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Syn-folding remagnetization of Cambro-Ordovician carbonates from the Pennsylvania Salient post-dates oroclinal rotation

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Abstract

Paleomagnetic directions of 35 sites of Cambro-Ordovician carbonates from 10 anticlines were analyzed to test models of curvature along the Pennsylvania Salient of the Appalachians and to constrain the relative timing of magnetization acquisition. The sites yield directions of magnetization that are almost all reversed with near-horizontal inclinations upon appropriate structural correction. The common, Late Paleozoic (Kiaman-aged) direction and incremental fold tests show that these directions represent remagnetizations carried by authigenic magnetite, acquired just before or during the earlier phases of folding. No convincing indications were found of primary magnetizations. Mean declinations from the northeastern and southwestern limbs of the salient differ by a few degrees, indicating negligible, if any, rotation between the limbs. The results are similar to prior studies of overlying Siluro-Devonian carbonates, showing coherent behavior of the entire Paleozoic cratonic cover. We conclude that the statistically negligible difference in declination indicates that (previously demonstrated) oroclinal bending occurred before carbonates of the Paleozoic stratigraphic cover were remagnetized during the Permian and before regional folding was completed.

Keywords: Remagnetization; Rotations; Pennsylvania; Carbonate rocks

1. Introduction

The development of arcuate mountain belts has been of interest since Carey (1995) introduced his orocline concept and outlined several examples around the world. The definition in its strictest sense is that an orocline is a curved belt in an orogen that has been bent from an originally straight(er) configuration. Marshak (1988) has called this a rotational orocline. To document that curvature of a mountain belt is a secondary feature, it has to be demonstrated that one or both limbs are rotated, and paleomagnetism is ideally suited to test relative rotations (e.g., Eldredge et al., 1985; Lowrie and Hirt, 1986). Paleomagnetic studies of various red bed formations of Ordovician through Early Carboniferous ages along the Pennsylvania Salient in the Central Appalachians show rotations up to 30° from primary magnetizations, whereas curvature in fold trends is as much as 60°. In contrast, remagnetization overprints of most likely Permian age in these same rocks show no rotation (Miller and Kent, 1986; Kent, 1988; Miller and Kent, 1989; Van der Voo, 1993; Stamatakos and Hirt, 1994; Stamatakos et al., 1996). Gray and Stamatakos (1997) tried to reconcile seemingly conflicting observations in the area by proposing early detachment behavior and deformation partitioning in the stratigraphic sequence. Our study potentially provides a test of this

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model by paleomagnetic analysis of the lower part of the Paleozoic sequence, for which Gray and Stamatakos would predict a different rotation pattern in space and time than that observed for the upper part of the sequence.

Paleomagnetic analysis of oroclinal rotations has typically been based on correlations between structural trends (strikes) and declinations. If the remanent magnetization predates the bending and provided that the belt was originally linear, then there should be a one-to-one correlation between the declinations of the remanent magnetization and the strike of the units (Schwartz and Van der Voo, 1983; Lowrie and Hirt, 1986; Weil and Sussman, 2004). If, however, the magnetization was acquired after the initiation of bending, or if the belt formed with a pre-existing curvature that was subsequently tightened, then the correlation should have a slope of less than unity. Finally, if a magnetization post-dates rotations, or if no oroclinal bending has occurred (i.e., the orogen formed in its curved orientation), then there should be no correlation at all, and all magnetic declinations should be similar, giving rise to a declination versus strike plot with zero slope.

2. Prior paleomagnetic results

Previous analyses of oroclinal rotation in the Pennsylvania Salient have concluded that it occurred before the Alleghanian (Permian) folding (Stamatakos and Hirt, 1994; Stamatakos et al., 1996), which is unusual compared to some other oroclines, such as Cantabria, where most of the folding preceded rotations (e.g., Parés et al., 1994; Van der Voo et al., 1997; Weil et al., 2000). This means that the structural trends developed after bending and that the strikes used in the analysis are only proxies for virtual reference lines in the rock sequences. This study was initiated to investigate whether the lower Paleozoic carbonates recorded rotations and to constrain the age relationships between rotations and development of the fold and thrust belt, utilizing the paleomagnetic directions recorded by Cambro-Ordovician carbonates. This particular sequence was chosen because of the likelihood of encountering Kiaman-aged remagnetizations, as previously shown for carbonates elsewhere in Pennsylvania (Kodama, 1988) as well as in West Virginia (Evans et al., 2000), Virginia and New York State (McCabe et al., 1983; McCabe and Elmore, 1989), which could conceivably be acquired during deformation. Moreover, numerous previous studies in the area on overlying Upper Ordovician, Silurian, Devonian and Lower Carboniferous red siliciclastic sediments yielded magnetizations presumed to be primary, as well as Kiaman-aged remagnetizations, as summarized in Stamatakos et al. (1996).

Kent (1988) concluded that oroclinal bending in the salient may account for about half (23°) of the difference in structural trends between the northeastern and southwestern limbs, based upon differences in magnetic declination in the Upper Ordovician Juniata (Miller and Kent, 1989), Upper Silurian Bloomsburg (Kent, 1988), Upper Devonian Catskill (Miller and Kent, 1986) and Lower Carboniferous Mauch Chunk Formations (Kent and Opdyke, 1985; Kent, 1988). While the relative rotations are well documented in all these formations, the authors found it to be difficult to determine the (absolute) magnitude of the rotation for each of the two limbs, because contemporaneous reference directions for the North American craton are ambiguous. Van der Voo (1993) has argued, on the basis of a comparison between the Silurian directions from the Bloomsburg Fm. and the Wabash Reef limestones in Indiana (McCabe et al., 1985), that it was the northeastern limb that underwent significant (clockwise) rotations, with respect to a non-rotated southwestern limb.

Stamatakos and Hirt (1994), incorporating results from previous studies, concluded that the Silurian Bloomsburg Formation, which yields a primary magnetization, shows 18±9° of oroclinal rotation that occurred prior to Alleghanian deformation. In contrast, the mean declinations they calculated from Kiaman-aged secondary magnetizations in the red beds were virtually identical for the northeastern and southwestern limbs (172° and 173°, respectively). They argued that, because these secondary magnetizations are “synchronous with, or even older than folding across the region, [ ] the curvature of the fold axes is an original feature of fold growth”. In a subsequent analysis, Stamatakos et al. (1996) found that these remagnetizations are generally post-folding on the hinterland side of the salient, syn-folding in the middle, and pre-folding on the foreland side of the salient, and concluded that folding progressed slowly from east to west, while the remagnetizations occurred rapidly during the interval 275–255 Ma (i.e., Late Permian).

