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Paleomagnetism of 122 Ma Plutons in New England and the Mid-Cretaceous Paleomagnetic Field in North America: True Polar Wander or Large-Scale Differential Mantle Motion?

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A paleomagnetic study of Cretaceous White Mountains plutonic complexes in New Hampshire and Vermont yields high unblocking temperature, dual polarity magnetizations in different types of igneous rocks. The resulting pole position for three plutons (71.9° N, 187.4° E, A_{95} = 6.9°, age = 122.5 Ma) agrees with previously published mid-Cretaceous poles for North America, which together give a mid-Cretaceous standstill reference pole slightly revised from *Globerman and Irving* [1988] at 71.2° N, 194.1° E (A_{95} = 3.7°, N = 5 studies). We argue on the basis of the wide geographic distribution of these studies, the variety in tectonic settings and rock types, positive reversal tests, and an overall reversal pattern consistent with geomagnetic polarity time scales, that this mean pole represents the North American mid-Cretaceous reference field for nominally 36 m.y. (124 to 88 Ma). The standstill pole limits to within ±4°, the motion of the North American plate relative to the Earth's spin axis. During the same mid-Cretaceous interval, the New England hotspot track (124 Ma Monteregian Hills, 122.5-Ma Cretaceous White Mountains, and 103- to 84-Ma New England seamounts) requires 11°±4° of north-poleward motion of North America, in direct conflict with the paleomagnetic standstill. A similar (~13°) discrepancy is independently demonstrated between the spin axis and the Tristan da Cunha hotspot track on the African plate during the mid-Cretaceous interval. The hotspot/spin axis discrepancies ended by ~90 Ma when it is shown that both Atlantic hotspots agree with North American and African dipole paleolatitudes and present-day locations. Nondipole fields are an unlikely explanation of the uniform motion of these two widely separated hotspots with respect to the spin axis, leaving as possible interpretations true polar wander and large-scale (but differential) mantle motion. The southerly motion of the mid-Cretaceous Louisville hotspot relative to the spin axis is ostensively at odds with what would be predicted under the true polar wander interpretation and points to differential mantle kinematics. The motions of the three widely separated mid-Cretaceous hotspots with respect to the spin axis may be related to the recently proposed increase in global oceanic lithosphere production rates which gave rise to the mid-Cretaceous "superplume."

INTRODUCTION

It has been long recognized that Cretaceous paleomagnetic poles for North America tended to fall relatively close together in the general area of the Bering Strait [e.g., *Irving*, 1964; *McElhinny*, 1973; *Mankinen*, 1978]. This tendency was most recently confirmed by *Globerman and Irving* [1988] who calculated a mid-Cretaceous reference pole at 71°N, 196°E (A_{95} = 4.9°, k = 352) on the basis of four published studies on rocks ranging in age from circa 88 Ma to 124 Ma. The mean pole position may therefore represent the paleomagnetic field relative to cratonic North America for some 36 million years of the Cretaceous, a "standstill" in apparent polar wander during which there was no discernible plate motion relative to the geographic axis according to the geocentric axial dipole hypothesis. Bracketing the mid-Cretaceous standstill are Late Jurassic/Early Cretaceous poles [*May and Butler*, 1986; *Van Fossen and Kent*, 1992] and Late Cretaceous poles [*Diehl*, 1991] which require relatively fast North American apparent polar wander (~1°/m.y.).

The mid-Cretaceous is itself an interesting interval in the annals of global change. Aside from being dominated by a ~30-m.y. interval of uniform normal geomagnetic polarity (the Cretaceous Normal Polarity Superchron, corresponding to the Cretaceous Quiet zones in the oceans), the mid-Cretaceous has been characterized as a period of fast seafloor spreading [*Larson and Pitman*, 1972; *Larson*, 1991], increased mantle plume activity [*Larson*, 1991; *Tarduno et al.*, 1991], and fast plate motion in the mantle hotspot framework [*Morgan*, 1972, 1983; *O'Connor and Duncan*, 1990]. It is less clear, however, how to characterize the mid-Cretaceous in terms of geometry, amount, and timing of relative motion between the hotspot and paleomagnetic reference frames. Previous studies that include the mid-Cretaceous interval are primarily based on global syntheses of paleomagnetic and relative plate reconstruction data sets and comparisons with models of plate motion in the hotspot reference frame [e.g., *Livermore, et al.*, 1984; *Andrews*, 1985; *Gordon and Livermore*, 1987; *Besse and Courtillot*, 1991]. The complexity of these analyses may contribute to the current lack of consensus on the subject and, furthermore, *Livermore et al.* [1984] suggested that the pre late Cretaceous motion between the hotspot and paleomagnetic reference frames might be better attributed to the errors in hotspot track identifications and/or paleomagnetic data.

In this study we examine North American mid-Cretaceous apparent polar wander through a paleomagnetic study of the youngest group of White Mountain Series plutons in New England (mean age = 122.5 Ma). This independent determination provides an additional test of overall consistency of the North American mid-Cretaceous paleomagnetic poles whose reliability can be further assessed by comparing reverse and normal polarity magnetizations among the new and published pole position data for a regional-scale reversal test. As we will show, the North American record of the mid-Cretaceous paleomagnetic field and hotspot activity also provides a more direct experiment to test various ideas on the nature of the paleomagnetic and hotspot reference frames.

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THE CRETACEOUS WHITE MOUNTAINS MAGMA SERIES

Geological Setting

The Cretaceous alkaline intrusions in southern New Hampshire and southeastern Vermont are the youngest group of igneous rocks associated with the White Mountains Magma Series (Figure 1). Their emplacement followed an initial late Triassic phase of igneous activity at ~230 Ma and a Jurassic phase at ~175 Ma [*Foland and Faul*, 1977]. The Cretaceous granites, monzonites, gabbros, basalts and andesites occur predominantly in five major plutonic and ring-dike complexes that intrude lower to middle Paleozoic metamorphic and igneous formations. These complexes are (north to south, Figure 1) Mount Tripyramid, Ossippee Mountains, Merrymeeting, Mount Ascutney, and Mount Pawtuckaway.

K/Ar biotite dating of numerous Cretaceous White Mountains plutons and stocks, including the five major plutonic complexes sampled here for paleomagnetism, suggests an age range of about 118 Ma to 125 Ma [*Foland et al.*, 1971; *Foland and Faul*, 1977]. Recently, a number of Cretaceous White Mountains plutons have been restudied using the $^{40}Ar/^{39}Ar$ biotite method by *Hubacher and Foland* [1991]. They suggest a shorter period of magmatic activity, perhaps only 3 m.y. in duration, centered on 122.5 Ma. These data, together with published zircon fission track (mean = 113 ± 10 Ma [*Doherty and Lyons*, 1980]) and apatite fission track ages (mean = 103 ± 15 Ma [*Zimmerman et al.*, 1975; *Doherty and Lyons*, 1980]), suggest that these plutons were emplaced at shallow depths (~3.5 km) and were subject to monotonic cooling since crystallization.

Paleomagnetism

In the pioneering study of the White Mountains Magma Series by *Opdyke and Wensink* [1966], a pole position was calculated from a variety of plutons considered then, with the exception of the Cretaceous Mount Ascutney, to be entirely Jurassic (~180 Ma). The wide age range of the White Mountains Magma Series has been subsequently documented [e.g., *Foland and Faul*, 1977] and renewed paleomagnetic studies of the Middle Jurassic and Triassic plutons have revealed a sensible relationship between inferred magnetization age and radiometric age [*Van Fossen and Kent*, 1990; *Wu and Van der Voo*, 1988]. Our experimental plan for the Cretaceous plutons was to apply further alternating field (AF) and new thermal demagnetization studies to samples from the original Opdyke and Wensink collection (10 sites), as well as demagnetization experiments on our own samples (7 sites). Because the peak AF field applied by Opdyke and Wensink was generally only 30 mT and because the thermal method was not used, further work was necessary to address the issue of contamination by secondary magnetizations with modern paleomagnetic methods.

