Sinemurian-Pliensbachian	200	60.8	74.1	8.0

See footnote for Table 1. (Note that Wingate and Kayenta Formation poles used in this table are corrected for plateau rotation.)

placement, in other cases previously discordant results become concordant, and, in at least one case, a previously concordant result becomes discordant.

Directional concordance/discordance was calculated according to the technique of Beck [1980] as modified by Demarest [1983] or by converting observed and expected inclination data into paleolatitudinal bands. Important in such calculations and their attendant interpretation is the realization that even the best constrained values generally provide a latitudinal resolution of no better than 500-800 km.

Cratonic reference poles which include or are based on Colorado Plateau poles were calculated with both CPP and UPP data sets. Since these data sets are very similar, it makes no difference to conclusions of concordance or discordance which is used, and thus only corrected plateau pole values are shown in Table 6.

Terrane 1

Stikinia and Quesnellia along with the Cache Creek terrane and the Eastern Assemblage comprise the inboardmost "superterrane" of the Canadian Cordillera which is tectonically juxtaposed on the east with Paleozoic miogeoclinal strata (Figure 8). Recent paleomagnetic studies from rocks of Stikinia and Quesnellia have been interpreted as evidence for significant latitudinal displacement of these terranes with respect to cratonic North America [Monger and Irving, 1980; Symons, 1983; Symons and Litalien, 1984]. Apparent discordance between observed and expected inclinations from Late Triassic and Early Jurassic rocks seemed to indicate approximately 1500 km of northward relative motion during the late Mesozoic and early Cenozoic. Reconsideration of these paleomagnetic data in light of the Harland et al. [1982] time scale and our revised list of reliable cratonic reference poles leads to an alternative scenario regarding terrane displacement. Most importantly, the revised set of cratonic reference poles (Table 5) implies that there are no significant inclination anomalies for Stikinia and Quesnellia during Late Triassic and Early Jurassic time.

Characteristic components of the Stikine terrane include Mississippian and Permian volcaniclastic, volcanic, and carbonate sedimentary rocks [Coney, 1981]. This upper Paleozoic submarine volcanic arc assemblage is overlain by Late Triassic through Middle Jurassic volcanic rocks, predominantly basaltic and andesitic subaerial flows and pillow lavas [Monger et al., 1982]. Paleomagnetic data from Stikinia come from the Tąkla and Hazelton Group volcanics of this latter assemblage [Monger and Irving, 1980].

The Takla Group volcanics of Stikinia are Carnian-Norian in age [Monger and Irving, 1980] or approximately 220-230 Ma. The most appropriate reference pole for this study is the Chinle Formation pole of Reeve and Helsley [1972] given in Table 5. The age of the Chinle Formation also is Carnian-Norian, based on correlations to Newark Group strata by Olsen et al. [1982]. Alternatively, we can compare the Late Triassic Stikine results with a reference pole based on an average of the 215±5 Ma Manicouagan pole and the Chinle Formation pole. This average pole (58.3°N, 84.4°E) and the Chinle pole are both very different from the Late Triassic reference pole used by Monger and Irving [1980] (68°N, 93°E).

Monger and Irving [1980] and Irving et al. [1980] presented paleomagnetic data from Takla Group volcanic rocks exposed along the eastern side of Stikinia. Samples were collected from 14 sites at two localities (Asitka Peak and Sustut Peak, Table 6) within the Savage Mountain Formation, a thick sequence of predominantly pillow lavas and subaerial basalt flows of late Carnian to earliest Norian age (Figure 8). The mean direction from the Asitka Peak locality differs by 19° in declination and 6° in inclination from the mean at the Sustut Peak locality (Table 6). The difference in declination may reflect a small amount of relative rotation. The difference in

TABLE 6. Concordance/Discordance Data: Terrane 1

Rock Unit	Age	Ma	λS, °N	φS, °E	D_o, deg.	I_o, deg.	α_{95}, deg.	Reference Pole	D_x, deg.	I_x, deg.	α_{95}, deg.	R±ΔR, deg.	F±ΔF, deg.	Reference
Takla Group														
Asitka Peak	Carnian-Norian	225	56.7	234.6	300	44	6	1	342.9	46.1	7.0	-42.9± 9.0	2.1± 8.1	A
Asitka Peak	Carnian-Norian	225	56.7	234.6	300	44	6	2	345.7	44.4	7.0	-45.7± 9.0	0.4± 8.4	A
Takla Group														
Sustut Peak	Carnian-Norian	225	56.6	234.5	281	38	7	1	342.8	46.0	7.0	-61.8± 9.3	8.0± 8.7	A
Sustut Peak	Carnian-Norian	225	56.6	234.5	281	38	7	2	345.7	44.3	7.0	-64.7± 9.2	6.3± 8.8	A
Takla Group														
Average	Carnian-Norian	225				41	6	1		46	7		5 ± ~8	A
Average	Carnian-Norian	225				41	6	2		43	7		2 ± ~8	A
Hazelton Group														
Nilkitkwa Formation	Toarcian	~190	55.6	234.6	359	55	16	3	345.4	49.9	2.3	13.6±22.5	-5.1±12.6	A
Hazelton Group														
Telkwa Formation 1	late Sinemurian	200-203	55.8	234.4	242	56	18	4	348.0	47.6	5.4	-106.0±25.9	-8.4±14.5	A
Telkwa Formation 1	late Sinemurian	200-203	55.8	234.4	242	56	18	5	351.1	44.4	8.0	-109.1±26.4	-11.6±15.7	A
Telkwa Formation 1	late Sinemurian	200-203	55.8	234.4	242	56	18	7	349.3	46.3	8.0	-107.3±26.3	-9.7±15.6	A
Hazelton Group														
Telkwa Formation 2	late Sinemurian	200-203	56.5	234.2	294	52	25	4	347.8	48.5	5.4	-53.8±33.3	-3.5±19.6	A
Telkwa Formation 2	late Sinemurian	200-203	56.5	234.2	294	52	25	5	350.9	45.3	8.0	-56.9±33.7	-6.7±20.4	A
Telkwa Formation 2	late Sinemurian	200-203	56.5	234.2	294	52	25	7	349.1	47.2	8.0	-55.1±33.7	-4.8±17.3	A
Guichon Batholith	K/Ar	~200	50.5	239.0	28.3	36.3	7.3	4	350.8	40.4	5.4	37.5± 8.5	4.1± 8.2	B
Guichon Batholith	K/Ar	~200	50.5	239.0	28.3	36.3	7.3	5	353.9	36.8	8.0	34.7± 9.9	0.5±10.9	B
Guichon Batholith	K/Ar	~200	50.5	239.0	28.3	36.3	7.3	6	350.3	40.9	6.3	38.0± 9.0	4.6± 8.9	B
Guichon Batholith	K/Ar	~200	50.5	239.0	28.3	36.3	7.3	7	352.1	38.9	8.0	36.2± 9.9	2.6±10.6	B
Copper Mountain Intrusions	K/Ar	~200	49.3	239.4	25.9	41.2	3.6	4	351.1	38.6	5.4	34.8± 5.9	-2.6± 6.7	C
Copper Mountain Intrusions	K/Ar	~200	49.3	239.4	25.9	41.2	3.6	5	354.1	35.0	8.0	31.8± 7.7	-6.2±10.0	C
Copper Mountain Intrusions	K/Ar	~200	49.3	239.4	25.9	41.2	3.6	6	350.6	39.2	6.3	35.3± 6.6	-2.0± 7.5	C
Copper Mountain Intrusions	K/Ar	~200	49.3	239.4	25.9	41.2	3.6	7	352.4	37.1	8.0	33.5± 7.7	-4.1± 9.6	C

λS, site latitude; φS, site longitude; D_o, declination observed; I_o, inclination observed; α_{95}, Fisher statistic; Reference pole, Table 5; D_x, declination expected; I_x, inclination expected; R, rotation; F, flattening; References: A, Monger and Irving [1980]; B, Symons [1983]; C, Symons and Litalien [1984].

