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Remagnetization in the Tennessee salient, Southern Appalachians, USA: Constraints on the timing of deformation

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ABSTRACT

The Appalachian fold–thrust belt is characterized by a sinuous trace in map-view, creating a series of salients and recesses. The kinematic evolution of these arcuate features remains a controversial topic in orogenesis. Primary magnetizations from clastic red beds in the Pennsylvania salient show Pennsylvanian rotations that account for about half of the curvature, while Kiaman-aged (Permian) remagnetizations display no relative rotation between the limbs. The more southern Tennessee salient shows a maximum change in regional strike from ~65° in Virginia to ~10° in northern Georgia. Paleomagnetic results from thirty-two sites in the Middle to Upper Ordovician Chickamauga Group limestones and twenty sites from the Middle Cambrian Rome Formation red beds were analyzed to constrain the relative age of magnetization as well as the nature of curvature in the Tennessee salient. Results from three sites of the Silurian Red Mountain Formation were added to an existing dataset in order to determine whether the southern limb had rotated.

After thermal demagnetization, all three sample suites display a down and southeasterly direction, albeit carried by different magnetic minerals. The syn-tilting direction of the Chickamauga limestones lies on the Pennsylvanian segment of the North American apparent polar wander path (APWP), indicating that deformation was about half completed by the Late Pennsylvanian. The Rome and Red Mountain Formations were also remagnetized during the Pennsylvanian. Both the Chickamauga limestones and Rome red beds fail to show a correlation between strike and declination along the salient, suggesting either that the salient was a primary, non-rotational feature or that secondary curvature occurred prior to remagnetization, as it did in Pennsylvania. Moreover, remagnetized directions from the Red Mountain sites show no statistical difference between the southern limb of the salient and the more northeasterly trending portion of the fold–thrust belt in Alabama. Thus, all of the studied units in the Tennessee salient are remagnetized and show no evidence for rotation. This confirms that remagnetization was widespread in the southern Appalachians and that any potential orogenic rotation must have occurred prior to the Late Pennsylvanian.

1. Introduction

Most fold–thrust belts worldwide display some degree of curvature (Carey, 1955; Eldredge et al., 1985; Marshak, 1988; Marshak et al., 1992; Macedo and Marshak, 1999; Marshak, 2004; Weil and Sussman, 2004), with curvature varying from tens of degrees to as much as 180°. Since Carey's (1955) development of the orocline hypothesis, many studies have focused on the evolution of arcuate orogens. While several classification schemes have been proposed for orogenic curvature, arcuate orogens can generally be thought of as primary, with the orogen forming in an initial curved state, secondary, with secondary rotations of limbs from straighter geometry, or some combination (Eldredge et al., 1985; Marshak, 1988; Hindle and Burkhard, 1999). Differentiating between the two endmembers is important in resolving the kinematic and mechanical evolution of curved orogens. Moreover, out-of-plane deformation limits the reliability of balanced cross-sections in curved belts (Hatcher, 2004; Pueyo et al., 2004; Hnat et al., 2008), making it imperative to constrain rotations before attempting palinspastic restoration and section balancing.

Because secondary curvature is characterized by rotations about a vertical axis, paleomagnetism provides an ideal method for curvature assessment (Eldredge et al., 1985; Lowrie and Hirt, 1986; McCaig and McClelland, 1992; Weil and Sussman, 2004). A coincident change in remanence declination and orogenic strike is representative of secondary curvature, whereas primary curvature will reveal no such correlation. However, the use of paleomagnetism requires that the magnetization of the units is acquired prior to curvature, in order to record the total amount of rotation. In orogenic settings, meeting this condition can be difficult, as remagnetizations are common. Therefore, paleomagnetic field-tests (fold test, conglomerate test, baked contact test, and reversal test) are essential when assessing orogenic curvature with paleomagnetism.

One of the most obvious and well-studied fold–thrust belts to display significant curvature is the Appalachians, which extends from Newfoundland in the northeast to Alabama in the southwest. It

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displays a sinuous pattern that consists of the Pennsylvania salient, the Roanoke recess, the Tennessee salient and the Alabama recess (Fig. 1). The general shape of the fold–thrust belt has been interpreted to have evolved from the irregular shape of Laurentia's rifted Iapetan margin, which subsequently influenced the position of the fold–thrust belt during Late Paleozoic Alleghanian deformation (Rankin, 1975; Thomas, 1977, 1991, 2004).

Some of the earliest investigations testing Carey's (1955) orocline hypothesis using paleomagnetism focused on the Pennsylvania salient (Fig. 1). Studies from multiple Paleozoic clastic red bed units displayed seemingly contradictory results (Irving and Opdyke, 1965; Roy et al., 1967; Knowles and Opdyke, 1968; Van der Voo et al., 1977; Schwartz and Van der Voo, 1983). Later studies recognized two magnetizations from many of these units, both carried by hematite. The lower-temperature component is typical of a Late Paleozoic Kiaman remagnetization, while the higher-temperature component proved to be a depositional remanent magnetization (DRM) for the Upper Ordovician Juniata (Miller and Kent, 1989), Silurian Bloomsburg (Kent, 1988; Stamatakos and Hirt, 1994), Upper Devonian Catskill (Miller and Kent, 1986) and Mississippian Mauch Chunk Formations (Kent and Opdyke, 1985; Kent, 1988). These results allowed Kent (1988) and Stamatakos and Hirt (1994) to conclude that about half (23° and 18°, respectively) of the curvature (~55°) is accounted for by relative rotation between the limbs. The absolute rotation has been argued by Van der Voo (1993) to have been a clockwise rotation that affected only the northern limb, based on the comparison of directions from the Silurian Rose Hill Formation (French and Van der Voo, 1979) with those from the Silurian Wabash Reef in Indiana (McCabe et al., 1985), part of the stable Laurentian craton.

The remagnetized components, in contrast, show no relative difference between the limbs of the Pennsylvania salient. Kiaman-aged remagnetizations also dominate carbonate units in the region, though the magnetization is carried by magnetite (Kodama, 1988; Evans et al., 2000; Cederquist et al., 2006). Although the remagnetizations fail to record rotation in Pennsylvania, they do show a toward-the-foreland development of the fold–thrust belt, as remagnetizations carried by hematite and by magnetite are postfolding in the hinterland, synfolding in the middle and prefolding toward the foreland (Stamatakos et al., 1996; Cederquist et al., 2006).

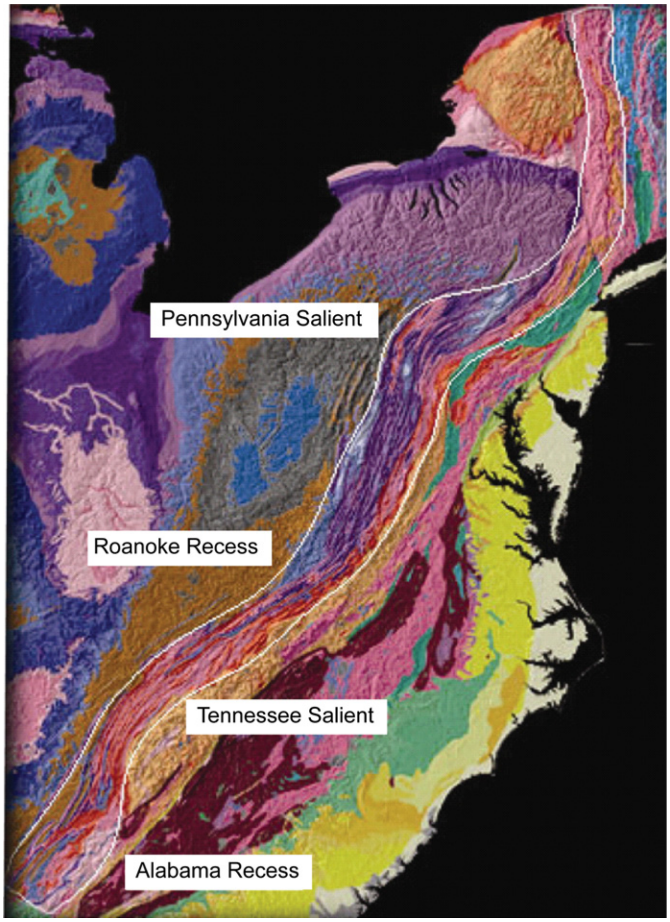

Fig. 1. Map of Appalachian thrust belt, highlighting curvature (Vigil et al., 2000).