The paleomagnetic sampling covers the five major Cretaceous White Mountains intrusions. While the recent $^{40}Ar/^{39}Ar$ dating of *Hubacher and Foland* [1991] provides a refined temporal assessment of Cretaceous magmatism. The specific and earlier published K/Ar age information from *Foland and Faul* [1977], unless otherwise indicated, is also quoted for reference. Gabbro has been sampled at three sites from Mount Ascutney (K/Ar biotite age = 119 ± 4 Ma) as well as at three sites from the Merrymeeting pluton (K/Ar biotite age = 117 ± 4 Ma). To the south at Mount Pawtuckaway, monzonite has been collected at two sites (K/Ar biotite age = 121 ± 4 Ma). Andesite and basalt flows within the Ossippee Mountains ring dike have been sampled at six sites (minimum age of 121 ± 4 Ma based on K-Ar biotite age of intruding Conway granite). These flows were tilted through differential subsidence above the intruding magma chamber [*Kingsley*, 1931; *Billings*, 1956]. Gabbro and a basalt dike at Mount Tripyramid have been sampled at three sites. Unfortunately, only a commercial radiometric date appearing on the map of *Hatch and Moench* [1984] is available (112 ± 5 Ma) and, although *Hubacher and Foland* [1991] do not list Tripyramid as one of the Cretaceous intrusions redated, we assume that it falls within the distinct interval of Cretaceous magmatism centered at 122.5 Ma.

Thermal and AF vector demagnetization profiles of White Mountains samples are straightforward with the exception of those from the Merrymeeting gabbro. Samples from Tripyramid, Pawtuckaway, and Ascutney contain a single component of magnetization with high unblocking temperature (~570° C) and high coercivity (Figures 2a, 2b, and 2c). This magnetization is of reversed polarity (declination ≈154°, inclination ≈-56°) in Mount Ascutney and Mount Tripyramid gabbros, and is of normal polarity (declination ≈343°, inclination ≈+59°) in Mount Pawtuckaway monzonite.

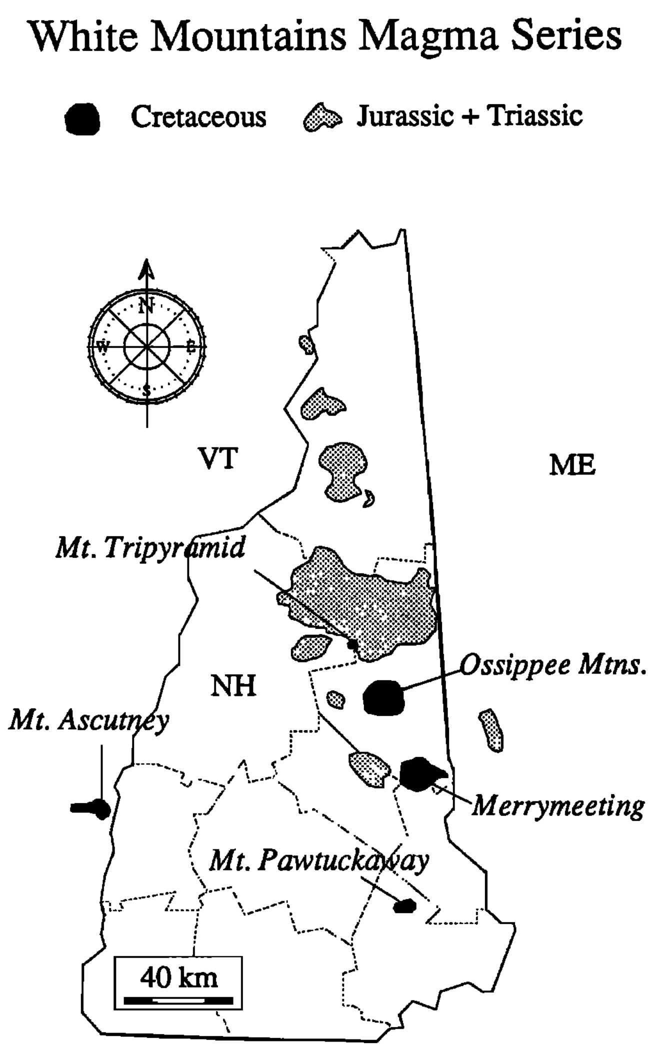

Fig. 1. Location map of the White Mountains Magma Series in New England. The five major Cretaceous igneous complexes sampled for paleomagnetism are highlighted.

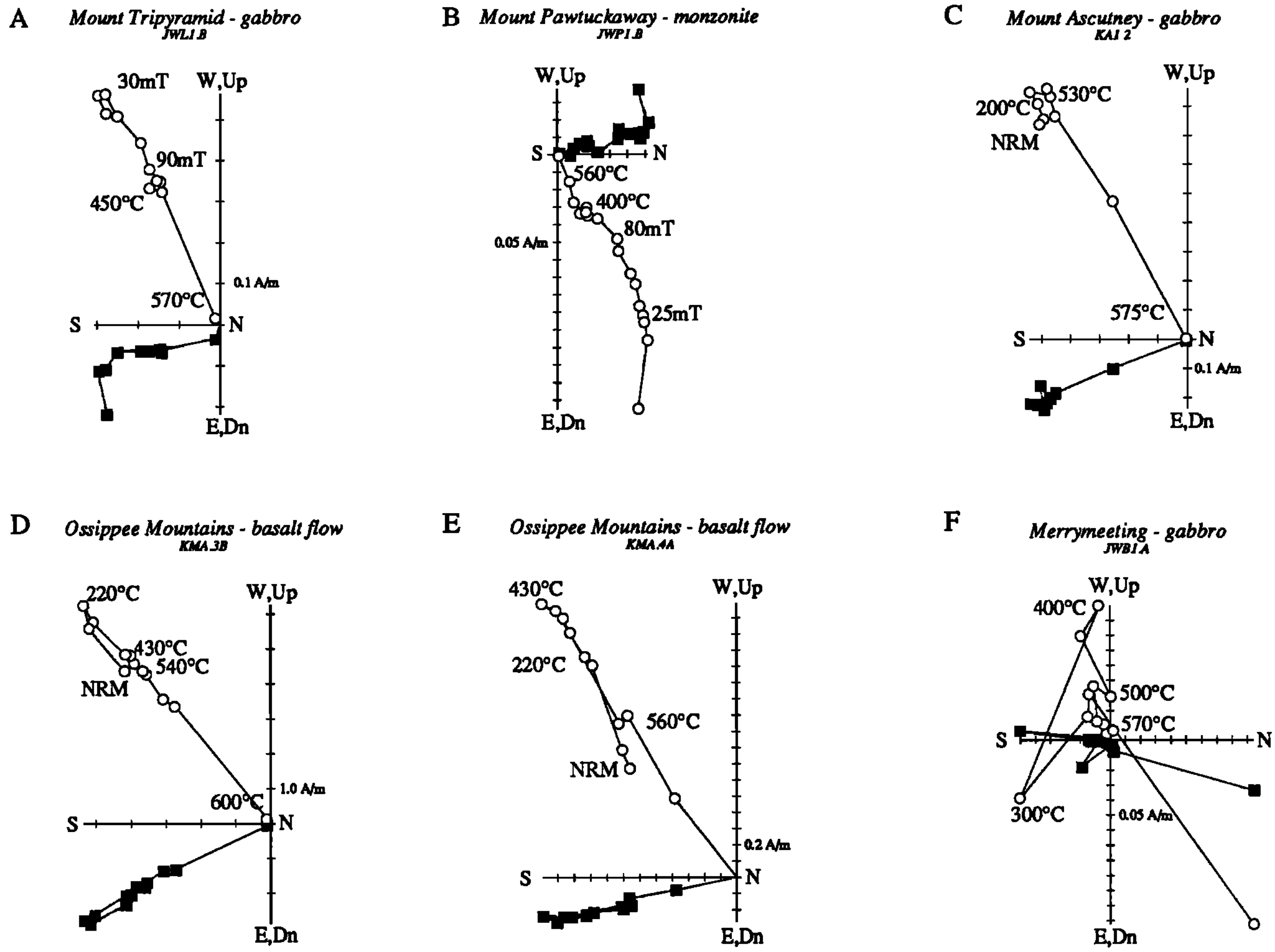

Fig. 2. Representative demagnetograms showing AF and/or thermal demagnetization of various Cretaceous White Mountains lithologies. (a) Gabbro from Mount Tripyramid, (b) Mount Pawtuckaway monzonite, (c) Mount Ascutney gabbro, (d, e) basalt flow from the Ossippee Mountains, and (f) unstable Merrymeeting gabbro. Open/closed symbols projected on to vertical/horizontal planes in geographic coordinates.

