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THE EARLY CARBONIFEROUS PALEOMAGNETIC FIELD OF NORTH AMERICA AND ITS BEARING ON TECTONICS OF THE NORTHERN APPALACHIANS

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We have obtained additional evidence for the Early Carboniferous paleomagnetic field for cratonic North America from study of the Barnett Formation of central Texas A characteristic magnetization of this unit was isolated after thermal demagnetization at four sites (36 samples) out of eight sites (65 samples) collected The mean direction of declination = 156 3°, inclination = 5 8° ($N = 4$, $k = 905$, $\alpha_{95} = 3$ 0°), corresponds to a paleomagnetic pole position at lat = 49 1°N, long = 119 3°E ($dp = 1$ 5°, $dm = 3$ 0°) Field evidence suggests that characteristic magnetization was acquired very early in the history of the rock unit whereas the rejected sites are comprised of weakly magnetized limestones dominated by secondary components near the present-day field direction Comparison of the Barnett pole with other Early Carboniferous (Mississippian) paleopoles from North America shows that it lies close to the apparent polar wander path for stable North America and that the divergence of paleopoles from the Northern Appalachians noted previously for the Devonian persisted into the Early Carboniferous We interpret this difference in paleopoles as further evidence for the Northern Appalachian displaced terrain which we refer to here as Acadia, and the apparent coherence of Late Carboniferous paleopoles as indicating a large (~1500 km) motion of Acadia with respect to stable North America over a rather short time interval in the Carboniferous

1 Introduction

One of the best ways to determine large-scale displacements between ancient continental crustal blocks is by comparison of paleomagnetic pole positions In an earlier paper [1] we interpreted a systematic difference in Devonian paleomagnetic poles between the coastal New England–Canadian Maritime region and the now contiguous part of North America as evidence for about a 1500-km relative tectonic displacement We consider the New England–Maritime region to form part of a displaced terrain, herein referred to as Acadia This terrain apparently reached its present position relative to stable North America sometime before the end of the Paleozoic, probably by the Late Carboniferous judging from the coherence of paleomagnetic poles of this age However, there are few reliable paleomagnetic data for Carboniferous rocks from stable North America for comparison with Acadia, and therefore the timing of the relative motion is not well constrained

We have studied the Barnett Formation of central Texas in an effort to document better the Lower Carboniferous (Mississippian) paleomagnetic field for stable North America An earlier paleomagnetic study of these rocks by Howell and Martinez [2] did not include any demagnetization analysis Although their data indicate the presence of a stable component of magnetization that differs from the present-day geomagnetic field direction, it is difficult to assess the importance of contributions from secondary magnetization in the absence of laboratory stability studies Consequently the derived paleomagnetic pole position reported by these authors may not be representative of the Mississippian North American pole position

2 Geology and sampling

The Barnett Formation crops out as part of the relatively thin Paleozoic sedimentary cover on the periphery of a dome-shaped upwarp of a Precambrian igneous and metamorphic complex This structural feature, referred to as the Llano Uplift, is located in central Texas, and tectonically is situated inboard of the Ouachita foldbelt that lies to the east and south To the north the Wichita Mountains represent a late Paleozoic orogen produced by reactivation of a Late Proterozoic aulocogen [3] However, there is no evidence of major displacements parallel to or across the Wichita system and the Llano Uplift area can therefore be considered an integral part of the North American craton during the Phanerozoic

The Barnett Formation in its type locality near San Saba is typically about 15 m thick and consists largely of brown shale, with characteristic large ellipsoidal limy concretions in the lower portion of the formation and calcareous, phosphatic and glauconitic strata in the upper 2–5 m However, in the southwestern and southeastern periphery of the Llano area rocks mapped as the Barnett Formation consist mostly of limestone [4] Biostratigraphic studies indicate the Barnett Formation is of Mississippian (Osage to perhaps Chester) age [5] Bedding dips are usually gentle (10° or less) except for some small local folds in the southwestern area of outcrop

A total of 65 oriented samples for paleomagnetic study were obtained from eight sites (Fig 1) Many of our sampling sites correspond to localities previously sampled by Haas [5] and Howell and Martinez [2]