The primary aim of this study is to provide a test of curvature in the Tennessee salient through paleomagnetic analysis of incompletely studied red beds from the Rome Formation, which were thought to preserve a primary remanence (Watts et al., 1980), and newly sampled limestones (Chickamauga Group). We also add results to existing data from Silurian red beds (Red Mountain Formation) from the Alabama thrust belt. This large new dataset allows us to test the timing of magnetization and origin of curvature in the Tennessee salient, and to compare the Tennessee and Pennsylvania salients in terms of age of magnetization and, if any, rotational history.

2. Tennessee salient

2.1. Regional structure

The Tennessee salient is defined by a change in regional strike from up to 65° in Virginia and northern Tennessee to approximately 10° in northern Georgia, before returning to a more northeasterly direction (~45°) into Alabama (Figs. 1 and 2). Instead of being defined by fold traces like in Pennsylvania, the curved geometry of Tennessee is primarily delineated by southeast dipping thrust faults, with the overlying stratigraphy dipping in the same general direction (Hatcher et al., 1989; Hatcher et al., 2007). The curvature is not uniform throughout the belt, as evidenced by the southern limb of the salient, where the frontal portion of the fold–thrust belt diverges from the northern limb by only 35°–40° while the hinterland deviates up to 65°.

The southern Appalachian fold–thrust belt is a classic thin-skinned fold–thrust belt. The structural style of the belt significantly differs from that in the central Appalachians, which is primarily attributed to stratigraphic differences. The southern Appalachian fold–thrust belt consists of a west-verging stack of thin-skinned thrusts, with the basal decollément contained primarily within the shales of the Cambrian Rome and Conasauga Formations. The thrust stack in Tennessee is dominated by stiff Cambro-Ordovician carbonates, with the entire sedimentary package thickening toward the east (Rodgers, 1970; Harris and Milici, 1977; Hatcher et al., 1989). Most of the currently exposed stratigraphic units in this region consist of the Cambro-Ordovician carbonates, including those of the Conasauga, Knox and Chickamauga Groups. Unlike the central Appalachians, the southern Appalachian belt lacks thick packages of Silurian through Mississippian units (Hatcher et al., 1989).

2.2. Previous paleomagnetic work

Compared to the Pennsylvania salient, the Tennessee salient has received much less attention. Paleomagnetic results from the thrust belt are few and were collected to constrain either the apparent polar wander path (APWP) for Laurentia (Watts and Van der Voo, 1979; Watts et al., 1980) or the timing of remagnetizations associated with Mississippi Valley-type (MVT) deposits (Bachtadse et al., 1987; Symons and Stratakos, 2002; Pannalal et al., 2003). Watts et al. (1980) sampled the Cambrian Rome Formation and argued that the unit carries a Cambrian magnetization, although the reliability of these data is questionable (Van der Voo, 1993). The eight sites were distributed primarily along the northern limb of the salient, although one site was located on its southern limb. Results from this single site led the authors to conclude that the curvature in Tennessee is primary and that no significant rotation had occurred in the salient. However,

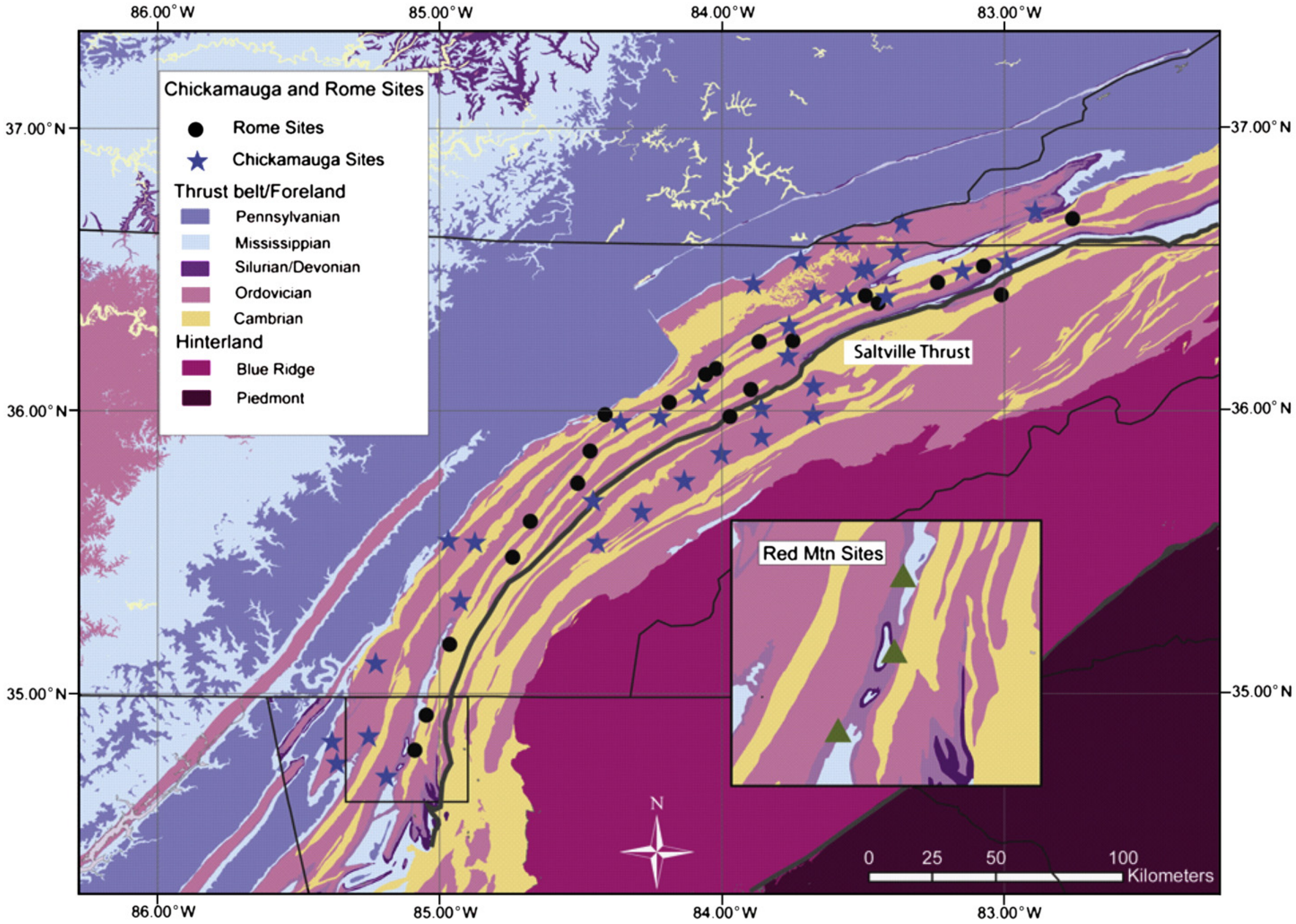

Fig. 2. Tennessee salient showing paleomagnetic sites sampled for this study. Stars show location of Chickamauga limestone sites. Saltville thrust is highlighted filled circles represent Rome Formation sites and triangles from the inset show the three Red Mountain sites (Hardeman, 1966; Lawton et al., 1976; McDowell et al., 1981; Osbourne et al., 1988). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

since the timing of magnetization relative to deformation is suspect (Van der Voo, 1993), it is difficult to sustain this conclusion.

