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Influence of inclination error in sedimentary rocks on the Triassic and Jurassic apparent pole wander path for North America and implications for Cordilleran tectonics

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[1] Because of paleomagnetic inclination error (*I* error) in sedimentary rocks, we argue that previous estimates of Triassic and Jurassic paleolatitudes of the North American craton have generally been too low, the record being derived mostly from sedimentary rocks. Using results from all major cratons, we construct a new composite apparent pole wander (APW) path for Triassic through Paleogene based on 69 paleopoles ranging in age from 243 to 43 Ma. The poles are from igneous rocks and certain sedimentary formations corrected for *I* error brought into North American coordinates using plate tectonic reconstructions. Key features of the new APW path are a 25° northward progression from 230 to 190 Ma to high latitudes (off northernmost Siberia) where the pole lingers until 160 Ma, a jump to the Aleutians followed by a hook in western Alaska by ~145 Ma that leads to the 130–60 Ma stillstand, after which the pole moves to its present position. As an example of the application of this new path we use paleomagnetic results to determine that southern Wrangellia and Stikinia (W/S), the two most westerly terranes in the Canadian Cordillera, lay 630 to 1650 km farther south than at present relative to the craton during the Late Triassic and Early Jurassic. This is consistent with an exotic Tethyan origin as paleontological and mantle geochemical evidences imply. During the Late Triassic through Early Cretaceous, W/S moved northward more slowly than the craton, implying oblique sinistral *net* convergence over this 130 Myr interval. This was followed by dextral shear in latest Cretaceous through Eocene.

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1. Introduction

[2] Determining quantitatively the latitude changes that the North American craton has undergone requires an accurate apparent polar wander (APW) path. Paleomagnetic directions in igneous rocks with known paleohorizontal can generally record the field in which they were acquired more accurately than sedimentary rocks, which sometimes have inclinations lower than the ambient field; this is the inclination error: *I* error, which not uncommonly can exceed 5°. Paleomagnetic estimates of latitude depend on inclination, so APW paths should ideally be freed of *I* error; this is desirable for instance in order to evaluate long-term variations in climate or to evaluate displacements and rotations that have occurred in adjacent orogenic belts. Magnetizations in Cordilleran rocks are generally strongly aberrant in either inclination (indicative of latitudinal displacements or offsets relative to the North American craton which are our principal concern) or declination (indicative of rotations about local vertical axes), commonly both. For example, when comparisons were first made between the APW path and results from Triassic and Jurassic strata from the Canadian Cordillera, displacements of about 1000 km from the south were found. These results were from the two largest exotic terranes in the Cordillera: Wrangellia on Vancouver Island [*Schwartz et al.*, 1980; *Yole and Irving*, 1980] and Stikinia on the British Columbia mainland [*Monger and Irving*, 1980; *Vandall and Palmer*, 1990]. Even larger displacements approaching 3000 km were obtained from Triassic lavas of the Wrangellian terrane in Alaska [*Hillhouse*, 1977; *Hillhouse and Gromme*, 1984]. These Cordilleran results were all from igneous rocks which are not subject to inclination error and whose bedding attitudes are well controlled. Later, as a result of revisions in the APW path for North America, only the Alaskan results showed any significant latitudinal displacement. However, by the early 1990s, large unresolved differences between various versions of the Triassic/Jurassic portion of the APW

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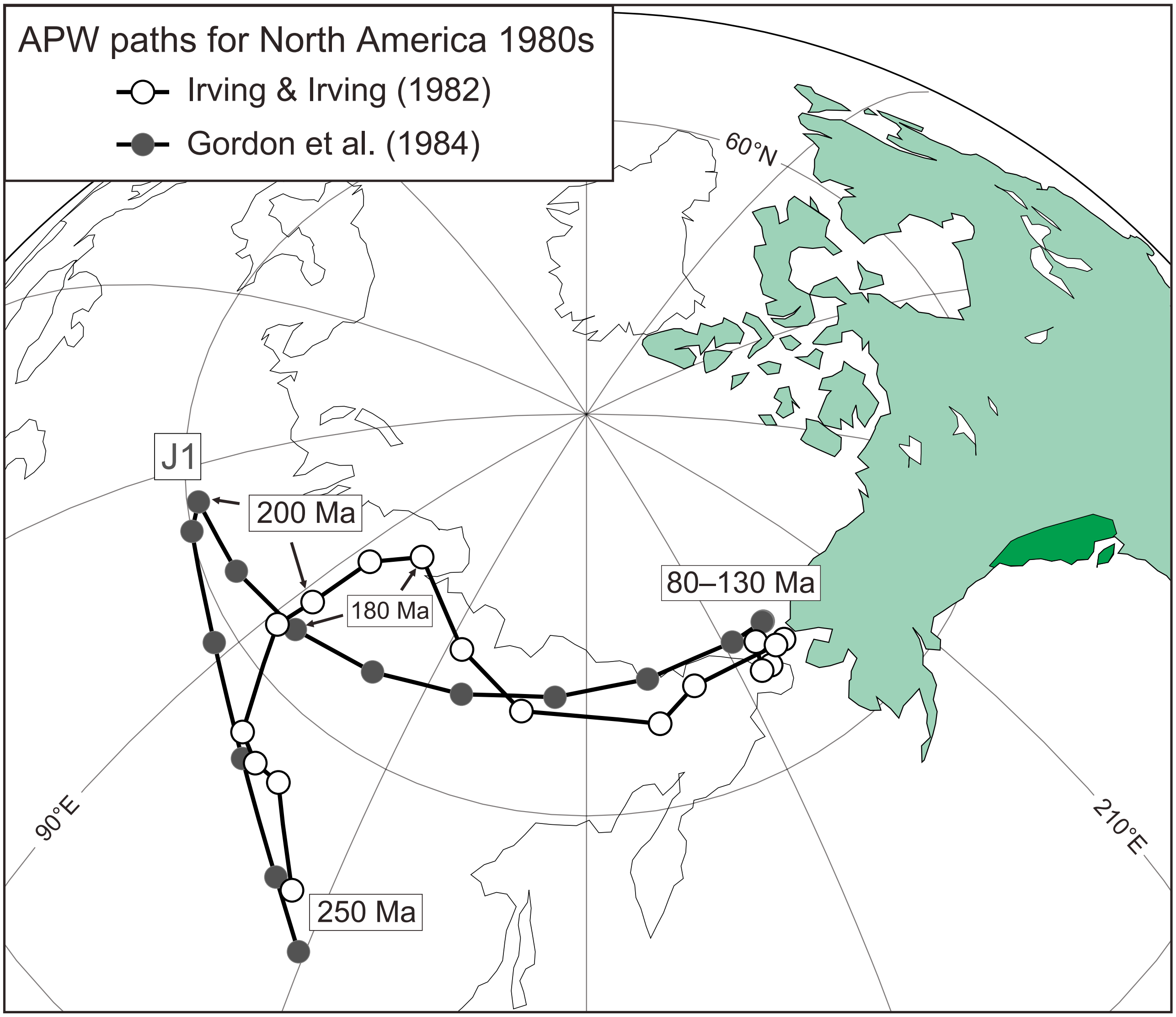


Figure 1. Comparison of PEP [*Gordon et al.*, 1984] and moving window (40 Myr [*Irving and Irving*, 1982]) APW paths for the North American craton drawn in the early 1980s. These paths or versions of them were influential in interpretations of early Mesozoic paleomagnetic data from the Canadian Cordillera (darkened area on the map of North America is approximate modern extent of W/S). The paths from around 250 Ma to 160 Ma (Late Triassic through Middle Jurassic) have critical differences that were substantially responsible for the conflicting estimates of terrane displacement as described in text.

paths for North America remained, and resolving these differences is a principle concern of this paper.

[3] APW paths were first constructed by connecting paleopoles obtained from paleomagnetic studies of individual rock formations all from single regions [*Creer et al.*, 1957]. (For brevity we designate ancient pole positions as "poles.") By the mid-1960s and especially by the 1970s there were sufficient poles to be grouped by geological periods and averaged [*Van der Voo and French*, 1974], or arranged on a common numerical time scale. Various statistical methods of constructing paths were tried, notably passing a moving window of 10 Myr, 20 Myr or longer over them [*Irving*, 1977] in an effort to smooth the path while preserving its shape. Paleomagnetic Euler pole (PEP) analysis [*Gordon et al.*, 1984] was an alternative approach whereby APW paths are modeled from selected data to consist of long small-circle tracks linked by loci of abrupt changes referred to as hairpins or cusps. Figure 1 shows PEP [*Gordon et al.*, 1984] and moving-window [*Irving and Irving*, 1982] paths for the North American craton drawn in the early 1980s. They had critical differences: at around 200 Ma, there is a prominent cusp in the PEP path (J1 cusp of *May and Butler* [1986]) which is absent in the moving-window path (and which is still not apparent in well-sampled sections in eastern North America [*Kent and Olsen*, 2008]); at around 180 Ma, the moving window path migrated to high latitudes whereas the PEP path follows a smooth track below the 70° parallel. Such differences among versions of the North American APW path were substantially responsible for the different estimates of terrane displacement based on Triassic and Jurassic data; for

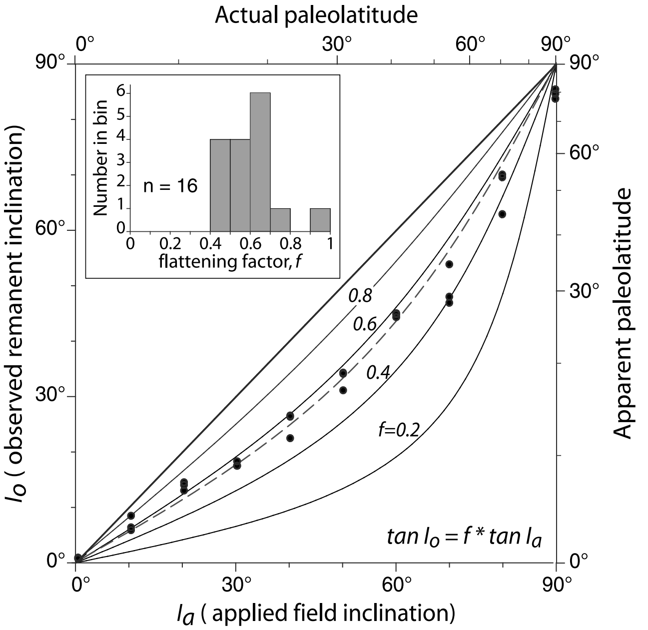


Figure 2. Experimental evidence and numerical model for sedimentary *I* error. Observed inclination versus applied field inclination (alternatively, the corresponding apparent versus actual paleolatitude according to geocentric axial dipole field model) for various values of the flattening factor, *f*, according to the *King* [1955]. Formula for sedimentary *I* error is shown at bottom. Solid circles are data from experiments on reconstituted hematite-bearing sediments characterized by a mean flattening factor of $f = 0.55$ (dashed curve [*Tauxe and Kent*, 1984]). Inset shows estimates of flattening factor using the *E/I* method [*Tauxe and Kent*, 2004] on a variety of sedimentary formations of Miocene to Triassic age [*Krijgsman and Tauxe*, 2004; *Tauxe and Kent*, 2004; *Kent and Tauxe*, 2005; *Krijgsman and Tauxe*, 2006; *Kent and Olsen*, 2008].

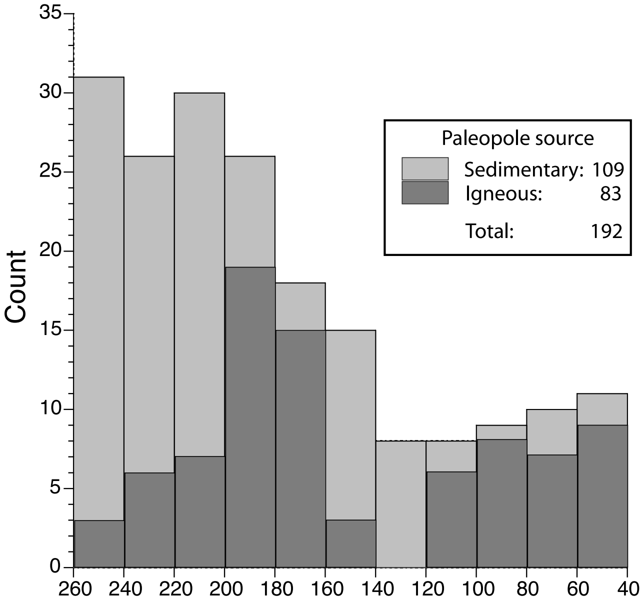
example, *May and Butler* [1986], *Irving and Wynne* [1990] and *Vandall and Palmer* [1990] found rotations but no significant latitudinal displacements.

[4] As confidence in plate reconstructions improved, it became realistic to rotate poles from all cratons into a global paleogeographic framework and thus construct a "world" mean APW path [*Phillips and Forsyth*, 1972], which *Besse and Courtillot* [1991] referred to as a "synthetic" APW path. By these means global data can be compactly summarized and applied to regional problems. The expanded database provides more robust moving-window averages and reduces gaps in the record, that is, intervals that have no data or data that are poor or suspect. Recent examples of such paths (we prefer to simply call them "composite," meaning "made of various parts," rather than "world" which is too encompassing since prior to the Jurassic there are no paleomagnetic poles from ocean plates, or "synthetic" which unfortunately also commonly means artificial or unnatural) are by *Besse and Courtillot* [2002] for 0–200 Ma, *Enkin* [2006] for 50–150 Ma, and *Torsvik et al.* [2008] for 0–320 Ma. We use their work as starting points for constructing a new composite APW path applicable to the North American craton. We transfer selected data from cratons worldwide to a common North American reference frame according to plate reconstructions. We then construct a composite APW path by calculating 20 Myr running window means from 230 Ma to 50 Ma, and compare it with previous paths. To illustrate the usefulness of our path, we estimate latitudinal offsets for certain Cordilleran terranes of western British Columbia and compare their rates of latitudinal motion with those of the North American craton.