The Ossippee volcanic rocks also contain a high stability, reversed polarity magnetization (declination ≈162°, inclination ≈-49°) but to slightly higher unblocking temperatures (~600° C). In addition, five of the six Ossippee sites show a consistent normal polarity overprint (declination ≈349°, inclination ≈+70°) that is usually removed with applied temperatures of ~200°C (Figure 2d), but which did extend to >400° C in some samples from sites KMA, C, and F (Figure 2e). This low unblocking temperature component is parallel to the present field direction and most likely represents a remanence of recent origin. However, the high unblocking temperature component also appears to be secondary with respect to tilt on the basis of the *McFadden* [1990] discordancy test, even though this reversed magnetization is obviously not compatible with the present field direction.

The origin of the unstable magnetization at Merrymeeting is not known. *Opdyke and Wensink* [1966] reported a reversed magnetization direction for these three gabbro sites following blanket AF treatments between 30 mT and 50 mT, but vector analysis of their data, including some samples that were subjected to alternating fields of 160 mT, indicates that a stable magnetization direction was not satisfactorily achieved. Our additional thermal demagnetization experiments were also unable to resolve consistent remanence in these samples (Figure 2f). Although the Merrymeeting magnetization is most probably of reversed polarity, in the absence of clear origin-bound demagnetization trajectories the directional data from the Merrymeeting samples were excluded from further study.

Isothermal remanent magnetization (IRM) experiments on representative samples from the Cretaceous White Mountain plutonic complexes (including the unstable Merrymeeting gabbro) show efficient acquisition of magnetization and saturation in moderate (~150 mT) magnetic fields (Figure 3). These data together with the observed peak unblocking temperatures of about 570°C suggest that the predominant carrier of remanence is (titano)magnetite. Slightly higher unblocking temperatures (~600°C) for the Ossippee volcanic flows suggests the additional presence of some (titano)hematite in these subaerial rocks, although the IRM curves would suggest that this contribution is not a significant one.

Interpretation and pole position

A mean pole position has been calculated using eight site mean magnetizations (Figure 4) converted to virtual geomagnetic poles (VGPs) from Mount Tripyramid, Mount Ascutney, and Mount Pawtuckaway plutons (71.3° N, 187.5° E, A_{95} = 4.2°, K = 172; Table 1 and Figure 5a). The Ossippee pole (69.8° N, 160.3° E) has been excluded from this calculation

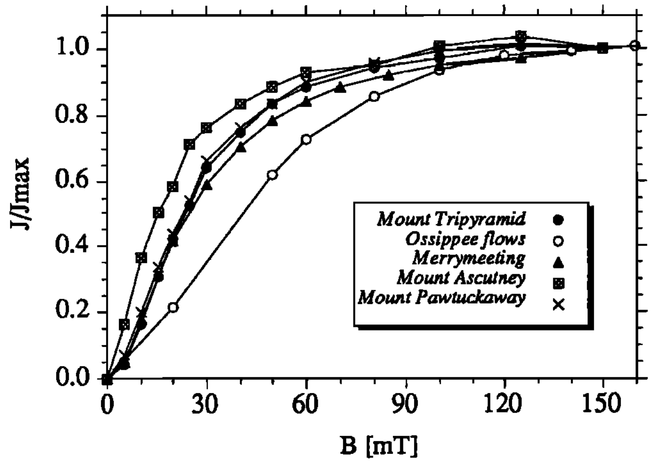

Fig. 3. Isothermal remanent magnetization (IRM) acquisition curves for representative samples from the Cretaceous White Mountains plutons. *J/Jmax* = normalized IRM; *B* = direct inductance in millitesla.

because it is far sided relative to the Tripyramid-Ascutney-Pawtuckaway mean (~9° arc distance, Figure 5a) and especially because it lacks a direct radiometric age constraint for maximum age. Based on the geological evidence [*Kingsley*, 1931; *Billings*, 1956] and the K-Ar age of the intruding granite [*Foland and Faul*, 1977], the Ossippee flows are no younger than 121 Ma. There is an additional constraint on minimum age of any thermal remagnetization from a zircon fission track age of 107 Ma [*Doherty and Lyons*, 1980] and we note that the Ossippee pole does not correspond with younger (late Cretaceous-Tertiary) published North American poles. The far sidedness could be the result of a shallowing bias on the reversed magnetization through incomplete removal of the steep normal polarity overprint found only at Ossippee. Alternatively, existing radiometric age control allows the rock age and possibly also the magnetization acquisition age to be considerably older than the Tripyramid-Ascutney-Pawtuckaway rocks/magnetization, and in this regard we note that the Ossippee pole falls near to older early Cretaceous/late Jurassic North American poles [*Irving and Irving*, 1982; *Gordon et al.*, 1984, see Figure 5a].

In the absence of direct age dating of the Ossippee volcanic flows, the Tripyramid-Ascutney-Pawtuckaway mean is selected as the representative Cretaceous White Mountains pole. The dual polarity of the high unblocking temperature magnetizations suggests that adequate time is represented to average paleosecular variation and, along with the mean of $^{40}Ar/^{39}Ar$ age determinations (122.5 Ma), is consistent with acquisition during the time of geomagnetic field reversals just prior to the Cretaceous Normal Polarity Superchron (~118 to 84 Ma on the *Kent and Gradstein* [1986] time scale). The mean of the two Pawtuckaway normal polarity VGPs is antipodal to within 7.5° of the mean of the six Triapyramid and Ascutney reverse polarity VGPs (Table 1 and Figure 5a). For these data the critical angle is 13°, at or above which a null hypothesis of a common mean can be rejected [*McFadden and McElhinny*, 1990]; the Cretaceous White Mountains pole therefore passes a C-class reversal test for an isolated observation. We attribute the small disagreement of normal and reverse polarity VGPs to paleosecular variation and regard the eight VGPs as vectors drawn from one population. Even if the departure from antipodality is due to slight contamination, the average of the normal and reverse polarity directions should cancel any bias.

MID-CRETACEOUS REFERENCE POLE FOR NORTH AMERICA

The four published pole positions used by *Globerman and Irving* [1988] in their calculation of a mid-Cretaceous North American reference pole are (Figure 5b): (1) Arkansas intrusions pole at 74° N, 193° E [*Globerman and Irving*, 1988, age = 100-88 Ma], (2) Niobrara Formation pole at 66° N, 192° E [*Shive and Frerichs*, 1974] (age = Coniacian-Santonian or 84 to 88.5 Ma on the *Kent and Gradstein* 1986 time scale), (3) Monteregian Hills pole at 73° N, 191° E [*Foster and Symons*, 1979] ($^{40}Ar/^{39}Ar$ date = 124 ± 1 Ma [*Foland et al.*, 1986] or K/Ar = 118 to 136 Ma [*Eby*, 1984]), and (4) Newfoundland dikes pole at 71° N, 207° E [*LaPointe*, 1979, age ~ 129 Ma].

The 122.5 Ma White Mountains pole (71.3° N, 187.5° E, A_{95} = 4.2°) falls within the age range of the above poles and is indistinguishable at the 95% confidence level from the mean pole position calculated by *Globerman and Irving* [1988] at 71° N, 196° E (A_{95} = 4.9°, N = 4 studies). This agreement provides independent support for a mid-Cretaceous standstill interval which, as suggested by Globerman and Irving, is reasonably bracketed by the Arkansas intrusions (88 Ma) and the Monteregian Hills intrusions of Quebec (118 Ma to perhaps 136 Ma). Considering the $^{40}Ar/^{39}Ar$ date of 124 Ma [*Foland et al.*, 1986] for the Monteregian Hills as the more definitive age, we suggest that the most likely duration for the standstill is ~36 m.y. (124 Ma to 88 Ma).