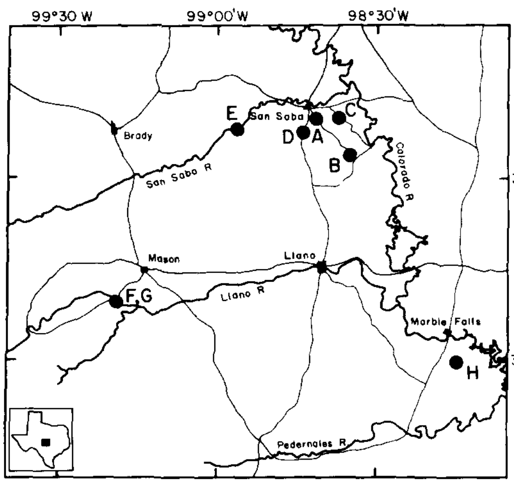

Fig 1 Location of paleomagnetic sampling sites of Barnett Formation

Wherever possible we sampled limy concretions, particularly since the brown shale was generally too friable to sample Two concretions (four samples) were collected at site *A* (with the remaining samples taken in several calcareous beds), ten concretions (eleven samples) at site *B*, and seven concretions (seven samples) at site *C* Shale was present at site *D* but no concretions were exposed and only a calcareous bed was sampled The remaining sites (*E*, *F*, *G*, and *H*) were located in exposures that consisted predominantly of light-colored limestones Stratigraphic distribution of samples ranged from 1 to 2 m at site *C* to approximately 5 m at site *A*, horizontal spread ranged to over 20 m (site *B* and site *D*)

3 Paleomagnetism

Measurement of the natural remanent magnetization (NRM) was carried out with a 7-Hz computerized spinner magnetometer described by Molyneux [6]. Sample intensities ranged between 30×10^{-7} and $0\ 3 \times 10^{-7}$ G, higher values typically associated with the calcareous concretions and low values with limestones The NRM directions of the samples are shown in Fig 2 A streaked distribution is evident between the present geomagnetic field direction and directions with southeastern declinations and shallow inclinations Closer inspection suggests two populations, one that has steep and northerly directions and another with shallower and southerly directions The latter grouping is similar to the distribution found by Howell and Martinez [2] and corresponds to the calcareous concretions and discrete calcareous beds at sites *A*, *B*, *C* and *D* The other population, corresponding to the very weakly magnetized limestones at the remaining sites, is evidently dominated by recent secondary magnetizations that could not be adequately removed by demagnetization as shown below

Demagnetization diagrams obtained by progressive alternating field (AF) and thermal treatments are plotted in Fig 3 according to the Zijderveld [7] method AF demagnetization performed on several pilot samples resulted in the initial removal of a component with a steep northerly direction, but a decay to the origin of a remaining vector could not be well established due to acquisition of spurious magnetizations at higher demagnetizing fields (Fig 3d) Conse-

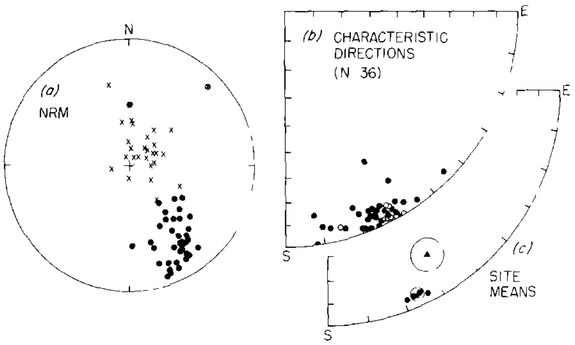

Fig 2 (a) NRM directions of sixty-five samples of the Barnett Formation Filled circles (crosses) are samples which gave reliable (unreliable) results after demagnetization Hexagon symbol corresponds to direction of geocentric axial dipole magnetic field at sampling locality All directions plotted on lower hemisphere of equal-area projection except encircled cross which is on upper hemisphere (b) Characteristic direction obtained by thermal demagnetization Filled (open) symbols on lower (upper) hemisphere qudrant of equal-area projection. (c) Site mean characteristic directions with formation mean (star symbol) and circle of 95% confidence Triangle symbol is mean direction of Barnett Formation from Martinez and Howell [8] based on NRM only

quently, all remaining samples were analyzed by thermal techniques which allowed complete demagnetization Generally, above temperatures of 250°C the trajectory of further demagnetization was linear towards the origin until the magnetization drops below the noise level by 500°C (Fig 3a, b, c) This last trajectory is interpreted as the removal of a single, remaining magnetization which on the basis of the similar direction from sample to sample can be considered characteristic of these rocks