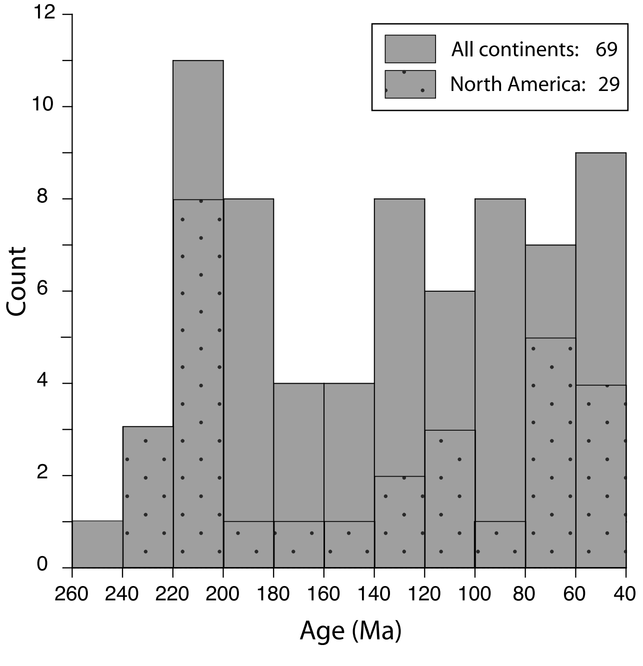
2. Sedimentary Bias in Jurassic and Triassic Cratonic Poles

[5] Triassic and Jurassic cratonic results come mostly from sedimentary rocks. For example, the recent compilation of Jurassic and Triassic (~145 Ma to 252 Ma) global data deemed reliable by *Torsvik et al.* [2008] has 67 poles from North America (144 poles from all continents), of which 49 from North America (92 from all continents) are from sedimentary rocks and may be subject to *I* error either by compaction or by initial depositional processes. Inclination error has long been demonstrated in laboratory redeposition experiments in both magnetite and hematite-bearing sediments [e.g., *Johnson et al.*, 1948; *King*, 1955; *Griffiths et al.*, 1957; *Tauxe and Kent*, 1984]. *I* error has sometimes been dismissed as being not very important because of bioturbation or lack of appreciable compaction [e.g., *Opdyke*, 1961; *Irving and Major*, 1964; *Irving*, 1967; *Kent*, 1973; *Van der Voo et al.*, 1995], as shown for many deep-sea sediments [*Opdyke and Henry*, 1969; *Schneider and Kent*, 1990]. Recently, however, especially in terrestrial sedimentary rocks, *I* error has been more widely recognized using the elongation/inclination (*E/I*) statistical method [*Tauxe and Kent*, 2004] on the distribution of directions [*Krijgsman and Tauxe*, 2004; *Krijgsman and Tauxe*, 2006] and by magnetic anisotropy measurements [*Garcés et al.*, 1996; *Kodama*, 1997; *Tan and Kodama*, 2002]; where they have been compared, these two methods yield consistent estimates of *I* error [*Kent and Tauxe*, 2005; *Tan et al.*, 2007; *Tauxe et al.*, 2008]. Igneous rocks are not subject to *I* error, and where comparisons between coeval layered igneous and sedimentary rocks have been made the shallowing of sedimentary inclinations is often apparent. For example, in his classic study of the late Permian Esterel rocks in France, *Zijderveld* [1975] showed that the mean inclination (neglecting sign) of sedimentary rocks (12.0 ± 5.3°) was significantly less than that of the associated volcanics (23.5 ± 6.1°). Similarly, early Jurassic sedimentary rocks of the Hartford rift basin in eastern North America have a mean inclination (22.2 ± 3.7°) that is significantly shallower than in interbedded volcanics (33.9 ± 8°) [*Kent and Olsen*, 2008]. Both examples were red beds. In contrast, inclinations in Cretaceous gray volcaniclastic sandstones and coeval igneous rocks in British Columbia are in excellent agreement [*Wynne et al.*, 1995; *Enkin et al.*, 2006] and application of the *E/I* test showed no *I* error [*Krijgsman and Tauxe*, 2006].

[6] The severity of *I* error is measured by the flattening factor, *f*, where $\tan (I_o) = f \tan (I_a)$ [*King*, 1955]. It is an empirical measure of how closely an observed sedimentary inclination (I_o) agrees with the ambient field (I_a) and ranges from $f = 0$ for total shallowing to $f = 1$ for no shallowing (Figure 2). The general form is similar for depositional and compaction-induced flattening [e.g., *Anson and Kodama*,



a) Reference poles from all continents



b) Selected igneous & E/I reference poles

Figure 3. (a) Age frequency distribution of Mesozoic and early Cenozoic paleomagnetic poles based on sedimentary or igneous results from all continental cratons. Data that were deemed reliable for the intervals 252 to 145 Ma are from *Torsvik et al.* [2008] and for 145 to 43 Ma are from *Enkin* [2006]. (b) Age frequency distribution of the Mesozoic and early Cenozoic igneous and *E/I* corrected sedimentary poles selected to construct the new composite APW path for cratonic North America (see Table 5 for listing).

1987]. Estimates of flattening using the *E/I* method ranged from $f = 0.40$ to 0.66 for Late Triassic and Early Jurassic continental red beds in eastern North America and magnetizations corrected in this way are in good agreement with coeval igneous rocks [*Kent and Tauxe*, 2005; *Kent and Olsen*, 2008]. As just mentioned, Cretaceous volcaniclastics from British Columbia show no flattening [*Krijgsman and Tauxe*, 2006] and demonstrate consistency between *E/I* and field tests. *E/I* tests on Cretaceous sedimentary rocks of the Nanaimo Group of Vancouver Island indicated either essentially no significant shallowing ($f = 0.95$) in terrestrial strata, or substantial flattening ($f = 0.68$) in fine-grained marine strata [*Krijgsman and Tauxe*, 2006]. In contrast, terrestrial and marine marls of Miocene age in the Mediterranean region gave consistent values of $f \sim 0.7$ [*Krijgsman and Tauxe*, 2004]. Much more severe shallowing ($f \sim 0.3$) has been reported in Cretaceous red beds from the Tarim Basin from modeling of magnetic anisotropy [*Gilder et al.*, 2003].

[7] Thus it is possible that records in sedimentary rocks, the main source of Jurassic and Triassic cratonic poles (Figure 3a), have been corrupted to varying degrees by *I* error. In the absence of diagnostic tests, such as comparisons of coeval igneous and sedimentary rocks or the application of the *E/I* method, *I* error may be difficult to recognize. Accordingly, we build on the recent assessment by *Enkin* [2006] of the Cretaceous to early Cenozoic cratonic record, which is well based on many (39) igneous results, and construct a new composite APW path for the North American craton for the Triassic and Jurassic based solely on results from igneous rocks or *E/I* corrected sedimentary rocks. In this way we hope to circumvent *I* errors for this interval.

3. Selection of Cratonic Poles

[8] In his comprehensive assessment of Cretaceous to early Cenozoic cratonic poles, *Enkin* [2006] found 20 of adequate quality from North America. He found 31 from elsewhere, and transferred them to the North American frame. The more recent compilation by *Torsvik et al.* [2008] extends Enkin's compilation back in time; it has 419 entries from 330 Ma to present, with 144 entries from ~252–145 Ma. Excluding results from sedimentary rocks that were not corrected for *I* error left 39 igneous results for the interval 145–45 Ma that we initially accepted from *Enkin* [2006], and 53 igneous results for 252–145 Ma from *Torsvik et al.* [2008]. These were evaluated for redundancies and age control, and augmented by data from other compilations [e.g., *Besse and Courtillot*, 2002] and from the literature. This eventually resulted in 69 poles for the interval 243 to 43 Ma. We now describe the time scale and the plate tectonic reconstruction model that we use in order to place these poles in time and to place them in the North American frame.

3.1. Mesozoic and Cenozoic Timescale

[9] The GTS2004 geological time scale [*Gradstein et al.*, 2004] and a recently updated version (GSA2009 [*Walker and Geissman*, 2009]) provide very good starting points for building a chronological framework integrating biostratigraphic assignments with radioisotopic dates to place poles in a numerical time scale. *Enkin* [2006] referred his compilation of Cretaceous and Cenozoic poles to the time scales of *Cande and Kent* [1995] and *Gradstein et al.* [1994]. Over this interval there are relatively minor differences with GTS2004 or GSA2009, hence we retain the

Table 1. Triassic and Jurassic Time Scale

Period	Epoch	Stage	Age[a] (Ma)	Reference
Cretaceous	Early	Berriasian	145.5	*Gradstein et al.* [2004]
Jurassic	Late	Tithonian	150.8	*Gradstein et al.* [2004]
Jurassic	Late	Kimmeridgian	155.7	*Gradstein et al.* [2004]
Jurassic	Late	Oxfordian	161.2	*Gradstein et al.* [2004]
Jurassic	Middle	Callovian	164.7	*Gradstein et al.* [2004]
Jurassic	Middle	Bathonian	167.7	*Gradstein et al.* [2004]
Jurassic	Middle	Bajocian	171.6	*Gradstein et al.* [2004]
Jurassic	Middle	Aalenian	175.6	*Gradstein et al.* [2004]
Jurassic	Early	Toarcian	185.2	*Pálfy et al.* [1997] and *Weedon and Jenkyns* [1999]
Jurassic	Early	Pliensbachian	191.9	*Weedon and Jenkyns* [1999]
Jurassic	Early	Sinemurian	199.5	*Schaltegger et al.* [2008]
Jurassic	Early	Hettangian	201.6	*Schaltegger et al.* [2008]
Triassic	Late	Rhaetian	207.6	*Muttoni et al.* [2004][b]
Triassic	Late	Norian	227.0	*Muttoni et al.* [2004][b]
Triassic	Late	Carnian	235.0	*Muttoni et al.* [2004][b] and *Furin et al.* [2006]
Triassic	Middle	Ladinian	241.0	*Mundil et al.* [1996]
Triassic	Middle	Anisian	247.0	*Lehrmann et al.* [2006]
Triassic	Early	Olenekian	251.0	*Szurlies* [2007]
Triassic	Early	Induan	252.5	*Mundil et al.* [2004]
Permian	Late			

[a]Age refers to the base (beginning) of each stage.
[b]Rescaled using 201.6 Ma (rather than 202 Ma) for end-Triassic event.

chronology used by *Enkin* [2006], adopting 145.5 Ma from GTS2004 (compared to 144.2 Ma) for the age of the Jurassic/Cretaceous (Tithonian/Berriasian) boundary (Table 1). We also adopt epoch boundary ages given by GTS2004 and GSA2009 for the Late and Middle Jurassic, i.e., back to the Toarcian/Aalenian (Early/Middle Jurassic) boundary at 176 Ma. However, we depart from GTS2004 for the Early Jurassic and practically the entire Triassic because of new age dates. A new estimate for the Triassic/Jurassic boundary is provided by a single-crystal zircon U-Pb date of 201.6 ± 0.3 Ma in marine beds from Peru at around the Rhaetian/Hettangian boundary [*Schaltegger et al.*, 2008], which is indistinguishable from a single-crystal zircon U-Pb date of 201.3 ± 0.3 Ma for the North Mountain Basalt [*Schoene et al.*, 2006] or from an earlier U-Pb zircon date of 202 ± 1 Ma [*Hodych and Dunning*, 1992]. The North Mountain basalt of Nova Scotia is a representative body of the Central Atlantic Magmatic Province (CAMP) [*Marzoli et al.*, 1999] and immediately overlies the continental expression of the end-Triassic mass extinction event in the Fundy Basin of Nova Scotia [*Olsen et al.*, 2002]. In contrast, the 199.6 Ma age for the Triassic/Jurassic boundary in GTS2004 based on multigrain zircon dating by *Pálfy et al.* [2000a] conflicts with single-crystal zircon U-Pb age determinations of 199.5 ± 0.3 Ma for the Hettangian/Sinemurian boundary [*Schaltegger et al.*, 2008] and 200.6 ± 0.3 Ma for a level in the middle Hettangian [*Pálfy and Mundil*, 2006]. Following GSA2009, we adopt 201.6 Ma for the Triassic/Jurassic (Rhaetian/Hettangian) boundary. Following *Schaltegger et al.* [2008], we accept 199.5 Ma for the Hettangian/Sinemurian boundary, and taking duration estimates of 7.6 Myr and 6.7 Myr for the Sinemurian and Pliensbachian epochs respectively [*Weedon and Jenkyns*, 1999], estimate ages of the Sinemurian/Pliensbachian boundary at 191.9 Ma and of the Pliensbachian/Toarcian boundary at 185.2 Ma. The resulting age range for the Toarcian (175.6–185.2 Ma) is about 2 Myr longer than in GTS2004 (175.6–183.0 Ma) or GSA2009 but is consistent with a zircon U-Pb date of 181.4 ± 1.2 Ma for a level referred to as late middle Toarcian [*Pálfy et al.*, 1997].

[10] Currently available chronostratigraphic data indicate that all Triassic epoch boundary ages are older by up to 10 Myr than in GTS2004. For the Late Triassic, magnetostratigraphic correlation of Tethyan stage boundaries with the Newark astronomical polarity time scale [*Kent and Olsen*, 1999; *Muttoni et al.*, 2004] (adjusted to 201.6 Ma for the end-Triassic event) puts the Norian/Rhaetian boundary at 207.6 Ma (versus 203.6 Ma in GTS2004), the Carnian/Norian boundary at 227 Ma (versus 216.5 Ma), and the Ladinian/Carnian (Middle/Late Triassic) boundary at 235 Ma (versus 228 Ma). A 227 Ma Carnian/Norian boundary age is supported by a single-crystal zircon U-Pb date of 230.9 ± 0.3 Ma from a late Carnian horizon in a marine section from northern Italy [*Furin et al.*, 2006]. Middle and Early Triassic epoch boundary ages have been somewhat more stable, with zircon U-Pb dates indicating that the Anisian/Ladinian boundary is 241 Ma [*Mundil et al.*, 1996] (versus 237.0 Ma in GTS2004), the Olenekian/Anisian (Early/Middle Triassic) boundary is 247 Ma [*Lehrmann et al.*, 2006] (versus 245 Ma), and the Permian/Triassic (Tatarian/Induan) boundary is 252.5 Ma [*Mundil et al.*, 2004] (versus 251.0 Ma), with an interpolated age for the Induan/Olenekian boundary age of 251 Ma [*Szurlies*, 2007] (versus 249.7 Ma). Many of these revised Triassic ages were also incorporated in GSA2009.