Rather than signifying no apparent polar wander for 36 m.y., the close agreement of the mid-Cretaceous paleopoles from North America could represent a widespread remagnetization event at some later stage of the mid-Cretaceous. In this regard, the paleomagnetic reliability of the three older standstill poles (Newfoundland dikes, Monteregian Hills, and White Mountains poles) would be of particular concern. There are no stability tests available for the Newfoundland dikes [*LaPointe*, 1979] which makes it difficult to judge the reliability of the Newfoundland pole without a comparison to coeval poles. However, as in the case of the 122.5-Ma White Mountains pole of this study, the 124-Ma Monteregian Hills pole [*Foster and Symons*, 1979] is based on dual polarity magnetizations which pass the reversal test (A-class, in this case). Another argument against remagnetization in the White Mountains and Monteregian Hills rocks are $^{40}Ar/^{39}Ar$ ages and apatite or zircon fission-track ages which show no evidence for later thermal disturbances [*Foland et al.*, 1986; *Eby*, 1984; *Hubacher and Foland*, 1991; *Doherty and Lyons*, 1980; *Zimmerman et al.*, 1975]. Moreover, dual polarity magnetizations in these rocks are consistent with what would be expected from geomagnetic polarity time scales for times prior to 118 Ma [e.g., *Kent and Gradstein*, 1986; *Harland et al.*, 1990], and therefore these poles carry no suspicion of remagnetization during the Cretaceous Normal Superchron. Finally, the antipode of the mean of two reversed polarity VGPs (mean reversed Monteregian Hills and mean reversed White Mountains plutons; 70.1° N, 180.8° E) is included within cone of 95% confidence about the mean of five normal polarity VGPs (mean normal Monteregian Hills, Mount Pawtuckaway from this study, Arkansas intrusions mean, Niobrara formation mean, and mean of the Newfoundland dikes; 72.8° N, 190.0° E, A_{95} = 5.9°). Based on this positive regional-scale reversal test, we suggest that no polarity-dependent bias exists in the mean standstill pole.

A remaining concern, however, is that post-Cretaceous tilting of the igneous rocks from which the constituent pole position data were derived somehow acted to bring the paleomag-

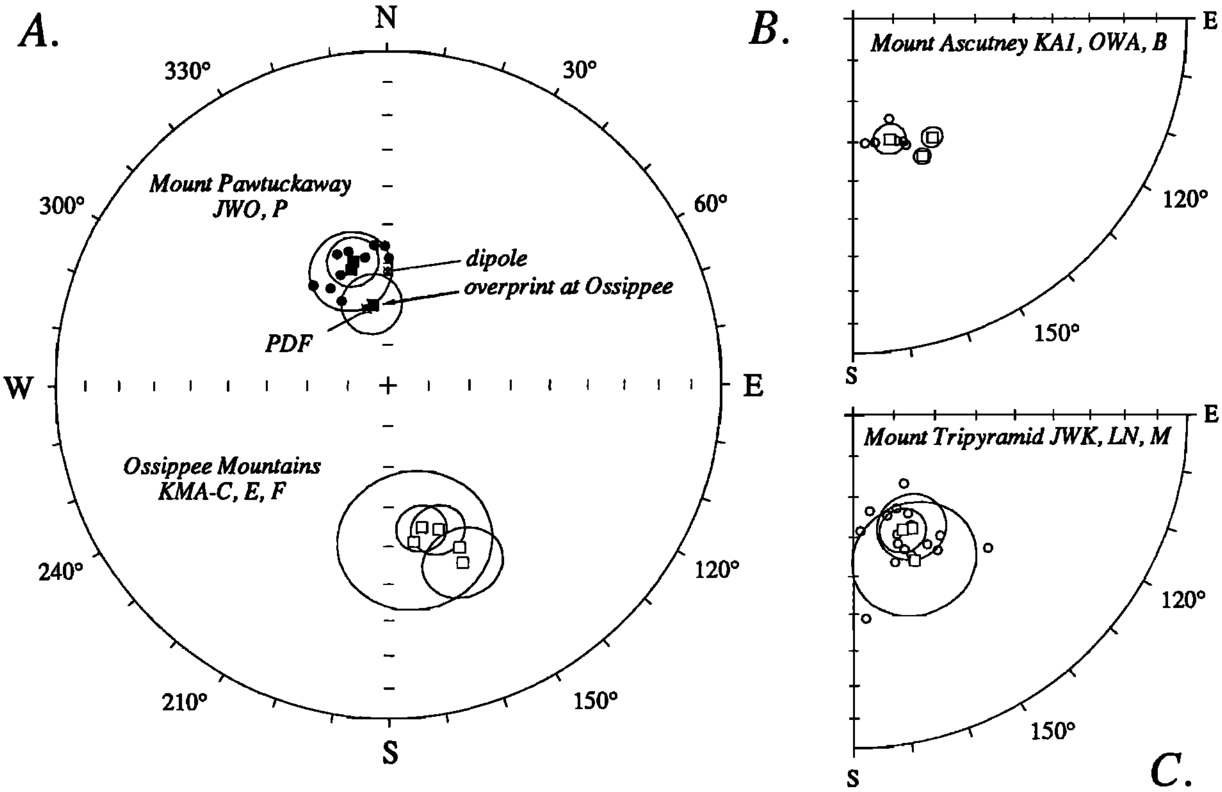

Fig. 4. Stereographic projection of site mean magnetizations (squares) with solid/open symbols indicating lower/upper hemisphere. (a) Normal polarity magnetization from Mount Pawtuckaway (two site means; circles indicate sample directions) and reversed polarity magnetization from Ossippee Mountains flows (five sites). The low unblocking temperature normal polarity overprint at Ossippee and present-day (PDF) and dipole field directions at the sampling sites are also shown. (b) Mount Ascutney reversed polarity magnetization (three sites), and (c) Mount Tripyramid reversed polarity magnetization (three sites; circles indicate sample directions).

netic poles fortuitously into close mutual agreement. Direct control on paleohorizontal is available only in the Niobrara shales [*Shive and Frerichs*, 1974] although in the case of the Arkansas intrusions, *Globerman and Irving* [1988] noted that vertical mid-Cretaceous dikes in that field area intrude flat-lying Lower Cretaceous strata as well as Paleozoic basement. The other three igneous poles (Monteregian Hills, White Mountains, and Newfoundland) lack direct control for a paleo-horizontal reference: the Monteregian plutons intrude Grenville basement whereas the White Mountains plutons and Newfoundland dikes cut lower and middle Paleozoic crystalline rocks, respectively. However, at each of these four igneous provinces, the mid-Cretaceous intrusions that were studied represent the last tectono-magmatic event recognized at that particular locality (the Niobrara shales underwent Laramide deformation). Thus while tilting cannot be excluded at every locality, we judge it to be highly improbable to account for the mid-Cretaceous standstill pole.

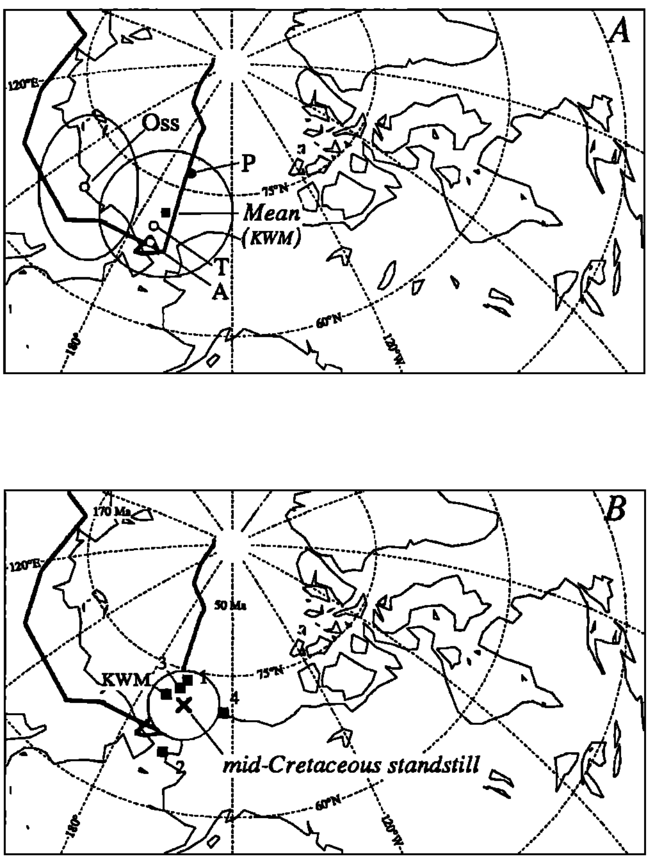

Fig. 5. (a) Cretaceous White Mountains pole positions compared to North American apparent polar wander path of *Irving and Irving* [1982]. The mean pole (KWM) is calculated using Mount Ascutney (A), Mount Tripyramid (T), and Mount Pawtuckaway (P) poles, while the Ossippee Mountains (Oss) pole, falling near older North American pole positions and having no direct radiometric age constraint, is omitted from mean. (b) New mid-Cretaceous "standstill" pole for North America at 71.2° N, 194.1° E (A_{95} = 3.7°) using the mean Cretaceous White Mountains (KWM) pole from this study and four other North American cratonic poles listed by *Globerman and Irving* [1988]: 1 = Arkansas intrusions [*Globerman and Irving*, 1988], 2 = Niobrara formation [*Shive and Frerichs*, 1974], 3 = Monteregian Hills [*Foster and Symons*, 1979], 4 = Newfoundland dikes [*LaPointe*, 1979].