3. Geological setting

The studied area of the Pennsylvania Salient is part of the Valley and Ridge Province and has two limbs in map view (Fig. 1). The southwestern limb trends north–northeast from west Virginia to central Pennsylvania where the structural trends change by approximately 45°

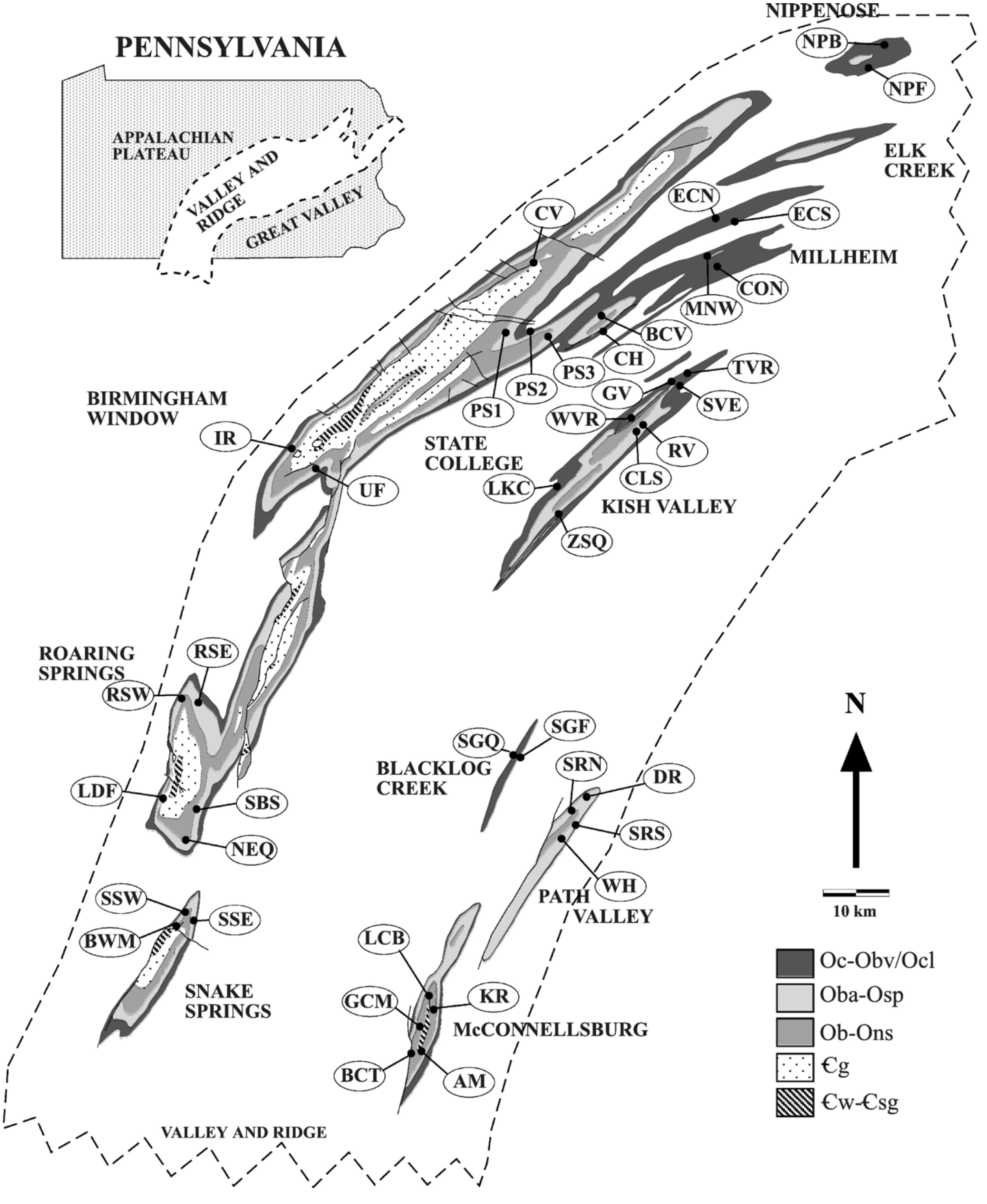
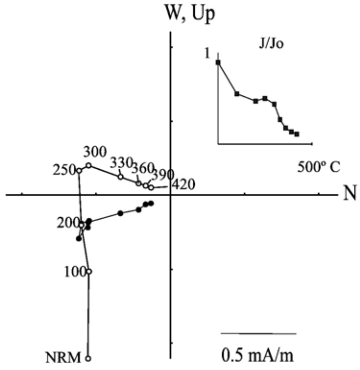
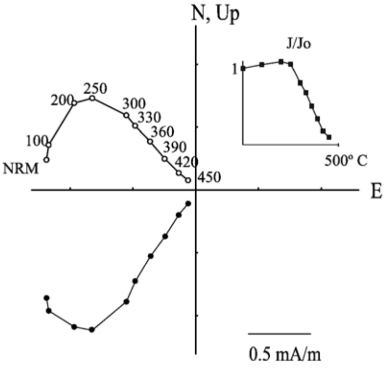


Fig. 1. Map showing main anticlinal structures in Cambro-Ordovician carbonates of the Pennsylvania Salient, identifying the eleven folds where 41 paleomagnetic sampling sites (labeled within ovals) are located. The map signatures are for various (undifferentiated) formations in the Cambrian (Є) and Ordovician (O).

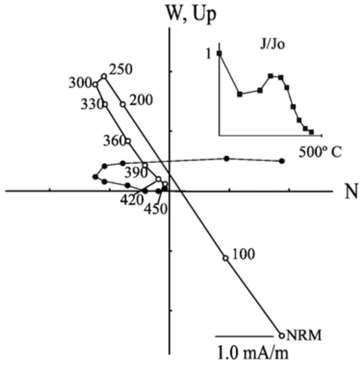
a. Nippenose, sample NPB1-2B
North-dipping limb



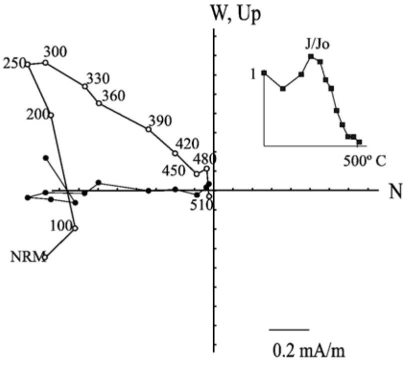
b. Elk Creek, sample ECN1-01
Northwest-dipping limb



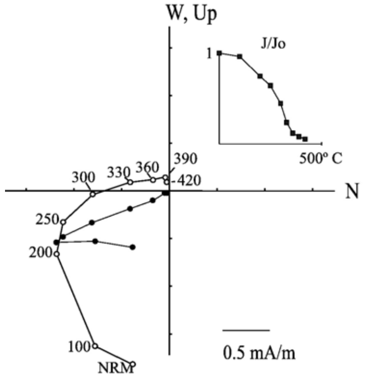
c. State College, sample BCV1-01A
Northwest-dipping limb