Other paleomagnetic efforts in the area were almost exclusively distributed in the northern limb. Watts and Van der Voo (1979) sampled Ordovician red beds from the Bays Mountain, Chapman Ridge and Moccasin Formations. There, prefolding, primary magnetizations carried by hematite revealed an Ordovician pole for the three units. A secondary magnetization, also apparently carried by hematite, was also identified in the Moccasin Formation and appears to be late Paleozoic. Morrison and Ellwood (1986) identified a direction from northwestern Georgia that is somewhat similar to the Ordovician direction, although this result only included data from a single geographic site, and therefore, like the Rome Formation, is not a reliable dataset for identifying the presence of rotations.

Results from carbonates of the Cambro-Ordovician Knox Group in the Tennessee salient have shown that this unit was remagnetized during the late Paleozoic, although interpretations of the inferred age of magnetization have ranged from Mississippian (Symons and Stratakos, 2002; Pannalal et al., 2003) to Pennsylvanian (Bachtadse et al., 1987). Because the distribution of sites is exclusive to the northern limb, and given that these rocks are clearly remagnetized, it remains to be determined whether rotation occurred within the Tennessee salient.

The lack of suitable paleomagnetic data to test the nature of curvature in the Tennessee salient has led us to sample a distribution of sites from multiple lithologies with the goal of determining whether regional rotations were involved in the development of the salient. Sampling focused primarily on limestones of the Chickamauga Group and red beds of the Rome Formation, although three sites of Red Mountain Formation red beds in northern Georgia were also collected. With this more expansive dataset, we hope to elucidate whether oroclinal bending has occurred in the Tennessee salient.

3. Paleomagnetic analysis of the Tennessee salient

3.1. Methods

Samples were collected from both limestone and red bed sites in roadcut and quarry exposures within the Tennessee salient. Between five and thirteen 2.5 cm diameter cores were collected from each limestone site using a portable gasoline-powered drill. Six to ten oriented hand samples were collected from each red bed site and either cored or cut into standard 2.2 cm cubes, depending on the lithology. All cores were subsequently cut into standard length specimens. Core and hand sample orientations, as well as bedding attitude, were measured using a magnetic compass.

Prior to demagnetization, anisotropy of magnetic susceptibility (AMS) was measured on all specimens. AMS has previously been used to analyze curved mountain belts (Cifelli et al., 2004; Somma, 2006). Specimens were measured in fifteen positions, according to the method of Jelinek (1978), on a Geofyzika Brno Kappabridge KLY—2.03 at 920 Hz. Linear perturbation analysis was used to produce a

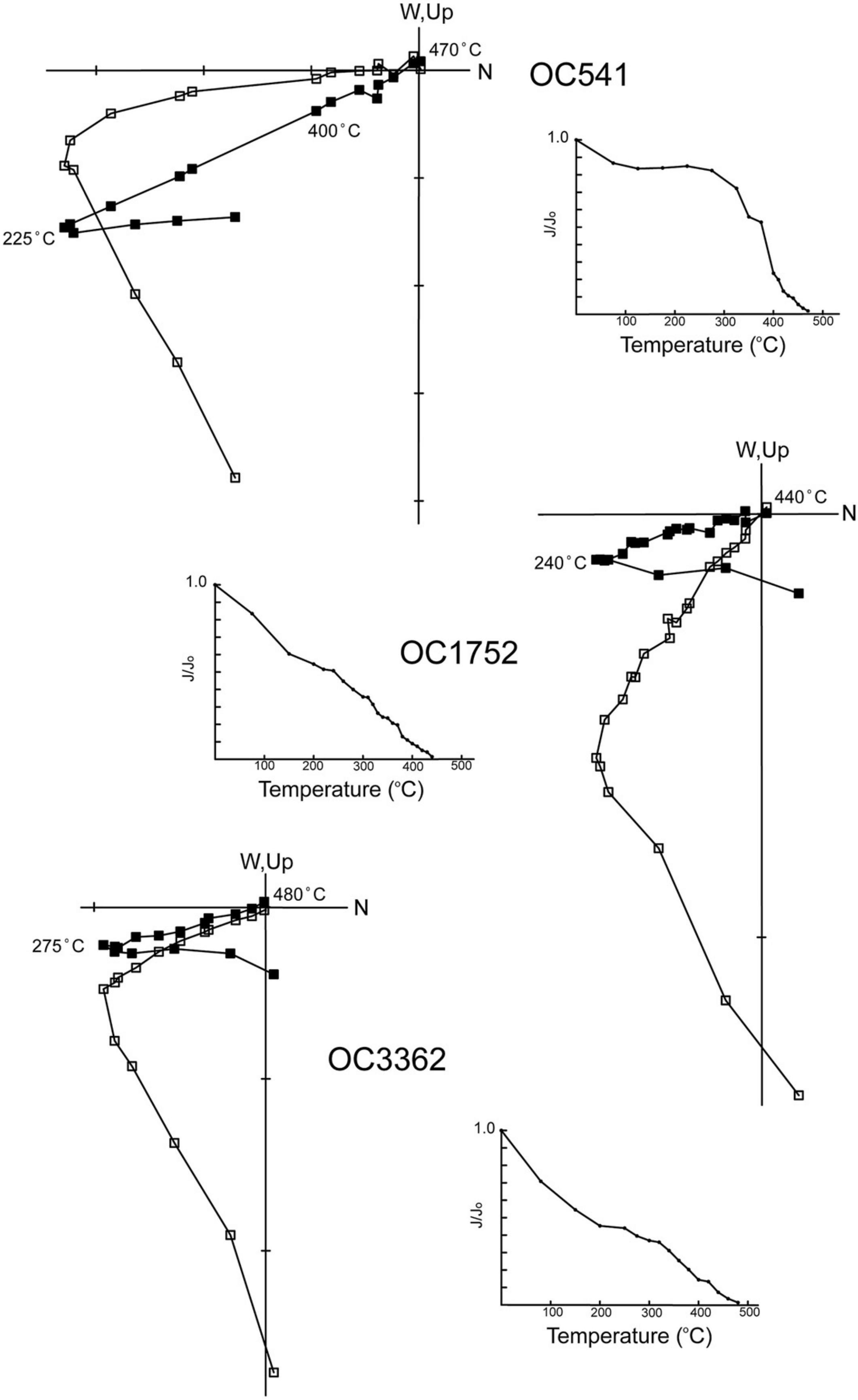

Fig. 3. Representative thermal demagnetization plots of the Chickamauga Group limestones in geographic coordinates with associated intensity plots, showing normalized intensity versus temperature in degrees Celsius. In the demagnetization plots, closed (open) symbols represent vector endpoints plotted in the horizontal (vertical) plane. Temperature steps are in degrees Celsius. Ticks represent 0.5 mA/m.