TABLE 1. Site Mean Directional and Pole Position Data From the Cretaceous White Mountains Magma Series

Site	n	Magnetization R	k	α95(A95)	Dec.	Inc.	paleo-λ	North Pole Latitude	Longitude	dp	dm
				Mount Tripyramid (43.97°N, 288.53°E)							
JWK	5	4.9543	88	8.2	152.6	-58.8	39.5	69.2	195.8	9.1	12.2
JWLN	5	4.9795	195	5.5	156.8	-59.0	39.7	72.3	192.7	6.1	8.2
JWM	5	4.8612	29	14.5	157.2	-50.9	31.6	68.3	171.5	13.2	19.6
Tripyramid	[3]	2.9929	282	7.4	155.6	-56.3	36.8	70.2	185.7	7.6	10.6
				Ossippee Mountains (43.80°N, 288.72°E)							
KMA	5	4.9728	147	6.3	160.9	-52.0	32.6	71.3	168.3	5.9	8.7
Tilt corrected		4.9725	145	6.4	150.1	-75.5		64.4	256.8	10.7	11.7
KMB	5	4.9761	168	5.9	166.8	-53.5	34.1	75.9	159.5	5.8	8.3
Tilt corrected		4.9761	168	5.9	164.8	-77.5		66.2	273.5	10.4	11.1
KMC	2	1.9920	--	-.-	155.8	-45.5	27.0	64.2	165.9	-.-	-.-
Tilt corrected		1.9920	--	-.-	124.0	-77.7		52.7	255.5	-.-	-.-
KME	4	3.9710	104	9.1	157.2	-41.6	24.0	62.8	159.4	6.8	11.1
Tilt corrected		3.9710	103	9.1	135.6	-74.9		58.7	249.0	15.1	16.5
KMF	6	5.6316	13	18.9	170.5	-50.4	31.1	75.3	142.5	17.0	25.3
Tilt corrected		5.6309	14	18.9	148.5	-26.8		50.0	160.8	11.1	20.5
Ossippee	[5]	4.9747	157	6.1	161.9	-48.7	29.7	69.8	160.3	6.8	10.6
Tilt corrected		4.6965	13	21.9	146.0	-67.5		66.2	226.6	30.4	36.5
				Mount Ascutney (43.45°N, 287.50°E)							
KA1	6	5.9842	317	3.8	162.7	-59.2	40.0	76.7	188.3	4.2	5.6
OWA	12	11.9710	384	2.0	153.0	-52.0	32.6	66.0	180.5	1.9	2.7
OWB	12	11.9640	308	2.5	146.0	-55.0	35.5	62.5	192.5	2.5	3.6
Ascutney	[3]	2.9895	190	9.0	153.6	-55.6	36.1	68.5	186.6	9.2	12.8
				Mount Pawtuckaway (43.10°N, 288.80°E)							
JWO	4	3.9656	87	9.9	341.8	60.3	41.3	76.4	197.1	11.4	15.0
JWP	6	5.9576	118	6.2	343.9	58.2	38.9	77.2	185.1	6.8	9.2
Pawtuckaway	[2]	1.9996	--	-.-	342.9	59.3	40.0	76.9	191.2	5.8	7.7
				Tripyramid, Ascutney and Pawtuckaway							
Reverse	[6]	5.9730	185	(4.9)				69.4	186.7		
Normal	[2]	1.9994	--	-.-				76.9	191.3		
Mean pole	3	2.9938	322	(6.9)				71.9	187.4		

The number (*n*)of sample mean [site] directions; *R*, resultant vector length of total number of site mean vectors; *k*, Fisher dispersion parameter; *α95(A95)*, radius of 95% confidence about the mean direction (mean pole position); *Dec.*, *Inc.*, the declination and inclination of the mean magnetization; *paleo-λ*, paleolatitude; *dp* and *dm*, 95% confidence ellipse semiaxes parallel and perpendicular (respectively) to the site-to-pole meridian.

On the basis of wide geographic distribution and variety in tectonic settings of sampling localities, the different rock types analyzed, the positive local and regional-scale reversal tests, and the presence of reversals consistent with geomagnetic polarity time scales, we conclude that the good agreement among paleomagnetic poles from these five studies records a standstill during the mid-Cretaceous (~124 Ma to 88 Ma) in North American apparent polar wander at 71.2° N, 194.1° E (A_{95} = 3.7°, K = 421). This mean pole is only slightly revised from that of *Globerman and Irving* [1988] but is now better defined with the addition of concordant results from our study of the 122.5-Ma White Mountains plutons.

Comparison With the New England Hotspot

In addition to providing suitable material for paleomagnetic study, the Cretaceous White Mountains plutons help document the New England hotspot track. *Duncan* [1984] has demonstrated a regular progression in K/Ar, $^{40}Ar/^{39}Ar$, and minimum biostratigraphic ages along the New England (Kelvin) seamounts (~103-84 Ma). The ages and positions of the Cretaceous White Mountains Magma Series plutons (122.5 ± 1.5 Ma [*Hubacher and Foland*, 1991]) and the Monteregian Hills (124 ± 1 Ma [*Foland et al.*, 1986]) extend this age progression on to the North American continent. The New England chain is thus one of the oldest and longest hotspot tracks with physical documentation [*Morgan*, 1972, 1981, 1983; *Crough et al.*, 1980; *Duncan*, 1984; *O'Connor and Duncan*, 1990]. The Great Meteor tablemount (at 30° N [*Morgan*, 1981, 1983]) or the approximate location of the central Atlantic geoid anomaly (at ~27° N [*O'Connor and Duncan*, 1990]) are two features which have been proposed as candidate sites of most recent New England hotspot activity.

While North America was apparently stationary with respect to the paleomagnetic reference frame from 124 Ma to 88 Ma, dated edifices along the New England hotspot track delineate a progressive apparent motion of more than 1500 km over a comparable time interval, from the Monteregian Hills at 124 Ma to the Nashville seamount at 90 Ma. By representing the mid-Cretaceous standstill pole as a paleolatitude grid for North America, it can be seen that the plutons and seamounts of the New England hotspot chain form a track from ~124 Ma to 90 Ma that trends almost perpendicular to the lines of paleolatitude (Figure 6). Thus the New England hotspot plume appears to have moved south relative to the spin axis by 11.0° ± 3.7° during the mid-Cretaceous and only arrived at ~30° N, the proposed modern latitude, by 90 Ma (Figure 6).