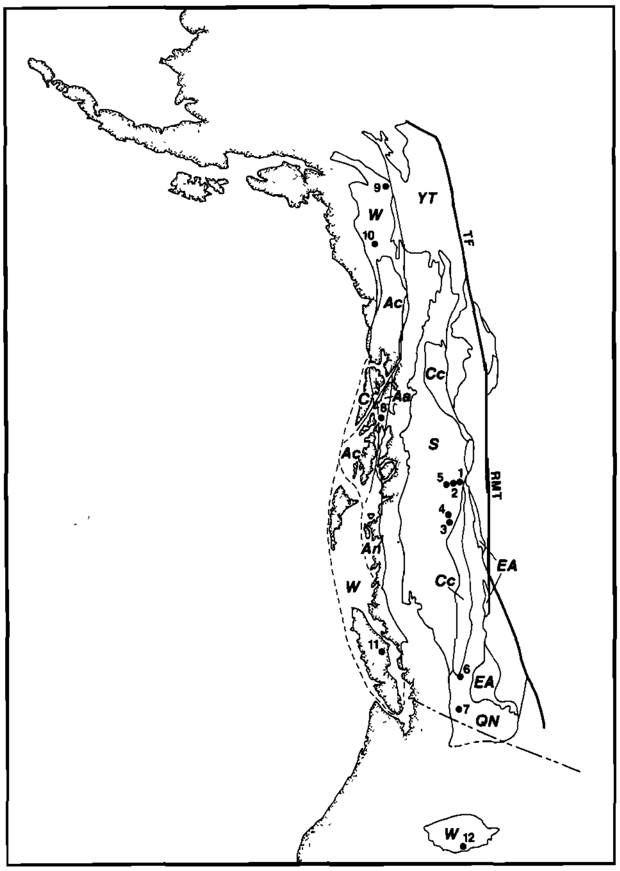


Fig. 8. Suspect terrane map of northwestern North America, modified from May et al. [1983]. Terranes include Ac, Alexander (Craig subterrane); Aa, Alexander (Admiralty subterrane); An, Alexander (Annette subterrane); C, Chugach; W, Wrangellia; S, Stikinia; Cc, Cache Creek; QN, Quesnellia; YT, Yukon-Tanana; and EA, Eastern assemblages. Paleomagnetic localities: 1, Takla Group, Asitka Peak; 2, Takla Group, Sustut Peak; 3, Hazelton Group, Nilkitkwa Formation; 4, Hazelton Group, Telkwa Formation 1; 5, Hazelton Group, Telkwa Formation 2; 6, Guichon Batholith; 7, Copper Mountain Intrusions; 8, Hound Island volcanics; 9, Alaska Range; 10, Wrangell Mountains; 11, Karmutsen volcanics, Vancouver Island; 12, "Seven Devils", southeast Oregon. TF, Tintina fault; RMT, Rocky Mountain Trench.

inclination is largely due to an obvious outlier in the Sustut Peak data set [Monger and Irving, 1980, Figure 4]. One of the eight sites from this locality has a WSW declination and an anomalously shallow inclination, which produces a low k value (18) and biases the locality mean direction toward a shallower inclination. Exclusion of this single outlier from the Sustut Peak locality brings the two locality mean directions into much closer agreement. Regardless, the mean inclinations at both localities as well as the formation average inclination of 41° given by Monger and Irving [1980] are concordant with expected directions predicted by either reference pole listed in Table 5. The simplest interpretation is that within the resolution provided by paleomagnetic data, Terrane 1 was situated at its present latitudinal position with respect to cratonic North America during the Late Triassic.

The mean declinations from the Takla Group volcanics are clearly discordant with "R" values of -43° to -65°. This rotation probably reflects local block rotation along the eastern side of Stikinia rather than wholesale rotation of the entire Terrane 1 composite.

The Hazelton Group volcanics of Stikinia are divided into two age groups of late Sinemurian and mid-Toarcian ages by Monger and Irving [1980]. The former with an approximate age of 200-203 Ma may be compared to reference poles calculated from the Wingate pole, the Wingate + Kayenta pole, and the Wingate + Kayenta + Newark Trend Group I pole. The mid-Toarcian group has an approximate age of 190 Ma, and thus may be compared to the Newark Group I pole. Each of these reference poles is different from the reference poles used for the Hazelton results by Monger and Irving [1980] (i.e., 60°-63°N versus 78°N present latitude).

Monger and Irving [1980] and Irving et al. [1980] present paleomagnetic data from the late Sinemurian Telkwa Formation and the mid-Toarcian Nilkitkwa Formation of the Hazelton Group in eastern central Stikinia (Figure 8). Four sites at each of two localities were collected from subaerial basalt flows and fine grained tuffs of the Telkwa Formation. Expected directions and concordance/discordance calculations based on our reference poles (Table 6) illustrate that irrespective of the reference pole selected, both localities have concordant inclinations. Thirty-seven cores from seven sites were studied by Monger and Irving [1980] from the Nikitkwa Formation in the Bait Range (Figure 8). Comparison of the observed mean direction with an expected direction calculated from the Newark Trend Group I pole reveals concordance in both declination and inclination (Table 6). At the 95% confidence level, Terrane 1 was situated at its present latitude relative to North America during the Early Jurassic based on paleomagnetic data from the Hazelton Group. However, owing to the very large α_{95} values for the three studies (16°, 18°, and 25°), the latitudinal resolution of the Hazelton data is quite limited.

Quesnellia is characterized by upper Paleozoic and Lower Triassic volcanic, volcaniclastic, and carbonate rocks and like Stikinia is interpreted as a submarine volcanic arc assemblage [Coney, 1981]. Quesnellia also contains Upper Triassic and Lower Jurassic volcanic and clastic rocks which are intruded by Late Triassic-Early Jurassic quartz dioritic to granitic plutons. Paleomagnetic data from Quesnellia have been reported from two of the early Mesozoic plutonic complexes (Guichon Batholith and Copper Mountain Intrusions) [Symons, 1983; Symons and Litalien, 1984].

The Guichon Batholith and the Copper Mountain Intrusions of Quesnellia are both dated at approximately 198 Ma [Symons, 1983; Symons and Litalien, 1984]. Four alternative reference poles are used for comparison with these two Terrane 1 poles in Table 6: (1) Wingate Formation pole, (2) Kayenta Formation pole, (3) Wingate + Kayenta pole, and (4) Wingate + Kayenta + Newark Trend Group I pole, all with estimated ages in the range of 194-206 Ma. Listed in Table 5, these four alternative reference poles are not statistically distinct, and it makes very little difference to concordance/discordance calculations which reference pole one chooses. Each of them is, however, significantly different from the reference pole (70°N, 94°E) chosen by Symons [1983] and Symons and Litalien [1984] for comparison with the Guichon and Copper Mountain results.

A mean direction of magnetization based on 49 specimens from 13 sites in the Guichon Batholith [Symons, 1983] (10 normal, 3 reversed) is concordant in inclination but discordant in declination with respect to all reference directions shown in Table 6. Approximately 35°-38° of clockwise rotation may be related to distributed shear "ball-bearing" style tectonics associated with dextral stike-slip along the southern Rocky Mountain Trench system. The observed inclination for the Guichon Batholith differs by only 0.5°-4.6° from expected 200 Ma inclinations. The same basic results are obtained if we compare the Guichon data with older Manicouagan or Manicouagan + Chinle reference poles.

Symons and Litalien [1984] report new paleomagnetic data from the Late Triassic-Early Jurassic Copper Mountain Intrusions of southern British Columbia. Like the Guichon Batholith, the Copper Mountain granitoids were emplaced into the Late Triassic volcanic and sedimentary Nicola Group rocks of Quesnellia (Figure 8). Symons and Litalien [1984] suggest an age of 198 Ma. Irrespective of the specific Early Jurassic reference pole chosen, concordance/discordance results are similar to the Guichon values. Positive "R" values indicate approximately 32°-35° of clockwise rotation, while "F" values are all concordant (Table 6). Once again, one must conclude on the basis of concordant inclination from the Copper Mountain Intrusions that Quesnellia was located at its present latitude relative with to cratonic North America during the Early Jurassic.

In summary, all of the available paleomagnetic data from Late Triassic and Early Jurassic rocks of Terrane 1 have concordant inclinations when compared to appropriate, reliable reference directions from cratonic North America. This conclusion is in direct conflict with the interpretations of Monger and Irving [1980], Symons [1983], and Symons and Litalien [1984]. These latter workers suggested as much as 10°-15° of relative latitudinal displacement between Terrane 1 and North America in late Mesozoic and early Cenozoic time.

Concordant Late Triassic and Jurassic paleomagnetic results from Stikinia and Quesnellia seem to be in conflict with geological and paleomagnetic data from younger rocks in the same terranes. These data seem to suggest 1000-2500 km of post-Middle Cretaceous northward translation outboard of the Tintina-Rocky Mountain Trench fault system. Paleomagnetic data of Rees et al. [1985] and Irving et al. [1985] have been interpreted to indicate as much as 2000-2500 km of post-Middle Cretaceous northward translation of Terrane 1. This conclusion is based on primary magnetizations observed in Cretaceous batholiths of the Coast Plutonic Complex and on secondary magnetizations observed in Late Triassic and Jurassic rocks of Stikinia.

Because late Paleozoic and early Mesozoic fossils from rocks in Terrane 1 indicate North American affinities, one possible scenario that will accommodate these various paleomagnetic data places Terrane 1 at roughly its present latitude with respect to the craton in the Late Triassic-Early Jurassic followed by southward translation until the ?Late Jurassic. Plate motion models of Engebretson [1982] show a change at about 145-150 Ma from SE to NE convergence of the Kula plate with respect to North America. Unfortunately, there are no reliable Middle or Late Jurassic paleomagnetic poles from Terrane 1 to test this south then north displacement model. Craton-derived detritus in the Bowser Basin indicates that Terrane 1 was juxtaposed with the craton by the Early Cretaceous [Eisbacher, 1974; Monger et al., 1982]. Alternatively, one might question the tectonic applicability of these paleomagnetic data from rocks with little or no paleohorizontal control. It is very likely that rocks in the Coast Plutonic complex of British Columbia have experienced post-Middle Cretaceous tilting in this region of complex Late Cretaceous and Tertiary deformation. Furthermore, the trend of a horizontal rotation axis that will most simply explain the discordant paleopoles from rocks such as the Spuzzum Pluton [Irving at al., 1985] is approximately parallel to the dominant regional structural trend (i.e., NW-SE) and would require modest tilt to the southwest.