3.2. Poles for Cratonic North America

[11] *Torsvik et al.* [2008] compiled data for Laurussia (North America, Greenland and stable Europe) and Gondwana (South America, Africa, Antarctica, Australia and India) using only those poles with a quality index [*Van der Voo*, 1993] of Q > = 3. Their global compilation comprised 419 poles from the Late Carboniferous (330 Ma). For the Triassic and Jurassic of North America their compilation contained 66 poles in the range ~147 to 252 Ma, which is virtually the same as listed previously by *Torsvik et al.* [2001]. Most (49) results are from sedimentary rocks, which ipso facto are suspected (or confirmed [*Kent and Tauxe*, 2005]) to suffer from *I* error and are excluded; two igneous poles (Canelo Hills and Corral Canyon volcanics) are also excluded because of large uncertainties in local tectonic rotations [*Hagstrum and Lipman*, 1991]. Of the remaining 17 igneous results, 11 are from Early Mesozoic dikes, sills and lavas from eastern North America with assigned ages from 175 to 201 Ma. However, virtually all of them are members of the widespread CAMP [*Sebai et al.*, 1991; *Marzoli et al.*, 1999], which was emplaced over a short (1–2 Myr, rather than ~25 Myr) interval at around 201 Ma [*Dunning and Hodych*, 1990; *Hodych and Dunning*, 1992; *Hames et al.*, 2000; *Olsen et al.*, 2003; *Knight et al.*, 2004; *Marzoli et al.*, 2004; *Schoene et al.*, 2006; *Whiteside et al.*, 2007]. Accordingly, we use the CAMP mean pole (66°N 97°E A95 (radius of circle of confidence) = 5°) of *Prévot and McWilliams* [1989] based on lavas from North America. Earlier estimates made in a variety of ways are similar, for example, the mean pole (65°N 94.7°E A95 = 4°) calculated by *Dalrymple et al.* [1975] from 16 studies of early Jurassic intrusive and extrusive rocks in eastern North

Table 2. Early Cenozoic and Mesozoic (North) Poles From the North American Craton Deemed Reliable From Igneous Rocks and Corrected Sedimentary Results[a]

Age (Ma)	ID	Rock Unit	Lat (°N)	Lon (°E)	A95(deg)	References
44.0	RAT	Rattlesnake Hills volcanics, Wy.	79.4	146.2	9.6	E06 and *Sheriff and Shive* [1980]
44.5	VIR	Virginia and West Virginia intr.	85.5	243.7	13.5	E06 and *Ressetar and Martin* [1980]
46.5	ABS	Absaroka basalts, Wyoming	83.5	177.4	10.1	E06 and *Shive and Pruss* [1977]
51.5	MIE	Eocene intrusions, Montana	82.0	170.2	3.5	E06 and *Diehl et al.* [1983]
63.0	GRG	Gringo Gulch volc., Arizona	77.0	201.0	1.4	E06 and *Vugteveen et al.* [1981]
63.0	MIP	Paleocene intrusions, Montana	81.8	181.4	5.4	E06 and *Diehl et al.* [1983]
71.5	TST	Tombstone igneous, Arizona	73.0	224.0	8.0	E06 and *Hagstrum et al.* [1994]
76.0	ADL	Adel Mountains volc., Montana	83.4	200.9	7.1	E06 and *Gunderson and Sheriff* [1991]
93.5	STF	Strand Fiord Fm, Arctic Canada	71.3	205.8	6.3	E06, *Wynne et al.* [1988], and *Tarduno et al.* [1998]
100.0	ARK	Arkansas alkalic intrusions	74.1	192.5	5.7	E06 and *Globerman and Irving* [1988]
101.5	NE3	Late New England intrusions	76.6	167.5	5.3	E06 and *McEnroe* [1996]
112.0	NE2	Middle New England intrusions	74.5	195.2	3.8	E06 and [*McEnroe*, 1996]
122.5	NE1	Early New England intrusions	71.9	194.1	2.4	E06 and *Enkin* [2006]
129.5	NDB	Notre-Dame Bay dykes, Newfld.	71.3	206.5	4.1	E06, *Lapointe* [1979], and *Prasad* [1981]
142.0	ITH	Ithaca kimberlite dikes	58.0	203.1	3.8	E06 and *Van Fossen and Kent* [1993]
169	MV	Moat volcanics	81.6	089.7	5.6	BC02 and *Van Fossen and Kent* [1990]
180	WM	White Mt. plutons	85.5	124.5	5.2	BC02 and *Opdyke and Wensink* [1966]
200	cH	Hartford basin sediments	66.6	088.2	2.3	*Kent and Olsen* [2008]
201	CAMna	Newark + Hartford volc.	66.3	097.3	5.0	T08, *Prévot and McWilliams* [1989], and *Hames et al.* [2000]
204	cM	Martinsville NBCP core	67.8	096.1	2.9	*Kent and Olsen* [1999] and *Kent and Tauxe* [2005]
207	cW	Weston NBCP core	66.6	086.5	2.9	*Kent and Olsen* [1999] and *Kent and Tauxe* [2005]
211	cS	Somerset NBCP core	61.7	095.3	2.0	*Kent and Olsen* [1999] and *Kent and Tauxe* [2005]
214	cR	Rutgers NBCP core	60.1	097.1	1.4	*Kent and Olsen* [1999] and *Kent and Tauxe* [2005]
215	MI	Manicouagan melt rocks	58.8	089.9	5.8	T08, *Larochelle and Currie* [1967], *Robertson* [1967], and *Hodych and Dunning* [1992]
217	cT	Titusville NBCP core	59.9	099.5	1.7	*Kent and Olsen* [1999] and *Kent and Tauxe* [2005]
221	cN	Nursery Road NBCP core	60.5	101.6	2.5	*Kent and Olsen* [1999] and *Kent and Tauxe* [2005]
221	cD	Dan River basin sediments	58.5	099.8	1.1	*Kent and Olsen* [1997] and *Kent and Tauxe* [2005]
227	cP	Princeton NBCP core	54.2	106.6	2.0	*Kent and Olsen* [1999] and *Kent and Tauxe* [2005]

[a] Ages (rounded to 0.5 Myr back to 142 Ma from *Enkin* [2006], otherwise to 1 Myr) are based on radioisotopic dates and geologic time scale in Table 1 except for the Hartford basin sediments, Newark Basin Coring Project (NBCP) cores and Dan River basin sediments whose mean ages are based on an orbital chronology according to cited references but scaled to a Triassic-Jurassic boundary age of 201.6 Ma. ID has acronyms for rock unit poles, with 3-letter codes from 44 to 142 Ma from *Enkin* [2006] and 1-letter codes with prefix 'c' sedimentary data corrected for I error using E/I method in cited reference; all other poles are from igneous units. Lat, Lon, and A95 are the latitude and longitude of the pole and the radius of its associated circle of 95% confidence. References are to primary literature but also include some key pole tabulations where entries were also listed: E06, *Enkin* [2006]; T08, *Torsvik et al.* [2008]; BC02, *Besse and Courtillot* [2002].

America is within a few degrees of the extrusive pole of *Prévot and McWilliams* [1989].

[12] The other 6 igneous poles for North America listed by *Torsvik et al.* [2008] also come from eastern North America. The result for the 143 Ma kimberlite dikes intruded into flat-lying Devonian strata from Ithaca, New York, has positive reversal and baked contact tests [*Van Fossen and Kent*, 1993] and is one of the few Mesozoic poles assigned the maximum Q value of 7; the Ithaca pole is the oldest igneous entry (with a slightly different assigned age of 142 Ma) in the compilation of *Enkin* [2006]. There are two separate results for the Manicougan impact structure in Quebec [*Larochelle and Currie*, 1967; *Robertson*, 1967], which we combine and assign an age of 215 Ma following *Hodych and Dunning* [1992] and *Ramezani et al.* [2005] compared to 230 Ma as inexplicably given by *Torsvik et al.* [2001] and *Torsvik et al.* [2008]. *Torsvik et al.* [2008] also include data from the 221 ± 8 Ma Abbott and 228 ± 5 Ma Agamenticus plutons from Maine [*Wu and Van der Voo*, 1988]. These results diverge from other Triassic results listed from North America and lack structural control for paleohorizontal; we therefore exclude them. We also exclude the 252 Ma Malpeque Bay Sill pole of Prince Edward Island [*Larochelle*, 1967] as it is based on only 12 samples from a sill that is only a few meters thick and unlikely to provide a sufficient time-average. This leaves the first half of the Triassic without igneous poles from North America.

[13] The much used 0–200 Ma (Cenozoic, Cretaceous and Jurassic) global compilation of *Besse and Courtillot* [2002] includes 17 Jurassic poles for the North American craton; 11 of the entries are for sills, dikes and lavas in eastern North America with assigned ages from 180 to 208 Ma all of which should be included in the short-lived CAMP at 201 Ma (as above), and 3 are for sedimentary formations that are excluded. Of the remaining 3 poles, one is for the Ithaca dikes already noted, and two are from the White Mountain Plutonic Series at 169 Ma and 180 Ma [*Opdyke and Wensink*, 1966; *Van Fossen and Kent*, 1990]; the presence of normal and reverse polarities, the concordance of poles from intrusions and extrusions, and the absence of evidence for thermal resetting or later tectonic disturbance indicate that these 3 poles reliably record the paleofield at about the time of emplacement [*Van Fossen and Kent*, 1992].

[14] In summary, for the Triassic and Jurassic (~100 Myr) from cratonic North America there are only 5 acceptable igneous results including that from the Ithaca kimberlites (Table 2). However, there are extensive sedimentary results that have been corrected for I error using the E/I method from Late Triassic strata in the Newark and Dan River basins [*Kent and Tauxe*, 2005] and Early Jurassic strata in the Hartford basin [*Kent and Olsen*, 2008], all in eastern North

Table 3. Jurassic and Triassic (North) Poles From Cratonic Igneous Rocks of Other Continents[a]

Age (Ma)	ID	Rock Unit	Lat (°N)	Lon (°E)	A95 (deg)	References
Eurasia (EUR)						
144	HD	Hinlopenstretet dikes, Svalbard	66	200	7.5	BC02 and *Halvorsen* [1989]
179	SC	Scania Basalts, Sweden	69	103	6.8	T08 and *Bylund and Halvorsen* [1993]
198	KD	Kerforne dykes, Brittany, France	61	79	7.5	T08, BC02, and *Sichler and Perrin* [1993]
214	RO	Rochechouart impact, France	54.6	114.9	5.2	*Carporzen and Gilder* [2006]
243	OD	Lunner Dykes, Oslo, Norway	53	164	5.9	T08 and *Torsvik et al.* [1998]
Northwest Africa (NwA)						
201	CAMaf	Africa CAMP mean	69.7	240.4	7.9	DV + FZ + LD + HN + HS + FC
184	DV	Draa Valley sills	65.5	230.5	3.5	*Hailwood and Mitchell* [1971]
184	FZ	Foum Zguid dike	58.0	259.0	4.0	*Hailwood and Mitchell* [1971]
186	LD	Liberian dikes and sills	68.5	242.4	5.3	T08; *Dalrymple et al.* [1975]
187	HN	Hank volc., North Mauritania	69.4	232.0	4.1	T08 and *Sichler et al.* [1980]
187	HS	Hodh volc., South Mauritania	71.4	240.2	6.1	T08 and *Sichler et al.* [1980]
193	FC	Freetown Complex, Sierra Leone	82.9	212.7	5.6	T08 and *Hargraves et al.* [1999]
Southern Africa (SAF)						
145	SB	Swartruggens and Bumbeni	31.7	274.3	6.3	*Hargraves et al.* [1997]
183	KL	Karroo lavas, 6 studies	69.2	278.3	3.3	*Hargraves et al.* [1997]
East Antarctica (EANT)						
184	FD	Ferrar Dolerite 77 site-means	51	43	2.7	*Lanza and Zanella* [1993]
Australia (AUS)						
168	PD	Prospect Dolerite, Sydney basin	53.0	359.6	6.4	BC02 and *Schmidt* [1982]
180	GN	Garrawilla and Nombi volcanics	46	355	10	BC02 and *Schmidt* [1976]
183	TD	Tasmanian Dolerite, west dec.	50.7	354.5	5.2	BC02 and *Schmidt and McDougall* [1977]
South America (SAM)						
157	EQ	El Quemado north, Patagonia	81	352	7.6	*Iglesia Llanos et al.* [2003]
167	CA	Chon Aike recalc., Patagonia	85	17	13.5	T08 and *Vizán* [1998]
183	MF	Marifil Fm., Patagonia	83	318	11	T08 and *Iglesia Llanos et al.* [2003]
187	LO	Lepa-Osta Arena Fm., Patagonia	75.5	309.4	6.8	*Vizán* [1998]
201	CAMsa	South America CAMP mean	75.9	57.6	6.8	AT + MB + GD + RD + CD + BD
197	AT	Anari-Tapirapua Fm., Brazil	65.5	70.3	3.6	T08 and *Montes-Lauar et al.* [1994]
198	MB	NE Brazil magmatism-2	78.1	43.9	5.2	*Ernesto et al.* [2003]
198	GD	French Guyana dikes	81.2	55.1	4.0	*Nomade et al.* [2000]
199	RD	Roraima dikes, Brazil	80.1	55.1	6.6	*Marzoli et al.* [1999]
200	CD	Cacipore dikes, Brazil	79.8	28.6	5.2	*Ernesto et al.* [2003]
203	BD	Bolivar Dykes, Venezuela	66.9	65.6	4.9	T08 and *MacDonald and Opdyke* [1974]

[a] These are deemed sufficiently reliable for transfer to North America. Ages are rounded to 1 Myr; ID are acronyms for poles; Lat, Lon, and A95 are the latitude and longitude of the pole (in local coordinates) and the associated circle of 95% confidence. References include some key tabulations where entries were listed: T08, *Torsvik et al.* [2008]; BC02, *Besse and Courtillot* [2002].

America. When corrected, sedimentary and coeval igneous results agree within errors and together they add 9 poles to the North American inventory. Ages of the 14 poles range from 142 to 227 Ma and provide an average temporal resolution of ~6 Myr, but they are far from uniformly distributed and there are age gaps of up to 25 Myr (e.g., between 143 and 169 Ma), which we now try to fill by transferring data from other continents.

3.3. Poles for Stable Europe

[15] Returning to other global compilations, *Torsvik et al.* [2008] has 28 poles from stable Europe for the interval 156.5 Ma to 251 Ma; most (23) are from sedimentary rocks and are not used. Of the 5 igneous results, three are accepted: the 179 Ma Scania basalts of Sweden [*Bylund and Halvorsen*, 1993], the 198 Ma Kerforne dikes of France [*Sichler and Perrin*, 1993], which most likely belong to the CAMP activity, and the 243 Ma Lunner dikes of Norway [*Torsvik et al.*, 1998]. Two are not used: the Early Jurassic volcanics from the northern Pyrenees [*Girdler*, 1968] because of structural complexities with stratal dips exceeding 70°, and the Sunnhordland dikes in Norway [*Walderhaug*, 1993] derived from only two thin (<1 m) dikes.

[16] The compilation of *Besse and Courtillot* [2002] for Europe has 13 poles ranging from 144 Ma to 202 Ma (the oldest age limit in their listing). Only 3 are from igneous rocks: the 144 Ma Hinlopenstretet dolerites of Svalbard [*Halvorsen*, 1989] (herein included), and the Scania basalts and the Kerforne dikes also listed by *Torsvik et al.* [2008] and included as just noted. A recently published result from the 214 Ma Rochechouart impact structure in France [*Carporzen and Gilder*, 2006] adds valuable new information from igneous (melt) rocks, bringing to 5 the European total for the Triassic and Jurassic (243 to 144 Ma) (Table 3).

3.4. Poles for African Craton

[17] *Torsvik et al.* [2008] subdivided Africa into three tectonic domains: southern, northwest and northeast. There are only two results from the northeast, both are sedimentary and are not used. Of the 13 results from northwestern Africa with ages ranging from 152.5 Ma to 221.5 Ma, 5 are not used: the age of the Beni Mellal basalts of Morocco (cited as mid-Jurassic to Early Cretaceous by *Bardon et al.* [1973]

and *Westphal et al.* [1979]) is too uncertain, results from Nigerian intrusive rocks [*Marton and Marton*, 1976] and CAMP-related lavas in Morocco [*Knight et al.*, 2004] have large errors (>15°), and no errors are given for results from the 'Morrocan intrusives' [*Bardon et al.*, 1973]. The remaining 4 igneous results have cited ages ranging from 185 to 193 Ma but they are all likely to belong to the ~201 Ma CAMP. From these, plus two results from the Draa Valley sills and the Foum-Zguid dike of Morocco [*Hailwood and Mitchell*, 1971], we calculate a 201 Ma pole for northwest Africa (CAMaf; Table 3), which is close to the pole (68.3°S 57.2°E A95 = 3.6°) calculated by *Dalrymple et al.* [1975] for this early Jurassic magmatic event.