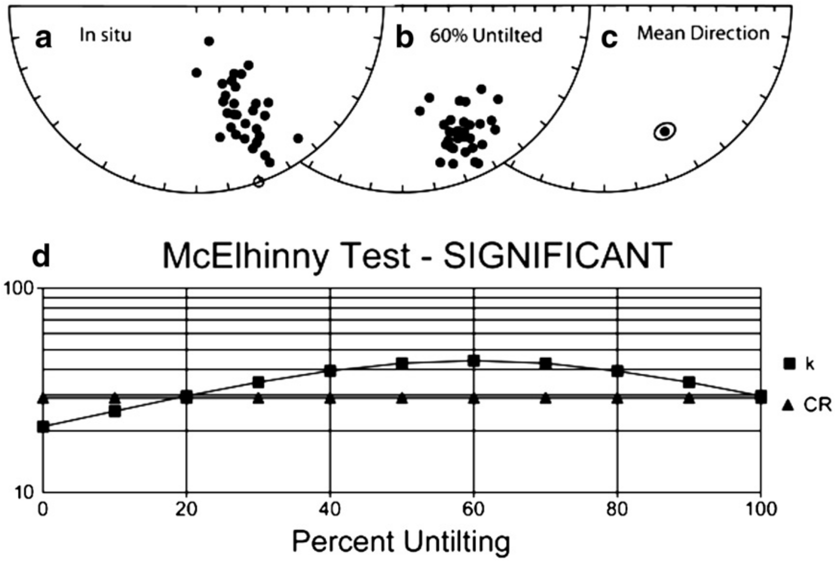

Fig. 4. Tilt-test of the Chickamauga Group limestones. Equal area projections of site means in geographic (a) and partially tilt-corrected coordinates (b), as well as mean direction (c). Solid (open) circles represent down (up) directions. (d) Incremental tilt-test of site means plotting *k* on logarithmic scale versus percent unfolding. Squares represent *k* values and triangles represent the critical ratio (CR) at which *k* values become significant at the 95% confidence level for the number of data entries (McElhinny, 1964).

statistical bootstrap using the 'bootams' program of Tauxe (1998). Site–mean eigenvectors were plotted and displayed as a scatter of points on an equal-area stereonet. Unfortunately, AMS fabrics were both weak and erratic for red beds and limestones at the site and specimen levels. Therefore, AMS was disregarded in our analysis of curvature formation in the Tennessee salient.

Thermal demagnetization was carried out on all specimens in a magnetically shielded, low-field room using an Analytical Service Co.

Table 1
Paleomagnetic results from the Chickamauga Group limestones.

Site	Latitude	Longitude	Strike	Dip	N/No	Geo Dec	Geo Inc	TC Dec	TC Inc	$\alpha95$	*k*
OC01	36.566	−83.382	59°	17°	6/6	164.1°	33.0°	162.7°	23.1°	8.4°	65.02
OC02	36.510	−83.492	250°	31°	6/7	162.9°	28.8°	163.8°	47.4°	18.9°	13.48
OC03	36.502	−83.503	58°	26°	5/7	146.5°	54.1°	146.8°	38.5°	15.6°	24.99
OC04	36.408	−83.424	62°	36°	8/8	164.3°	45.9°	161.4°	24.7°	3.7°	227.36
OC05	34.851	−85.260	166°	3°	9/9	154.9°	8.3°	155.2°	8.6°	8.2°	40.1
OC06	35.112	−85.234	25°	15°	7/9	157.4°	32.4°	154.1°	25.6°	19.6°	10.46
OC07	35.331	−84.931	11°	10°	7/8	158.4°	19.1°	156.8°	15.8°	4.2°	209.8
OC08[a]	35.550	−84.973	37°	72°	8/9	201.0°	−35.3°	–	–	8.6°	42.37
OC09	35.543	−84.444	37°	44°	6/11	138.9°	55.3°	134.5°	29.2°	8.3°	65.52
OC10	35.754	−84.138	47°	11°	7/9	153.9°	27.7°	153.0°	21.4°	7.7°	62.27
OC11	35.644	−84.285	52°	15°	7/8	151.6°	36.5°	150.7°	27.6°	7.3°	70.23
OC12	35.981	−84.221	57°	34°	7/10	161.5°	53.9°	157.2°	34.0°	4.9°	150.9
OC13	35.539	−84.878	151°	3°	8/8	154.1°	23.6°	154.9°	23.5°	5.4°	107.4
OC14	35.852	−84.009	46°	23°	6/9	148.6°	38.8°	146.8°	25.3°	7.3°	84.81
OC15	36.309	−83.760	64°	33°	6/7	179.9°	60.8°	170.7°	42.3°	11.3°	35.97
OC16	36.022	−83.858	53°	59°	5/10	154.2°	50.3°	150.2°	15.4°	11.6°	44.16
OC17	36.200	−83.768	57°	39°	10/10	154.7°	53.6°	152.3°	30.3°	3.0°	257.89
OC18	36.498	−83.155	69°	31°	13/13	160.9°	38.6°	160.5°	20.0°	4.5°	87.63
OC19	36.536	−82.993	53°	57°	5/8	160.2°	73.8°	148.9°	40.2°	10.9°	50.4
OC20	36.714	−82.895	62°	33°	4/9	162.0°	48.3°	159.6°	28.7°	7.1°	168.11
OC21	36.612	−83.575	209°	12°	8/9	142.5°	11.7°	143.3°	18.3°	9.6°	33.93
OC22	36.479	−83.851	283°	21°	0/8	–	–	–	–	–	–
OC23	36.661	−83.390	248°	11°	6/10	156.3°	21.0°	156.2°	27.6°	9.8°	47.38
OC24	36.533	−83.722	238°	13°	11/11	160.0°	25.4°	160.9°	33.0°	10.2°	20.88
OC25	36.419	−83.677	53°	24°	9/12	159.7°	37.9°	157.4°	24.0°	7.5°	48.34
OC26	36.411	−83.563	49°	28°	12/12	169.8°	29.4°	166.5°	14.7°	6.9°	40.05
OC27	36.117	−83.658	246°	88°	0/12	–	–	–	–	–	–
OC28	35.913	−83.866	45°	21°	9/9	143.3°	35.8°	142.3°	23.3°	9.7°	29.07
OC29	35.992	−83.677	228°	15°	8/9	148.0°	31.5°	149.2°	40.3°	10.2°	30.23
OC30	36.068	−84.089	58°	28°	11/11	158.9°	43.4°	156.9°	26.8°	5.5°	70.5
OC31	35.969	−84.364	59°	33°	10/10	163.9°	40.2°	161.1°	20.9°	6.2°	62.1
OC32	35.690	−84.463	17°	36°	10/13	150.9°	56.0°	136.7°	38.5°	7.5°	42.81
OC33	34.708	−85.192	14°	14°	9/9	156.0°	21.5°	153.8°	16.2°	5.0°	107.06
OC34	34.756	−85.369	26°	13°	6/7	155.3°	13.1°	154.4°	7.0°	7.2°	86.85
OC35	34.832	−85.385	197°	35°	11/13	160.5°	−0.2°	162.3°	12.1°	4.7°	95.01
Chickamauga Mean					32/35	–	–	154.5°	26°	3.9°	44.02

Mean directions are calculated from site means (Fisher, 1953); N/No, number of specimens (sites) accepted/studied; Geo Dec, In situ declination; Geo Inc, In situ inclination; TC Dec, Tilt-corrected declination; TC Inc, Tilt-corrected inclination; $\alpha95$, radius of confidence circle in degrees; *k*, precision parameter (Fisher, 1953). Tilt-correction is 60% untilting.

[a] OC08 excluded from calculation of mean.

(ASC) thermal demagnetizer. Specimens were measured in a three-axis, cryogenic 2G Enterprises Model 755 Superconducting magnetometer after each heating step, with thermal demagnetization steps ranging from 100°C to 690°C. Demagnetization was discontinued when the specimen intensity approached zero percent of the natural remanent magnetization (NRM) or became erratic because of spurious magnetizations acquired during cooling.