The magnetizations removed at low temperatures are more variable in direction from sample to sample although they typically have steep downward inclinations, and in many cases northerly declinations that suggest acquisition in the present-day geomagnetic field Curvature in the demagnetization trajectories to somewhat higher temperatures on some samples (Fig 3b) is interpreted as due to a broader, although not complete overlap in the blocking temperature distribution of the secondary and characteristic components There may also be more complicated behavior, as for the sample shown in Fig 3c, which may reflect several secondary components These multiple low-temperature directions, however, are not consistent from sample to sample and may reflect magnetizations acquired since sampling

All samples were demagnetized in a minimum of three temperature steps over 250°C to isolate the characteristic component However, only half of the sites collected (36 samples) yielded well-defined characteristic directions which are shown in Fig 2b and group very well about a mean of $D = 156\ 3°$, $I = 6\ 1°$ (Table 1) These sites were from the northern area of outcrop where the calcareous concretions and interlayered brown shale that are typical of the Barnett Formation are present The site localities that did not give reliable paleomagnetic data represent exposures that were entirely limestone, mostly from the southern area of outcrop but also including one site (*E*) in the northern area As described earlier, the 29 samples from these sites typically have low NRM intensities and directions that are near to the present-day magnetic field direction (Fig 2a) Progressive thermal demagnetization of these samples does however show a change in direction toward a shallow, southerly direction but there is considerable scatter and no stable end point is apparently reached before the magnetizations approach the noise level of the magnetometer (Fig 4a). The directions of all 29 samples after 250°C thermal treatment also show a tendency to lie in the southeastern quadrant (Fig 4b) There is some indication therefore that the same characteristic magnetization observed at the other sites is also present in these samples However, a characteristic component cannot be as effectively resolved because of its smaller relative contribution to the NRM, and because these samples have very weak initial magnetizations which limit the level of demagnetization with the available equipment

Martinez and Howell [8] studied thin sections of the Barnett Formation and found that the most likely ferromagnetic mineral present is hematite which they suggested formed as a result of oxidation of syngenetic pyrites However, we can find no positive indication of hematite in the magnetic properties of these rocks For example, saturation of isothermal remanence (IRM) is apparently achieved in only a few thousand oersteds (Fig 5a) whereas much higher fields are usually required if hematite is the dominant magnetic mineral The stability of NRM is comparable to that of saturation IRM and of anhysteretic remanence (ARM) (Fig 5b) which suggests that the NRM is car-