[18] Of the 9 Jurassic and Triassic igneous results from southern Africa [*Torsvik et al.*, 2008], 7 of them have cited ages between 171 Ma and 186 Ma and probably belong to the short-lived Karroo Large Igneous Province (LIP). Accordingly, we use the mean pole calculated for the Karroo LIP by *Hargraves et al.* [1997] based on 6 independent determinations and with an assigned age of 183 ± 5 Ma [*Duncan et al.*, 1997]. We also include an important pole at ~145 Ma obtained by *Hargraves* [1989], who combined results for the Swartruggens kimberlite and Bumbeni Complex.

3.5. Poles for East Antarctic Craton

[19] Essentially coeval with the Karroo LIP of southern Africa are the Ferrar dolerites of East Antarctica, which have yielded nearly identical zircon and baddeleyite U-Pb dates of 183.7 ± 0.6 Ma and 183.6 ± 1.0 Ma, respectively [*Encarnación et al.*, 1996] which we accept as the best estimate of their age. There are numerous paleomagnetic studies of the Ferrar dolerites: the list of *Torsvik et al.* [2008] has 4 Ferrar poles all with assigned ages of 176.5 Ma, whereas *Besse and Courtillot* [2002] gave 5 poles and assigned ages of 172 Ma to 177 Ma. We use a mean pole for the Ferrar calculated by *Lanza and Zanella* [1993] from 77 site-mean VGPs from the literature (Table 3), which compares well with other summary results, for example, 54.8°N 40.3°E (A95 = 3.9°) calculated by *Grunow et al.* [1987] from 15 studies of the Ferrar.

[20] The Vestfjella lavas and Vestfjella dykes have virtually identical directions and have scattered K-Ar dates ranging from 156 Ma to 231 Ma [*Lovlie*, 1979], and like the Storm Peak Lavas in the Queen Alexandra Range [*Ostrander*, 1971], may in fact be coeval with the Ferrar igneous event; these results are given separate entries of various different ages in the pole listings of *Torsvik et al.* [2008] and *Besse and Courtillot* [2002] but we exclude them due to the large age uncertainties.

3.6. Poles for Australian Craton

[21] For the Triassic and Jurassic of Australia, *Torsvik et al.* [2008] list only 2 results, both from sedimentary units that are excluded. *Besse and Courtillot* [2002], however, include several igneous results which we accept: the 168 Ma Prospect dolerite from the Sydney basin [*Schmidt*, 1982], the 180 Ma Garrawilla and Nombi volcanics of New South Wales [*Schmidt*, 1976], and the 183 Ma Tasmanian Dolerites [*Schmidt and McDougall*, 1977] (Table 3). The latter, together with the Ferrar dolerites of East Antarctica and the Karroo LIP from southern Africa (and probably the Marifil Formation of Argentina, see below) likely were one huge LIP marking the initial break-up of Gondwana.

3.7. Poles for South American Craton

[22] *Torsvik et al.* [2008] subdivided the South American craton into three tectonic blocks and list 6 Jurassic or Triassic poles (5 igneous) from the northernmost block, 2 (one igneous) from the Parana-Salado block, and 2 (both igneous) from the southernmost Colorado block. They configured these blocks in part by fitting selected poles and, since the parameters that they use to reconstruct them to southern Africa differ by only a few degrees, we consider the South American craton as a single tectonic entity. In any case, only one entry (175 Ma Maranhao basalts [*Schult and Guerreiro*, 1979]) overlaps with the compilation of *Besse and Courtillot* [2002], which has no other entries from South America for the Jurassic. According to more recent age assessments [*Baksi and Archibald*, 1997], the west Maranhao basalts are likely to be part of the 201 Ma CAMP [*Sebai et al.*, 1991; *Marzoli et al.*, 1999]. This may also be so for the poorly dated (and thus excluded) dike swarms in Rio Grande do Norte of northeast Brazil [*Bucker et al.*, 1986] and in Surinam [*Veldkamp et al.*, 1971] [e.g., see *Deckart et al.*, 1997]. To again avoid giving undue weight to multiple results from the same magmatic province, we calculate a mean CAMP pole for South America (CAMsa; Table 3) from the following 6 results: the Anari and Tapirapua formations of western Brazil [*Montes-Lauar et al.*, 1994], the Bolivar dikes of Venezuela [*MacDonald and Opdyke*, 1974] also listed by *Torsvik et al.* [2008], updated results for NE Brazil dikes [*Ernesto et al.*, 2003], the French Guyana dikes [*Nomade et al.*, 2000], and the Roraima dikes [*Marzoli et al.*, 1999] and Capicore dikes [*Ernesto et al.*, 2003] of Brazil, all estimated to be about 201 Ma.

[23] From elsewhere in South America, we exclude a venerable result for the Mendoza lavas from South Nihuil, Argentina [*Creer et al.*, 1970], their reported age (Triassic or Permian) being poorly constrained. On the other hand, comprehensive isotopic dating shows that the silicic volcanics of the Marifil Formation in Patagonia are essentially coeval with the Karroo-Ferrar-Tasmanian magmatic province at ~183 Ma [*Pankhurst et al.*, 2000]; accordingly its pole [*Iglesia Llanos et al.*, 2003] is assigned that age. Although the Lepa and Osta Arena formations of Patagonia [*Vizán*, 1998] are biostratigraphically dated as late Pliensbachian-early Toarcian, and may therefore also belong to this magmatic province, we have listed the result separately. Finally, we include poles for the 167 Ma Chon Aike Formation of Patagonia, summarized from the literature by *Vizán* [998], and for the 156.5 Ma El Quemado Formation of Patagonia [*Iglesia Llanos et al.*, 2003].

4. A New Composite APW Path for the North America Craton

4.1. Euler Plate Rotations

[24] To bring poles from different continental cratons into a common North American frame we use the Euler plate rotations of *Lottes and Rowley* [1990], which incorporate the Euler rotations for the North Atlantic region of *Rowley and Lottes* [1988]. Lottes and Rowley's reconstructions of Pangea (Laurasia and Gondwana) for the Late Triassic/Early

Table 4. Euler Rotation Parameters for Construction of Composite APW Path for Triassic and Jurassic in North American Coordinates[a]

Age (Ma)	Lat (°N)	Lon (°E)	Delta (deg)	References
Laurasia: Europe (EUR) to North America (NAM)				
118–200	*68.9*	*154.8*	*−23.1*	*Srivastava and Roest* [1989] and *Torsvik et al.* [2008]
200–425	*88*	*27*	*−38*	*Bullard et al.* [1965] and *Torsvik et al.* [2008]
118–252	**72.8**	**154.7**	**−24.3**	*Rowley and Lottes* [1988]
Laurasia: Greenland (GRE) to NAM				
118–245	*67.5*	*241.5*	*−13.8*	*Roest and Srivastava* [1989] and *Torsvik et al.* [2008]
130–252	**63.8**	**228.6**	**−10.9**	*Rowley and Lottes* [1988]
Gondwana: South Africa (SAF) to Northwest Africa (NwA)				
120–600	*16.5*	*6.7*	*−1.2*	*Torsvik et al.* [2008]
120–252	**9.3**	**5.7**	**−7.8**	*Lottes and Rowley* [1990]
Gondwana: South America (SAM) to SAF				
135–320	*50.0*	*327.5*	*55.1*	*Torsvik et al.* [2008]
135–252	**46.8**	**329.5**	**55.8**	*Lottes and Rowley* [1990]
Gondwana: East Antarctic (EANT) to SAF				
160–360	*−10.5*	*328.8*	*58.2*	*Torsvik et al.* [2008]
160–252	**−12.6**	**331.9**	**59.1**	*Lottes and Rowley* [1990]
Gondwana: Australia (AUS) to SAF				
160–320	*−19.5*	*297.8*	*56.2*	*Torsvik et al.* [2008]
160–252	**−29.2**	**302.8**	**54.0**	*Lottes and Rowley* [1990]
Pangea Connection: Gondwana to Laurasia (NwA to NAM)				
139.2	***66.2***	***341.7***	***−59.7***	*Roest et al.* [1992]
148.5	***66.2***	***341.7***	***−62.1***	*Roest et al.* [1992]
154.2	***66.7***	***344.1***	***−64.9***	*Roest et al.* [1992]
170	***67.0***	***346.8***	***−72.1***	*Klitgord and Schouten* [1986]
175	***67.0***	***348.0***	***−75.6***	*Klitgord and Schouten* [1986]
180–252	**66.4**	**345.9**	**−75.1**	fit; *Lottes and Rowley* [1990]
215–340	*67*	*348*	*−79.0*	fit; *Torsvik and Van der Voo* [2002]

[a]Reconstruction parameters are given as the angular rotation (Delta, positive for clockwise and negative for counterclockwise) about the latitude (Lat) and longitude (Lon) of the Euler rotation pole. Rotation parameters in bold were used for construction of composite APW path and are for total fits between continental elements except for incremental rotations between Northwest Africa and North America. Rotation parameters in italics were used by *Torsvik et al.* [2008] and are shown for comparison.

Jurassic should encompass the older age limit (~243 Ma) of the poles we are concerned with.

[25] The most notable difference between the tectonic models of *Lottes and Rowley* [1990] and *Torsvik et al.* [2008] is the smaller and simpler rotation employed by the former to close the northernmost Atlantic. Their smaller rotation accounts for the arrangement of the continents around the Arctic basin better than the *Bullard et al.* [1965] fit which is incorporated into the model of *Torsvik et al.* [2008]. Also, the complexities in the model of *Torsvik et al.* [2008], arising from the way they place Europe relative to North America prior to opening of the northernmost Atlantic, are based in part on matching pole paths, a procedure that might compromise independence. We therefore use the single-rotation fit of *Rowley and Lottes* [1988], which we note is similar to the reconstruction incorporated by *Torsvik et al.* [2008] and adopted from *Srivastava and Roest* [1989], but which we extend over the entire pre-separation interval of 118 Ma to 243 Ma relevant to our discussion. In doing this, only minor differences of a few degrees in reconstruction parameters remain between *Torsvik et al.* [2008] and *Lottes and Rowley* [1990]. We neglect the subdivision of South America [*Torsvik et al.*, 2008], relative rotations being small. We retain a multiple block model for Africa and note that the rotation of northwest Africa with respect to southern Africa used by *Lottes and Rowley* [1990] is about 5° larger than that used by *Torsvik et al.* [2008]. The fit of northwest Africa to North America using *Lottes and Rowley* [1990] is nearly identical to that estimated by *Klitgord and Schouten* [1986] for 175 Ma and also used by *Torsvik et al.* [2008], who favor a slightly tighter fit before 215 Ma (Table 4). Otherwise, when reconstructing the opening history of the Central Atlantic (motions of northwest Africa relative to North America), we use the same incremental rotation poles as *Torsvik et al.* [2008]. *Besse and Courtillot* [2002] used the relative plate motion model of *Royer et al.* [1992] that *Enkin* [2006] also followed and which is similar to that listed by *Torsvik et al.* [2008] for ocean opening histories.

4.2. New Composite APW Path for North America

[26] The 17 Triassic/Jurassic cratonic poles from elsewhere (Table 3) were rotated into North American coordinates (parameters in Table 4) and merged with the 14 from North America (Table 2). These 31 poles range in age from 243 to 144 Ma (Table 5) and although far from uniformly distributed they average ~3 poles per 10 Myr. There are 39 igneous poles globally (15 from North America) from 142 to 43 Ma in the pole list of *Enkin* [2006], with a somewhat higher average density of ~4 poles per 10 Myr (Figure 3b). The grand total of 69 poles were ranked by age from 243 Ma to 43 Ma, smoothed using a 20 Myr sliding window and mean poles at 10 Myr (or sometime closer) intervals calculated. Prior to 230 Ma there is only one Triassic

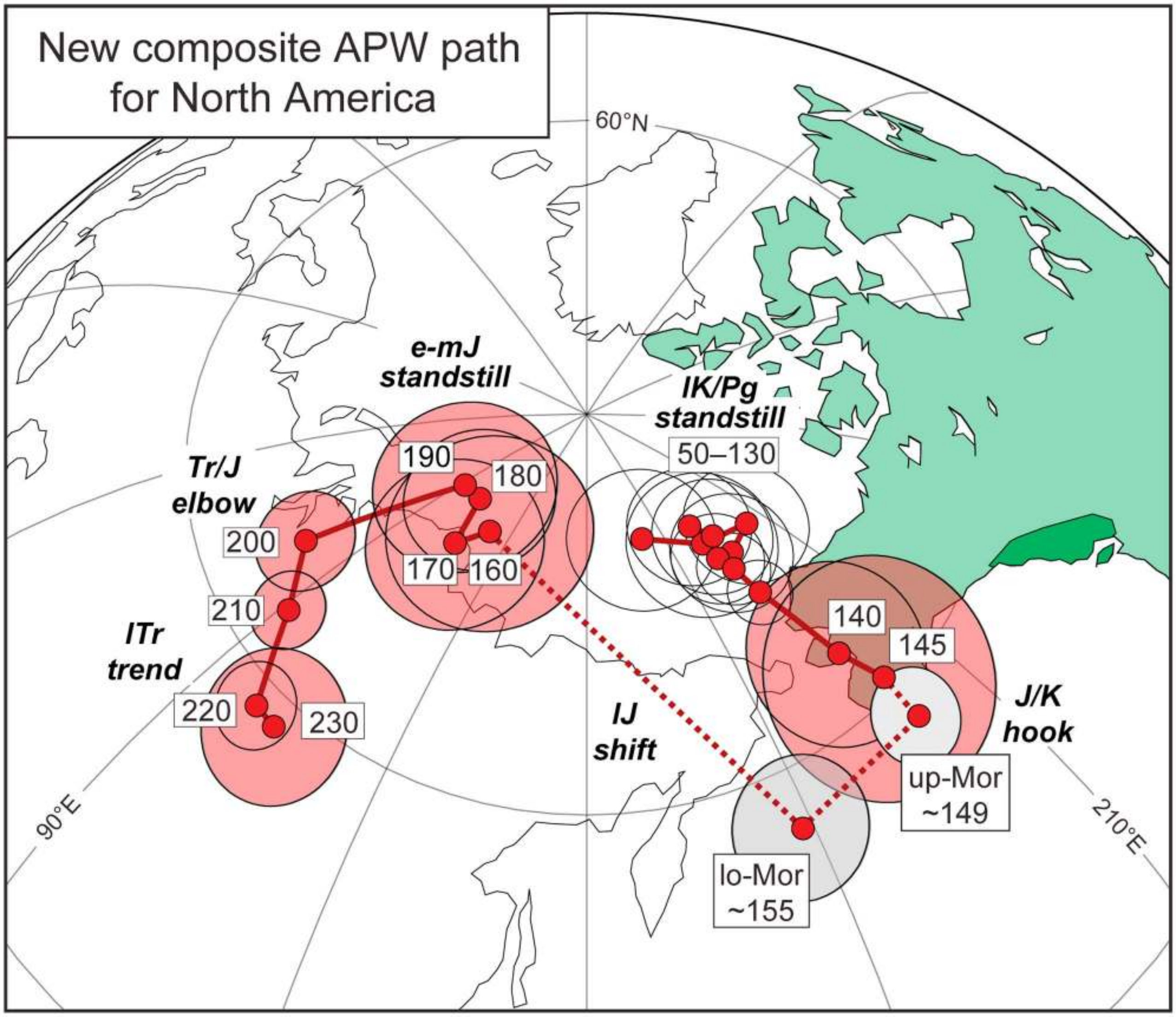


Figure 4. New composite APW path for North America for the Late Triassic to early Cenozoic (230 to 50 Ma) based on a 20 Myr running mean of global igneous and *E/I*-corrected sedimentary poles transferred to North American coordinates. The approximate modern position of the Stikinia and Wrangellia terranes in British Columbia is darkened. Mean poles for 130 to 50 Ma (open 95% confidence circles) are based on igneous poles from compilation of *Enkin* [2006]; mean poles for 230 to 140 Ma (solid 95% confidence circles) are based on compilation in Table 5. Mean poles and statistics are listed in Table 6. Dashed line tentatively connects poles for lower Morrison (lo-Mor, ~155 Ma) and upper Morrison (up-Mor, ~149 Ma) Formation of from *Steiner and Helsley* [1975] after correction for presumed inclination flattening corresponding to *f* = 0.55 and net 13° clockwise rotation of the Colorado Plateau relative to the craton of eastern North America (see text and Table 7).