Terrane 2

Wrangellia is a well-known tectonostratigraphic terrane, fragments of which are now recognized from NE Oregon to SE Alaska. It is characterized by a Pennsylvanian and Early Permian andesitic arc sequence overlain by Middle and/or Late Triassic tholeiitic basalt flows and pillow lavas, in turn overlain by Late Triassic platform carbonates [Jones et al., 1977]. A number of paleomagnetic studies of Triassic volcanic rocks from Wrangellia have been interpreted to show latitudinal displacements of up to 3000 km with respect to the craton. The magnitude of paleomagnetic discordance from Wrangellia is modified by the revised Late Triassic-Jurassic APW path.

Paleomagnetic investigation of Middle-Late Triassic basalts from four different regions of Wrangellia all predict approximately the same paleolatitude even though these fragments are now distributed over 2500 km along the Cordilleran margin. The most appropriate reference pole with which to compare Late Triassic Wrangellia results is the Carnian-Norian age Chinle Formation pole (Table 5). Reference poles for Wrangellia studies have consistently been chosen at significantly higher latitudes and more easterly longitudes: 64°N, 92°E [Hillhouse, 1977], 68°N, 93°E [Yole and Irving, 1980], 65.3°N, 94.2°E [Hillhouse et al., 1982], and 61.4°N, 92.5°E [Hillhouse and Gromme, 1984]. These reference poles suffer from including both unreliable data and numerous results from rocks now known to be of Early Jurassic age. For example the reference pole of Hillhouse and Gromme [1984] is calculated from nine paleopoles, only two of which are from Late Triassic rocks. The reliability of the pole from the Watchung Basalts [Opdyke, 1961] has recently been questioned by McIntosh et al. [1985] (see the appendix) and is Early Jurassic in age. Similar-

TABLE 7. Paleolatitude Results From Wrangellia

Locality	Observed Paleolatitude °N	Expected Paleolatitude °N	Poleward Displacement, km
Wrangell Mountains, Alaska [Hillhouse, 1977]	7.7-13.1	27.3-40.8	2541*
Alaska Range, Alaska [Hillhouse and Gromme, 1984]	10.1-17.7	29.1-43.4	2387*
Vancouver Island, British Columbia [Yole and Irving, 1980]	15.3-19.3	15.1-24.5	253*
Southeast Oregon, "Seven Devils," [Hillhouse et al., 1982]	13.4-21.6	9.7-17.9	-429†

*Northern hemisphere interpretation.
†Northern hemisphere, south translation.

ly, poles from the Newark Trend intrusive and extrusive rocks are known to be Early Jurassic, as is the Kayenta Formation pole. On the other hand, the Moenkopi Formation, from which two poles were used by Hillhouse and Gromme, is Early Triassic and significantly older than the Wrangellia basalts. The reference pole of Hillhouse and Gromme therefore includes poles whose ages range from 245 to 195 Ma and which fall on both the Tr-J1 and J1-J2 APW tracks of the North American APW path.

We have compared the observed paleolatitudes for Wrangellia compiled by Hillhouse and Gromme [1984] with expected paleolatitudes based on the Chinle reference pole (Table 7). Inclinations from both the northeastern Oregon (Seven Devils and Huntington Arc rocks) and the Vancouver Island (Karmutsen Volcanics) (Figure 8) are concordant, suggesting no significant latitudinal displacement of these fragments since the Late Triassic. Inclinations from the Wrangell Mountains and Alaska Range (Nikolai Greenstone) (Figure 8) are discordant and suggest approximately 2300-2500 km of northward latitudinal displacement, consistent with their present geographic separation from the southerly fragments of Wrangellia. Assuming a northern hemisphere location in the Late Triassic, concordance/discordance calculations based on the revised reference pole suggest that all of Wrangellia was located at the approximate latitude of northern Oregon-southern British Columbia.

Expected paleolatitudes were also calculated using a reference pole (57.3°N,90.1°E) which is the average of the Chinle and Moenkopi poles. This reference pole is appropriate for rocks slightly older than the Carnian-Norian Chinle Formation and allows for the fact that the Nikolai Greenstone may be as young as Ladinian. The resulting paleolatitudes are all within 1.6° of those listed in Table 7 so the basic conclusions are unaffected by choice of either Chinle or Chinle+Moenkopi reference poles.

One of the more enigmatic paleomagnetic results from the western Cordillera has been the Hound Island Volcanics pole published by Hillhouse and Gromme [1980]. The Hound Island Volcanics are part of a submarine volcanic arc assemblage consisting of pillow basalts, pillow breccias, andesitic breccia, aquagene tuffs, and minor limestones assigned to the Admiralty subterrane [Hillhouse and Gromme, 1980]. As originally interpreted, the Hound Island paleomagnetic pole was concordant with respect to a North American Late Triassic reference. However, this apparent concordancy is simply an artifact of the reference pole used. Hillhouse and Gromme [1980] use a "Late Triassic" cratonic pole at 65.3°N, 94.2°E, which is based entirely on paleopoles from Early Jurassic Newark Trend igneous rocks and from the Early Jurassic Kayenta Formation. A more appropriate reference pole is either the Chinle Formation pole of Carnian-Norian age or an average Chinle + Manicouagan pole with a somewhat younger average age (Table 5). The Hound Island observed direction is discordant in both declination and inclination with respect to expected values calculated from either reference pole. Rotation values suggest counterclockwise rotation of $110° \pm 30°$, while negative flattening values can be interpreted either as evidence for southward translation of the Alexander terrane or extreme northward translation from the southern hemisphere. In the Late Triassic the Alexander terrane was located at approximately 47° either north or south, while the expected North American latitude was 27°-29° north.

Conclusions

The Jurassic APW path for North America presented in this paper differs from previously published paths generated with various smoothing techniques. The new path generally predicts more southerly paleolatitudes for North America than do any of several APW paths now in use. Belief in the accuracy of our selected data base allows confident recognition of APW cusps in the Late Triassic-Early Jurassic and Late Jurassic (J1 and J2). Cusps and intervening tracks are well described by PEP modeling and indicate periods of constant velocity of North American plate motion from the Sinemurian to early Tithonian and from the early Tithonian to the early? Berriasian. The timing of the J1 and J2 cusps corresponds with Atlantic Ocean and western North America tectonic events. Finally, PEP analysis accentuates the spatiotemporal relationships of reliable cratonic paleopoles, allowing more confident selection of reference poles for terrane displacement studies. Revised Late Triassic-Early Jurassic reference poles for North America indicate different amounts of tectonic transport for some western Cordilleran terranes than have been previously proposed. Previously published paleomagnetic data from Stikinia and Quesnellia yield concordant inclinations implying that these terranes were at approximately their present relative latitude with respect to cratonic North America during the Late Triassic-Early Jurassic. Southern fragments of Wrangellia also yield concordant inclinations with respect to revised Late Triassic reference poles if a northern hemisphere origin is assumed.

Appendix

In this appendix, paleomagnetic poles from Jurassic rocks of North America are reviewed. Discussion of reliable poles is given first, followed by brief explanations of why certain poles that have been used in past compilations were rejected.

Reliability criteria employed in the present analysis include (1) demonstration that a stable, primary component of magnetization was isolated through standard alternating field (af) and/or thermal demagnetization techniques (preferrably both), (2) $N \geq 10$ (number of sites = number of independent geomagnetic field readings, each preferrably determined from multiple samples), (3) Fisher precision parameter associated with VGP dispersion, $20 \leq k \leq 150$ (Important criteria for acceptance of a paleomagnetic pole include assurances that secular variation of the geomagnetic field has been averaged and that secondary components of magnetization have been removed. These criteria are in part evaluated on the basis of observed "k" values that reflect the dispersion of directions or VGPs. Models concerning paleosecular variation including expected dispersion values have been discussed by Cox [1970], McElhinny and Merrill [1975], and Merrill and McElhinny [1983]. Very high k values (i.e., $k>150$) often indicate failure to average secular variation (except in slowly cooled plutonic terrains), whereas very low k values (i.e., $k<20$) suggest the presence of uncleaned secondary components causing greater dispersion than expected from paleosecular variation. Another cause of low k values is improper tilt correction which can be important in studies of mildly deformed volcanic sequences [Beck and Burr, 1979]. The limiting values chosen for this analysis are somewhat arbitrary and are only used in conjunction with other data such as α_{95} and demagnetization results. No study was rejected solely on the basis of an unacceptable k value.), (4) $\alpha_{95} \leq 15°$, (5) age known to within ± 10 m.y. (assuming the absolute precision of the Harland et al. [1982] time scale), and (6) sufficient discussion of geologic setting such as to demonstrate an appropriate understanding of necessary structural corrections.