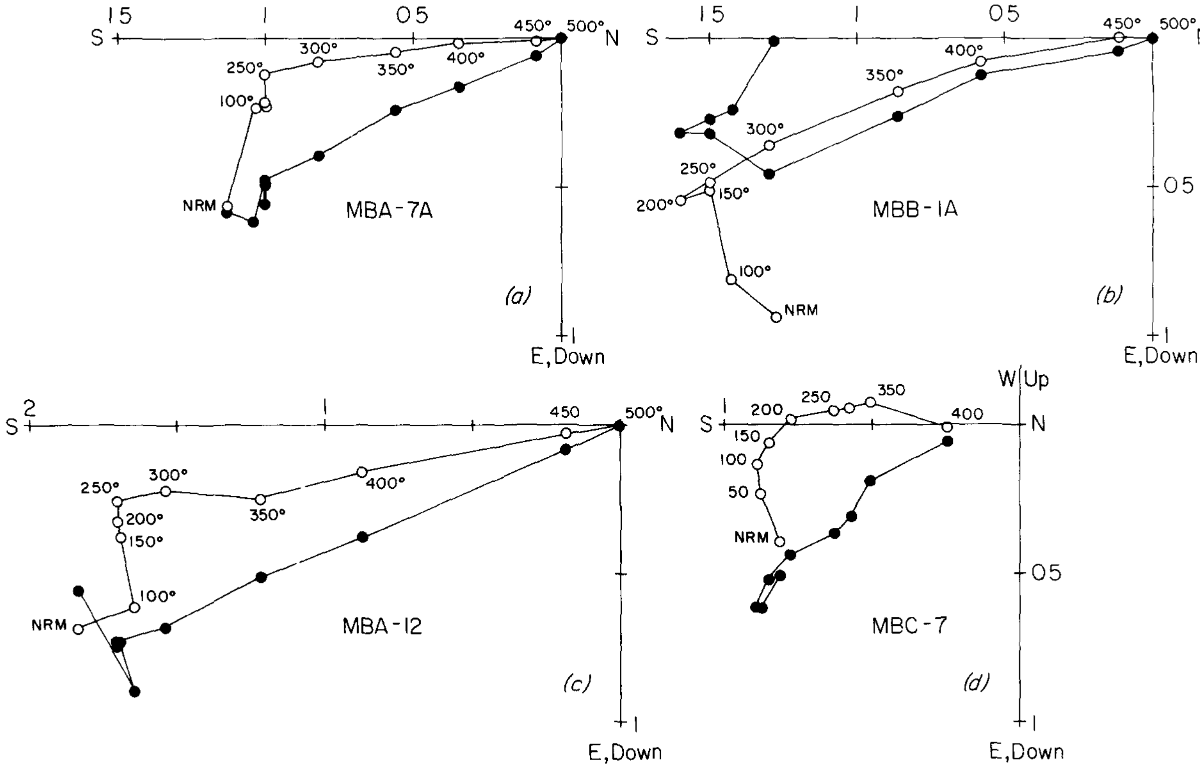

Fig 3 Vector demagnetization diagrams Closed (open) symbols are vector end points on horizontal (vertical) plane and adjacent numbers are demagnetization temperatures in (a), (b) and (c) and alternating field peak oersteds in (d) Axes are in units of 10^{-6} G (a) and (b) are from calcareous concretions, (c) and (d) are from calcareous beds

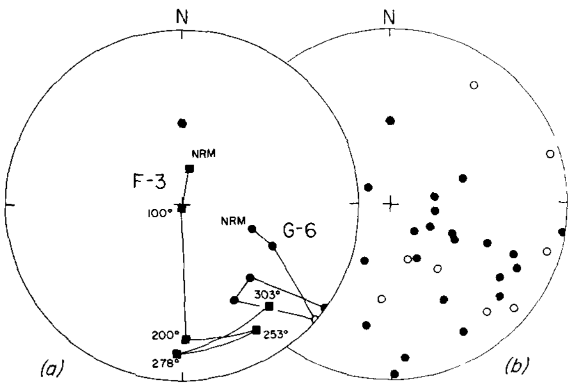

Fig 4 (a) Directional behavior of samples from rejected sites during progressive thermal demagnetization (b) Remanent directions after 250°C thermal demagnetization of 29 samples from rejected sites Closed (open) symbols on lower (upper) hemisphere of equal-area projection Hexagon symbol corresponds to direction of geocentric axial dipole magnetic field at sampling locality

ried by a representative fraction of the total magnetic mineralogy, the relatively small differences in stability of these magnetizations may be related to the magnetic grain size [9] The inference that the NRM is representative of the same bulk magnetic mineralogy of these rocks that contributes to the IRM is supported by the similar thermal demagnetization curves of these magnetizations (Fig 5c) both of which indicate a distribution of blocking temperatures to about 500°C or less, far below the Curie point of hematite of 680°C Although the rock magnetic data can be interpreted to exclude hematite as a significant source of the rock magnetization, they do not provide strong positive evidence for any particular mineral, like magnetite or possibly maghemite, with which they appear to be consistent On the other hand, some hematite may be present in the rocks but in insufficient quantity to be detected magnetically or to sensibly contribute to the NRM

TABLE 1

Summary of characteristic magnetizations

Site	N	D (°)	I (°)	α_{95} (°)	k
MBA	12	155 3	6 9	5 6	60
MBB	11	157 7	6 8	3 3	189
MBC	7	153 5	4 5	4 3	197
MBD	6	158 9	5 1	11 1	37