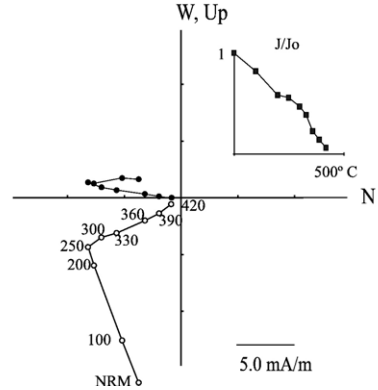
d. Millheim, sample MNW4-01
Northwest-dipping limb

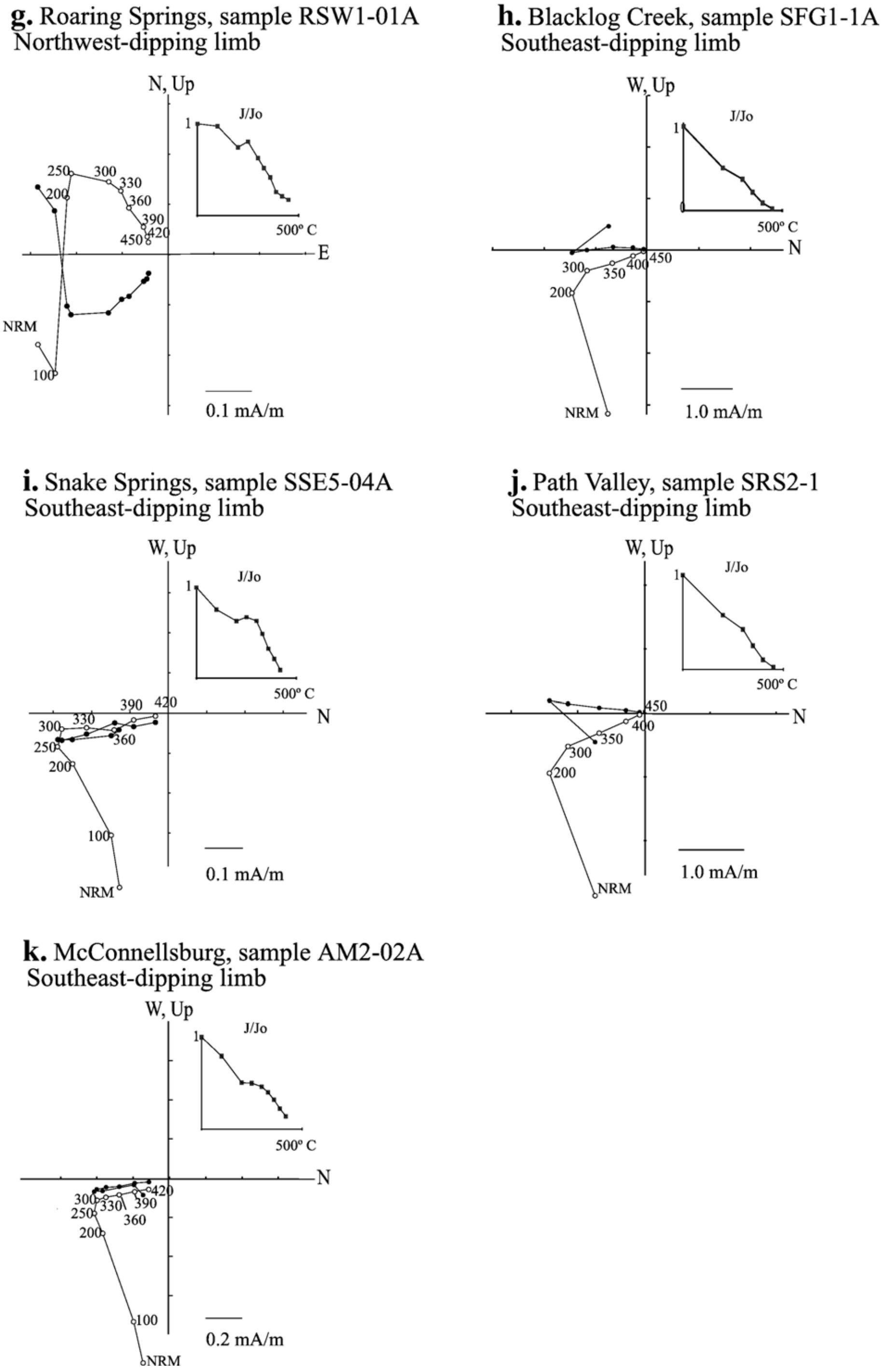


e. Birmingham Window, sample UF7-5B
Southeast-dipping limb



f. Kish Valley, sample ZSQ5-02A
Southeast-dipping limb





g. Roaring Springs, sample RSW1-01A
Northwest-dipping limb

h. Blacklog Creek, sample SFG1-1A
Southeast-dipping limb

i. Snake Springs, sample SSE5-04A
Southeast-dipping limb

j. Path Valley, sample SRS2-1
Southeast-dipping limb

k. McConnellsburg, sample AM2-02A
Southeast-dipping limb

Fig. 2. (a–k) Orthogonal demagnetization diagrams (Zijderveld, 1967) and normalized intensity plots (J/J_o) for a representative sample from each of the eleven folds, generally showing two components, a first-removed northerly and down component and a southerly and shallow characteristic component. Open (closed) symbols represent projections onto the vertical (horizontal) plane. Sample numbers include letters indicative of the site label (see Table 1). Thermal demagnetization temperatures are indicated in °C and scale bars indicate the NRM intensity.

clockwise to continue in the northeastern limb in an east–northeast direction toward New Jersey and southern New York state. The area may have experienced two minor and one major phase of compressional deformation: the minor Taconic (Ordovician) and Acadian (Devonian) orogenies and the dominant Alleghanian Orogeny (Late Carboniferous to Permian). The Paleozoic strata of the Valley and Ridge Province are composed of Cambro-Ordovician carbonates and younger siliciclastic and carbonate rocks, which have been thrust northwestward. The Early Paleozoic carbonates were initially deposited on Grenvillian basement and are now found in folded thrust sheets as duplexes confined between detachments. The folds and thrusts have been attributed to the Alleghanian Orogeny when Gondwana collided with Laurentia (e.g., Hatcher et al., 1989). The Upper Ordovician to Carboniferous siliciclastic rocks comprise a roof sequence above a detachment that is folded but not faulted. To the northwest and towards the foreland lies the Appalachian Plateau and to the southeast and towards the hinterland is the Great Valley Province (Fig. 1, inset).