Late Jurassic: 144-163 Ma

Three paleopoles from Late Jurassic rocks of North America are considered reliable. Two poles from the Morrison Formation in Colorado and one from the Glance Conglomerate in southeastern Arizona record APW during late Kimmeridgian and Tithonian time (Figure 2). No reliable poles are available from Oxfordian or early Kimmeridgian rocks.

Morrison Formation. The youngest reliable Jurassic poles for cratonic North America are from the upper and lower Morrison Formation of the Colorado Plateau (Table 1). Steiner and Helsley [1975] studied the polarity stratigraphy of a 165-m-thick section of Morrison sandstone and mudstone near Norwood, Colorado, and Steiner [1980] discussed further results from this same locality. The 425 samples collected at an average spacing of 30 cm were subjected to progressive thermal demagnetization to 660°C. Approximately 50% of these samples retained a large component of Brunhes field overprint even after thermal cleaning so that a selected data set of only well-behaved sample directions was used to calculate pole positions.

Steiner and Helsley [1975] calculate poles in a variety of different ways. Poles for individual polarity zones segregate into two stratigraphically distributed clusters: a lower group R1, R4, and N2 and an upper group R5, R6, R7, and N5. We have converted polarity interval mean directions to VGPs for averaging, recognizing these are not true VGPs but probably are viable paleomagnetic poles themselves. Thus the formation mean poles (upper and lower) can be viewed as averages of multiple Morrison poles. Both subsets of poles pass the reversals test at 95% confidence. These considerations do not affect the mean pole positions but do affect the associated confidence regions. That is, the radius of the confidence circle is probably overestimated.

Following Steiner and Helsley [1975], the difference in pole positions for the upper and lower Morrison Formation is interpreted to reflect APW during Morrison deposition. The outcrop expression of this apparent temporal separation is unclear, but it may reflect a hiatus between the Salt Wash and Brushy Basin members of the Morrison Formation at the Norwood locality.

The biggest problem associated with the Morrison poles is the controversial age of this formation. In their original paper, Steiner and Helsley [1975] cite the "Portlandian" affinity of the dinosaur fauna and the pre-Purbeckian, post-Oxfordian estimation of Imlay [1952]. Steiner [1980] again cites Imlay [1952] but this time for a mid-late Oxfordian age for the lower part of the Morrison near Norwood, Colorado. Although not explicitly stated, the main reason for suggesting this older age for the Morrison seems to be Steiner's [1980] belief that the observed polarity zonation best correlates with magnetic polarity chrons M22-M25. However, this part of the magnetic polarity sequence is now considered to be entirely Oxfordian in age or approximately 156-163 Ma [Harland et al., 1982]. The correlation proposed by Steiner is based largely on the dominance of reversed polarity observed in the Morrison rather than on detailed matching of polarity patterns.

An alternative age assignment which is more consistent with both magnetostratigraphic and paleontologic data is that the Morrison Formation is dominantly Tithonian to late Kimmeridgian in age and that the polarity zonation is best correlated with chrons M16 to M19 [May, 1985]. Fossil mammals from the Brushy Basin Member of the Morrison Formation in Colorado and Wyoming have many taxa in common with the lower Purbeck Beds (late Tithonian) in England [Clemens et al., 1979], and Colbert [1973] has discussed the similarity in dinosaur faunas between Morrison, Purbeck, and Tendaguru (Africa) localities. The latter occurrence is considered late Kimmeridgian or early Tithonian on the basis of ammonites.

Steiner [1983] shows the age of the Morrison Formation as mid-Oxfordian to mid-Tithonian citing Imlay [1980], but she also states that the uppermost 25 samples from the Norwood locality were actually collected from the overlying Burro Canyon Formation which is generally considered to be Early Cretaceous in age [Tschudy et al., 1984]. The cleaned directions from these 25 samples are indistinguishable from those of the upper Morrison Formation (Brushy Basin Member), suggesting close temporal proximity. Imlay's [1980] belief that the Morrison may be as old as middle Oxfordian appears to be based on the fact that the underlying Sundance Formation contains fossils only as young as early Oxfordian. However, Pipiringos and O'Sullivan [1978] recognize a principal unconformity (J5) between the Morrison and Sundance formations which exhibits as much as 46 m of relief over a distance of 6 km near Escalante, Utah. Thus considerable time could separate deposition of the Sundance and Morrison formations at least on a local scale.

Therefore, on the basis of vertebrate fossils and a revised magnetostratigraphic correlation, the Morrison Formation is probably late Kimmeridgian through Tithonian in age or approximately 152-144 Ma. Using the alternative magnetostratigraphic correlation of May [1985], we have assigned absolute ages of 145 and 149 Ma to the upper and lower Morrison poles, respectively. These ages are somewhat younger than those assigned by Gordon et al. [1984] (147-152 and 152-156 Ma) and still may err in being somewhat too old. While Harland et al. [1982] pick the Kimmeridgian-Tithonian boundary at 150 Ma, their chronogram for this interval is poorly constrained and includes no data for 142-148 Ma. This stage/age boundary may therefore be somewhat younger, as suggested by Van Hinte [1976], and the Morrison poles may be as young as 136-141 Ma.

Glance Conglomerate. Kluth et al. [1982] report a paleomagnetic pole from Late Jurassic ash flow tuffs in southeastern Arizona (Table 1). Although originally considered to be a "lower member" of the Canelo Hills Volcanics, these rocks have recently been shown to rest depositionally on the "middle and upper" members of this unit and furthermore to be indistinguishable from the Glance Conglomerate [Kluth, 1982; Vedder, 1984]. This pole is referred to here as the Glance Conglomerate pole rather than the Canelo Hills pole to avoid confusion with recent paleomagnetic data from the Canelo Hills volcanics sensu strictu [May, 1985].

A stable primary component of magnetization was isolated in 15 sites through af and thermal cleaning techniques. Both a positive reversals test and a conglomerate test indicate that the isolated remanence is primary. The age of the ash flow tuffs in the lower Glance Conglomerate is well constrained by a Rb/Sr isochron date of 151$\pm$2 Ma [Kluth et al., 1982].

Steiner [1983] expresses some reservation regarding the use of the Glance Conglomerate (Canelo Hills) pole because these rocks are "in the tectonically disturbed area, southern basin and range of Arizona." She states that "no independent evidence exists to prove a lack of rotations subsequent to magnetization." Kluth et al. [1982] address this question and point to a number of reasons why vertical axis rotation is unlikely. Paleomagnetic sites were distributed in two sections with different attitudes and separated by numerous faults yet simple structural correction significantly improves clustering. Pre-basin and range paleogeographic reconstructions restoring about 20% crustal extension do not require vertical axis rotation [Coney, 1978]. May et al. [this issue] discuss the various forms of structural orientation data and paleomagnetic data which indicate that no significant vertical axis tectonic rotation took place in southeastern Arizona during the Laramide or Basin and Range orogenies. Perhaps most importantly, the Corral Canyon pole [May et al., this issue] from the Patagonia Mountains is consistent spatially and temporally with the Glance Conglomerate pole even though these two areas are separated by a major Laramide structure (Lampshire Canyon-Dove Canyon fault, see Kluth [1982]). Similarly, both poles are consistent in terms of age and location with both older and younger reliable paleopoles from other parts of the craton.

Middle Jurassic: 163-188 Ma

Two paleopoles are considered to be reliable indicators of the Middle Jurassic paleofield for North America. The 171$\pm$3 Ma Corral Canyon pole from southeastern Arizona [May et al., this issue] and the 179$\pm$3 Ma Newark Trend Group II pole provide reference poles for Bathonian and Bajocian time respectively (Figure 2). No reliable paleopoles are known from Callovian or Aalenian age rocks in North America.

Corral Canyon. A paleomagnetic pole from the Corral Canyon rocks in the Patagonia Mountains of southeastern Arizona has been discussed by May et al. [this issue]. This pole was based on 11 sites within welded ash flow tuffs and a single site in red mudstone all of which were shown to carry stable magnetizations by extensive af and thermal demagnetization. The data satisfy all reliability criteria, and the age is well constrained isotopically as 172$\pm$5.8 Ma. The Patagonia Mountains pole can be criticized on the same grounds as the Glance Conglomerate pole (see above), and the same arguments in defense of its tectonic stability can be invoked.

Newark Trend Group II. A plethora of paleomagnetic results have been published from Early and Middle Jurassic igneous rocks of the Newark trend intrusive series. Rather than discuss each of these poles separately, many of which are VGPs rather than true paleopoles, the reader is referred to the comprehensive summary of Smith and Noltimier [1979]. These workers recognized that VGPs from the Newark Trend intrusives cluster into two groups that correspond to temporally distinct intrusive episodes. The older (Pliensbachian equivalent) Group I or "prefolding" dikes and sills yield a mean pole position at 63.0°N, 83.2°E (Figure 2) based on data from 72 sites with k=56 and α_{95}=2.3°. The Group II or "postfolding" intrusives yield a pole at 65.3°N, 103.2°E (Figure 2) based on 156 sites with k=92 and α_{95}=1.4°.