Mean of 4 sites D = 156 3°, I = 5 8°, α_{95} = 3 0°, k = 905

Mean of 36 samples D = 156 3°, I = 6 1°, α_{95} = 2 6°, k = 82

Pole position from site means lat = 49 1°N, long = 119 3°E, dp = 1 5°, dm = 3 0°

N is the number of samples, D and I are mean declination and inclination, α_{95} and k are the semi-angle of the core of 95% confidence and the precision parameter, respectively [17], dp and dm are the semi-axes of the oval of 95% confidence around the mean pole position, along the paleomeridian and perpendicular to it, respectively Note that all samples collected from each of the sites are included in calculation of site mean directions whereas 29 samples from four other sites have been excluded due to unstable magnetization

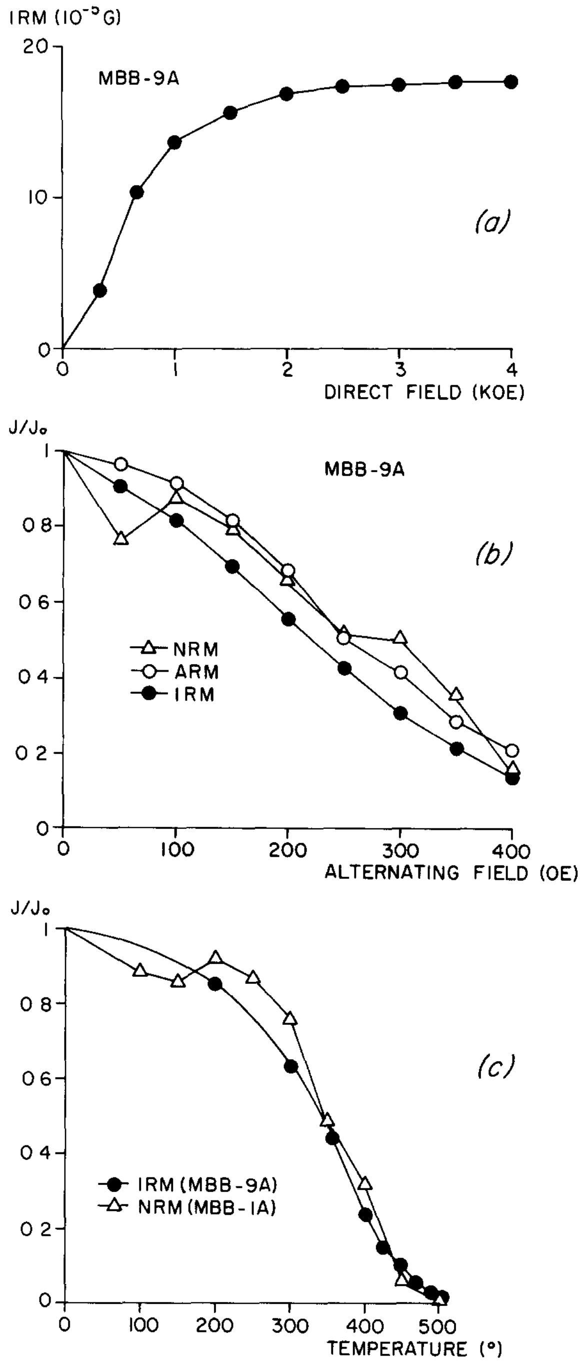

Fig 5 (a) Acquisition curve of isothermal remanent magnetization (IRM) (b) Normalized AF demagnetization curves of natural (NRM), anhysteretic (ARM, 1 0 Oe, 2000 Oe AF) and isothermal (IRM, 2000 Oe) remanent magnetizations (c) Thermal demagnetization of NRM and IRM All samples are from calcareous concretions

4 Discussion of results

The site mean characteristic directions for the four sites which gave reliable data are summarized in Table 1 and shown in Fig 2c These give a formation mean of D = 156 3°, I = 5 8° (k = 905, α_{95} = 3 0°) which is essentially the same mean direction calculated from the 36 sample directions Although we have rejected half of the sites collected, we consider the derived mean direction representative of the Barnett Formation The samples which yielded characteristic magnetizations are all from sites where the lithology is typical of the Barnett in its type area, that is, a brown shale with calcareous concretions and discrete calcareous beds, whereas the rejected sites come from a more atypical, limestone lithology The rejection criteria were based on a certain instability of the individual samples during demagnetization that was in large part related to the very weak remanent intensities of the limestones, which we feel prohibited the complete removal of an apparently dominant secondary component near the present-day field direction No different characteristic magnetization direction is suggested in the limestones and indeed there are indications that it is similar to that at the accepted sites In other words, the difference in magnetic behavior is probably simply related to lithologic differences