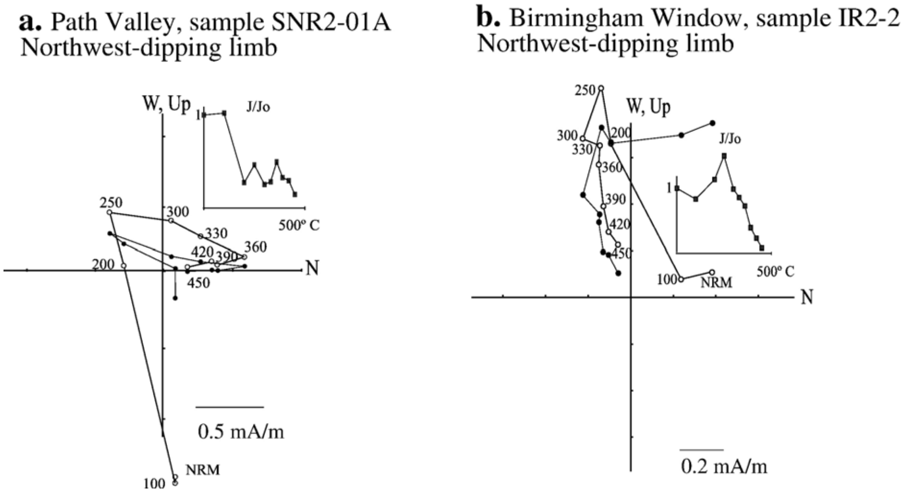
The sampled Cambro-Ordovician carbonates are exposed in a series of anticlinal structures (Fig. 1), which are found below the upper detachment that separates the earlier Paleozoic sequence from the younger, predominantly clastic, roof sequence surrounding them.

4. Sampling and demagnetization methods

Three to six field-oriented hand samples were collected from each of 41 sites in the Cambro-Ordovician carbonates within 11 anticlines throughout the salient (Fig. 1). In the laboratory at the University of Michigan, typically three to five oriented cores with a diameter of 2.5 cm were drilled from each hand sample, and cut to specimens of 2.2 cm length.

Natural remanent magnetizations (NRMs) were measured for 6–18 specimens from each site with a 2G Cryogenic Magnetometer. A pilot study of the samples utilizing both thermal and alternating field demagnetization yielded similar results and thermal demagnetization was chosen for the remaining samples as it was more expeditious. Specimens were thermally demagnetized in a field-free room (rest field about 200 nT), with typically the following steps: 100, 200, 250, 300, 330, 360, 390, 420, 450, 480, 510, 540 and 570 °C, using an ASC demagnetizer (model TD-48). Characteristic magnetizations were identified by visual inspection of Zijderveld (1967) diagrams (Figs. 2 and 3), and their directions were calculated using the least-squares technique of Kirschvink (1980). The directions for the specimens were then combined into site means (Table 1) using conventional statistical treatment (Fisher, 1953).

The paleomagnetic fold test (Graham, 1949; McFadden and Jones, 1981; McFadden, 1990) was used to determine the temporal and spatial relationships between magnetization acquisition and deformation during the development of the mountain belt. We used an incremental test (Scotese and Van der Voo, 1983; McClelland-Brown, 1983; for description see Van der Voo, 1993, p. 54) in order to determine whether the magnetic acquisition was pre-, syn- or post-deformational. In-situ site-mean directions from each of the anticlines were progressively and incrementally tilt corrected in these tests to determine the percentage



a. Path Valley, sample SNR2-01A
Northwest-dipping limb

b. Birmingham Window, sample IR2-2
Northwest-dipping limb

Fig. 3. Zijderveld diagrams (as in Fig. 2) showing unusual or anomalous directions. (a) A sample that shows a (rare) normal-polarity direction. (b) A sample revealing a higher temperature composite direction which is westerly and intermediate-up that has not been used in the overall analysis.

Table 1
Summary of paleomagnetic results for each site grouped according to fold structure

Fold	Site	Lat	Lon	Strike	Dip	No. obs.	Dec.	Inc.	k	α_{95}	Dec.#[a]	Inc.#[a]
Birmingham Window												
	ir	40.7	281.8	194		[b]						
	uf	40.7	281.8	64	30	9/9	160	15	155.1	4.1		
Kish Valley												
	cls	40.7	282.4	68	32	11/11	177	14	95.9	4.7	176	−4
	gv	40.7	282.5	239	118	12/12	211	−45	112.9	4.1	188	5
	lkc	40.6	282.2	223	20	7/11	175	−2	131.5	5.3	176	7
	rv	40.7	282.4	65	42	12/12	181	34	41.0	6.9	177	11
	sve	40.7	282.5	69	35	12/12	170	16	41.8	6.8	169	−4
	tvr	40.8	282.5	252	36	16/16	180	−4	138.5	3.1	181	16
	wvr	40.7	282.3	251	56	10/10	185	−22	42.8	7.5	184	9
	zsq	40.5	282.2	63	56	12/12	192	34	20.4	9.8	184	6
Elk Creek												
	ecn	40.9	282.6	271	35	13/13	188	−18	15.0	11.1	188	−8
	ecs	40.9	282.6	84	30	12/12	185	2	87.6	4.7	185	−7
Millheim												
	con	40.8	282.6	80	22	9/9	185	−6	28.0	9.9	185	−14
	mnw	40.8	282.6	261	53	12/12	176	−33	29.5	8.1	175	−12
Nippenose												
	npb	41.2	282.8	275	13	18/18	181	−17	45.4	5.2	181	−5
	npf	41.2	282.8	78	26	17/17	161	14	44.8	5.4	161	−6
State College												
	bcv	40.8	282.3	69	28	9/9	164	19	19.3	12.0	164	−1
	ch	40.7	282.3	63	51	6/6	169	17	17.3	16.5	169	−17
	cv	40.9	282.2	256	60	8/12	191	−54	1214.4	1.6	181	−14
	ps1	40.8	282.2	46	19	[b]						
	ps2	40.8	282.2	252	52	[b]						
	ps3	40.8	282.2	70	5	[b]						
Blacklog Creek												
	sgf	40.1	282.2	34	61	6/6	183	31	62.5	8.5	172	5
	sgq	40.1	282.2	206	47	8/8	166	−20	79.2	6.3	162	3
McConnellsburg												
	am	39.8	282.0	50	24	14/14	170	13	300.4	2.3	169	−2
	bct	39.8	282.0	133	16	16/16	175	12	157.0	3.0	176	5
	gcm	39.8	282.0	210	60	15/15	183	−13	83.7	4.2	181	8
	kr	39.9	282.0	23	33	12/16	176	20	34.9	7.4	171	8
	lcb	39.9	282.0	208	71	12/12	186	−20	76.6	5.0	179	2
Path Valley												
	dr	40.2	282.3	230	40	13/13	179	−10	40.0	6.6	179	6
	srn	40.2	282.2	253	37	13/13	182	−14	61.0	5.3	182	3
	srs	40.1	282.2	53	43	7/7	183	15	42.2	9.4	181	−2
	wh	40.1	282.2	37	34	12/12	182	20	192.9	3.1	179	9
Roaring Springs												
	ldf	40.2	281.6	208	132	15/15	252	−22	14.8	10.3	162	−13
	neq	40.1	281.6	21	33	16/16	176	15	123.7	3.3	172	0
	rse	40.3	281.6	359	20	15/16	175	−2	29.5	7.2	176	−3
	rsw	40.3	281.6	211	98	12/12	220	−40	38.2	7.1	170	−2
	sbs[c]	40.2	281.6	265	18	12/12	121	−10	33.2	7.6		