The ages of these two intrusive groups are well constrained by $^{39}Ar/^{40}Ar$ and $^{40}K/^{40}Ar$ radiometric data reported by Sutter and Smith [1979]. Their work suggests ages of 179±3 Ma and 195±4 Ma for the Group II and Group I poles, respectively. Some controversy exists regarding the age range of various extrusive volcanic units within the Newark Supergroup sequence and included within the Group I average pole. Although the Watchung basalts, the Granby tuff and the Holyoke basalt yield VGPs interpreted as belonging to the Group I cluster by Smith and Noltimier [1979], both fossil fish and fossil pollen from surrounding sediments indicate an age of Hettangian to Sinemurian (200-213 Ma). Using VGPs from the West Rock, Mt. Carmel, and East Rock intrusives only, Smith and Noltimier report a paleopole located at 63.1°N, 82.5°E (k=107, α_{95}=2.8°) which is nearly identical with the Group I pole indicating that the inclusion of data from the extrusive rocks does not significantly affect the mean. The Watchung basalts have been recently restudied by McIntosh et al. [1985], who conclude that the number of flows sampled was probably insufficient to average secular variation even though the associated k value was only 26. Interestingly, the mean pole position calculated for the Watchung basalts is intermediate between the Group I and Group II poles of Smith and Noltimier [1979] perhaps suggesting that the older lavas were partially or wholly remagnetized during regional heating associated with the Early and Middle Jurassic phases of dike and sill emplacement. The radiometric age of the Group II pole is correlative with the Bathonian-Bajocian boundary of Harland et al. [1982].

Steiner [1978, 1980, 1983] has investigated the paleomagnetism of other Middle Jurassic formations in northern Arizona and northern Wyoming. These include the Bajocian Gypsum Spring and Piper formations, the Bathonian to early Callovian Carmel and Rierdon formations, and the late Callovian to Oxfordian Swift Formation. No reliable Jurassic paleomagnetic poles have been obtained from any of these rocks because of ubiquitous and dominant secondary magnetizations attributed by Steiner to postdepositional overprint. Steiner [1980] suggests that low NRM intensity and complex multicomponent magnetization also may reflect Jurassic geomagnetic field properties of low intensity and/or frequent polarity reversals. Paleomagnetic results from late Bathonian equivalent volcanic rocks and red mudstones in the Patagonia Mountains, SE Arizona [May et al., this issue], do not exhibit anomalous NRM intensities, retain stable primary magnetizations, and are dominantly of normal polarity through 650 m of section. It seems likely that the complicated magnetizations reported for Jurassic sedimentary rocks from the western interior United States reflect sedimentologic and diagenetic processes rather than geomagnetic field behavior.

Summerville Formation. Nearly all recent analyses of Jurassic APW have included a reference pole from the Middle Jurassic Summerville Formation published by Steiner [1978]. In eastern Utah the Summerville consists of approximately 120 m of thin bedded red siltstone and fine-grained sandstone and is overlain unconformably by the Morrison Formation. The age of the Summerville is considered to be middle to early late Callovian by Pipiringos and O'Sullivan [1978] and late Callovian by Imlay [1980] or approximately 163-167 Ma.

The Summerville paleomagnetic results suffer from a strong Cenozoic normal polarity overprint, although Steiner [1978] concludes that much of the section has a reversed polarity primary component. Thermal demagnetization to 630°-660°C was considered to have isolated a stable primary magnetization, but in only 15 out of 391 samples collected. Steiner [1978] argues that because this set of normal and reversed directions is antipodal, their mean is a "good estimate" of the Summerville direction but admits that the Summerville pole is "approximate at best." Because the unambiguous isolation of a stable primary component has not been demonstrated and the number of samples is very low, the pole position from the Summerville Formation is considered unreliable.

Twin Creek Formation. McCabe et al. [1982] published a paleomagnetic pole from the Middle Jurassic Twin Creek Formation in Wyoming. Seven of 10 sites considered stable by McCabe et al. [1982] are located within the Prospect and Darby thrust sheets of the Wyoming overthrust belt. Paleomagnetic data from the Chugwater Group (Early Triassic) in these same thrust sheets were cited by Grubbs and Van der Voo [1976] as evidence for differential tectonic rotation of frontal thrusts associated with impingement on basement cored uplifts of the foreland.

McCabe et al. [1982] acknowledge these earlier results but argue that because the mean directions observed for three sites from the Twin Creek on the Gros Ventre foreland block are statistically indistinguishable from site directions in the thrust sheets, the formation mean pole is representative of cratonic North America. Of these three foreland sites, however, two have k values of less than 15 and $_{95}$ greater than 20° leaving only a single site that passes the acceptance criteria described above. Also, deletion of these two sites decreases the total number of sites to eight, less than the 10 site acceptance criterion. In addition, McCabe et al. [1982] state that the anomalous easterly location of the Twin Creek pole may be the result of postdepositional chemical remagnetization.

Stump Formation. A Jurassic paleomagnetic pole from the Wyoming overthrust belt published by Schwartz and Van der Voo [1984] for the

Oxfordian Stump Formation is not included within our set of reliable poles for reasons similar to those discussed above for the Twin Creek Formation. Most importantly, only seven sites were studied, and the between site k value is less than 20. Although the Stump magnetization seems to pass a fold test, the overlying Early Cretaceous sediments also studied by Schwartz and Van der Voo [1984] show clear evidence for remagnetization during folding.

White Mountain Magma Series. Often used as a reliable 180 Ma paleopole for cratonic North America, the White Mountain magma series pole of Opdyke and Wensink [1966] is considered unreliable. The White Mountain pole is indistinguishable from the geographic North pole in contrast to all other reliable Early through Middle Jurassic poles which fall along a band of present latitude at 60°-65° N. The distribution of VGPs from the 12 stable sites is markedly streaked ranging from 71.5°N, 46.0°E to 75.5°N, 188.5°E. In a general sense, this VGP streak mimics the Early Jurassic-Early Cretaceous APW path but is displaced into higher latitudes, suggesting both a protracted and complex Mesozoic magnetization history as well as incorrect structural corrections or present field overprints. Furthermore, there are systematic directional differences between individual intrusions, as pointed out by Steiner and Helsley [1972].

The intrusive history of the White Mountains magma series is known to be complex with radiometric dates ranging from 235 to 100 Ma [Foland and Faul, 1977]. K-Ar dates for the intrusions sampled by Opdyke and Wensink range from 180 to 118 Ma, although no thermal demagnetization results were reported by these workers. Five of the 12 stable sites were collected from intrusions with K-Ar dates of 118 and 121 Ma, while only three sites were from the White Mountains pluton for which dates of 168-180 Ma have been obtained by Foland and Faul [1977]. Until a systematic pluton-by-pluton paleomagnetic study of the White Mountains magma series incorporating detailed thermal demagnetization is conducted, this pole cannot be considered a reliable Jurassic reference pole for North America.

Early Jurassic: 188-213 Ma

Three reliable paleopoles are known from Early Jurassic rocks and one from rocks whose estimated age includes the Triassic-Jurassic boundary. The 195±4 Ma Newark Trend Group I pole discussed above, the Kayenta Formation pole, and the Wingate Formation pole record APW during Pliensbachian and Sinemurian time (Figure 2).

Kayenta Formation. A paleomagnetic pole from the Kayenta Formation was reported by Steiner and Helsley [1974]. At that time, the Kayenta was thought to be upper Triassic, but Olsen et al. [1982] and Imlay [1980] have shown it to be Pliensbachian in age, or approximately 194-200 Ma. As discussed in relation to the Morrison Formation, the sampling scheme of Steiner and Helsley is not especially well suited for paleomagnetic pole position calculation because "sites" are represented by single cores closely spaced throughout a stratigraphic interval or by polarity intervals.

Data listed in Table 1 of Steiner and Helsley [1974] do not allow a paleomagnetic pole to be calculated from the mean of site (=sample) VGPs. Resorting to polarity interval mean poles as VGPs, a formation mean pole based on N=7 is located at 62.1°N, 70.2°E (α_{95}=6.3°, k=92.2). The confidence interval on this calculation is probably larger than it should be. The α_{95} values for poles cited by Steiner and Helsley are 6.8° for polarity zones (N=7) and 2.5° for samples (N=105); the weighted standard error confidence parameter used by Gordon et al. [1984] is 4°.

A disturbing feature of the Kayenta data set is the noncircular distribution of polarity zone VGPs. These poles are elongate along the path of Early and Middle Jurassic APW, from about the position of the Wingate Formation pole (i.e., Sinemurian) almost to the Newark Trend Group II pole (179±3 Ma). Steiner and Helsley [1974] suggested a great circle fit to these poles approximately 90° away from the sampling locality which they attributed to possible long-term variation of the geomagnetic field. Within-zone directions are not obviously streaked (except for zone N2), but there is a clear difference between VGPs calculated from normal polarity zones and those calculated from reversed zones. A pole calculated from the four reversed-zone VGPs at 61.4°N, 63.0°E (α_{95}=5.0°, k=357.1) is identical to the paleopole from the underlying Wingate Formation. The mean pole of the three normal polarity zone VGPs lies farther east, although it is not statistically distinct (62.3°N, 80.1°E, α_{95}=17.6°, k=50). These features of the Kayenta Formation paleomagnetism are puzzling and deserve further investigation. However, we do consider the Kayenta pole of Steiner and Helsley to be a reliable Early Jurassic reference.