Principal component analysis (Kirschvink, 1980) of linear vectors selected from orthogonal projection demagnetization plots (Zijderveld, 1967) was used to calculate the characteristic remanent magnetization (ChRM) with the SuperIAPD software package (Torsvik et al., 1999). Individual specimen ChRM directions were used to determine site means using Fisher's (1953) method. Maximum angular deviation (MAD) up to 20° was accepted for each specimen, although most had MAD values less than 10°. The timing of magnetization acquisition relative to deformation was tested using a fold-test on the site mean directions (Graham, 1949; McElhinny, 1964; McFadden and Jones, 1981).

3.2. Chickamauga limestone results

A total of 323 samples were collected from thirty-five sites in limestones of the Chickamauga Group (Fig. 2). These limestones were chosen because, unlike the underlying Cambro-Ordovician Knox Group, they are relatively undolomitized and are not typically affected by alteration related to Mississippi Valley-type (MVT) mineralization, two phenomena that have been associated with remagnetizations (Bachtadse et al., 1987; Kesler and van der Pluijm, 1990; Leach et al., 2001; Pannalal et al., 2003). Therefore, these limestones were considered more likely to hold a primary remanence.

The Chickamauga Group consists of all of the formations that lie between the pervasive Middle Ordovician unconformity above the Knox

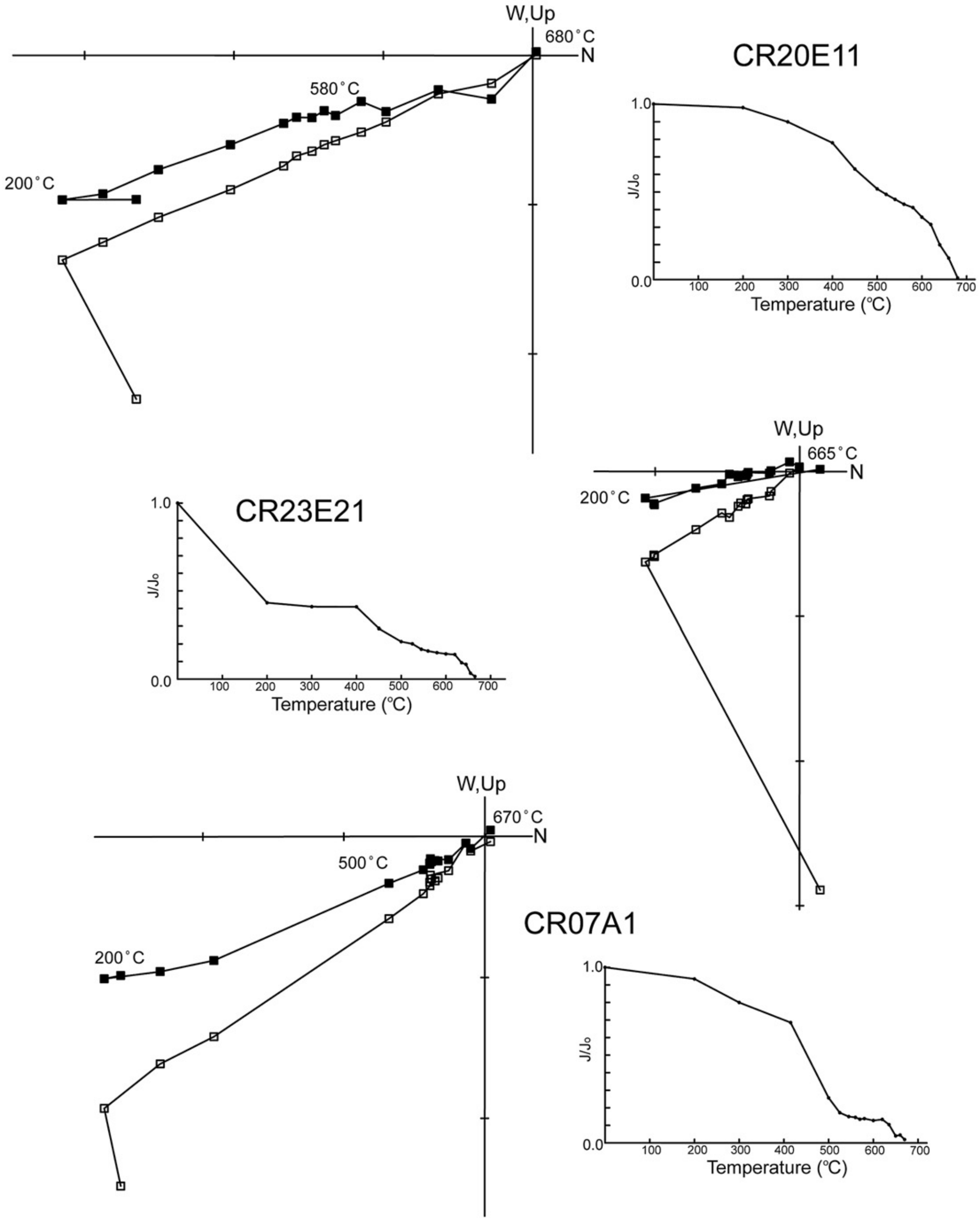

Fig. 5. Representative thermal demagnetization plots of the Rome Formation in geographic coordinates and associated intensity plots. Symbols as in Fig. 3. Ticks represent 5.0 mA/m.

Table 2
Paleomagnetic results from the Rome Formation red beds.

Site	Latitude	Longitude	Strike	Dip	N/No/H	Geo Dec	Geo Inc	TC Dec	TC Inc	α95	k
Cr01	36.249	−83.756	45°	70°	7/8/8	164.5°	44.8°	155.6°	6.3°	11.5°	28.37
Cr02	36.132	−84.062	35°	38°	8/8/8	155.2°	45.2°	148.0°	24.7°	19.2°	9.3
Cr03	36.514	−83.072	67°	60°	0/7/6	–	–	–	–	–	–
Cr04	36.449	−83.239	60°	50°	6/10/10	120.7°	57.8°	132.5°	30.0°	25.6°	7.8
Cr05	36.381	−83.450	63°	32°	7/7/7	160.9°	47.7°	159.0°	28.6°	16.5°	14.35
Cr06	36.408	−83.492	66°	37°	8/8/8	152.8°	45.8°	153.6°	23.6°	11.2°	19.42
Cr07	36.075	−83.900	65°	41°	6/7/7	165.7°	18.6°	165.2°	−5.6°	9.6°	50.1
Cr08	36.030	−84.187	57°	44°	8/8/6	171.2°	38.0°	166.4°	13.4°	16.8°	11.76
Cr09	35.984	−84.418	56°	33°	7/9/7	155.4°	39.5°	153.7°	19.9°	12°	26.22
Cr10	35.856	−84.466	41°	33°	6/10/6	179.0°	58.9°	163.0°	43.5°	13.6°	25.09
Cr11	35.981	−83.971	62°	66°	8/11/7	75.5°	66.6°	121.5°	40.4°	26.0°	5.51
Cr12	35.743	−84.512	35°	28°	6/7/6	158.4°	34.8°	153.8°	20.4°	14.5°	22.38
Cr13	35.611	−84.682	44°	47°	7/9/7	192.6°	48.5°	174.7°	29.8°	28.3°	5.49
Cr14	36.151	−84.024	53°	42°	11/13/7	192.4°	49.8°	177.8°	30.8°	13.5°	12.41
Cr15	35.172	−84.969	25°	69°	13/13/8	246.1°	60.0°	164.1°	60.1°	9.3°	20.86
Cr17	35.486	−84.746	60°	55°	7/11/6	147.8°	56.3°	148.7°	23.3°	22.0°	8.49
Cr18	34.802	−85.090	3°	75°	9/11/5	195.2°	64.8°	128.8°	44.7°	26.0°	4.87
Cr19	36.249	−83.873	50°	47°	10/14/7	153.0°	46.0°	149.5°	18.3°	15.4°	10.86
Cr20	36.411	−83.008	45°	38°	8/9/7	162.4°	30.5°	158.7°	9.9°	8.3°	46
Cr21	36.680	−82.759	66°	37°	7/7/7	158.5°	22.2°	158.3°	0.0°	11.3°	29.53
Cr23	34.927	−85.052	5°	45°	11/11/6	158.2°	29.2°	148.7°	14.8°	15.8°	9.34
Rome Mean					20/21	–	–	154.4°	24.4°	8.2	16.83

N/No/H, number of specimens accepted/studied/number of hand samples collected. Other labels as in Table 1. Tilt-correction is 60% untilting.