(continued on next page)

Table 1 (*continued*)

Fold	Site	Lat	Lon	Strike	Dip	No. obs.	Dec.	Inc.	k	α_{95}	Dec.#[a]	Inc.#[a]
Snake Springs												
	bwm	40.0	281.5	223	99	10/10	203	− 67	86.5	5.2	155	− 2
	sse	40.0	281.5	28	42	16/16	168	17	46.5	5.5	165	− 6
	ssw	40.0	281.5	226	65	16/16	185	− 48	108.0	3.6	167	− 6

Lat = site latitude, lon = site longitude, strike = strike of bedding (90° counterclockwise from dip direction), dip = dip of bedding (>90° when overturned), no. obs. = the ratio of the number of specimens accepted into a site mean over the total number measured, dec. and inc. = in-situ declination and inclination (in degrees), k and α_{95} are the statistical parameters for each site (Fisher, 1953), and dec.# and inc.# are the declination and inclination after partial to full structural correction at which the k value for each fold is maximum.

[a] Dec. and inc. at peak κ during unfolding.

[b] Magnetization unable to be isolated or specimen magnetizations "blew up".

[c] Direction switched to reversed polarity.

unfolding at which the precision parameter k was maximum, i.e., the percentage unfolding at which clustering is optimal. The fully to partially tilt-corrected mean directions for each of the folds (also called area-mean directions) were combined to give two overall mean directions for the northeastern and southwestern limbs of the salient.

5. Results

The intensity of the NRMs of the specimens typically ranged from 0.2 to >10 mA/m with no obvious regional or stratigraphic variation, as the range was generally observed within each of the individual folds. The specimens yielded two components of magnetization upon thermal demagnetization. The first-removed component (A) is northerly and intermediate to steeply down (Fig. 2). This magnetization is generally parallel to the present-day field direction, is typically unblocked by 250–330 °C, and is interpreted as a viscous magnetization of recent origin. The second component (B) is southerly with shallow to intermediate-up or intermediate-down inclinations, and is herein called the characteristic magnetization. Fig. 2 shows representative orthogonal vector diagrams (Zijderveld, 1967) for a sample from each of the 11 folds. The maximum unblocking temperatures of this component usually are about 420–450 °C but can range up to 540 °C. These unblocking temperatures and the general behavior during demagnetization are similar to those of many of the other carbonate sequences in the Appalachians and their foreland (McCabe et al., 1983; McCabe and Elmore, 1989) and indicate that the magnetization in the rocks we investigated is similarly carried by magnetite. The characteristic (B) directions roughly correspond to the Late Carboniferous to Triassic segment of the apparent polar wander path (APWP) for cratonic North America (Van der Voo, 1993) and are considered to be remagnetizations acquired during the Kiaman reversed polarity superchron. At four sites characteristic directions could not be obtained either because the directions became spurious before a B-component could be isolated or because the individual specimen directions were scattered within a site. Only one of the sites (SBS in the Roaring Springs fold) yielded the typical east–west and shallow directions that are characteristic for the Late Cambrian or Early Ordovician paleopoles from cratonic North America (Van der Voo, 1993). This indicates that any primary magnetization has been completely overprinted by the later remagnetization in all but possibly one of the sites. Because site SBS is the only exception, it is not clear that we should give it much credibility. Fig. 3b shows an anomalous high-temperature component that was observed in only a few specimens from site IR in the Birmingham Window fold. This WSW and intermediate-up component is possibly a composite magnetization of the A and B components. The sample from site SRN of the Path Valley anticline shown in Fig. 3a may show a normal polarity direction, but such directions were observed in too few specimens to have much credibility.

In-situ site-mean directions are listed in Table 1 together with their statistical parameters. The effects of the structural corrections upon the site means were analyzed for 10 of the 11 structures with an incremental fold test. The Birmingham Window fold yielded only one characteristic site-mean direction and one anomalous direction (e.g., Fig. 3b) and is therefore not included. The site-mean directions for each site were incrementally rotated about their strikes and for each fold the degree of clustering represented by the precision parameter k was plotted versus percent unfolding (Fig. 4). In general, the characteristic magnetization directions become more clustered during incremental tilt