Wingate Formation. A pole from the Wingate Formation has been discussed by Steiner [1983] and Gordon et al. [1984] based on original data of Reeve [1975]. Steiner [1983] concluded that a reliable paleopole could not be calculated from Reeve's data because of extensive present field overprint that was not completely removed. Gordon et al. [1984] concluded differently and calculated a pole position based on 156 samples from two localities. They describe a small reversed overprint removed by thermal demagnetization at 550°-630°C. After having reviewed Reeve's thesis we are inclined to agree with the conclusion of Gordon et al. [1984]; however, the locality mean k values reported by Reeve are quite low. The Wingate Formation pole is tentatively included as the earliest reliable Jurassic reference for North America (Table 1, Figure 2). Peterson and Pipiringos [1979] and Imlay [1980] both consider the Wingate to be Sinemurian in age or approximately 200-206 Ma.

Manicouagan Impact Structure. The youngest reliable Triassic paleopole for North America is from igneous rocks of the Manicouagan Impact structure in Quebec, Canada, whose radiometric age (215±4 Ma) includes the Triassic-Jurassic boundary. This date is based on concordant whole rock and mineral separate K/Ar data published by Wolfe [1971] (revised for new decay and abundance constants). A combination of paleomagnetic results based on the work of Robertson [1967] and Larochelle and Currie [1967] yields a pole position at 58.8°N, 89.9°E (α_{95}=5.8°) (Figure 2). Paleomagnetic properties of a variety of rock types were studied with both af and thermal demagnetization. We have averaged VGPs from six sites from Robertson [1967] with the five site mean VGPs of Larochelle and Currie [1967].

Irving and Irving [1982] list 10 equally weighted poles from northeastern North America igneous rocks of supposed Late Triassic and Early Jurassic age. All of these poles are now considered to belong to either the Group I or Group II Newark Trend poles of Smith and Noltimier [1979] or to be unreliable VGPs. The postfolding intrusions pole (49) is essentially the Group II pole of Smith and Noltimier [1979] which is the reference cited by Irving and Irving [1982], but they misquote the age as 170 Ma rather than 179 Ma and they cite the pole at 68.4°N, 98.9°E rather than at 65.3°N, 103.2°E as given by Smith and Noltimier. The prefolding intrusions pole (53) of Irving and Irving is basically identical to the Group I pole of Smith and Noltimier.

The Anticosti Island diabase dike pole (50) is clearly a VGP only and should not be given equal weighting. Larochelle [1971] stated that the mean pole based on 11 cores from two sites (α_{95} =2°) was not a valid paleomagnetic pole. The high latitude of the Anticosti dike VGP tends to bias the 170, 180, and 190 Ma reference poles of the Irving and Irving APW path toward high latitudes.

The so called "Newark Series, New Jersey" pole (52) of Irving and Irving [1982] is attributed to Opdyke [1961] and is apparently taken from Table 4 of that paper. This pole is based in part on five sites from the Wachtung basalts and six sites from intrusives both of which have already been discussed and were included in the Group I data set of Smith and Noltimier [1979]. The remaining 18 sites contributing to the "Newark Series" pole are uncleaned directions from sediments of the Passaic Formation. A recent reinvestigation of the paleomagnetism of the Passaic Formation concludes that it carries an "unremovable" secondary magnetization of presumed Cenozoic age [McIntosh et al., 1985]. Site mean directions fail the fold test and k values for normal and reverse polarity sites are extremely low (8 and 6).

The "Connecticut Volcanic rocks," "Diabase dikes and sills," "Newark Diabase," and "North Mountain Basalt" poles of Irving and Irving [1982] also are based on data included by Smith and Noltimier [1979] in their Group I and Group II poles.

Acknowledgments. We thank Greg Cole for supplying the computer program used in the PEP analysis. The authors benefited from numerous discussions of this work with Myrl Beck, Peter Coney, and Bill Dickinson and from a helpful review by Jack Hillhouse. This research was funded by National Science Foundation grant EAR-8314113.

References

Baag, C., and C.E. Helsley, Evidence for penecontemporaneous magnetization of the Moenkopi Formation, J. Geophys. Res., 79, 3308-3320, 1974.

Beck, M.E., Jr., Paleomagnetism of Upper Triassic diabase from Pennsylvania: Further results, J. Geophys. Res., 77, 5673-5687, 1972.

Beck, M.E., Jr., Discordant paleomagnetic pole positions as evidence of regional shear in fthe western Cordillera of North America, Am. J. Sci., 276, 694-712, 1976.

Beck, M.E., Jr., Paleomagnetic record of plate margin tectonic processes along the western edge of North America, J. Geophys. Res., 85, 7115-7131, 1980.

Beck, M.E., Jr., On the mechanism of tectonic transport in zones of oblique subduction, Tectonophysics, 93, 1-11, 1983.

Beck, M.E., Jr., Introduction to the special issue on correlations between plate motions and Cordilleran tectonics, Tectonics, 3, 103-105, 1984.

Beck, M.E., Jr., and C.D. Burr, Paleomagnetism and tectonic significance of the Goble Volcanic Series, southwestern Washington, Geology, 7, 175-179, 1979.

Bogen, N.L., D.V. Kent, and R.A. Schweickert, Paleomagnetism of Jurassic rocks in the western Sierra Nevada metamorphic belt and its bearing on the structural evolution of the Sierra Nevada block, J. Geophys. Res., 90, 4627-4638, 1985.

Briden, J.C., A.M. Hurley, and A.G. Smith, Paleomagnetism and Mesozoic-Cenozoic paleocontinental maps, J. Geophys. Res., 86, 11,631-11,656, 1981.

Bryan, P., and R.G. Gordon, Maximum likelihood estimates of the rotation of the Colorado Plateau inferred from paleomagnetic data, Eos Trans. AGU, 66, 254, 1985.

Christensen, F.D., A paleomagnetic investigation of the Permo-Carboniferous Maroon and upper Permian-lower Triassic State Bridge Formations in north central Colorado, M.S. thesis, Univ. of Tex. at Dallas, Richardson, 1974.

Clemens, W.A., J.A. Lillegraven, E.H. Lindsay, and G.G. Simpson, Where, when, and what--A survey of known Mesozoic mammal distribution, in Mesozoic Mammals: The First Two-Thirds of Mammalian History, edited by J.A. Lillegraven, Z. Kielan-Jaworowska, and W.A. Clemens, pp. 7-58, University of California Press, Berkeley, Calif., 1979.

Colbert, E.H., Continental drift and the distribution of fossil reptiles, Implications of Continental Drift to the Earth Sciences, edited by D.H. Tarling, and S.K. Runcorn, NATO Adv. Stud. Inst. Sec., Ser. C, 1, 395-412, 1973.

Collinson, D.W., and S.K. Runcorn, Polar wandering and continental drift: Evidence of paleomagnetic observations in the United States, Geol. Soc. Am. Bull., 71, 915-958, 1960.

Coney, P.J., The plate tectonic setting of southeastern Arizona, Land of Cochise, edited by J.F. Callender, J.C. Wilt, and R.E. Clemons, Fieldl Conf. Guideb. N. M. Geol. Soc., 29, 285-290, 1978.

Coney, P.J., Accretionary tectonics in western North America, Relations of Tectonics to Ore Deposits in the Southern Cordillera, edited by W.R. Dickinson and W.D. Payne, Ariz. Geol. Soc. Dig., 14, 23-38, 1981.