igneous pole (243 Ma Lunner dikes from Norway), hence we start the series at 230 Ma for the new APW path (Figure 4). The 68 remaining poles (Table 5) provide an average of 7 entries (range 3 to 11) in the windows from 230 to 50 Ma; the mean poles have an average error (A95) of 5° (range: 2.4° to 9.0°) and average precision, K, of 208 (range: 70 to 578). Because of earlier averaging, some mean poles are more robust than the number of entries might suggest; for example we combined 6 poles for the mean northwest African CAMP pole, 6 poles for the South American CAMP pole, and utilized several published averages for other closely related studies such as on the Ferrar LIP of East Antarctica and the Karroo LIP of southern Africa (see Table 3). All 20 Myr windows contain at least one pole from North America, which is the continent best represented by poles over the Mesozoic and Cenozoic. The mean poles from 230 to 50 Ma (Mesozoic and early Cenozoic) in North American coordinates are given in Table 6.

[27] The Early and Middle Triassic record is poor and mean poles for 250 and 240 Ma were not calculated as noted above. The mean poles from 230 Ma to 200 Ma (the lTr northward trend) chart a steady ~10° progression to higher latitudes straddling the 90°E meridian (Figure 4). Notable is the 200 Ma window with 7 pole entries that includes ele-

ments of CAMP in Europe, North America, Africa and South America as well as corrected sedimentary data, and the mean pole is remarkably well defined (A95 = 3.8°), considering the disparate transfers required to bring the constituent poles into common North American coordinates.

[28] After 200 Ma (Tr/J elbow) the pole moves ~10° farther north with a more easterly trajectory to Severnya Zembya off the northernmost coast of Siberia at 190 Ma lingering at about 80°N until 160 Ma (e-mJ standstill). The reality of high latitude poles for the Jurassic of North America, formerly much disputed on the basis of North American data [e.g., *Butler et al.*, 1992; *Van Fossen and Kent*, 1992; *Hagstrum*, 1993] although well supported by data transferred from other continents [e.g., *Van der Voo*, 1992; *Van Fossen and Kent*, 1992; *Courtillot et al.*, 1994], is confirmed by the excellent agreement of poles from different continents within each of the 190, 180, 170 and 160 Ma windows of the composite path (Table 6). In particular, the 180 Ma mean pole (latitude 79.9°N, A95 = 5.5°), which is based on 8 igneous poles from 6 continents (North America, Europe, South America, southern Africa, East Antarctica and Australia) including results from the now dispersed Karroo-Ferrar-Tasmanian-Marifil LIPs of Gondwana and the White Mountain magmatic series in North America, shows a highly significant increase in Fisher's precision parameter (K) after the continents are restored to their past relative positions (Figure 5). The greatly improved precisions and resulting high accuracies for many windows (e.g., those illustrated in Figure 5) and especially those centered at 180 Ma and 200 Ma, which are based on independent results from well-dated igneous provinces of now widely dispersed continents, attest to the overall reliability of the pre-drift reconstructions and the good approximation of the time-averaged field by a geocentric dipole model during and since the Triassic [*Carlut and Courtillot*, 1998; *Kent and Smethurst*, 1998; *Courtillot and Besse*, 2004]).

[29] In the Late Jurassic, there is a ~30° polar shift from high latitude at 160 Ma to a lower latitude and much more easterly position by the end of the Jurassic at around 140 Ma (rapid lJ pole shift) (Figure 4). The limits of this monster shift are well established from igneous results but intermediate igneous poles are rare, in fact, there is only the 157 Ma El Quemado pole from South America in the 22 Myr interval between the 167 Ma Chon Aike pole from South America (included in the 160 Ma window) and the 145 Ma Swartruggens and Bumbeni kimberlites pole from southern Africa. It is the latter together with nearly coeval poles from the 142 Ma Ithaca dikes of New York State and the 144 Ma Hinlopenstretet dikes of Svalbard that form this coherent

Table 5. Early Cenozoic and Mesozoic (40–250 Ma) Poles in North American Coordinates From Selected Igneous Rocks and Sedimentary Rocks Corrected for *I* Error[a]

Item	Age (Ma)	Continent	Pole ID	Lat (°N)	Lon (°E)	A95 (deg)
1	43.0	AFR	JNE	83.5	110.9	3.7
2	44.0	NAM	RAT	79.4	146.2	9.6
3	44.0	NAM	VIR	85.5	243.7	13.5
4	44.5	AFR	WAT	69.5	165.5	4.4
5	46.5	NAM	ABS	83.5	177.4	10.1
6	51.5	NAM	MIE	82.0	170.2	3.5
7	53.5	AUS	BAR	79.3	151.6	3.9
8	58.5	GRE	GTI	66.8	193.6	4.9
9	58.5	EUR	BTI	75.0	183.8	6.3
10	63.0	NAM	GRG	77.0	201.0	1.4
11	63.0	NAM	MIP	81.8	181.4	5.4
12	65.5	IND	DEC	71.9	216.7	2.4
13	71.5	SAM	PAT	70.6	196.7	6.3
14	71.5	NAM	TST	73.0	224.0	8.0
15	72.0	SAM	IPQ	71.2	198.3	5.7
16	76.0	NAM	ADL	83.4	200.9	7.1
17	80.5	SAM	SSI	73.1	180.3	4.9
18	83.0	SAM	PCA	77.0	182.8	2.7
19	87.0	AFR	MDG	74.6	181.6	5.5
20	90.5	AFR	KP1	70.5	175.3	5.2
21	92.0	SAM	CSA	78.7	190.4	4.5
22	92.5	AFR	WNA	76.3	218.0	3.1
23	93.5	NAM	STF	71.3	205.8	6.3
24	98.5	AUS	DRM	78.8	196.1	6.5
25	100.0	NAM	ARK	74.1	192.5	5.7
26	101.5	NAM	NE3	76.6	167.5	5.3
27	105.0	AUS	CYG	84.6	235.8	10.0
28	111.0	AFR	LUP	78.2	195.3	3.8
29	112.0	NAM	NE2	74.5	195.2	3.8
30	118.0	IND	RAJ	80.9	179.2	2.5
31	120.5	SAM	FLO	74.3	178.9	2.6
32	122.5	NAM	NE1	71.9	194.1	2.4
33	124.0	SAM	SLC	72.9	192.2	3.3
34	126.5	SAM	EMA	71.7	198.6	1.9
35	128.5	SAM	PRN	70.9	192.5	1.2
36	129.5	NAM	NDB	71.3	206.5	4.1
37	131.5	AFR	ETN	69.8	201.6	3.1
38	135.5	GRE	GDY	69.5	181.0	5.0
39	142.0	NAM	ITH	58.0	203.1	3.8
40	144	EUR	HD	61.5	188.0	7.5
41	145	SAF	SB	63.1	209.6	6.3
42	157	SAM	EQ	84.4	122.5	7.6
43	167	SAM	CA	76.4	113.6	13.5
44	168	AUS	PD	70.7	118.7	6.4
45	169	NAM	MV	81.6	89.7	5.6
46	179	EUR	SC	75.0	91.7	6.8
47	180	AUS	GN	76.4	120.4	10.0
48	180	NAM	WM	85.5	124.5	5.2
49	183	SAM	MF	79.9	126.3	11.0
50	183	AUS	TD	72.7	114.2	5.2
51	183	SAF	KL	74.3	51.5	3.3
52	183	EANT	FD	77.6	72.8	2.7
53	187	SAM	LO	85.0	174.0	6.8
54	198	EUR	KD	68.1	56.6	7.5
55	200	NAM	cH	66.6	88.2	2.3
56	201	SAM	CAMsa	67.6	81.2	6.8
57	201	NwA	CAMaf	68.5	87.8	7.9
58	201	NAM	CAMna	66.3	97.3	5.0
59	204	NAM	cM	67.8	96.1	2.9
60	207	NAM	cW	66.6	86.5	2.9
61	211	NAM	cS	61.7	95.3	2.0
62	214	NAM	cR	60.1	97.1	1.4
63	214	EUR	RO	59.9	99.1	5.2
64	215	NAM	MI	58.8	89.9	5.8
65	217	NAM	cT	59.9	99.5	1.7
66	221	NAM	cN	60.5	101.6	2.5
67	221	NAM	cD	58.5	99.8	1.1
68	227	NAM	cP	54.2	106.6	2.0
69	243	EUR	OD	52.7	150.2	5.9

Notes to Table 5:

[a] Poles (north axes located at latitude, Lat, and longitude, Lon, with radius of 95% confidence circle, A95) are listed in order of increasing age from various continents (NAM, North America; EUR, Europe; GRE, Greenland; IND, India; AUS, Australia; EANT, East Antarctica; SAM, South America; SAF, southern Africa; NwA, northwest Africa) and designated by an identification acronym (Pole ID). Items 1 to 39 are from *Enkin* [2006], who gives references to poles and rotation parameters; other entries are listed in Tables 2 and 3 and rotated according to parameters listed in Table 4.

Table 6. Mean Composite Poles for the Early Cenozoic and Mesozoic in North American Coordinates Based on 20 Myr Running Mean of Data From Selected Igneous Rocks and *E/I* Corrected Sedimentary Rocks[a]

							Mt. Tatlow	
Central Age (Ma)	Mean Age (Ma)	N	Lat (°N)	Lon (°E)	A95 (deg)	K	pLat (°N)	Dec
50	49.4	9	79.4	171.8	5.4	92.5	54.8	343.3
60	59.1	7	77.0	189.8	5.5	123.4	59.0	341.5
70	68.9	7	75.9	204.7	4.6	169.8	62.5	344.0
80	77.4	7	75.2	195.0	4.5	181.2	61.0	339.7
90	89.7	8	75.5	190.6	3.4	266.1	59.9	339.1
100	96.7	8	77.0	194.1	4.4	160.7	59.9	342.5
110	107.9	6	78.6	190.2	4.5	220.5	58.3	344.3
120	121.4	9	74.2	192.2	2.7	370.8	60.9	337.1
130	127.3	8	71.7	193.4	2.4	577.7	62.3	332.7
140	139.8	5	64.7	197.3	6.8	129.2	66.0	318.7
145	143.7	3	61.2	200.2	9.0	189.3	68.1	310.7
160	165.3	4	78.5	112.5	7.5	152.7	44.1	346.7
170	170.8	4	76.3	105.9	6.5	200.0	41.5	350.3
180	182.3	8	79.9	100.4	5.5	102.9	43.6	350.3
190	184.6	8	79.7	91.6	6.7	69.9	42.6	351.9
200	201.7	7	67.8	81.8	3.8	253.2	30.6	349.1
210	207.7	11	64.2	91.2	2.9	241.1	28.7	343.5
220	217.5	8	59.3	98.8	2.3	570.4	25.9	337.4
230	223.0	3	57.8	102.8	5.7	467.1	25.6	334.6

[a]Mean poles were calculated with sliding 20 Myr window on data listed in Table 5 (N is number of poles in window of central age and corresponding mean age giving a mean pole position at latitude; Lat, and longitude; Lon, and associated radius of 95% confidence circle, A95; and Fisher's precision parameter, K) except mean pole with central age of 145 Ma (mean age of 143.7 Ma), which is based on a non-overlapping 10 Myr average of poles between 140 and 149 Ma. Listed for reference are paleolatitude (pLat) and declination (Dec) projected using a geocentric axial dipole field model to Mt. Tatlow (51.3°N, 123.8°W), which was also used by *Enkin* [2006] as a representative locality in Canadian Cordillera.

group after tectonic reconstructions (Figure 5) giving a mean pole in western Alaska in modern geography.

[30] To help constrain Late Jurassic APW we examined sedimentary results listed by *Torsvik et al.* [2008] and *Besse and Courtillot* [2002]. Interestingly, in both compilations, the 20 Myr windows centered on 140 Ma and 150 Ma have few results and some are poorly defined with complicated magnetizations (e.g., Jura blue limestones). It is the results from the sedimentary Morrison Formation of Colorado [*Steiner and Helsley*, 1975], that (although not listed by *Besse and Courtillot* [2002]) have been mainstays of Late Jurassic APW paths, and which merit attention. *Steiner and Helsley* [1975] found that the lithologic change that divides the sedimentary formation into two members marks a change of pole position; there are distinct lower Morrison (Oxfordian to early Kimmeridgian, ~155 Ma) and upper Morrison (Kimmeridgian to early Tithonian, ~149 Ma; age from *Kowallis et al.* [1998]) poles (Table 7). PEP analyses [*May and Butler*, 1986; *Bazard and Butler*, 1994; *Beck and Housen*, 2003] have used the lower Morrison pole to essentially define the J2 cusp and together with the upper Morrison pole, help delineate the ensuing polar track. These seemingly well-determined Morrison poles are far removed from almost all other coeval poles (Figure 6). However, if it is assumed that the Morrison directions have been affected by *I* error corresponding to $f = 0.55$ (a representative value obtained from redeposition experiments and from *E/I* analyses of a number of sedimentary formations (Figure 2)) and if, being on the Colorado Plateau it is assumed that they have been rotated clockwise by ~13° (Table 7), then the 'corrected' upper Morrison pole (~58°N, 200°E) falls close to the 145 Ma mean pole (Figure 6); this is certainly credible being reasonably consistent with the age of the upper Morrison. The 'corrected' lower Morrison pole (~6°N, 178°E) might therefore be evidence of a novel boomerang feature (J/K hook) of North American APW located far to the east of J2 as defined by PEP analysis. The correction for assumed flattening is more important than that for rotation because Morrison inclinations are in the most sensitive range for *I* error (Figure 2). An *E/I* analysis of the Morrison Formation and other sedimentary formations from the Colorado Plateau is called for.