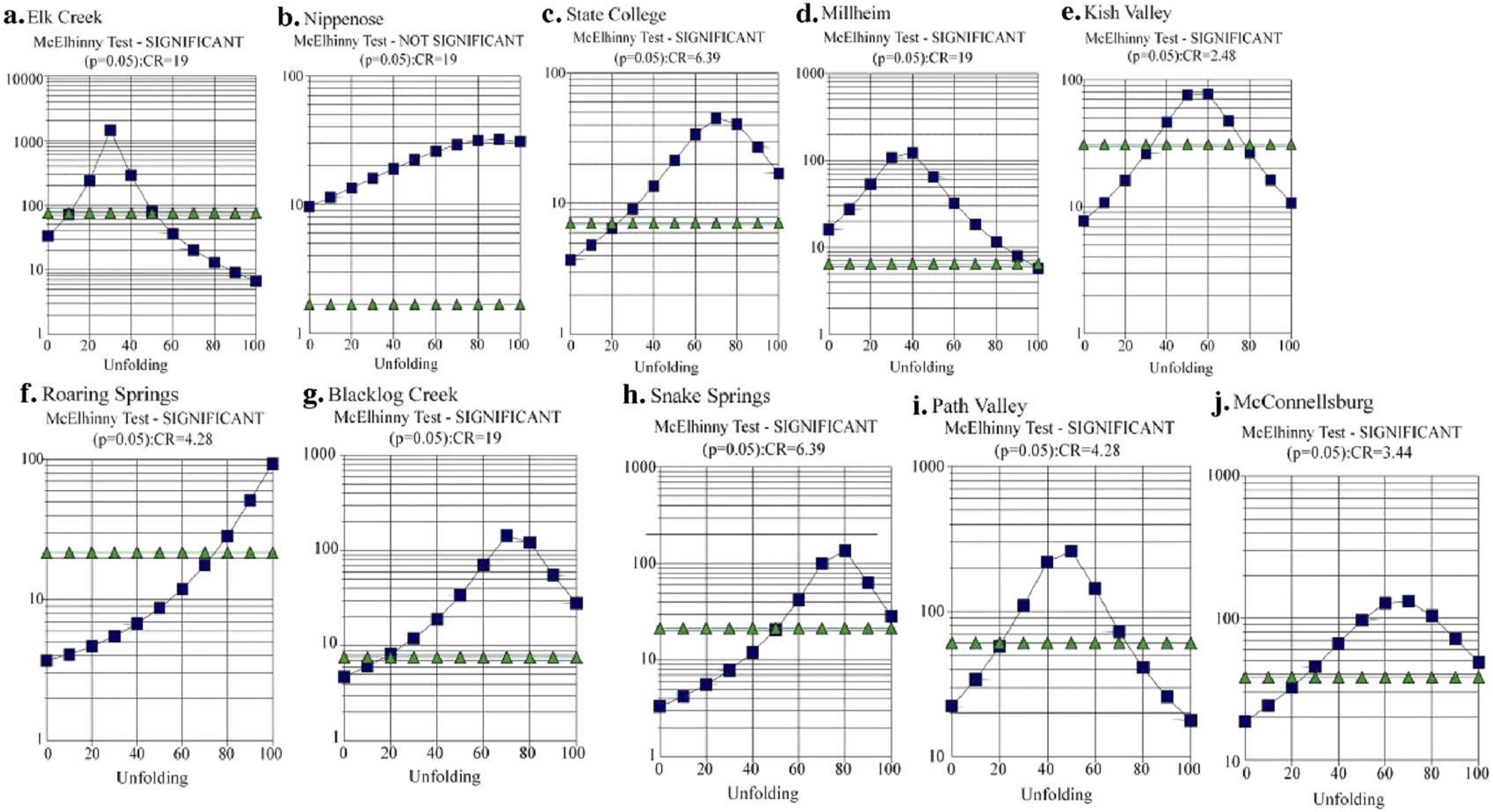


Fig. 4. Results of incremental fold tests for 10 of the 11 sampled anticlines, showing the *k* parameter (squares) on a logarithmic scale versus percent unfolding. CR values (listed) are the critical ratios for the number of data entries (from McElhinny, 1964), with which the significance of the tests can be determined. Triangles represent the values of k_{max}/CR, below which the *k* values are significantly different from k_{max}. All but one of the tests are significant with respect to either k_0 or k_{100} or both.

Table 2
Summary of paleomagnetic results from each anticlinal fold

Fold	Mean site lat	Mean site lon	DEC[a]	INC[a]	% unfold.	κ	α_{95}	Pole lat	Pole lon	dp	dm
Birmingham Window[b]	40.7	281.8									
Elk Creek	40.9	282.6	187	−8	30	1437.3	6.6	51.9	91.3	3.3	4.1
Kish Valley	40.7	282.4	179	6	60	77.2	6.3	46.3	103.8	3.2	4.4
Millheim	40.8	282.6	180	− 13	40	122.5	22.8	55.8	102.6	11.8	13.2
Nippenose	41.2	282.8	171	− 6	90	32.0	45.7	51.0	117.2	23.0	28.9
State College	40.8	282.2	171	− 11	70	45.2	18.6	53.8	117.5	9.6	11.2
Mean for northeast limb	40.9	282.5	178	− 6		65.6	9.5	52.3	106.4	4.8	5.8
Blacklog Creek	40.1	282.2	167	4	70	143.6	21.0	46.2	121.2	10.5	14.6
McConnellsburg	39.8	282.0	175	4	70	162.0	6.0	47.9	109.5	3.0	4.0
Path Valley	40.2	282.2	180	4	50	261.0	5.7	47.8	102.2	2.9	3.8
Roaring Springs	40.2	281.6	170	− 5	100	93.2	9.6	51.2	117.7	4.8	6.0
Snake Springs	40.0	281.5	162	− 5	80	136.5	10.6	49.1	129.6	5.3	7.0
Mean for southwest limb	40.1	281.9	171	0		90.2	8.1	48.8	116.0	4.1	5.3

Mean site lat and lon = average coordinates of a fold, % unfold. = that percentage unfolding at which k is maximum, pole lat and lon = coordinates of the paleomagnetic pole position, dp and dm are the semi-minor and semi-major axes of the ellipse of 95% confidence around the pole. Other abbreviations as in Table 1.

[a] Declination (DEC) and inclination (INC) at peak κ from unfolding.

[b] Fold test could not be carried out because only one site yielded characteristic directions.

corrections, with the in-situ intermediate-up and intermediate-down directions becoming shallowly inclined, but the percent unfolding at which this happens, and at which clustering becomes optimal, varies from 30% to 100% (Fig. 4). Results for each fold are summarized in Table 2, whereas Table 1 also includes two columns listing the optimally tilt-corrected site means. Fig. 5 shows the tilt-corrected mean declinations for each site in map view.

A majority of the anticlines achieve their best clustering at high percentages of unfolding (Figs. 4 and 6), suggesting that their magnetizations are pre-folding or early syn-folding. The magnetizations of the sites in the outermost zone are generally older than all or most of the folding, whereas towards the hinterland the magnetizations are more clearly syn-folding (Fig. 6); this confirms observations presented by Stamatakos et al. (1996) for remagnetizations in the younger red beds.

6. Discussion

In order to test for oroclinal rotations, the folds were divided into two groups representing the northeastern and southwestern limbs of the salient (Table 2), with the dividing line running north of the Blacklog Creek and Roaring Springs anticlines. The mean declinations from the NE and SW limbs (178° and 171°, respectively; Table 2) are 7°±9.6° apart. We used the method of Demarest (1983) to calculate the error margins, which indicate that the difference is not statistically significant. One can see the spatial distribution of declinations and the lack of significant patterns also in Fig. 5. Moreover, plotting the paleopoles calculated from the NE and SW mean directions next to the North American APWP (Van der Voo, 1993), we see that the two poles have overlapping confidence ovals (Fig. 7), and that they fall near the Permo-Triassic section of the APWP. The pole of the northeast limb would appear slightly younger than that of the southwest limb, but this difference falls within error. Lastly, we recall that the mean NE and SW declinations obtained from the generally syn-folding remagnetizations in the redbeds are only 1° apart (Stamatakos and Hirt, 1994), further corroborating that the relative rotations between the limbs of the salient, which have been deduced from the (near-primary) magnetizations in the Paleozoic redbeds, took place before the Permian folding of the strata. Our results are also similar to prior studies of overlying carbonates of Silurian–Devonian age (McCabe et al., 1983), thus showing coherent behavior of the entire Paleozoic cratonic cover.