Coney, P.J., and S.J. Reynolds, Cordilleran Benioff zones, Nature, 270, 403-406, 1977.
Coney, P.J., D.L. Jones, and J.W.H. Monger, Cordilleran suspect terranes, Nature, 288, 329-333, 1980.
Cordell, L., Extension in the Rio Grande rift, J. Geophys. Res., 87, 8561-8569, 1982.
Cox, A., Latitude dependence of the angular dispersion of the geomagnetic field, Geophys. J. R. Astron. Soc., 20, 253-269, 1970.
Dalrymple, G. B., C.S. Gromme, and R.W. White, Potassium-argon age of diabase dikes in Liberia: Initiation of central Atlantic rifting, Geol. Soc. Am. Bull., 86, 399-411, 1975.
Damon, P.E., M. Shafiqullah, and K.F. Clark, Age trends of igneous activity in relation to metallogenesis in the southern Cordillera, Relations of Tectonics to Ore Deposits in the Southern Cordillera, edited by W.R. Dickinson and W.D. Payne, Ariz. Geol. Soc. Dig., 14, 137-154, 1981.
Demarest, H.H., Jr., Error analysis for the determination of tectonic rotation from paleomagnetic data, J. Geophys. Res., 88, 4321-4328, 1983.
deBoer, J., Paleomagnetic-tectonic study of Mesozoic dike swarms in the Appalachians, J. Geophys. Res., 72, 2237-2250, 1967.
deBoer, J., Paleomagnetic differentiation and correlation of the Late Triassic volcanic rocks of the central Appalachians (with special reference to the Connecticut Valley), Geol. Soc. Am. Bull., 79, 609-626, 1968.
DuBois, P.M., E. Irving, N.D. Opdyke, S.K. Runcorn, and M.R. Banks, The geomagnetic field in upper Triassic times in the United States, Nature, 180, 1186-1187, 1957.
Eby, G.N., Geochronology of the Monteregian Hills alkaline igneous province, Quebec, Geology, 12, 468-470, 1984.
Eisbacher, G.H., Evolution of successor basins in the Canadian Cordillera, Modern and Ancient Geosynclinal Sedimentation, edited by R.H. Dott, and R.H. Shaver, Spec. Publ. Soc. Econ. Paleontol. Mineral., 19, 274-291, 1974.
Engebretson, D.C., Relative motions between oceanic and continental plates of the Pacific Basin, Ph.D. dissertation, Stanford Univ., Stanford, California, 1982.
Fisher, R.A., Dispersion on a sphere, Proc. R. Soc. London, Ser. A, 217, 295-305, 1953.
Foland, K.A., and H. Faul, Ages of the White Mountain intrusives - New Hampshire, Vermont, and Maine, USA, Am. J. Sci., 277, 888-904, 1977.
Forsyth, D.W., and S. Uyeda, On the relative importance of the driving forces of plate motion, Geophys. J. R. Astron. Soc., 43, 163-200, 1975.
Francheteau, J., and J.G. Sclater, Paleomagnetism of the southern continents and plate tectonics, Earth Planet. Sci. Lett., 6, 93-106, 1969.
Ghosh, N., S.A. Hall, and J.F. Casey, Seafloor spreading magnetic anomalies in the Venezuelan Basin, The Caribbean-South American Plate Boundary and Regional Tectonics, edited by W.E. Bonini, R.B. Hargraves, and R. Shagam, Mem. 162, Geol. Soc. Am., 65-80, 1984.
Gordon, R.G., A. Cox, and S. O'Hare, Paleomagnetic Euler poles and the apparent polar wander and absolute motion of North America since the Carboniferous, Tectonics, 3, 499-537, 1984.
Gradstein, F.M., and R.E. Sheridan, On the Jurassic Atlantic Ocean and a synthesis of results of Deep Sea Drilling Project leg 76, Initial Rep. Deep Sea Drill. Proj., 76, 913-943, 1983.
Grubbs, K.L., and R. Van der Voo, Structural deformation of the Idaho-Wyoming overthrust belt, as determined by Triassic paleomagnetism, Tectonophysics, 33, 321-336, 1976.
Hamilton, W., Plate-tectonic mechanism of Laramide deformation, Contrib. Geol., 19, 87-92, 1981.
Harland, W.B., A.V. Cox, P.G. Llewellyn, C.A.G. Pickton, A.G. Smith, and R. Walters, A Geologic Time Scale, Cambridge University Press, New York, 1982.
Harrison, C.G.A., and T. Lindh, A polar wandering curve for North America during the Mesozoic and Cenozoic, J. Geophys. Res., 87, 1903-1920, 1982.
Herrero-Bervera, E., and C.E. Helsley, Paleomagnetism of a polarity transition in the lower (?)Triassic Chugwater Formation, Wyoming, J. Geophys. Res., 88, 3506-3522, 1983.
Hillhouse, J.W., Paleomagnetism of the Triassic Nikolai Greenstone, McCarthy Quadrangle, Alaska, Can. J. Earth Sci., 14, 2578-2592, 1977.
Hillhouse, J.W., and C.S. Gromme, Paleomagnetism of the Triassic Hound Island Volcanics, Alexander terrane, southeastern Alaska, J. Geophys. Res., 85, 2594-2602, 1980.
Hillhouse, J.W., and C.S. Gromme, Northward displacement and accretion of Wrangellia: New paleomagnetic evidence from Alaska, J. Geophys. Res., 89, 4461-4477, 1984.
Hillhouse, J.W., C.S. Gromme, and T.L. Vallier, Paleomagnetism and Mesozoic tectonics of the Seven Devils volcanic arc in northeastern Oregon, J. Geophys. Res., 87, 3777-3794, 1982.
Imlay, R.W., Correlation of the Jurassic formations of North America exclusive of Canada, Geol. Soc. Am. Bull., 63, 953-992, 1952.
Imlay, R.W., Jurassic paleobiogeography of the coterminous United States in its continental setting, U.S. Geol. Surv. Prof. Pap., 1062, 67-99, 1980.
Irving, E., Paleomagnetism and its Application to Geological and Geophysical Problems, 399 pp., John Wiley, New York, 1964.
Irving, E., Drift of the major continental blocks since the Devonian, Nature, 270, 304-309, 1977.
Irving, E., Paleopoles and paleolatitudes of North America and speculations about displaced terrains, Can. J. Earth Sci., 16, 669-694, 1979.
Irving, E., and G.A. Irving, Apparent polar wander paths Carboniferous through Cenozoic and the assembly of Gondwana, Geophys. Surv., 5, 141-188, 1982.
Irving, E., and Park, J.K., Hairpins and superintervals, Can. J. Earth Sci., 9, 1318-1324, 1972.
Irving, E., J.W.H. Monger, and R.W. Yole, New

paleomagnetic evidence for displaced terranes in British Columbia, The continental crust and its mineral deposits, edited by P.W. Strangway, Spec. Paper. Geol. Assoc. Can., 20, 441-456, 1980.

Irving, E., G.J. Woodsworth, P.J. Wynne, and A. Morrison, Paleomagnetic evidence for displacement from the south of the Coast Plutonic Complex, British Columbia, Can. J. Earth Sci., 22, 584-598, 1985.

Jones, D.L., N.J. Silberling, and J.W. Hillhouse, Wrangellia: A displaced terrane in northwestern North America, Can. J. Earth Sci., 14, 2565-2577, 1977.

Klitgord, K.D., P. Popenoe, and H. Schouten, Florida: A Jurassic transform plate boundary, J. Geophys. Res., 89, 7753-7772, 1984.

Kluth, C.F., Geology and mid-Mesozoic tectonics of the northern Canelo Hills, Santa Cruz County, Arizona, Ph.D. dissertation, Univ. of Ariz., Tucson, 1982.

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

Larochelle, A., Note on the paleomagnetism of two diabase dykes, Anticosti Island, Quebec, Proc. Geol. Assoc. Can., 23, 73-76, 1971.

Larochelle, A., and K.L. Currie, Paleomagnetic study of igneous rocks from the Manicouagan Structure, Quebec, J. Geophys. Res., 72, 4163-4169, 1967.

Mankinen, E.A., Paleomagnetic evidence for a Late Cretaceous deformation of the Great Valley sequence, Sacramento Valley, California, J. Res. U.S. Geol. Surv., 6, 383-390, 1978.

Manspeizer, W., Early Mesozoic basins of central Atlantic passive margins, in Geology of Passive Continental Margins: History, Structure, and Sedimentologic Record (With Special Emphasis on the Atlantic Margin), edited by A.W. Bally, Educ. Course Note Ser., vol. 19, pp. 4-1 - 4-60, American Association of Petroleum Geologists, Tulsa, Okla., 1981.

May, S.R., Paleomagnetism of Jurassic volcanic rocks in southeastern Arizona and North American Jurassic apparent polar wander, Ph.D. dissertation, Univ. of Ariz., Tucson, 1985.

May, S.R., R.F. Butler, M. Shafiqullah, and P.E. Damon, Paleomagnetism of Jurassic volcanic rocks in the Patagonia Mountains, southeastern Arizona: Implications for the North American 170 Ma reference pole, J. Geophys. Res., this issue.

May, S.R., P.J. Coney, and M.E. Beck, Jr., Paleomagnetism and suspect terranes of the North American Cordillera, U.S. Geol. Surv. Open File Rep., 83-799, 8 pp., 1983.

McCabe, C., R. Van der Voo, and B.H. Wilkinson, Paleomagnetic and rock magnetic results from the Twin Creek Formation (Middle Jurassic), Wyoming, Earth Planet. Sci. Lett., 60, 140-146, 1982.

McElhinny, M.W., Paleomagnetism and Plate Tectonics, 358 pp., Cambridge University Press, New York, 1973.

McElhinny, M.W., and R.T. Merrill, Geomagnetic secular variation over the past 5 m.y., Rev. Geophys., 13, 687-708, 1975.

McIntosh, W.C., R.B. Hargraves, and C.L. West, Paleomagnetism and oxide mineralogy of upper Triassic red beds and basalts in the Newark Basin, Geol. Soc. Am. Bull., 96, 463-480, 1985.

Merrill, R.T., and M.W. McElhinny, The Earth's Magnetic Field: Its History, Origin, and Planetary Perspective, Int. Geophys. Ser., vol. 32, 401 pp., Academic, Orlando, Fla., 1983.

Monger, J.W.H., and E. Irving, Northward displacement of north-central British Columbia, Nature, 285, 289-294, 1980.