Group and the Upper Ordovician Juniata Formation (Rodgers, 1953; Milici, 1973). Toward the east, near the Blue Ridge, the Chickamauga Group consists primarily of clastic sediments (Sevier shale) while in the western thrust belt, limestones dominate the group, although some terrigenous sediments are intercalated. Limestones vary from extremely fine-grained mudstones to coarsely crystalline, reefal grainstones.

NRM intensities for the Chickamauga limestone specimens range between 0.05 and 3.00 mA/m. Such low intensities are typical of limestone units in eastern North America (McCabe et al., 1984; McCabe and Elmore, 1989; Cederquist et al., 2006). Initially, thermal demagnetization was carried out in increments of 50 °C and progressively decreased to 10 °C heating steps, typically above 350 °C depending on the specimen's behavior. Specimen demagnetization trajectories were usually well behaved and commonly revealed two components (Fig. 3). The lower temperature (A) component shows a moderately steep downward direction to the north. The A component is typically removed by 300 °C, and parallels to present-day field, and is thus interpreted as a recent viscous overprint. The higher temperature (B) component

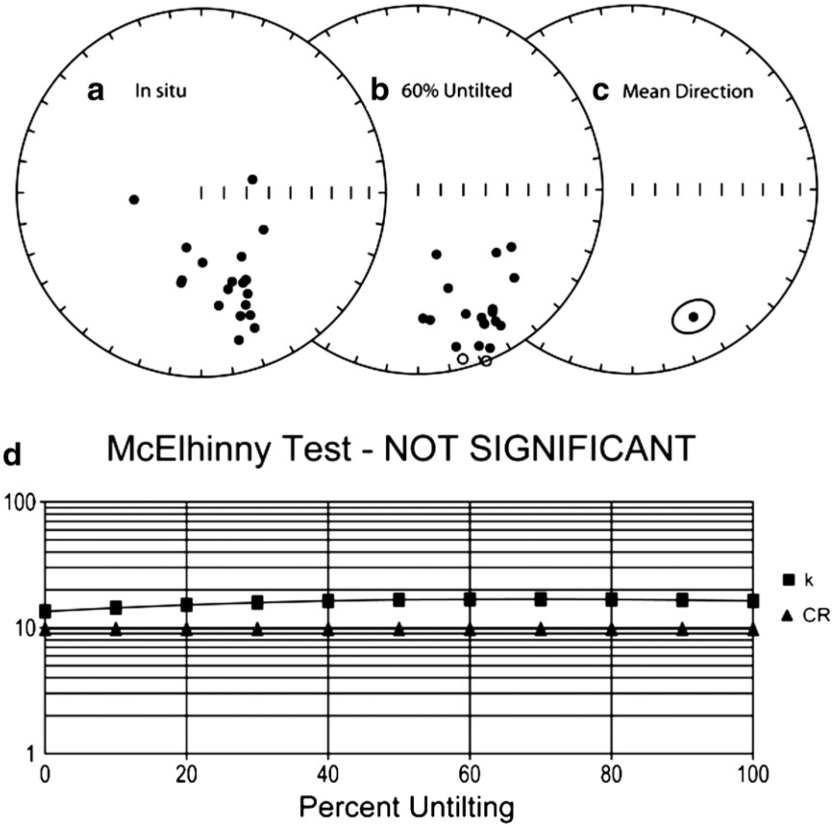

Fig. 6. Equal area projections of site means for the Rome Formation in geographic (a) and 60% tilt-corrected coordinates (b), as well as the mean direction (c). Solid (open) circles represent down (up) directions. (d) Incremental fold test of site means plotting k on logarithmic scale versus percent unfolding. Symbols as in Fig.4.

typically decays between ~300 °C and 450 °C, although it unblocks at temperatures as high as 520 °C in a few specimens. This temperature range has been observed in numerous paleomagnetic and rock magnetic studies of Paleozoic carbonates having a magnetization carried by magnetite. In general, the in situ site–mean directions for the B component lie in a southeast and down orientation, although inclination tends to vary considerably (Fig. 4; Table 1). The B component is considered to represent the ChRM of the Chickamauga Group limestones and roughly corresponds to the late Paleozoic segment of the Laurentian apparent polar wander path (APWP), indicating that the rocks have been remagnetized. Two sites (OC2 and OC27) carry magnetizations that are irresolvable due to weakly magnetized samples, while a third (OC8) has a magnetization that clusters in a southwest and up direction, which, when compared to other North American paleomagnetic data, yields a pole on the Jurassic portion of the path. These three sites were discarded from further analysis.

As evidenced in Pennsylvania and other orogens, resolving the age of remagnetization relative to deformation is quite important for curvature analysis. The fold-test performed on these rocks is better described as a tilt-test, since most of the sites were taken from limestones that are dipping gently to steeply to the southeast. Incremental untilting of the ChRM directions for the thirty-two sites reveals a statistically significant tilt-test, with the precision parameter (k) reaching a maximum at 60% untilting (Fig. 4). This optimal untilting percentage indicates a syntilting magnetization of the Chickamauga Group limestones in the Tennessee fold–thrust belt, with a mean direction of $D = 154.6°$, $I = 26.2°$, $\alpha95 = 3.9°$, and $k = 44$ (Table 1).

3.3. Rome Formation red bed results

The Lower to Middle Cambrian Rome Formation is the oldest exposed unit in the Tennessee salient (Milici, 1973; Harris and Milici,