[31] The 140 Ma pole already falls 4° away from the 145 Ma pole and is followed by an ~7° northerly shift to the clustered 130–60 Ma poles of the lK/Pg standstill, a well-established feature of Late Cretaceous to Paleogene APW of North America, followed by a movement of ~10° toward the present geographic pole during the Cenozoic.

5. Comparison of New Composite APW Path With Other APW Paths

[32] The new APW path, based only on igneous rocks and *E/I* corrected sedimentary rocks differs from previous APW paths for North America in several respects. We remark on some of these beginning with paths derived entirely from North America. The most glaring differences are with the PEP model paths of *Gordon et al.* [1984] (Figure 1) and especially *May and Butler* [1986] (Figure 6), which were derived largely from sedimentary rocks. In the Late Triassic and becoming more pronounced in the Early Jurassic, the PEP path of *May and Butler* [1986] is more distant from North America than our APW path placing North America in lower latitudes than ours. This is to be as expected from a record derived predominantly from sedimentary rocks subject to *I* error, as is the record used by May and Butler; it is the westerly swing culminating in their J1 cusp (Figure 6) that complicates the issue, being based on results from

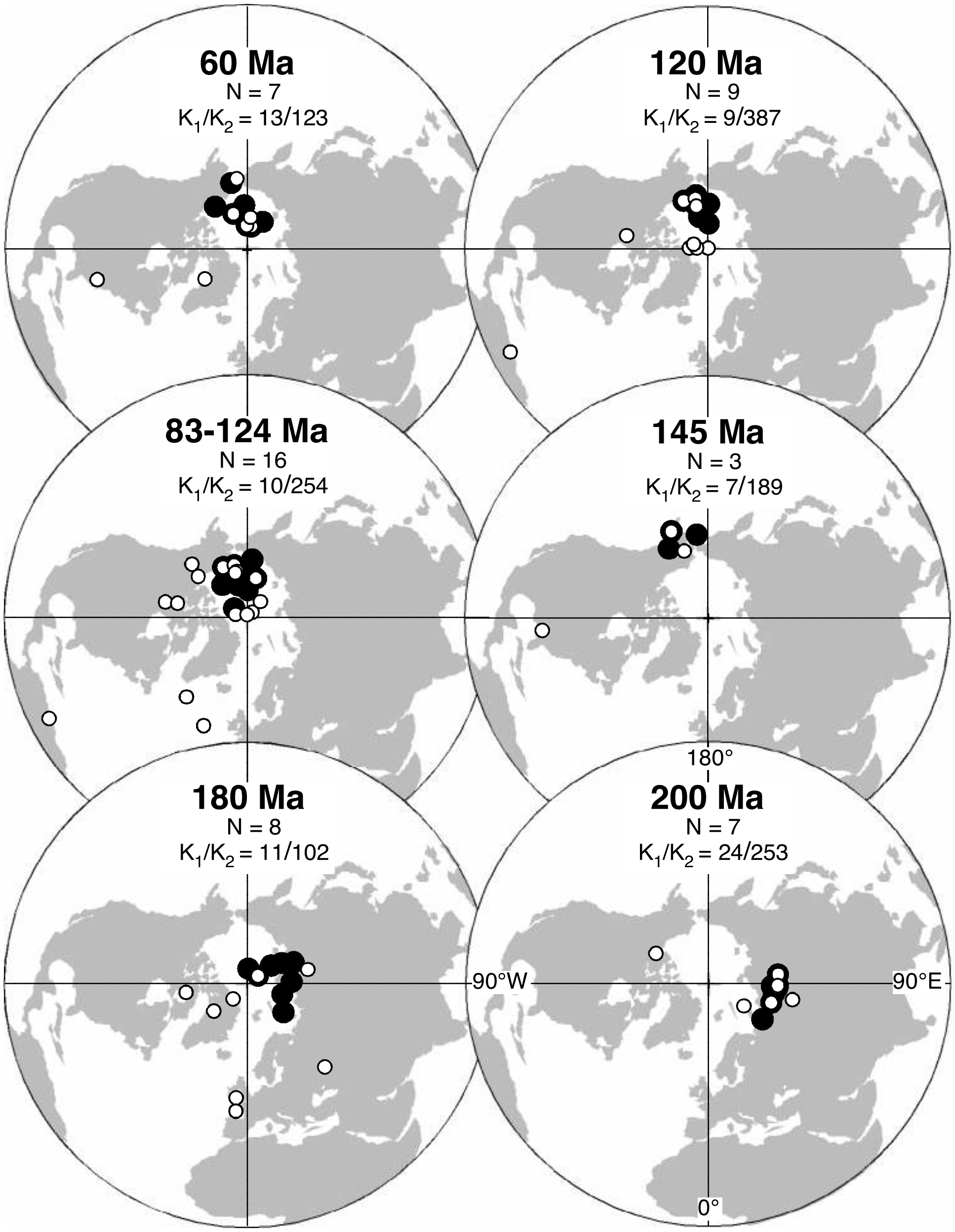


Figure 5. Poles before (open circles) and after (solid circles) reconstruction of continental cratons to North American coordinates within averaging windows as listed in Table 6 or for the interval 83–124 Ma are poles corresponding in age (Table 5) to the Cretaceous Long Normal superchron. N is the number of poles, K_1 is the estimate of Fisher's precision parameter (the inverse of dispersion) for poles in present-day coordinates and K_2 that for poles after continental reconstruction to North American coordinates. In all cases the increase from K_1 to K_2 is large and highly significant [*Watson and Irving*, 1957; *McElhinny*, 1964].

sedimentary rocks from the Colorado Plateau which has undergone clockwise rotation by an amount disputably from ~5° to almost 15°. The defining features of the PEP path of *May and Butler* [1986] are the J1 and J2 cusps at ~200 Ma and ~145 Ma respectively and these diverge 10° to 20° from coeval mean poles on our APW path. These large differences have major implications for interpretations of Cordilleran terrane motions, as described below.

[33] The composite APW path for North America of *Besse and Courtillot* [2002] back to 200 Ma, and, more recently, that of *Torsvik et al.* [2008] back to 320 Ma incorporate results from the major continental cratons including many from igneous rocks. They link the global cratonic results by plate reconstructions and hence their composite paths are far less dominated by sedimentary data than the path from North American data only. Artifacts arising from *I* errors are greatly reduced in their composite paths in which Jurassic poles fall at higher latitude and cusps J1 and J2 of *May and Butler* [1986] vanish (Figure 6). There are usually overlaps between the circles of confidence of

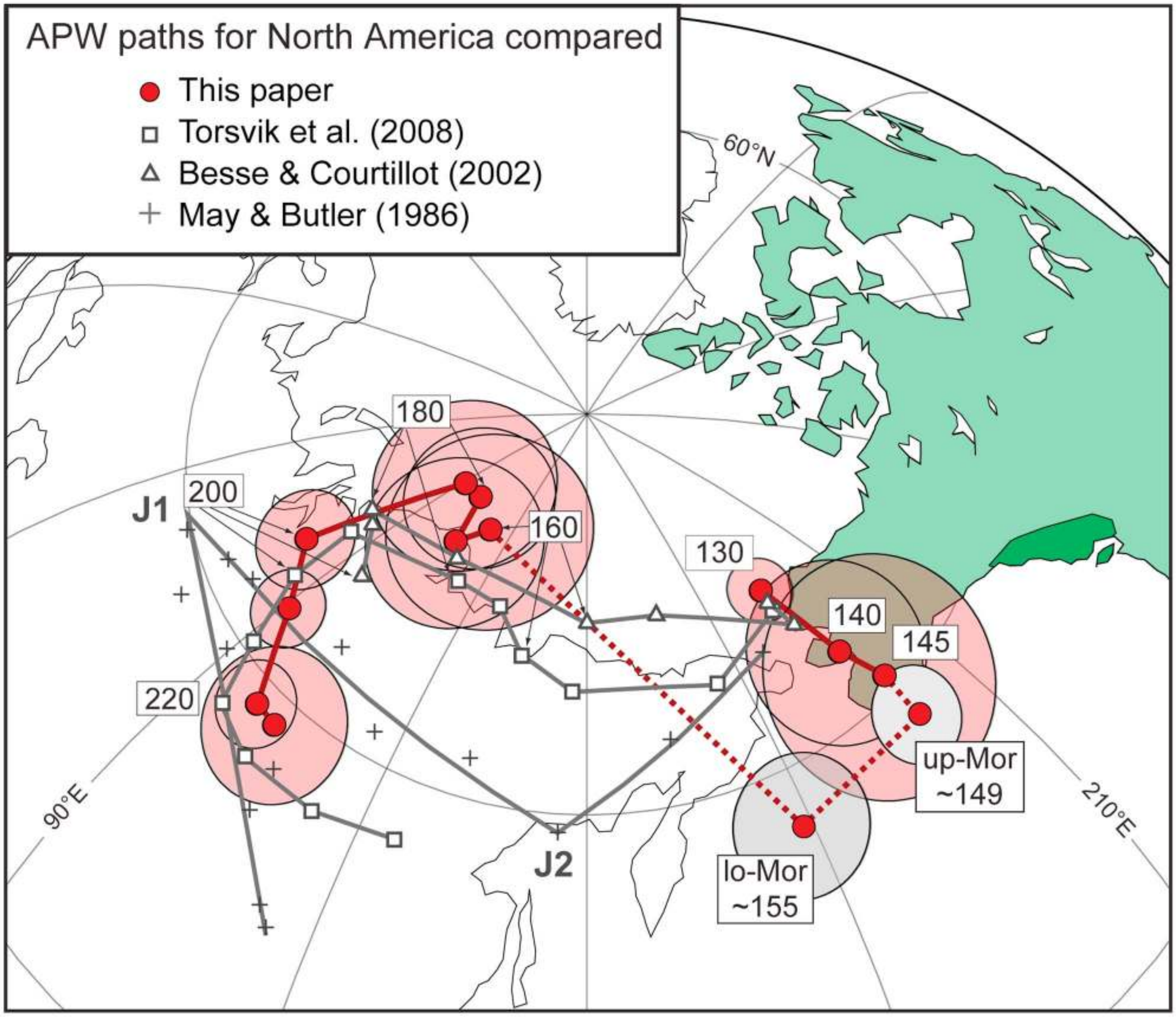


Figure 6. The new composite APW path (with 95% confidence circles) for North America from 230 to 130 Ma based on global igneous and *E/I*-corrected sedimentary poles compared with the PEP model path based on North American data only [*May and Butler*, 1986] and the running-mean composite paths of *Besse and Courtillot* [2002] and *Torsvik et al.* [2008], all in North American coordinates. Key poles for comparison are labeled by numerical ages (Ma) of midpoint of 20 Myr averaging window. The tentative dashed path and poles lo-Mor and up-Mor are explained in the caption to Figure 4. The darkened area in western North America is approximate modern extent of Stikine and Wrangell terranes in British Columbia.

Table 7. Selected Paleomagnetic Results From Late Jurassic Morrison Formation From Colorado Plateau Corrected for Assumed *I* Error and Clockwise Tectonic Rotation[a]

							f = 0.55			r = 5°		r = 9°		r = 13°	
Age (Ma)	Unit	a95 (deg)	D (deg)	I (deg)	LA (°N)	LO (°E)	Ic (deg)	LAc (°N)	LOc (°E)	LAcr (°N)	LOcr (°E)	LAcr (°N)	LOcr (°E)	LAcr (°N)	LOcr (°E)
149	up-Mor	3.6	332.3	54.2	67.5	161.8	68.4	66.4	205.7	63.2	202.9	60.6	201.4	58.0	200.4
155	lo-Mor	5.3	330.3	42.4	61.4	142.2	58.9	66.9	175.0	62.9	176.2	59.6	177.2	56.4	178.3

[a] Selected results from lower and upper units of Late Jurassic Morrison Formation from Norwood, Colorado (locality 38°N, 108°W), are from *Steiner and Helsley* [1975]: a Kimmeridgian-Tithonian (~149 Ma [*Kowallis et al.*, 1998]) age is tentatively assigned for the upper unit (up-Mor) and an Oxfordian-Kimmeridgian (~155 Ma) age for the lower unit (lo-Mor). Flattening factor *f* = 0.55 was assumed to calculate corrected inclination (Ic) and corresponding pole position latitude (LAc) and longitude (LOc), which were then used to calculate latitude (LAcr) and longitude (LOcr) of pole using a Euler pivot at 34.6°N 254.6°E [*Hamilton*, 1988] for an estimated Plateau clockwise rotation (r) of r = 5° [*Bryan and Gordon*, 1990], r = 9° [*Steiner*, 2003], and r = 13° [*Kent and Witte*, 1993] with respect to eastern North American craton.

time-equivalent poles of these two paths and ours indicating that they are not always significantly different. However, the 190 to 160 Ma (Early and Middle Jurassic) mean poles of *Besse and Courtillot* [2002] place North America at lower latitudes than ours, by up to 7° in case of the 180 or 190 Ma poles, and this tendency is even greater between the Early and Middle Jurassic mean poles of *Torsvik et al.* [2008] and ours (Figure 6). These differences between our path and those of Besse and Courtillot and Torsvik et al. are just as expected from variable *I* error, our path being based on results from igneous rocks (and *E/I* corrected sedimentary rocks), theirs to a substantial but varying extent on sedimentary rocks also.

[34] The largest disparities among the APW paths are in the Late Jurassic and Early Cretaceous, reflecting the aforementioned sparseness of both igneous and sedimentary results between 160 and 140 Ma. Although all the APW paths shown in Figure 6 agree at around 130 Ma at the beginning of the Cretaceous standstill, they differ markedly in the way they arrive there. Noteworthy in the new composite APW path for North America is the J/K hook close to the Jurassic Cretaceous boundary. This feature is anchored by the 145 Ma mean pole which is based on igneous data from three continents; the additional "corrected" Morrison poles indicate that it may be a much more pronounced feature. It is notable also that *Channell* [1996] has identified a comparable hook-like feature in the APW path recorded in Late Jurassic and Early Cretaceous sedimentary sections of the Apennines and Southern Alps of Italy. The key Ithaca kimberlite pole from North America and Hilopenstretet dikes pole from Svalbard (although not the Swartsruggens kimberlite pole from southern Africa) were included in the composite APW compilation of *Besse and Courtillot* [2002] and their mean pole for 140 Ma (using a 10 Myr window: 66.7°N 197.2°E A95 = 8.1°, in North American coordinates) is within a few degrees of ours (64.7°N 197.3°E A95 = 6.8°, in North American coordinates); *Torsvik et al.* [2008] included only the Ithaca kimberlite pole and hence their composite APW path is not as close to the J/K hook. It is ironic that the J2 cusp, a linchpin of PEP analyses [e.g., *Beck and Housen*, 2003], may transform into quite a different feature of North America APW if the defining lower Morrison pole can be reproduced [see *Bazard and Butler*, 1994] and has indeed been affected by significant *I* error, as we speculate. In the virtual absence of igneous data for the latter part of the Jurassic, the roles of *I* error and local tectonic rotations for sedimentary sections from the Colorado Plateau [e.g., *Steiner*, 2003] as well as from the Apennines and Southern Alps [e.g., *Muttoni et al.*, 2005; *Satolli et al.*, 2007] urgently need to be reassessed.