Monger, J.W.H., R.A. Price, and D.J. Tempelman-Kluit, Tectonic accretion and the origin of the two major metamorphic and plutonic welts in the Canadian Cordillera, Geology, 10, 70-75, 1982.

Moore, G.F., and D.E. Karig, Structural geology of Nias Island, Indonesia: Implications for subduction zone tectonics, Amer. J. Sci., 280, 193-223, 1980.

Morgan. W.J., Hotspot tracks and the early rifting of the Atlantic, Tectonophysics, 94, 123-139, 1983.

Oldow, J.S., H.G. Ave'Lallemant, and W.J. Schmidt, Kinematics of plate convergence deduced from Mesozoic structures in the western Cordillera, Tectonics, 3, 201-227, 1984.

Olsen, P.E., A.R. McCune, and K.S. Thompson, Correlation of the early Mesozoic Newark Supergroup by vertebrates, principally fishes, Am. J. Sci., 282, 1-44, 1982.

Opdyke, N.D., The paleomagnetism of the New Jersey Triassic: A field study of the inclination error in red sediments, J. Geophys. Res., 66, 1941-1949, 1961.

Opdyke, N.D., and H. Wensink, Paleomagnetism of rocks from the White Mountain plutonic-volcanic series in New Hamshire and Vermont, J. Geophys. Res., 71, 3045-3051, 1966.

Palmer, A.R., The decade of North American geology 1983 geologic time scale, Geology, 11, 503-504, 1983.

Peterson, F., and G.N. Pipiringos, Stratigraphic relations of Navajo Sandstone to Middle Jurassic formations, southern Utah and northern Arizona, U.S. Geol. Surv. Prof. Pap., 1035-B, 43 pp., 1979.

Pindell, J. L., Alleghenian reconstruction and subsequent evolution of the Gulf of Mexico, Bahamas, and Proto-Caribbean tectonics, Tectonics, 4, 1-40, 1985.

Pipiringos, G.N., and R.B. O'Sullivan, Principal unconformities in Triassic and Jurassic rocks, western interior United States - a preliminary survey, U.S. Geol. Surv. Prof. Pap., 1035-A, 29 pp., 1978.

Rees, C. J., E. Irving, and R.L. Brown, Secondary magnetization of Triassic-Jurassic volcaniclastic rocks of the Quesnel terrane, Quesnel Lake, B.C., Geophys. Res. Lett., 12, 498-501, 1985.

Reeve, S.C., Paleomagnetic studies of sedimentary rocks of Cambrian and Triassic age, Ph.D. dissertation, Univ. of Tex. at Dallas, Richardson, 1975.

Reeve, S.C., and C.E Helsley, Magnetic reversal sequence in the upper portion of the Chinle Formation, Montoya, New Mexico, Geol. Soc. Am. Bull., 83, 3795-3812, 1972.

Robertson, W.A., Manicouagan, Quebec, paleomagnetic results, Can. J. Earth Sci., 4, 641-649, 1967.
Saleeby, J.B., Ocean floor accretion and volcanoplutonic arc evolution of the Mesozoic Sierra Nevada, in The Geotectonic Development of California, edited by W.G. Ernst, pp. 132-181, Prentice-Hall, Englewood Cliffs, N. J., 1981.
Saleeby, J.B., G.C. Harper, A.W. Snoke, and W.D. Sharp, Time relations and structural-stratigraphic patterns in ophiolite accretion, west central Klamath Mountains, California, J. Geophys. Res., 87, 3831-3848, 1982.
Schouten, H., and K.D. Klitgord, The memory of the accreting plate boundary and the continuity of fracture zones, Earth Planet. Sci. Lett., 59, 255-266, 1982.
Schwartz, S.Y., and R. Van der Voo, Paleomagnetic study of thrust sheet rotation during foreland impingement in the Wyoming-Idaho overthrust belt, J. Geophys. Res., 89, 10,077-10,086, 1984.
Shive, P.N., and W.E. Frerichs, Paleomagnetism of the Niobrara Formation in Wyoming, Colorado, and Kansas, J. Geophys. Res., 79, 3001-3007, 1974.
Shive, P.N., M.B. Steiner, and D.T. Huycke, Magnetostratigraphy, paleomagnetism, and remanence acquisition in the Triassic Chugwater Formation of Wyoming, J. Geophys. Res., 89, 1801-1815, 1984.
Smith, T.E., Paleomagnetic study of lower Mesozoic diabase dikes and sills of Connecticut and Maryland, Can. J. Earth Sci., 13, 597-609, 1976.
Smith, T.E. and H.C. Noltimier, Paleomagnetism of the Newark trend igneous rocks of the north central Appalachians and the opening of the central Atlantic Ocean, Am. J. Sci., 279, 778-807, 1979.
Steiner, M.B., Mesozoic apparent polar wander and Atlantic plate tectonics, Nature, 254, 107-109, 1975.
Steiner, M.B., Magnetic polarity during the Middle Jurassic as recorded in the Summerville and Curtis Formations, Earth Planet. Sci. Lett., 38, 331-345, 1978.
Steiner, M.B., Investigation of the geomagnetic field polarity during the Jurassic, J. Geophys. Res., 85, 3572-3586, 1980.
Steiner, M.B., Mesozoic apparent polar wander and plate motions of North America, in Mesozoic Paleogeography of West-Central United States, edited by M.W. Reynolds and E.D. Dolly, pp. 1-11, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, Denver, Colo., 1983.
Steiner, M.B., Is the Colorado Plateau rotated?, Eos Trans. AGU, 65, 864, 1984.
Steiner, M.B., and C.E. Helsley, Jurassic polar movement relative to North America, J. Geophys. Res., 77, 4981-4993, 1972.
Steiner, M.B., and C.E. Helsley, Magnetic polarity sequence of the Upper Triassic Kayenta Formation, Geology, 2, 191-194, 1974.
Steiner, M.B., and C.E. Helsley, Reversal pattern and apparent polar wander for the Late Jurassic, Geol. Soc. Am. Bull., 36, 1537-1543, 1975.
Sundvik, M., R.L. Larson, and R.S. Detrick, Rough-smooth basement boundary in the western North Atlantic basin: Evidence for a seafloor-spreading origin, Geology, 12, 31-34, 1984.
Sutter, J.F., and T.E. Smith, $^{40}Ar/^{39}Ar$ ages of diabase intrusions from Newark trend basins in Connecticut and Maryland: Initiation of central Atlantic rifting, Am. J. Sci., 279, 801-831, 1979.
Symons, D.T.A., Paleomagnetism of the Jurassic Island Intrusions of Vancouver Island, British Columbia, Can. J. Earth Sci., 8, 1388-1396, 1970.
Symons, D.T.A., New paleomagnetic data for the Triassic Guichon batholith, southcentral British Columbia, and their bearing on Terrane I tectonics, Can. J. Earth Sci., 20, 1340-1344, 1983.
Symons, D.T.A., and C.R. Litalien, Paleomagnetism of the lower Jurassic Copper Mountain Intrusions and the geotectonics of Terrane I, British Columbia, Geophys. Res. Lett., 11, 685-688, 1984.
Tschudy, R.H., B.D. Tschudy, and L.C. Craig, Palynological evaluation of Cedar Mountain and Burro Canyon formations, Colorado Plateau, U.S. Geol Surv. Prof. Pap., 1281, 24 pp., 1984.
Van Alstine, D.R., Apparent polar wandering with respect to North America since the late Precambrian, Ph.D. dissertation, Calif. Inst. of Technol., Pasadena, 1979.
Van Alstine, D.R., and J. deBoer, A new technique for constructing apparent polar wander paths and the revised Phanerozoic path for North America, Geology, 6, 137-139, 1978.
Van Eysinga, F.W.B. (compiler), Geological Timetable, 3rd ed., Elseview, Amsterdam, 1975.
Van Hinte, J.E., A Jurassic time scale, Am. Assoc. Pet. Geol. Bull., 60, 489-497, 1976.
Vedder, L.K., Stratigraphic relationship of Late Jurassic Canelo Hills Volcanics and Glance Conglomerates, southeastern Arizona, M.S. thesis, Univ. of Ariz., Tucson, 1984.
Vilas, J.F.A., Paleomagnetism of South American rocks and the dynamic processes related with the fragmentation of western Gondwana, in Paleoreconstruction of the Continents, Geodyn. Ser., vol. 2, edited by M.W. McElhinny and D.A. Valencio, pp. 106-114, AGU/GSA, Washington, D. C., 1981.
Wolfe, S.H., Potassium-argon ages of the Manicouagan-Mushalagan Lake structure, J. Geophys. Res., 76, 5424-5436, 1971.
Yole, R.W., and E. Irving, Displacement of Vancouver Island: Paleomagnetic evidence from the Karmutsen Formation, Can. J. Earth Sci., 17, 1210-1288, 1980.

R. F. Butler, Department of Geosciences, University of Arizona, Tucson, AZ 85721.
S. R. May, Exxon Production Research Co., P.O. Box 2189, Houston, TX 77242.

(Received January 16, 1986;
revised June 19, 1986;
accepted June 24, 1986.)