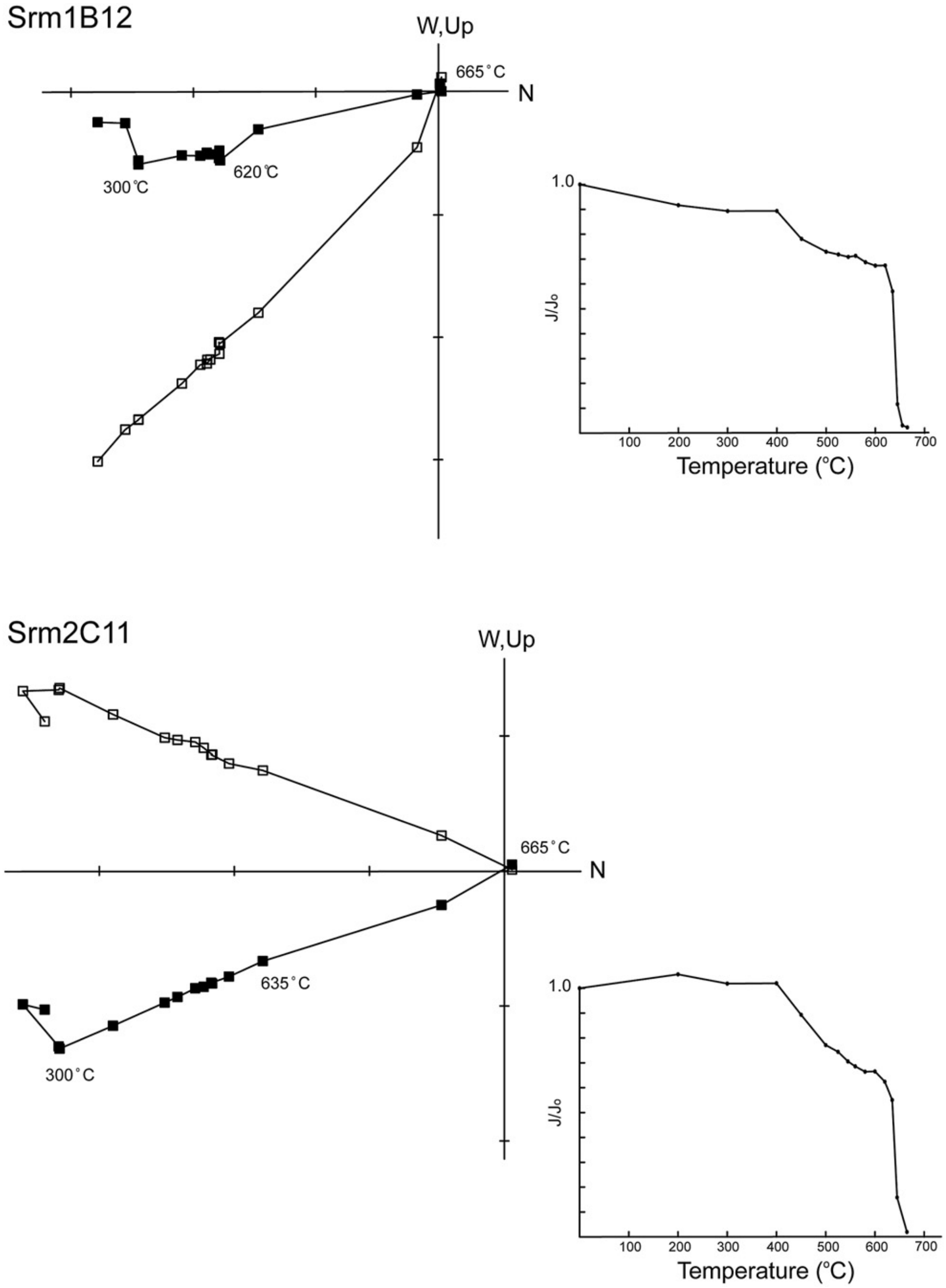

Fig. 7. Representative thermal demagnetization plots of the Red Mountain Formation in geographic coordinates and associated intensity plots. Symbols as inFig. 3. Ticks represent 10.0 mA/m.

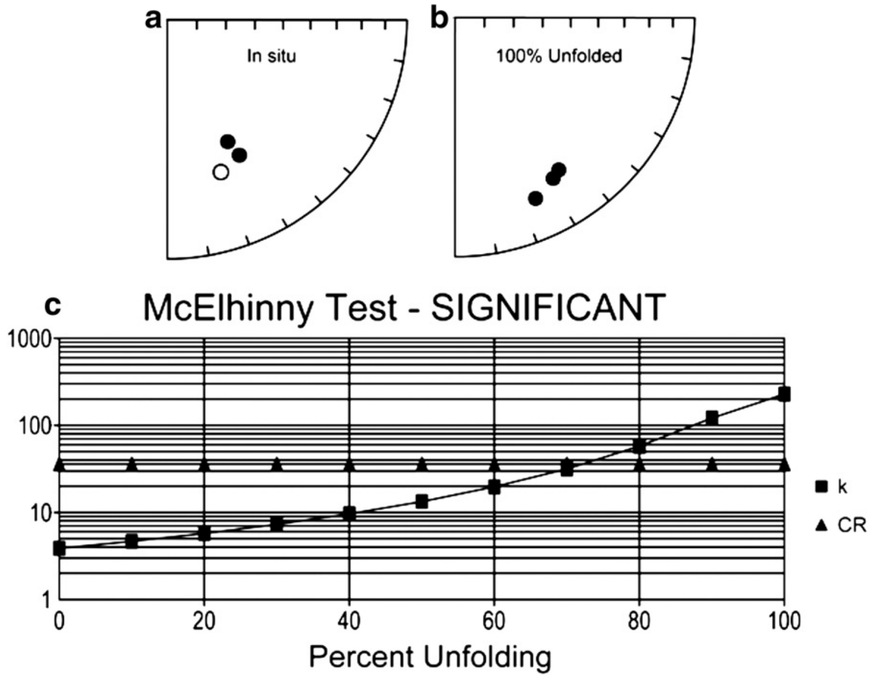

Fig. 8. Equal area projections of site means for the Red Mountain Formation in geographic (a) and tilt-corrected coordinates (b). Solid (open) circles represent down (up) directions. (c) Incremental fold test of site means plotting k on logarithmic scale versus percent unfolding. Symbols as in Fig. 4.

1977; Watts et al., 1980; Hatcher et al., 1989). As the major basal décollement unit of the fold–thrust belt, it is commonly exposed along the leading edges of the major thrust faults in the Valley and Ridge. Lithologically, the Rome Formation is quite heterogeneous, consisting of variegated shales and siltstones, as well as reddish to buff sandstones and in the lower portion, dolomitic beds (Milici, 1973; Watts et al., 1980).

Twenty-one sites were collected from the Rome Formation in the Tennessee salient, with sampling focusing on reddish sandstones and siltstones. Site distribution was chosen to maximize coverage of the curvature but was limited by outcrop distribution, especially on the southern limb of the salient (Fig. 2). Since drilling of the Rome units in the field proved to be difficult, six to eight hand-samples were collected from each site, from which one or two cubes were cut to yield a total of 203 specimens.

Typical NRM intensities for the Rome Formation vary between 0.70 and 69.00 mA/m. Stepwise thermal demagnetization was carried out in intervals of 100 °C starting at 200 °C, with steps decreasing to 10 °C above 600 °C. Most specimens produce well behaved demagnetization trajectories, although some have MAD angles that approached the 20° maximum typically accepted for paleomagnetic data. As with the Chickamauga limestones, two components are observed. A present-day, viscous overprint is typically removed entirely by the first step at 200 °C. Univectorial decay dominates between 200 °C and endpoint temperatures ranging from 630 °C to 690 °C (Fig. 5). The high unblocking temperature represents a hematite carrier of magnetization, although some specimens show a significant drop in intensity below 580 °C (Fig. 5), suggesting that some of the magnetization may be carried by magnetite. Only one site (Cr03) is completely irresolvable and is therefore omitted from subsequent analysis.

Individual site mean directions typically have individual $\alpha95'$s that are larger than those of the Chickamauga limestones, ranging between 8.3° and 28.3° (Table 2). The site–mean directions from the twenty sites are generally in the southeast quadrant with intermediate down inclinations (Fig. 6). As with the Chickamauga limestones, this corresponds to the middle to late Paleozoic segment of the Laurentian APWP. The magnetization of the Rome Formation, therefore, can also be considered a remagnetization. Although this contradicts the claim of Watts et al. (1980) that the Rome holds a primary remanence, its reliability as a primary magnetization has long been suspect (see Van der Voo, 1993, Table A1).

All Rome sites were collected from southeast dipping outcrops, with a limited range of dips. The incremental untilting of the ChRM directions reveals an insignificant tilt test, with only minor changes in the precision parameter k over the various untilting percentages (Fig. 6). However, since the tilt-test of the younger Chickamauga Group limestones reveals 60% untilting, this amount can also be applied to the Rome data. At 60% untilting, the mean direction for the Rome Formation is $D = 154.4°$, $I = 24.4°$, $\alpha95 = 8.2°$, $k = 16.8$ (Fig. 6; Table 2), similar to the Chickamauga direction.

4. Red Mountain Formation red bed results

The Red Mountain Formation consists of massive and laminated reddish hematitic sandstones, oolitic ironstones, interbedded shales

Table 3
Paleomagnetic results from the Red Mountain Formation red beds.