The formation mean direction we obtain is near to but is shallower than the mean reported by Howell and Martinez [2] (Fig 2c) This difference is predictable because they measured only NRM which was probably contaminated by a secondary component in the present-day field direction The close agreement between the two studies is impressive nonetheless considering the weak magnetization of these rocks and the early date of the initial work Unfortunately we were not able to relocate site *J* of Howell and Martinez [2] which gave shallow, northerly directions Our effort at site *E*, the presumed location of their site, did not yield reliable data

There is no reason to suspect that the characteristic direction was not acquired during Early Carboniferous (Mississippian) time Moreover, although a fold test is not possible to limit the age of the magnetization, other field evidence can be interpreted to support an origin early in the history of the rocks In particular, the calcareous concretions are evidently syngenetic and were formed prior to compaction of the surrounding sediment, as indicated by the bending of bedding surfaces around them It is therefore likely that the remanent magnetization of the concretions was also acquired prior to compaction The magnetization may be some form of chemical remanence related to the processes that formed the concretions, as suggested by Martinez and Howell [8] Alternatively, the concretions have locked-in and preserved a depositional remanence in the enveloped part of the shales Traces of what appear to be original bedding laminae can bee seen within the concretions and give some support to this mechanism In either case, there is good agreement between the results obtained from all of the concretions and from the discrete calcareous beds at the same and nearby sites The between-site directions, is smaller than the within-site dispersion in directions, suggesting that paleosecular variation is averaged by the stratigraphic distribution of samples at each site and perhaps to some extent within individual samples as well Finally, later remagnetization is considered unlikely because the underlying Wilberns Formation is apparently unaffected since it gives directions consistent with other Late Cambrian paleomagnetic data and 90° away from the Barnett characteristic directions [10]

5 Comparison with other data

The mean direction from the four site means corresponds to a paleomagnetic (north) pole position, assuming this magnetization is of reversed polarity, at lat = 49 1°N, long = 119 3°E (dp = 1 5°, dm = 3 0°) There are surprisingly few other published results for the Lower Carboniferous of North America for comparison, particularly those which meet reasonable minimum reliability criteria Those paleomagnetic poles that are based on at least some demagnetization analysis are plotted with respect to the Late Paleozoic segment of the apparent polar wander path for stable North America in Fig 6

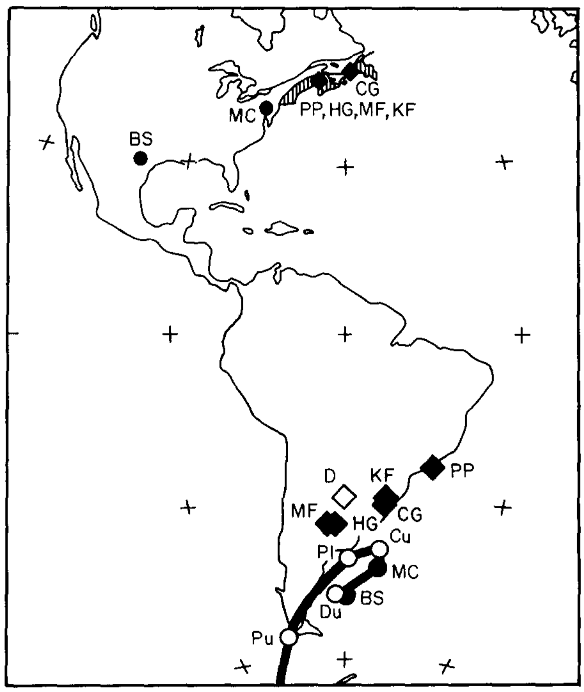

Fig 6 Lower Carboniferous paleomagnetic south poles and sampling localities from stable North America (filled circles) and Acadia (filled diamonds) compared to Late Paleozoic apparent polar wander path for stable North America (open circles, Du = Upper Devonian, Cu = Upper Carboniferous, Pl = Lower Permian, Pu = Upper Permian) [14] Acadia displaced terrain is sketched with shading MF = Maringouin Formation [18], HG = Hopewell Group [19], CG = Codroy Group, KF = Kennebecasis Formation, PP = pre-Pictou sediments [11], MC = Mauch Chunk Formation [20], BS = Barnett Formation (this paper) D (open diamond) = mean Devonian pole for Acadia from Kent and Opdyke [1]