Fig. 8 clearly shows the absence of a significant correlation between the structural trend (strikes) and the declination of the (partially to fully) tilt-corrected site-mean directions. For convenience, the plot is normalized such that the regression through the 35 site means passes through the origin, where the declination and strike values equal their area-wide averages (175° and 52°, respectively). The slope of the best-fit line is not zero, but this is insignificant and an artifact of the data scatter; the correlation coefficient is 0.13, which indicates that only 2% of the total dispersion is accounted for by the linear regression shown in Fig. 8. The other 98% results from other causes of dispersion.

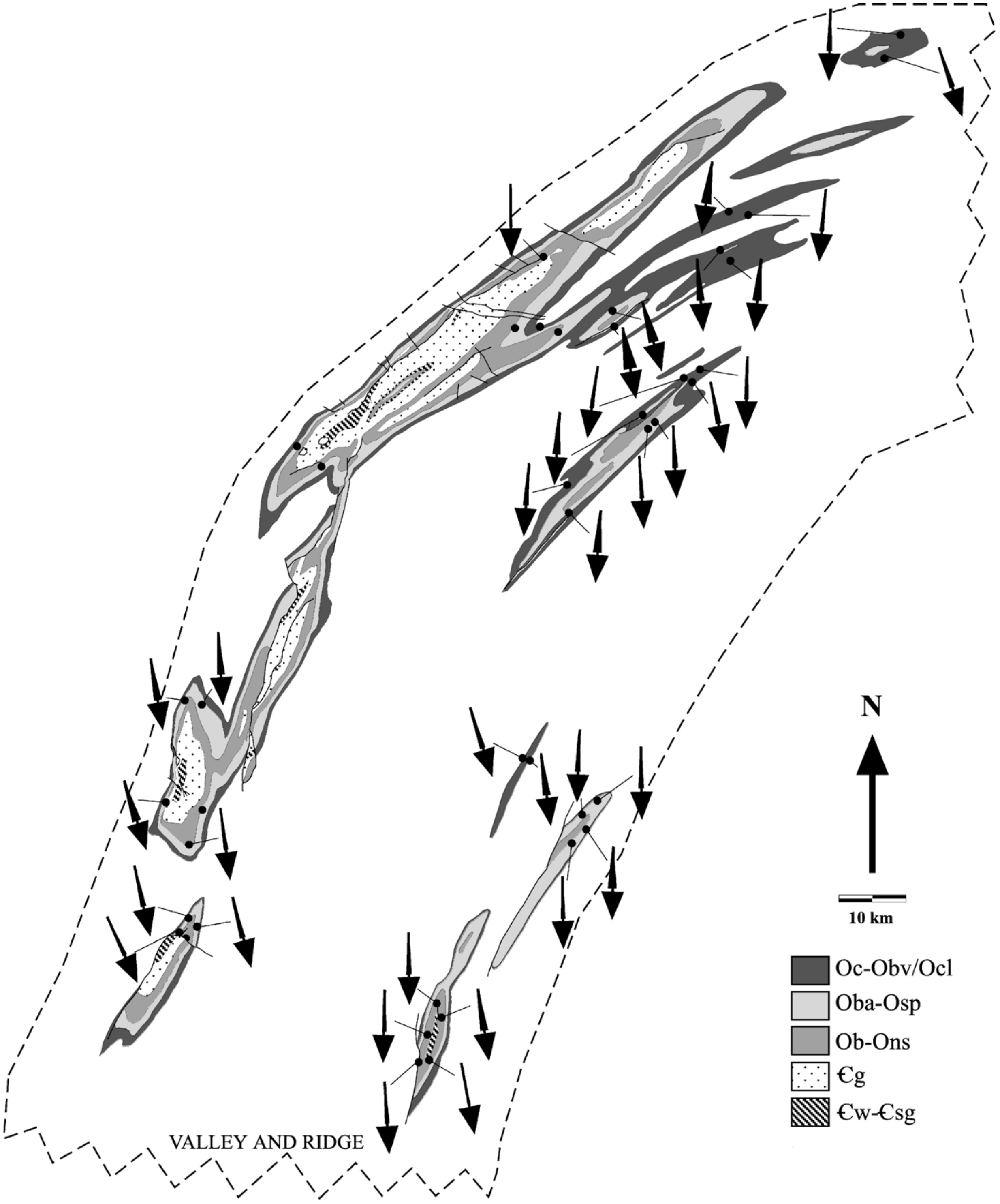


Fig. 5. Map (as in Fig. 1) showing the mean declinations for each site after partial to complete structural correction at which the *k* parameter is maximum. The cone on the tail of each arrow denotes the α_{95} for each site. The six sites without arrows did not yield results that could be used in the fold tests (see text).