This southerly drift of the New England hotspot plume at an average rate of 0.27°/m.y (Figure 7a) may be evidence for a systematic shift of the mantle reference frame with respect to the rotation axis; i.e., true polar wander. Alternatively, either the New England hotspot plume drifted independently and is not representative of the mantle reference frame, or the mid-

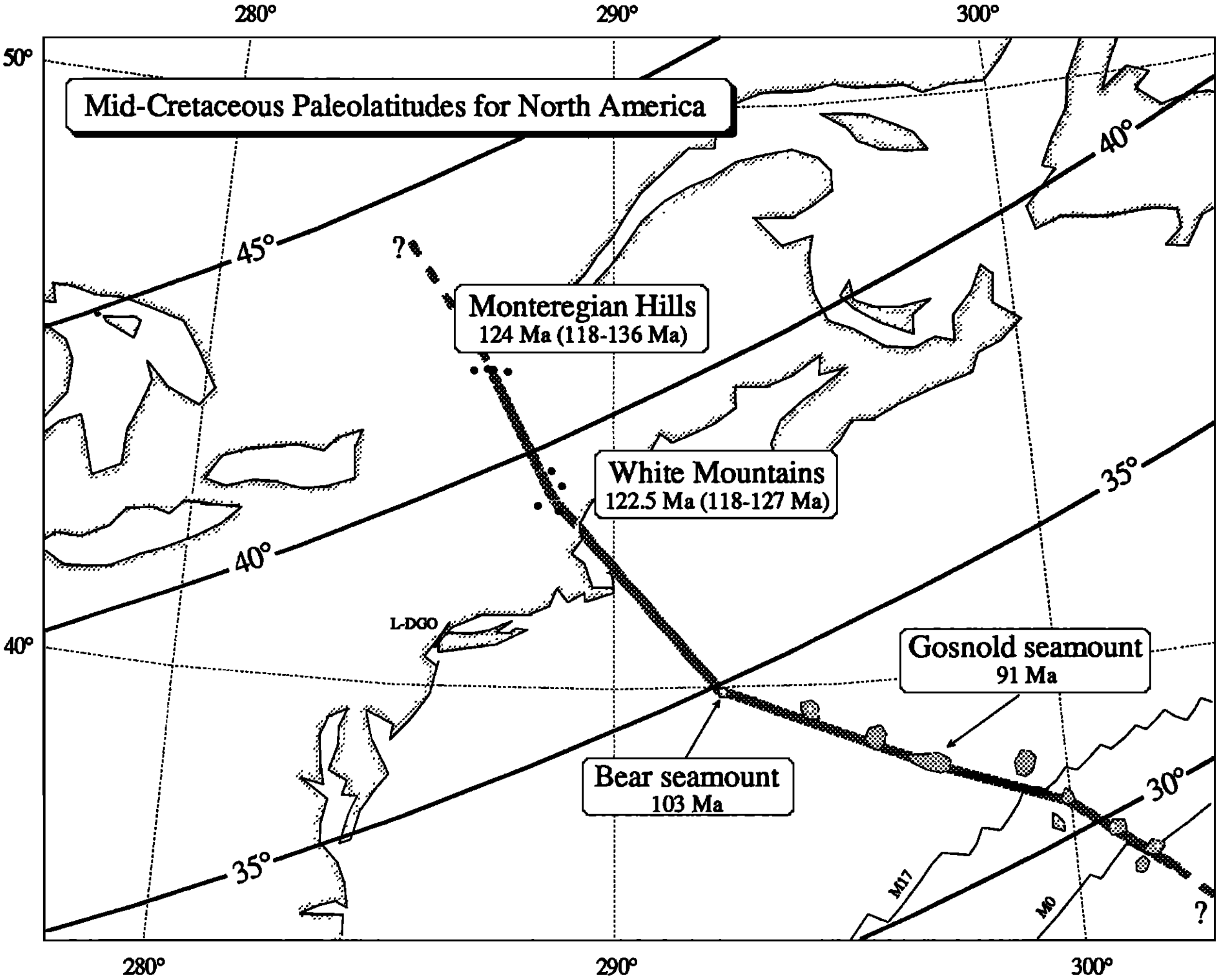

Fig. 6. New England hotspot track compared to field of mid-Cretaceous (90-124 Ma) paleolatitudes drawn over North America using the new standstill pole (71.2° N, 194.1° E), with 95% confidence limit of ±3.7°. The New England hotspot track is nearly orthogonal to this field, requiring about 11° of poleward motion for North America.

Cretaceous paleomagnetic field did not always correspond to a geocentric axial dipole and, for example, contained a large nondipole field component. To evaluate these possible explanations, we need to make an independent comparison of the mid-Cretaceous paleomagnetic field with hotspot tracks on different plates.

Comparison With the Tristan da Cunha Hotspot

The Tristan da Cunha hotspot track in the South Atlantic defines the post-125 Ma motion of the African plate relative to a mantle hotspot presently located beneath the island of Tristan da Cunha at 38° S, 011° W [*Duncan*, 1981; *Morgan*, 1981, 1983]; it is perhaps the only hotspot track other than the New England chain with good documentation back through the mid-Cretaceous. New $^{40}Ar/^{39}Ar$ radiometric dates have further documented the age progression in Walvis Ridge seamounts to about 82 Ma [*O'Connor and Duncan*, 1990]. Locations of the hotspot between about 90 Ma and 120 Ma are inferred from seamounts on the eastern Walvis Ridge, constrained by recovery of lower Aptian (113-119 Ma) sediments above basement (DSDP site 363 [*Bolli et al.*, 1978]). These seamounts formed shortly after eruption of the Entendeka flood basalts in western Namibia (ages 120-130 Ma [*Erlank et al.*, 1984]) which apparently represent the earliest surface expression of the Tristan da Cunha plume.

Analysis of the Tristan da Cunha hotspot track in a mid-Cretaceous paleomagnetic reference frame is not as straightforward as in the case of North America, simply because Africa not only moved relative to the hotspots but also with respect to the paleomagnetic pole [*Hargraves*, 1989]. One can, however, calculate paleolatitudes for positions along the Tristan da Cunha track based on the Africa apparent polar wander path. Six of 10 Cretaceous poles listed by *Hargraves* [1989] have been selected for this analysis (poles with mid-Cretaceous ages and A95 <10°). The selected African poles are (1) Madagascar volcanics (69.1° N, 240.0° E; age = ~90 Ma [*McElhinny and Cowley*, 1978]), (2) South African kimberlites (64.1° N, 226.1° E; age = 83-101 Ma [*Hargraves*, 1989]), (3a) Wadi Natash pole A, age ≈ 90 Ma (69.3° N, 258.1° E [*Schult et al.*, 1981]), (3b) Wadi Natash pole B (64.6° N, 251.8° E [*Ressetar et al.*, 1981]), (4) Lupata lavas (61.8° N, 259.0° E; age = 109-113 Ma [*Gough and Opdyke*, 1963]), and (5) Namibia lavas (48.3° N, 266.6° E; age = 113-131 Ma [*Gidskehaug et al.*, 1975).

These African paleomagnetic data indicate a southerly drift of the Tristan da Cunha plume relative to the spin axis during the