The principal observation is that all the available Early Carboniferous (Mississippian) paleopoles from Acadia lie consistently away from the relevant portion of the North American apparent polar wander path This is in contrast to the paleopoles for the Barnett Formation, and the Mauch Chunk Formation, a clastic unit exposed in the folded Appalachians that was deposited on the margin of the North American craton [20] Both of these poles lie near the shortest distance join between the mean Late Devonian and Late Carboniferous poles for stable North America and can be considered to provide additional constraints on this portion of the apparent pole path Perhaps the statistically significant difference between the Barnett and the Mauch Chunk paleopoles is related to the difference in age of the two formations The Barnett, whose pole is near the Late Devonian mean, is at least in part of Early Mississippian age whereas the Mauch Chunk is younger, of Late Mississippian age, and its pole falls closer to the mean Late Carboniferous (Pennsylvanian) position This would imply some 8° of apparent polar shift for North America during Mississippian time but this suggestion obviously needs confirmation

The Early Carboniferous paleopoles from Acadia are somewhat scattered but fall consistently at lower latitudes than nearly contemporaneous or younger poles from stable North America The paleomagnetic results from the Maringouin Formation (MF) and the Hopewell Group (HG) of New Brunswick are each well determined experimentally and it is noteworthy that their pole positions are in very close mutual agreement Together these two paleopoles, which can be considered the best available data for Lower Carboniferous rocks of Acadia, differ by some 12° or 15° from the Mauch Chunk or Barnett paleopoles The other Early Carboniferous paleopoles from Acadia (PP, KF, Fig 6) diverge from the Maringouin and Hopewell poles but in a sense that makes them differ even more widely from the Barnett and Mauch Chunk poles of stable North Amwrica The divergence of these poles may well be related to poor experimental control in these early studies [11] For example, the result for the pre-Pictou sediments (PP) was based on just eight samples and the alternating field treatment applied in the study of these redbeds and those of the Kennebecasis Formation (KF) may not have been adequate to remove secondary components and to isolate a characteristic magnetization

An interesting exception to the overall pattern of Lower Carboniferous paleopoles is the paleomagnetic result from the Codroy Group of Newfoundland ([11], CG in Fig 6) This paleopole should lie near the Barnett or the Mauch Chunk pole if western Newfoundland in fact belongs to North America (e g [12]) but instead the Codroy pole falls within the cluster of pole positions from the Acadia displaced terrain We again question the adequacy of the experimental procedures in obtaining this result from the Codroy redbeds (i e , no thermal demagnetization) and note that Nairn et al [13] earlier had derived a paleomagnetic pole position from Codroy Group rocks using similar techniques that is more compatible with other stable North American data The discrepancy between the two studies suggests renewed investigations using modern standards of demagnetization analysis may be worthwhile to verify some of these early results

6 Conclusions

The difference in Early Carboniferous paleopoles between Acadia and stable North America is similar in magnitude and sense to the difference in Devonian paleopoles we [1] have earlier described (Fig 6) As far as can be estimated this difference is no longer apparent by the Late Carboniferous when paleopoles of this age that are available show reasonable agreement [1,14] We have interpreted the difference in paleopoles as evidence for original separation between the two areas and the agreement in younger paleopoles as indicative of the time the displaced terrain reached its present position with respect to North America [1] Our study of the Barnett Formation lends support to the idea that Acadia was still far (~1500 km) from its present position relative to stable North America in the Early Carboniferous and consequently the relative motion of this displaced terrain with respect to North America must have occurred in a rather short time within the Carboniferous Since there is little evidence of any closed or subducted oceans of Carboniferous age in the northern Appalachians, we assume the relative motion was taken up predominantly along shear zones This is consistent with evidence for extensive Carboniferous strike-slip faulting in the Canadian Maritimes [15] If the relative motion (1500 km) occurred over say one-third (~20 m y) of the duration of the Carboniferous (~60 m y [16]), an average rate of 7 5 cm/yr would have been required This rough estimate compares favorably to present-day rates of relative motion between lithospheric plates The geological consequences of this relative motion and the possible involvement of other continents remain to be explored

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