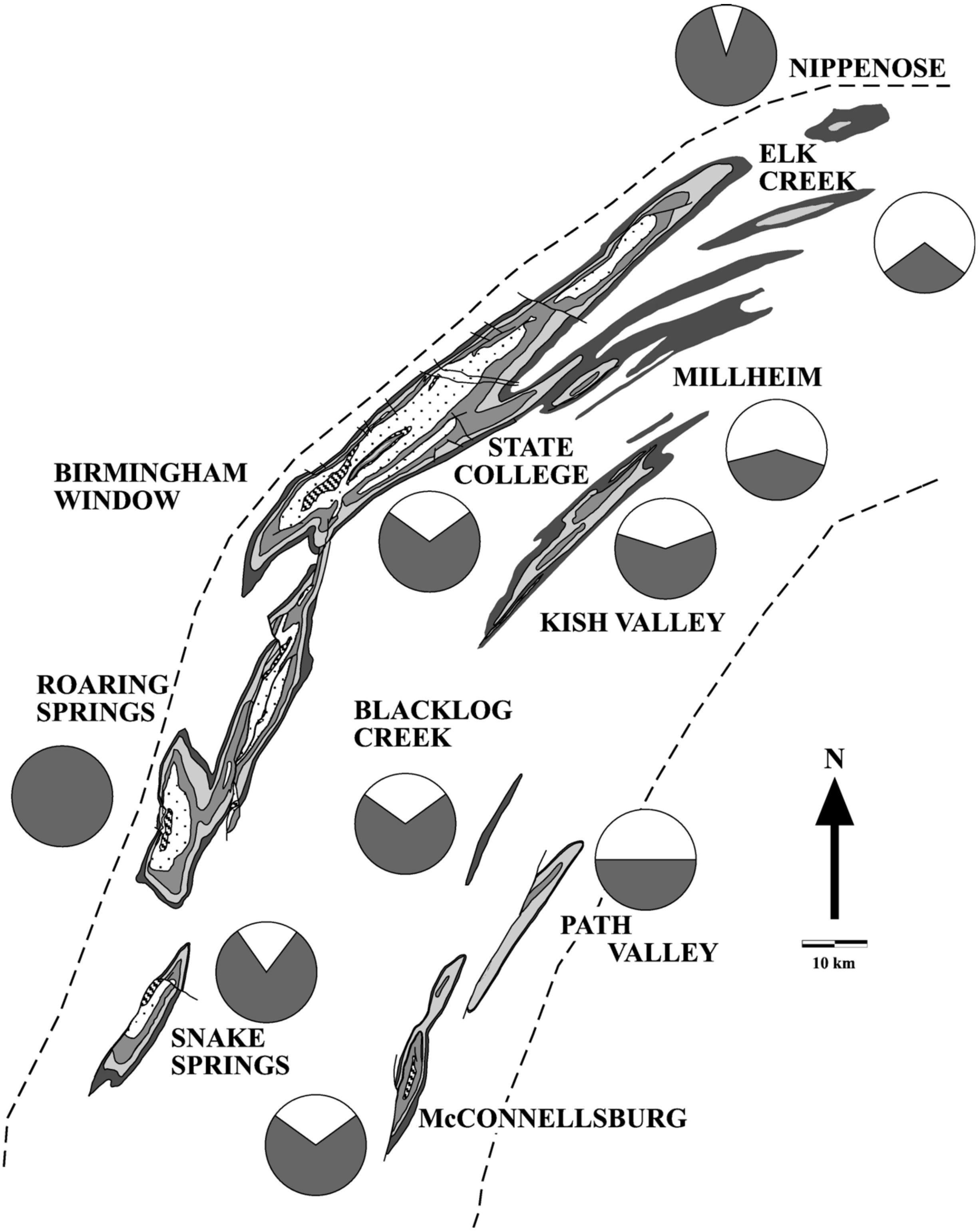


Fig. 6. Map (as in Fig. 1) showing the optimum percent unfolding, as derived from the diagrams in Fig. 4, represented by the dark areas in the pie-diagrams.

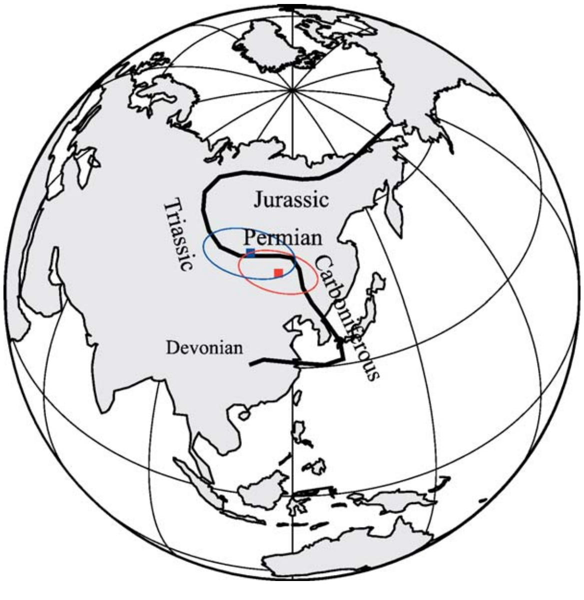


Fig. 7. Mean paleopoles (filled squares) for each of the two limbs with their ovals of 95% confidence (based on dp and dm in Table 2) plotted next to the North American apparent polar wander path of Van der Voo (1993).

Thus there is no noticeable difference in the data between the thrust sheets with the Early Paleozoic carbonates and those containing the younger red beds and carbonates. The similarity in the declination patterns of the remagnetizations observed in the Early Paleozoic carbonates and the younger red beds strengthens our interpretation that the same kinematic story applies to both upper and the lower thrust-sheet packages, namely the units above the roof thrust in the Middle Ordovician shale and the units in the Cambro-Ordovician duplex below. These packages apparently did not undergo differential rotations, such as proposed by Geiser (1989) and Gray and Stamatakos (1997).

7. Conclusions

Our results indicate that the Cambro-Ordovician limestones of the Pennsylvania Valley and Ridge Province have been remagnetized during the Kiaman reversed superchron and that authigenic magnetite is the likely carrier of the magnetization. Fold tests demonstrate that the magnetization in these carbonates is generally older than all or most of the folding in the outer zone of the salient and becomes progressively more syn-deformational towards the hinterland. A minimal declination difference between the northeastern and the southwestern limbs of the salient is shown to be statistically insignificant, so our study preserves no evidence for oroclinal rotation during and after remagnetization. The oroclinal bending that is observed in primary magnetizations of the overlying Upper Ordovician, Silurian, Devonian and Lower Carboniferous red beds (Kent, 1988) must have mostly ceased when folding commenced. Remagnetization occurred before and in the earlier stages of folding, but after rotations recorded by the overlying red beds was completed. Our results do not support the hypothesis of a detachment horizon within the Paleozoic rock sequence to explain the varied observations (Geiser, 1989; Gray and Stamatakos, 1997). In a complementary study, we will document the preservation of oroclinal rotation from calcite twinning analysis in these rocks (Ong et al., in press), which indicates that the kinematic evolution of the area cannot be readily interpreted from the regional folding patterns that are associated with remagnetization.

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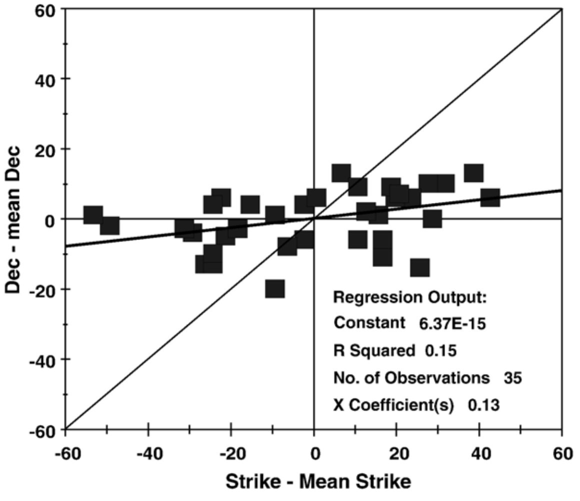

Fig. 8. Declination versus strike plot (after Schwartz and Van der Voo, 1983) for the sites, showing regression analysis, based on the partially to fully tilt-corrected site-means of Table 1. Declination and strike values were normalized by subtracting the mean declination (175°) and mean strike (52°), allowing the regression line to pass through the origin. Six sites were not included because their characteristic magnetization could not be isolated or because their directions were anomalous.

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