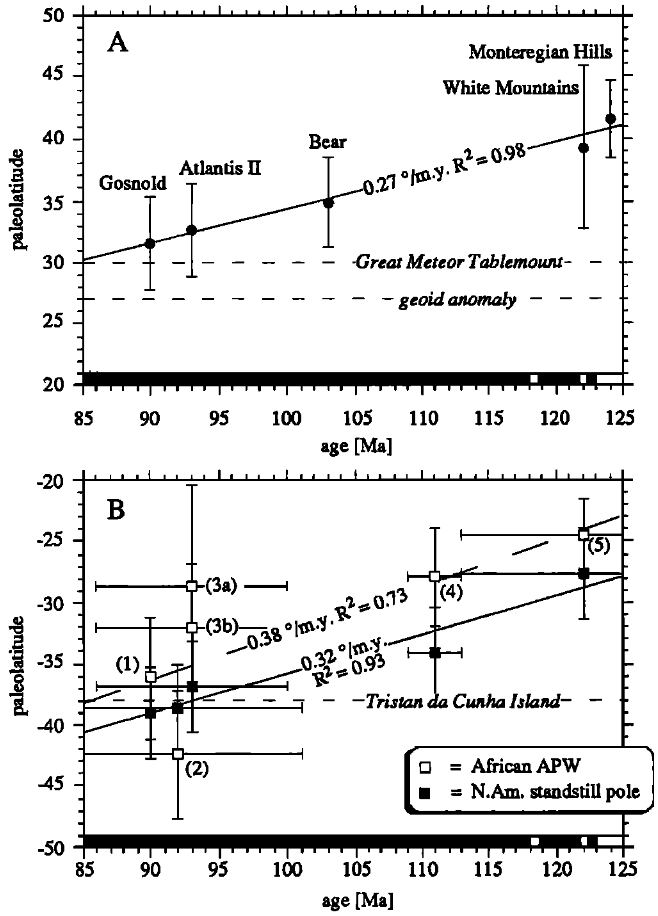

Fig. 7. Mid-Cretaceous paleolatitudinal drift of Atlantic hotspots. (a) Paleolatitudes with 95% confidence limits for selected dated edifices of the New England hotspot relative to the North American standstill pole. Errors for the New England seamounts (Bear, Atlantis II, and Gosnold) are ±4° as inferred from the mean standstill pole. (b) Tristan da Cunha hotspot relative to (open symbols) selected African poles listed by *Hargraves* [1989]: (1) Madagascar volcanics, ~90 Ma [*McElhinny and Cowley*, 1978], (2) South African kimberlites, 83-101 Ma [*Hargraves*, 1989], (3) Wadi Natash, 86-100 Ma (3a data from *Schult et al.* [1981]; 3b data from *Ressetar et al.* [1981]), (4) Lupata lavas, 109-113 Ma [*Gough and Opdyke*, 1963], and (5) Namibia lavas, 113-131 Ma [*Gidskehaug et al.*, 1975]. Closed symbols, Tristan da Cunha hotspot relative to the North American standstill pole (with 95% confidence limits =±4°) using central and South Atlantic reconstructions. Locations along the Tristan hotspot track are calculated from model B of *O'Connor and Duncan* [1990]. Linear fits to the data suggest southerly drift rates of 0.27 °/m.y. (= 3 cm/yr) for the New England hotspot, and a higher but less well-defined rate of 0.38°/m.y. (= 4.2 cm/yr) for the Tristan da Cunha hotspot using African paleomagnetic data. If the North American standstill pole transferred to African coordinates is used, the drift rate for the Tristan hotspot is 0.32 °/m.y (= 3.5 cm/yr).

mid-Cretaceous (Figure 7b). At 124 Ma the African poles place the Tristan da Cunha hotspot at 25°S (beneath the Entendeka flood basalt province), whereas by 90 Ma, the plume is located at 38°S (beneath the eastern Walvis Ridge). The 124-Ma position is therefore 13°±4° north of 38°S, the calculated paleolatitude of the hotspot at 90 Ma and its location today. This disagreement at 124 Ma and subsequent southerly drift until ~90 Ma at an average rate of 0.38°/m.y. (Figure 7b) is similar to that demonstrated independently for the New England plume (11°±4° at 124 Ma and rate of 0.27°/m.y., Figure 7a). Furthermore, for both hotspots the discrepancy with the paleomagnetic field is terminated at about 90 Ma when the plumes arrived at their most recently occupied latitudes. Therefore in independent comparisons with paleomagnetic reference frames, the widely separated New England and Tristan da Cunha hotspot tracks show a remarkable consistency during the mid-Cretaceous interval.

The consistent relative motion between the Atlantic hotspots (New England and Tristan da Cunha) and the paleomagnetic reference frame can be illustrated in a series of reconstructions of the southern African plate in North American paleomagnetic coordinates at 124 Ma, 105 Ma, and 90 Ma (Figures 8a-8c). These "paleomagnetic/paleogeographic" reconstructions are achieved by superimposing the North American mid-Cretaceous paleomagnetic field onto relative restorations of western Africa, southern Africa, South America, and North America based on the published seafloor spreading models of *Pindell et al.* [1988] and *Rabinowitz and LaBrecque* [1979]. Shown on these mid-Cretaceous reconstructions are the African pole position data (converted to paleolatitude error bars), along with two South American results at 124 Ma [*Schult and Guerreiro*, 1979; *Ernesto et al.*, 1990].

The reconstructions show the internal consistency of African, South American, and North American paleomagnetic data as well as the general consistency between the New England and Tristan da Cunha hotspots. At 124 Ma these hotspots begin drifting southward relative to the spin axis from locations which are ~12° too far north than what would be predicted by a dipole field (Figures 8a-8c). The reconstructed age-equivalent positions along the New England and Tristan da Cunha hotspot chains are in fact separated by a consistent arc distance of 69° ± 1° during the interval 124 - 90 Ma. This consistency suggests that inter-hotspot motion was small, nominally of the order of the 1°-2° of post-Late Cretaceous inter-hotspot motion suggested by *Molnar and Stock* [1987], and much less than the uniform southerly 12° shift of the New England and Tristan da Cunha hotspots with respect to the spin axis during the mid-Cretaceous.

Discussion

The consistent discrepancy of the New England and Tristan da Cunha hotspots with respect to the mid-Cretaceous paleomagnetic field allows the possibility of true polar wander; the uniform shift of the Earth (represented by the hotspots) with respect to the spin axis (represented by the paleomagnetic field). However, variable nondipole fields and large-scale differential mantle motion in the mid-Cretaceous are still two alternative interpretations given the available information.

At 124 Ma, a 25-30% quadrupole field contribution at the Monteregian Hills and Entendeka observation localities alone could account for the ~12° discrepancy between the assumed constant hotspot paleolatitudes and paleomagnetic paleolatitudes (i.e., those calculated according to the dipole formula). This nondipole field contribution would need to decrease systematically over 36 m.y. because by 90 Ma, hotspot and dipole paleolatitudes are in good agreement. *Livermore et al.* [1984] have suggested Cretaceous quadrupole field contributions of nominally 10% or less, with a maximum of 15% between 80 and 90 Ma at which time we would, in fact, deem a nondipole effect unnecessary. In an independent analysis, *Schneider and Kent* [1990] have estimated quadrupolar contributions of ~10% or less in the earliest Tertiary. In fact, the high overall consistency of mid-Cretaceous paleomagnetic data for North America and Africa, as discussed by *Hargraves* [1989] and presented here (Figure 8a-c), argues strongly for a close approximation to an