[35] The 130 Ma and younger mean poles (and hence comparisons with terrane data) are changed very little from *Enkin* [2006] because most poles he selected are based on igneous results and retained. The mean poles from 130 Ma to 50 Ma, dominated by the Cretaceous standstill, differ only marginally from coeval mean poles of *Besse and Courtillot* [2002] and *Torsvik et al.* [2008].

6. Motions of North American Craton

[36] The new composite APW path shows that during the Triassic and Jurassic the North American craton moved rapidly northward and rotated somewhat clockwise relative to the paleomeridian (Figure 7). Despite an apparent pause in latitudinal motion between 190 and 160 Ma, by the end of the Jurassic the western margin of the craton had traversed about 45° of latitude: using the Mt. Tatlow locality in western British Columbia as reference, from 23° (more or less within the tropics) at 230 Ma to 68° (more or less within what nowadays would be the Arctic circle) at 145 Ma at an average rate of more than 0.5° per Myr (nearly 6 cm/yr) (Table 6). Motion of the western margin of the craton then switched, from 145 Ma to around 120 Ma becoming generally southward at 0.3° per Myr accompanied by counterclockwise rotation. The magnitude of the clockwise followed by anticlockwise rotation relative to the pole between 140 and 60 Ma as shown in Figure 7 is muted by the wide spacing in time of the maps. The craton stayed essentially parked with respect to Earth's spin axis for the next 60 Myr and then drifted southward ~10° to its present position during the Cenozoic.

[37] How did the motions of the craton compare with the motions of the terranes that now reside within the Cordillera? It is already clear that conclusions drawn from the Triassic and Jurassic APW paths for North America of *Gordon et al.* [1984] and *May and Butler* [1986], which have been very influential in discussions of terrane motions in the Cordillera, need to be reconsidered and substantially revised. We begin to address that question with a brief illustration, considering only certain key data from a geographically restricted part of the Canadian Cordillera.

7. Implications for Movements of the Wrangellia and Stikinia Terranes in Central and Western British Columbia

[38] In the later 1970s it was suggested that as much as 70% of the Cordillera may be non-North American in origin [see, e.g., *Coney et al.*, 1980]. Many lines of evidence supported this distinction between autochthonous craton and allochthonous terranes, notably in the present context they were found to be paleomagnetically incompatible [*Beck and Noson*, 1972; *Irving and Yole*, 1972; *Hillhouse*, 1977; *Irving*, 1979]. *Beck and Noson* [1972] in their pioneering study proposed that the Late Cretaceous (90 Ma) Mount Stuart batholith of the Cascade Terrane likely was originally situated ~2000 km farther south relative to the North American craton than at present. Similar discoveries, from other bodies mainly intrusions in British Columbia [*Symons*, 1977], led *Rees et al.* [1985] to build on the speculations of *Beck and Noson* [1972] to propose that the terranes that now comprise much of British Columbia and adjacent parts of Washington State, and which had been amalgamated by the Cretaceous, were situated well south of their present position relative to the craton and have since moved north (i.e., the hypothesis of Baja British Columbia [*Irving*, 1985]).

[39] Contemporary studies of Triassic and Jurassic bedded volcanic rocks from southern Wrangellia and Stikinia, the most westerly terranes of Baja British Columbia, gave smaller displacements, ~1000 km. The reference APW paths used to make these determinations were tailored for the time of each study, but were close to that of *Irving and Irving* [1982] (Figure 1). These studies indicated that from a Late Triassic position somewhat south of at present, Baja British

Figure 7. Positions of North America relative to the geographic pole (shown with present coastline for ease of recognition) from 220 to 60 Ma (as labeled) at independent 20 Myr intervals based on new composite APW path; present-day position of the northwestern portion of North America is in green in upper left background. Latitude and longitude grid spacing is 15° as viewed from space; tropics and Arctic circles are dashed. Longitudes are arbitrary from reconstruction to reconstruction, only the position and orientation of the continent with respect to lines of latitude are constrained by the paleomagnetic data, which have 95% circles of confidence of ~5° (Table 6). Notice the absence of significant polar movement (APW standstills of Figure 4) from 180 to 160 Ma and from 120 to 60 Ma and the intervening large rapid motion that brought northwestern North America close to the pole at around 140 Ma.

Columbia (at least its westerly components) moved farther south and then north relative to the craton, although not necessarily close to the craton [*Irving et al.*, 1985]; alternatively, during the early Mesozoic Baja British Columbia could have been in the southern hemisphere and since moved only northward. However, its Mesozoic faunas are uniformly boreal [see, e.g., *Smith et al.*, 2001] and the magnetization of bedded Permian rocks of the Asikta Group of Stikinia have, with the exception of a thin siltstone horizon [*Irving and Monger*, 1987], the polarity that most probably was acquired in the Northern Hemisphere during the Kiaman Reverse Polarity Superchron. Permian rocks of allochthonous terranes in Alaska [*Panuska and Stone*, 1981], northern California [*Mankinen et al.*, 1989], and British Columbia [*Richards et al.*, 1993] all have similar northern hemisphere magnetizations. It seems very likely therefore that the allocthonous terranes of the northern Cordillera (e.g., those that comprise Baja British Columbia) have been in the Northern Hemisphere since the Permian.

[40] The notion that the allochthonous terranes should be far-traveled has been much criticized. For example, *Butler et al.* [1989] argued that the Cretaceous plutons with their apparent latitudinal offsets (the original basis of the idea of Baja British Columbia) had been systematically tilted. Also, reassessments of the offsets determined from Triassic and Jurassic rocks by *May and Butler* [1986] using a reference

APW path based on PEP analysis, and by *Irving and Wynne* [1990] and *Vandall and Palmer* [1990] using reference paths based predominantly on sedimentary results, indicate that they were not significant. Since 1990, new evidence from Cretaceous bedded rocks, for which the paleohorizontal can be accurately estimated, has appeared and tilt as a general explanation for the offsets has been extensively criticized [e.g., *Ague and Brandon*, 1996; *Irving et al.*, 1996; *Enkin*, 2006]. There have also been many new age dates. Up till now little attention has been paid to the possible general effect that *I* errors might have on the APW paths and how they might have affected estimates of tectonic displacement in orogenic belts. With these new paleomagnetic and age data in hand, and having an APW path freed of *I* error, we can reassess the general question of latitudinal offsets. *Enkin* [2006] has effectively already done this for Cretaceous and Cenozoic results and we build on his analysis. Here we illustrate the use of the new composite APW path focusing primarily on the available paleomagnetic results from Triassic and Jurassic bedded volcanic rocks from the largest and most westerly terranes just referred to: southern Wrangellia and Stikinia (plus the tiny associated Catwalder terrane in the southernmost Coast Mountains of British Columbia) of western British Columbia.

7.1. Latitudinal Offsets of Southern Wrangellia/Stikinia Relative to the Craton

[41] The results selected from W/S range in age from Permian to Neogene. They were selected for two principal reasons: they comprise one of the longest stratigraphically defined paleomagnetic records in the Cordillera, and with the exception of one sedimentary sequence (in which E/I studies show *I* error absent), they are from volcanic rocks, which are not subject to inclination error and whose attitudes and paleohorizontal are well determined from interbedded sedimentary rocks. They are subaerial basalts and andesites, commonly amygdaloidal, and a few associated sills, typified by square-shouldered demagnetization decay curves with unblocking temperatures that cluster just below the Curie temperature of magnetite (500–560°C) or hematite (600–675°C) [see, e.g., *Irving and Yole*, 1987, Figure 3]. Both normal and reversed polarities are present. These are essentially stable, single-domain-like magnetizations, likely to have survived the sub-greenschist burial metamorphism [*Pullaiah et al.*, 1975] to which all might have been subjected.

[42] The paleomagnetic declinations in these Triassic and Jurassic formations are often dispersed, and because they are bedded, the results can be referred to paleohorizontal and the dispersion shown to be caused by tectonic rotations about local vertical axes [*Monger and Irving*, 1980; *Yole and Irving*, 1980; *Irving and Yole*, 1987; *Irving and Wynne*, 1990; *Vandall and Palmer*, 1990]. These locally observed rotations are well documented, large (commonly > 40°) and systematically sinistral. Consequently, mean inclinations (from which latitudes are obtained) have been calculated using inclination-only statistics; we use the method of *Enkin and Watson* [1996].

[43] The Late Triassic Karmutsen Formation (225 Ma [*Greene et al.*, 2009]) studied at 38 sampling sites [*Irving and Yole*, 1972; *Schwartz et al.*, 1980; *Yole and Irving*, 1980; *Irving and Yole*, 1987], has a mean inclination of 32.1 ± 3.0° ($P = 0.05$). This corresponds to a paleolatitude of 17.5 ± 1.8°N compared with an expected 24.5 ± 5.9°N giving a small but significant offset of 7.0 ± 6.0° or 780 ± 660 km from the south. This result is labeled KM and shown in two ways in Figure 8, as latitudinal displacement relative to present position of the Karmutsen Formation and, in the inset, as latitudinal position relative to the craton in the Late Triassic. Data from 12 sites from the Late Triassic Savage Mountain Formation of the Stuhini Group (220 Ma; SM in Figure 8) of central British Columbia [*Monger and Irving*, 1980] have a mean inclination 43.8 ± 11.7° corresponding to a paleolatitude of 25.6 ± 9.4°N. The error from this small study is correspondingly large indicating no significant offset (5.1 ± 9.7°).

[44] Results (42 sites) from the late Sinemurian to early Pliensbachian volcanics of the Hazelton Group in Stikinia (HZ in Figure 8) are well-dated biostratigraphically. They are from the Telkwa (mainly) and the overlying Nilkitwa formations [*Monger and Irving*, 1980], and have a mean inclination 51.3 ± 3.0° corresponding to a paleolatitude of 32.0 ± 2.7°N. The time scale of Table 1 would indicate an age of about 192 Ma, which is confirmed by U-Pb zircon dates of 192.8 (+5.0 −0.6) Ma and 191.5 (±0.8) Ma obtained from zircons in volcaniclastic sediments in the Telkwa Formation [*Pálfy et al.*, 2000b]. Unfortunately, for the interval 188 to 197 Ma, there are no cratonic poles from igneous rocks to provide results freed of *I* error (Table 5) so the window centered at 190 Ma is too young (mean age of poles is 185 Ma; Table 6) whereas the window at 200 Ma (CAMP) is too old, being based on poles with a mean age of 202 Ma. Poles within a 20 Myr window centered on 195 Ma are likewise strongly skewed; the poles of Table 5 in that interval have a mean age of 199 Ma, which is too old for comparison with the Hazelton. However, we suggest that as the craton was moving northward from the Late Triassic through Early Jurassic (Figure 7), offset calculations using the reference pole at 190 Ma with its mean age of 185 Ma provides an upper limit to displacement; this is 14.9 ± 5.3°. A lower limit (lower because it is based substantially on sedimentary rocks susceptible to *I* error) is given by displacement determined relative to the 190 Ma poles of *Torsvik et al.* [2008] (6.8 ± 4.4°) and *Besse and Courtillot* [2002] (8.0 ± 5.0°); their mean, is 7.4°. The limits determined paleomagnetically therefore are 14.9° and 7.4°. We take the mid-point between them as the best paleomagnetic estimate of Hazelton displacement from the south, 11.2 ± 6.1° or 1200 ± 680 km.

[45] The Bonanza Formation in Wrangellia (BZ in Figure 8; 20 sites from Vancouver Island [*Irving and Yole*, 1987]) is similar in age to the Hazelton and likewise suffers from the absence of a closely corresponding cratonic record. We apply the same arguments. The Bonanza mean inclination is 42.5 ± 4.3° and corresponding paleolatitude of 24.6 ± 3.2°. The maximum offset estimate using the 190 Ma window of Table 6 is 17.8 ± 6.7°, the two minimal estimates are 11.0° ± 5.2 from *Besse and Courtillot* [2002] and 9.2 ± 4.8° from *Torsvik et al.* [2008] with a mean of 10.1°. The midway point between maximum and minimum is 14.9 ± 5.9° or 1650 ± 560 km. The mean latitudinal displacements from Wrangellia are greater than from Stikinia but as errors overlap there is no evidence that they were very far apart at that time.

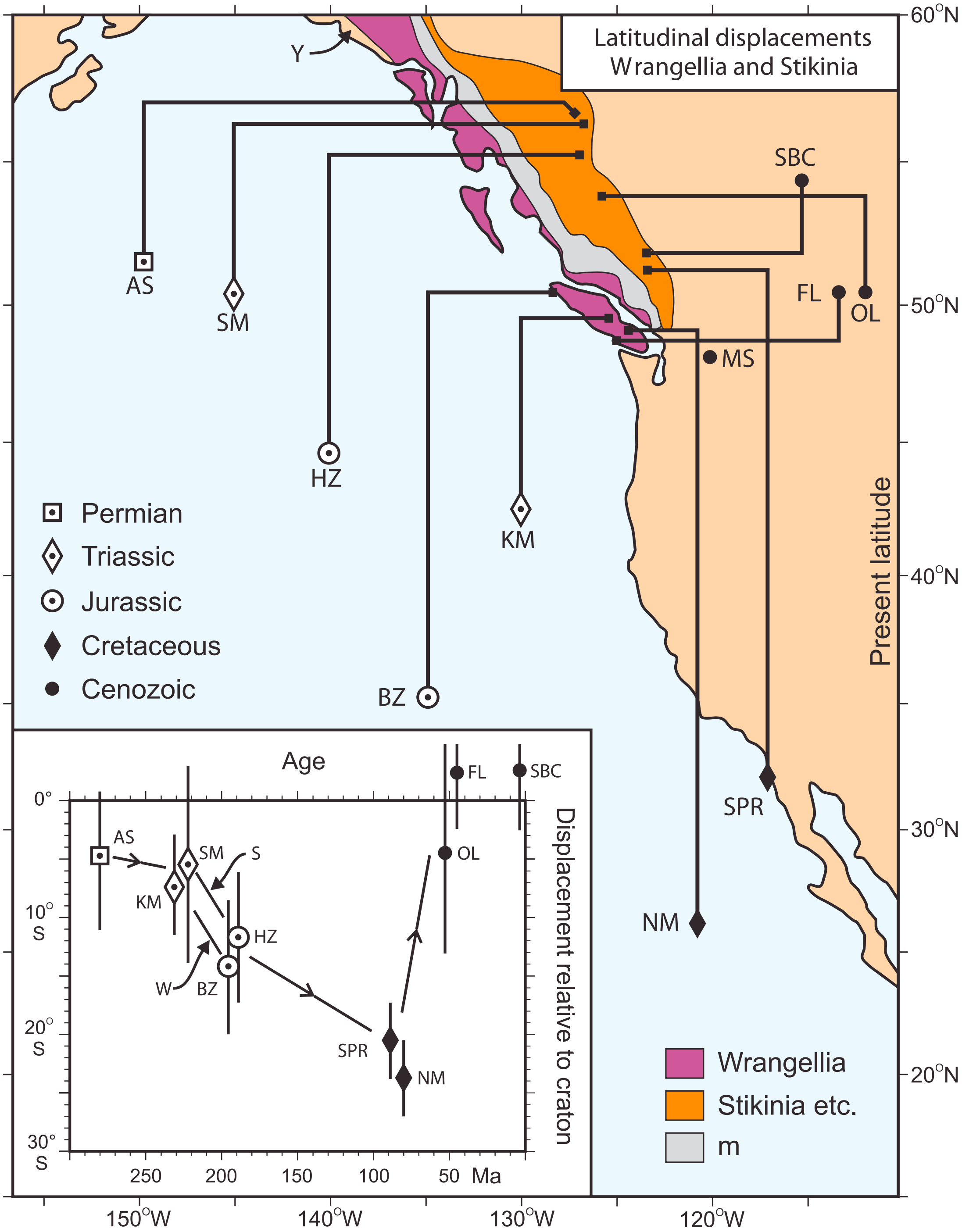


Figure 8. Latitudinal displacements with respect to their present positions of formations from southern Wrangell and Stikine terranes based on the new composite APW path of Figure 4, and in the inset latitudinal displacements relative to the craton with 95% error bars of results from southern Wrangellia and Stikinia labeled W and S. Y is the Yukatat block and m is the zone of metamorphic rocks into which the Cretaceous/Cenozoic Coast Belt plutons are intruded [*Gabrielse and Yorath*, 1992]. Triassic and Jurassic results for Wrangellia are from the Karmutsen (KM, ~225 Ma) and Bonanza (BZ, 195 Ma) formations, and for Stikinia are from the Savage Mountain (SM, ~210 Ma) and Hazelton (HZ, ~195 Ma) formations. Cretaceous results are from the Silverquick and Powell Creek formations (SPR) with no *E/I* evidence of *I* error, and *E/I*-corrected results from the Nanaimo Group of Vancouver Island (NM). Cenozoic results are from Flores volcanics of Vancouver Island (FL), the Ootsa Lake volcanics of central British Columbia (OL), and late Neogene basalts of southern British Columbia (SBC). To extend the time coverage, we have added the Permian Asitka Group of the basement of Stikinia with a paleolatitude of 27 ± 4°giving a not significant offset of 5 ± 6° [*Irving and Monger*, 1987]. See text for further details.