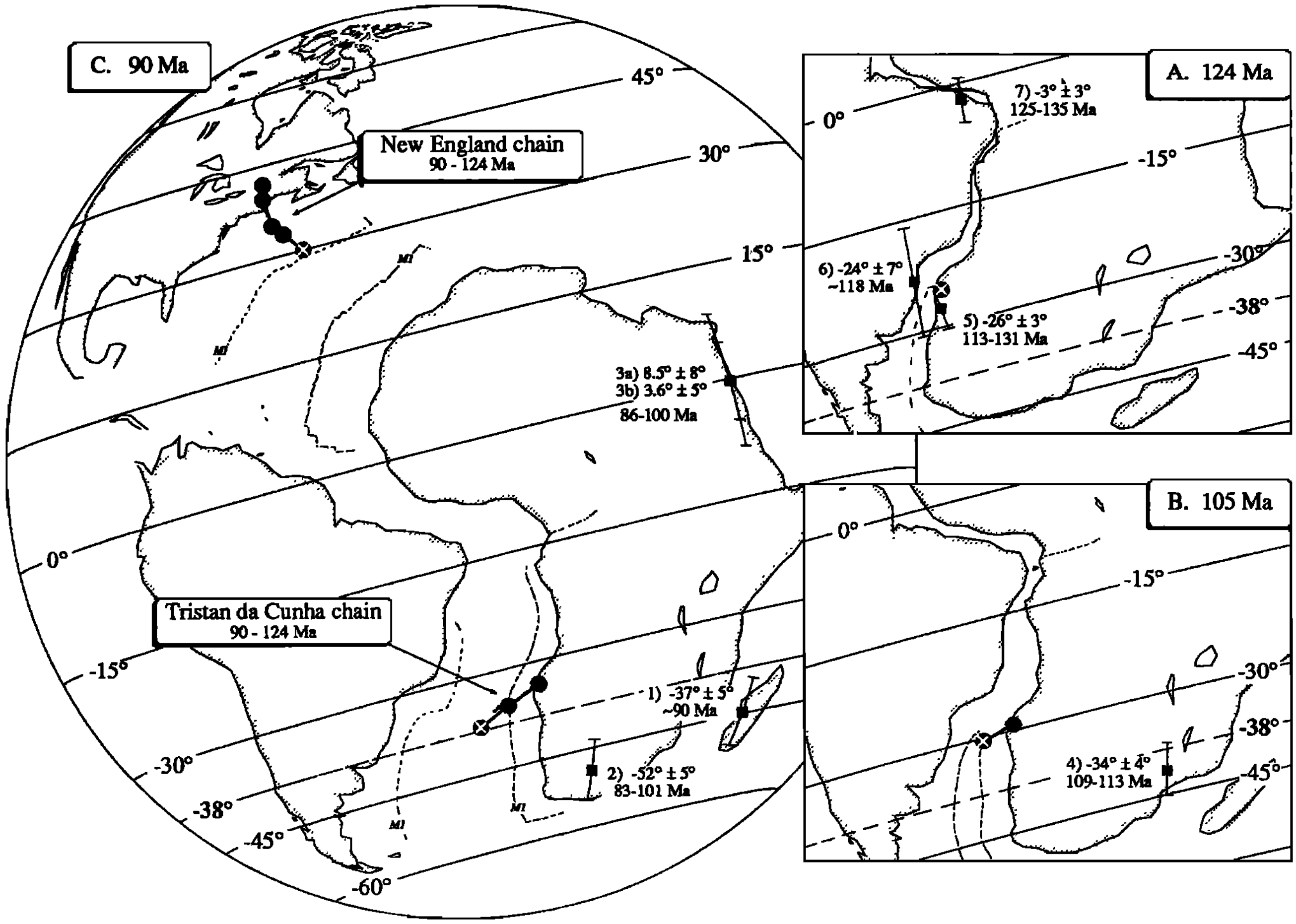

Fig. 8. Mid-Cretaceous paleogeographic reconstructions based on relative seafloor spreading models of *Pindell et al.* [1988] and *Rabinowitz and LaBrecque* [1979], and the North American standstill pole represented as a paleo-latitudinal grid (applicable for ~90 to 124 Ma). African paleomagnetic data (listed by *Hargraves* [1989], with symbols as in Figure 7b), shown here as paleolatitudinal bars confirm the paleogeography. (a) Reconstruction at 124 Ma with additional paleolatitudinal data from South America (6 data from *Ernesto et al.* [1990]; 7 data from *Schult and Guerreiro* [1979]), (b) reconstruction at 105 Ma, and (c) reconstruction at 90 Ma. The Tristan da Cunha hotspot arrives at its present-day latitude of 38°S (dashed line) by 90 Ma; the present-day location of the New England hotspot plume is not known, but by 90 Ma it has arrived at 30° S, near the present latitude of the Great Meteor tablemount [see *O'Connor and Duncan*, 1990].

axial geocentric dipole specifically over this time interval. Furthermore, *Besse and Courtillot* [1988] have found excellent overall agreement among global paleomagnetic poles which was interpreted as evidence against large nondipole field contributions in the Mesozoic, certainly none large enough to account for the 12° discrepancy between hotspot and paleomagnetic paleolatitudes at 124 Ma. Consequently, the evidence suggests that a large, time-varying nondipole field contribution can be regarded as an extraneous hypothesis to account for the observed disagreement between hotspots and paleomagnetic reference frames.

We therefore suppose that the 12° difference documented between the Atlantic hotspots and paleomagnetic reference frame at 124 Ma is real and reflects motion of the mantle, at least in the Atlantic hemisphere, with respect to the spin axis. If the whole mantle was involved, this would constitute evidence for true polar wander [*Goldreich and Toomre*, 1969]. Under such an interpretation, the entire mid-Cretaceous Earth rotated about an equatorial axis by ~12° such that the Atlantic hemisphere migrated southward while the Pacific hemisphere migrated northward. Southerly true polar wander along an Atlantic meridian would imply that seafloor spreading in the central Atlantic accommodated northerly motion of the North American plate so that it maintained constant paleolatitude as indicated by the mid-Cretaceous standstill in North American apparent polar wander. This sense of true polar wander would also predict that a mid-Cretaceous hotspot antipodal to the Atlantic hotspots should show a northerly migration relative to the spin axis (or paleomagnetic reference frame) and specifically at about 124 Ma, the dipole paleolatitude for a western Pacific hotspot should be 12° south of what would be expected for a stationary mantle plume. The Louisville hotspot in the eastern Pacific, to our knowledge the lone mid-Cretaceous hotspot documented on the Pacific plate, may have formed the Ontong Java Plateau approximately 120 m.y. ago [*Engebretson et al.*, 1985; *Duncan and Clague*, 1985]. Based on the Pacific apparent polar wander path of *Gordon* [1990], *Tarduno et al.* [1991] suggest that at about 120 Ma, the Louisville hotspot was located at paleolatitudes about 10° farther north than its present location (50°S, 138°W), therefore implying southerly motion of the Louisville plume relative to the spin axis since 120 Ma. Thus although not optimally located for a definitive test, the Louisville hotspot gives a sense of offset with respect to the paleomagnetic field that is ostensively in disagreement with what is predicted by the Atlantic hotspots if true polar wander occurred in the mid-Cretaceous.

CONCLUSIONS

New paleomagnetic data from 122.5-Ma plutons in New England provide supportive evidence for a standstill in the apparent polar wander path for mid-Cretaceous North America. The mean standstill pole is located at 71.2° N, 194.1° E (A_{95} = 3.7° for N = 5 studies) representing the paleomagnetic field in North America from about 124 Ma to 88 Ma. The standstill pole constrains motion of the North American plate relative to the spin axis to within ±4°. Yet the mid-Cretaceous New England hotspot track clearly shows 11°±4° of northward North American plate motion relative to the mantle. In an independent analysis, a discrepancy of similar sense and magnitude (~13°) between the African apparent polar wander path and the mantle was found in the mid-Cretaceous portion of the Tristan da Cunha hotspot track. By about 90 Ma, the discrepancy between reference frames appears to end when both the New England and Tristan da Cunha hotspots arrive at dipole paleolatitudes compatible with present-day (or most recently occupied) locations of the hotspot plumes.

If a globally coherent mantle hotspot reference frame existed during the mid-Cretaceous, then true polar wander could explain the ~12° southerly drift of the Atlantic New England and Tristan da Cunha hotspots relative to the spin axis from about 124 to 88 Ma. The geometry of the true polar wander event would predict about 12° of northerly hotspot motion in the western Pacific relative to the paleomagnetic field. The only available Pacific hotspot for comparison, the Louisville hotspot in the eastern Pacific, is reported to show southerly motion with respect to the spin axis during the mid-Cretaceous [*Tarduno et al.*, 1991]. This would favor large-scale, but differential, mantle motion although being only ~90° away from the Atlantic hotspots, the Louisville plume may not constitute a definitive test for true polar wander.

Whether the data are interpreted in terms of mid-Cretaceous true polar wander or large-scale differential motion of the mantle, there remains an interesting correlation with proposed global changes in production of oceanic lithosphere. *Larson* [1991] has suggested a sudden increase in the rate of oceanic lithosphere production at about 125 Ma, a large portion of which was manifested as the so-called Pacific "superplume"; this corresponds to when there is a large discrepancy between the hotspot and paleomagnetic latitudes. Following this climax, oceanic lithosphere production steadily declined over the mid-Cretaceous and has not changed much since about 85 Ma; this corresponds to about the time when for at least the Atlantic hotspots (New England and Tristan da Cunha) the latitudinal discrepancy is no longer apparent. To the extent that the superplume mechanism can trigger relative motion between the hotspot and paleomagnetic frameworks, then considering the more modest rates of oceanic lithosphere production for 150-125 Ma and for 85 Ma-present [*Larson*, 1991], we would expect to find little or no relative motion between the hotspots and paleomagnetic reference frames for these intervals preceding and following the mid-Cretaceous. For the period 90 Ma-present, it is interesting to note that *Livermore et al.* [1984] have suggested only minor discrepancies (<5°) between hotspots and global pole position data, even though *Besse and Courtillot* [1991] appear to favor continuous true polar wander since the Late Cretaceous. As for times prior to the mid-Cretaceous, comparisons between the hotspots and paleomagnetic reference frames will have to await resolution of pole position controversies [e.g., *Van Fossen and Kent*, 1992] and a clearer definition of older hotspot tracks.

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