[46] Late Pliensbachian (somewhat younger than Hazelton) north-south climate zonation based on ammonites has long been recognized in Europe and in western North America [*Tipper*, 1981]. In British Columbia the zones are offset in Wrangellia and Stikinia; the "minimum post-Pliensbachian northward displacement of Stikinia is slightly in excess of 1000 km" [*Smith et al.*, 2001, p. 1447]. The distribution of pectinoid bivalves also reveals a north-south zonation that in Stikinia (where the Hazelton is located) is offset to the south; estimated offsets "exceed 1000 km" since the Pliensbachian [*Aberhan*, 1999, p. 491]. The late Pliensbachian ammonites of Vancouver Island all have Tethyan affinities also indicating a more southerly latitude relative to the craton than at present [*Smith et al.*, 2001]. The agreement between the paleomagnetic and paleontological latitudinal offset is excellent.

[47] The Late Cretaceous Silverquick and Powell Creek formations lie on the tiny Cadwalder Terrane then attached to southern Stikinia. The result (90 Ma; SPR in Figure 8) from 80 sites in interbedded andesites and volcanogenic sedimentary rocks is one of the best established in the Cordillera [*Wynne et al.*, 1995; *Enkin et al.*, 2006]; there are positive tilt, conglomerate and igneous contact tests, excellent agreement between lavas and associated volcanigenic sedimentary rocks and an *E/I* test on the later showing no evidence of *I* error [*Krijgsman and Tauxe*, 2006]. The mean inclination is 58.8 ± 1.7° and the paleolatitude is 39.5 ± 2.2°, which amounts to an offset of 20.3 ± 3.4° or 2360 ± 380 km to the south relative to the craton. Also the *E/I* corrected result [*Krijgsman and Tauxe*, 2006] from 67 sites in the Late Cretaceous Nanaimo Group of Vancouver Island (75 Ma; NM in Figure 8) contains a stratigraphic sequence of reversals and has a mean inclination (55.2 ± 2.6°) [*Enkin et al.*, 2001] corresponding to a paleolatitude of 36° (−7°/+9°) that gives an offset of 25 ± 3.7° or 2750 ± 400 km to the south.

[48] Results from the Eocene Ootsa Lake volcanics (49.6 Ma; OL in Figure 8) of central British Columbia [*Vandall and Palmer*, 1990], the Flores volcanics (50 Ma; FL) of Vancouver Island [*Irving and Brandon*, 1990] and the late Neogene basalts of southern British Columbia (SBC) [*Mejia et al.*, 2002] show no significant offset, indicating that Baja British Columbia was in place relative to the craton by the Eocene.

[49] The historically important result from the Mount Stewart batholith (90 Ma [*Beck and Noson*, 1972; *Beck et al.*, 1981; *Housen et al.*, 2003]) is from the Cascade Terrane southeast of Stikinia and for that reason its offset is not included in Figure 8. It has been extensively updated paleomagnetically [*Beck et al.*, 1981; *Housen et al.*, 2003] and detailed studies of paleobarometry [*Ague and Brandon*, 1996] constrain the amount of post-emplacement tilting. The offset of 24.5 ± 6.3° is in excellent agreement with those from the Nanaimo Group and the Silverquick and Powell Creek formations.

[50] A result from later Early Cretaceous (Albian) bedded andesites indicates a displacement from the south of only ~1000 km [*Haskin et al.*, 2003; *Enkin et al.*, 2003, Figure 10], less than half that of the overlying Late Cretaceous Silverquick/Powell Creek formations. However, *Miller et al.* [2006] using plant leaf-margin analysis from the nearby, essentially contemporaneous (Albian) Winthrop Formation have obtained a displacement of 2200 km, in excellent accord with the essentially coeval Silverquick/Powell Creek formations. Because of this baffling conflict (which is in sharp contrast to the excellent accord between latitudes and fossils in the Jurassic and Triassic of W/S) and because there is doubt about the time of magnetization acquisition of these andesites and their equivalent further east, the Spences Bridge Group [*Irving et al.*, 1995; *Haskin et al.*, 2003], this result is not given in Figure 8; it is important to note, however, that it is not at variance with the general trends of Figure 8 but does imply very rapid southward motion of W/S during the Cretaceous [see *Enkin*, 2006, p. 240].

7.2. Reconstructing Motions of Southern Wrangellia/Stikinia Relative to Craton

[51] Latitudes of S/W are compared directly with those of the North American craton in Figure 9. From around 225 Ma to 90 Ma, W/S moved ~20° northward (at ~0.15°/Myr in latitude) during which time the western margin of the North American craton (using Mt. Tatlow that was used by *Enkin* [2006] as a reference locality; Table 6) also moved northward, by 35°, about twice as far at ~0.25°/Myr, much faster than W/S. The result is that between the Late Triassic and mid-Cretaceous there was a net 15° *southward* motion of W/S with respect to the craton at a relative rate of ~0.1°/Myr (Figure 8 inset). The craton moved northward faster than W/S, thus the net effect of their convergence (see below) was likely oblique and sinistral. This is consistent with locally observed systematically sinistral rotations observed in bedded volcanic rocks noted above. Sinistral rotation are recorded paleomagnetically both locally and regionally.

[52] Longitudes are not determined paleomagnetically, but *Johnston and Borel* [2007] and *Johnston* [2008] argue that the faunas and the DUPAL-anomaly basalts of the Cache Creek Terrane immediately east of Stikinia place it in the Tethyan realm at the end of the Triassic, across an ocean far to the west of the North American craton margin. The Permian faunas of Cache Creek are Tethyan [*Monger and Ross*, 1971] as are the Late Triassic [*Tozer*, 1982] and Early Jurassic [*Smith et al.*, 2001] faunas of Vancouver Island. Hence between Wrangellia/Stikinia and the craton there was probably a large closing ocean in the early Mesozoic. For this reason in Figure 9, W/S and the western margin of the craton are drawn a substantial distance apart in the Late Triassic. We assume that by the mid-Cretaceous, W/S was alongside North America as it is improbable that there was then still a substantial ocean between them. From 90 to 50 Ma, W/S moved northward by another 20° (at ~0.5°/Myr) and we assume in Figure 9 that it did so in a linear way. In contrast, the western margin of the craton had been moving southward since ~145 Ma and from 90 to 50 Ma moved a further ~5° southward (~0.125°/Myr). This resulted in a net ~25° northward motion of W/S with respect to the craton at a relative rate of ~0.6°/Myr; thus their sense of relative motion became dextral. After 50 Ma, the craton with W/S now attached moved a few degrees farther southward.

[53] There is a history of conjecture concerning the source of Cordilleran exotic terranes and the manner of their accretion to the North American craton. For the past four decades since plate tectonics began to be applied to orogenic belts, Cordilleran orogenesis has been considered to be the result of easterly directed subduction of oceanic lithosphere beneath the North American craton [e.g., *Dewey and Bird*,

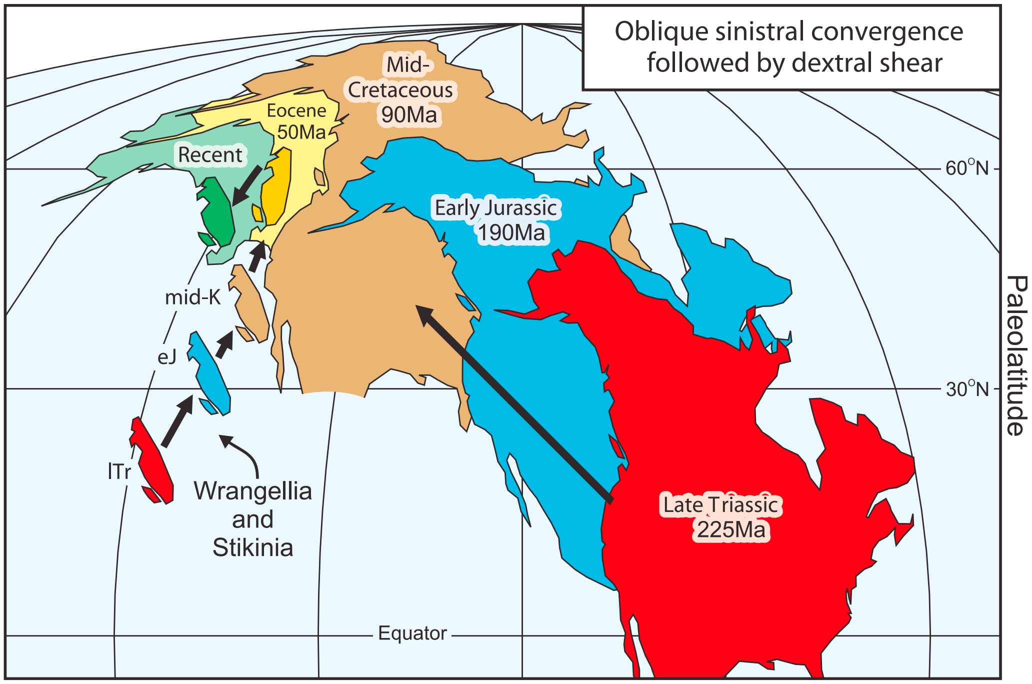


Figure 9. Paleogeographic cartoon (Mollweide projection) comparing latitudes of cratonic North America and southern Wrangellia and Stikinia (W/S). Craton latitudes as given in or by interpolation from Figure 7. The four progressive paleopositions of W/S are based on results from the 225 Ma Karmutsen, the ~195 Ma Hazelton, the 90 Ma Silverquick/Powell Creek formations, and the 50 Ma Flores volcanics; they are keyed by color to the corresponding latitudinal positions of the North American craton and labeled: lTr, Late Triassic; eJ, Early Jurassic; mid-K, mid-Cretaceous; Eocene. See text for discussion.

1970; *Burchfiel and Davis*, 1972, 1975; *Dickinson*, 1977]; the oceanic lithosphere carried the far-traveled terranes which were accreted to the craton during the Mesozoic [see, e.g., *Coney*, 1971; *Monger et al.*, 1972; *Nur and Ben-Avraham*, 1982]. This essentially unanimous interpretation has recently been vigorously challenged. *Johnston* [2001, 2008] argues that during the early Mesozoic, a "Cordilleran ribbon continent" was assembled far out in the Panthalassa Ocean, and *Hildebrand* [2009] proposes an extension south into the USA of this same former ribbon continent. Both maintain that the convergence of the far-traveled terranes resulted from west-facing subduction of an oceanic plate attached to North America, the terranes colliding with the craton in the Cretaceous as *Chamberlain and Lambert* [1985] had earlier maintained. The results summarized in Figures 7, 8, and 9 help provide the paleogeographical framework for discussion of the generally accepted ideas and these more recent speculations concerning Cordilleran tectonics.

8. Concluding Remarks

[54] The advantage of using igneous rocks exclusively to construct composite APW paths is that the record from cratonic igneous rocks is not contaminated by *I* errors. The disadvantage of using them exclusively is that the record is not evenly spread in time; there are major gaps, in the Early Jurassic as we have discussed, in the Late Jurassic and through much of the Triassic during which igneous rocks are poorly represented in the cratonic record. There is also often a nagging concern about averaging secular variation. The advantage of deriving composite APW paths from cratonic sedimentary rocks is that in principle they provide more complete time coverage and Steno's principles for attitude control and correlation can be applied; studies of such rocks can ensure adequate averaging of secular variation and offer sweeping coverage over geological periods of time. Consequently, sedimentary rocks are the more likely to capture the salient features of motions of cratons relative to Earth's axis of rotation along which the geomagnetic field tends to be aligned. The disadvantage of using cratonic sedimentary rocks is that the record from them is likely to be corrupted to some degree by *I* error.

[55] The concept of paleomagnetically derived APW paths (first illustrated in Figure 1 of *Creer et al.* [1954]) combined with plate tectonic reconstructions for the modern (Jurassic to recent) era of seafloor spreading, allows us to summarize numerous paleomagnetic observations into a single composite APW path; this approach was pioneered by *Phillips and Forsyth* [1972] and subsequently greatly extended by *Besse and Courtillot* [1991] and others. These numerous paleomagnetic surveys doubtless were motivated in the first place by general ideas (the need in the 1950s to test the theory of continental drift for instance) and now to address more specific tectonic, paleogeographic, and geodynamic models as illustrated by *Besse and Courtillot* [2002], *Torsvik et al.* [2008], and in this paper. A considerable effort is needed, and one may wonder therefore where future paleomagnetic surveys should be focused. Our answer is twofold. First the study of igneous rocks in the

time gaps made evident here, but we face the real possibility that there may in fact be very few suitable cratonic igneous rocks in these gaps. Second and perhaps more promising, would be surveys or resurveys of cratonic sedimentary sequences planned with the objective of testing for *I* error and, if it should be found, correcting for it. Finally, in the absence of independent and accurate plate tectonic reconstructions, there lies ahead of us the difficult (and tedious) task of reassessing possible *I* error in those pre-Mesozoic APW paths that are based in part on sedimentary rocks.

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