Site	Latitude	Longitude	Strike	Dip	N/No/H	Geo Dec	Geo Inc	TC Dec	TC Inc	α95	k
Srm01	34.690	−85.189	27°	22°	10/12/7	153.7°	42.7°	145.8°	24.1°	7.5°	41.93
Srm02	34.801	−85.110	215°	60°	11/11/6	160.7°	−33.1°	156.0°	18.4°	5.2°	78.31
Srm03	34.907	−85.099	37°	15°	11/11/7	152.0°	36.2°	148.6°	22.4°	6.8°	45.60
SrmMean					3/3			150.2°	21.7°	8.7°	200.53
Perroud and Van der Voo, 1984					27/29			150.0°	20.0°	3.5°	64.00
Hnat et al., 2008					21/21			150.2°	19.0°	3.5°	107.74

Labels as in previous tables. Tilt-correction is 100% unfolding.

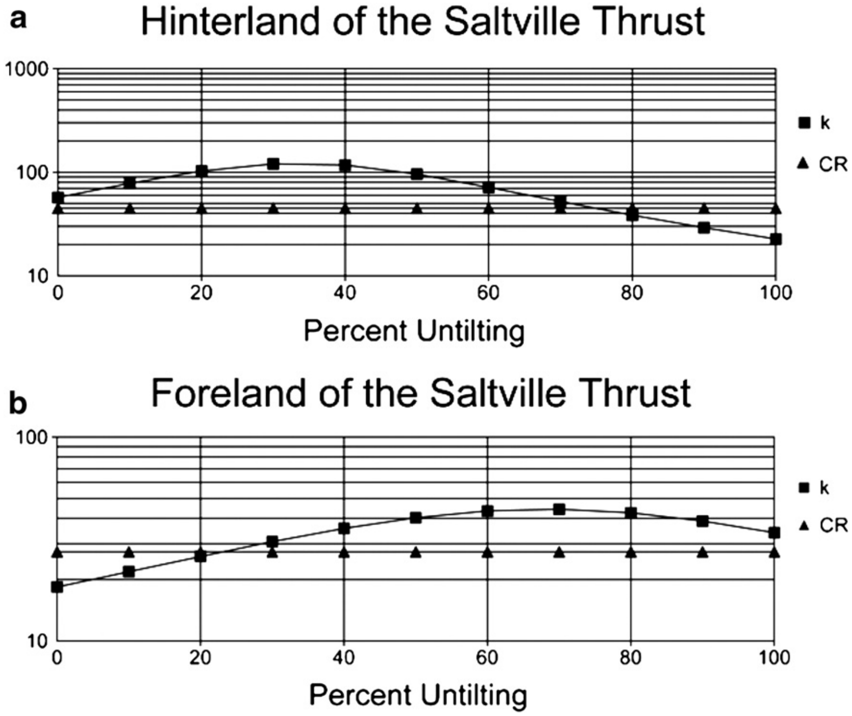

Fig. 9. Incremental tilt-test results from Chickamauga sites located both in the hinterland (a) and foreland (b) of the Saltville thrust. Symbols as in Fig. 4.

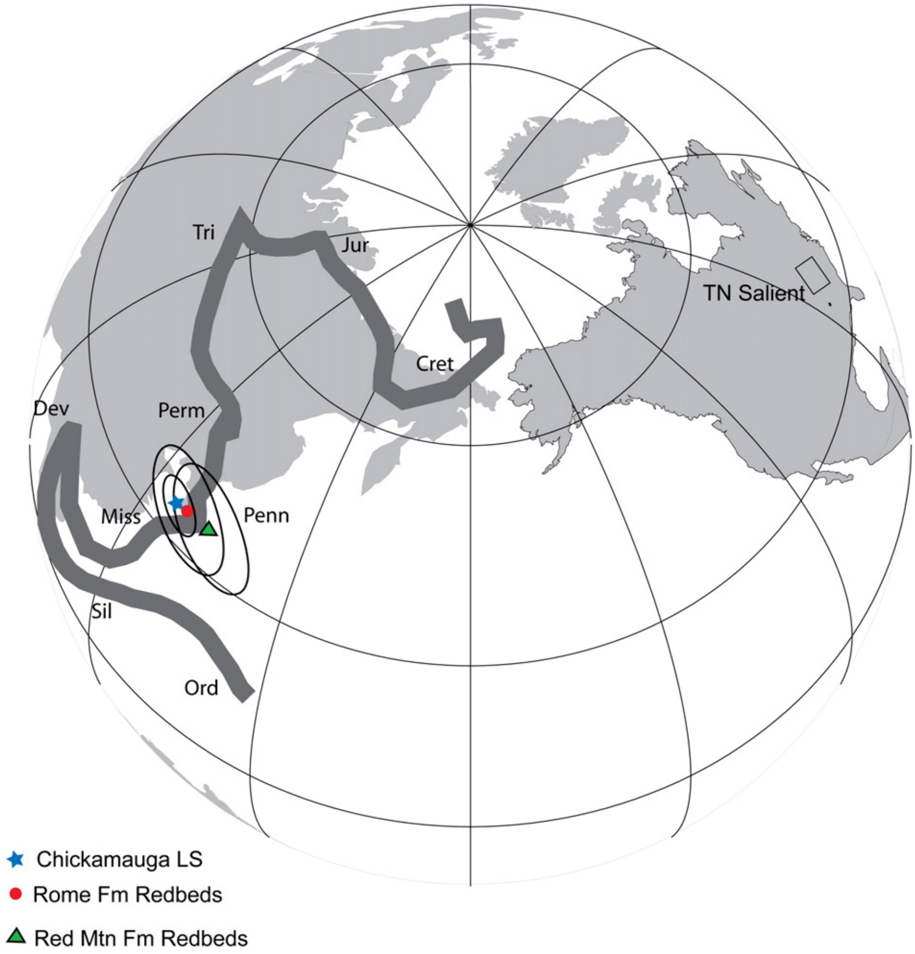

Fig. 10. Calculated paleopoles and associated confidence ovals (dp, dm) for the Chickamauga Group limestones (star), Rome Formation red beds (circle) and Red Mountain Formation red beds (triangle). North American APWP derived from Torsvik et al. (2008); Table 3) and Van der Voo (1993; Table A1), as shown in Table 4.

and gray sandstones, lesser pebble conglomerates and limestone lenses. Sampling focused primarily on the hematitic sandstones, was restricted to the north–south striking thrust belt rocks in northwestern Georgia because of a lack of outcrop in Tennessee. In northwestern Georgia, the Red Mountain Formation's age ranges from Early Silurian (Llandoverian; Berry and Boucot, 1970) to Late Silurian (Pridolian; Berdan et al., 1986), with many internal disconformities as recognized by biostratigraphic work.

Six to seven hand-samples were collected from three sites of the Silurian Red Mountain Formation, with one to two specimens being cored from each sample totaling 32 specimens. Two sites from east-dipping strata and one from west-dipping strata were collected to obtain a fold-test. NRM intensities vary between 7.0 and 86.0 mA/m. Stepwise thermal demagnetization typically reveals univectorial decay to the origin, with intensity commonly dropping sharply between 630 °C and 680 °C (Fig. 7), which is expected for the Red Mountain Formation based on previous results (Perroud and Van der Voo, 1984; Hodych et al., 1985; Hnat et al., 2008). The high unblocking temperature is indicative of a hematite carrier of magnetization.

In situ site mean directions are southeast and moderately down for the east-dipping sites and moderately up for the west-dipping site (Fig. 8). A fold-test carried out on all sites shows that after 100% tilt-correction, all sites are well clustered with $k = 200.53$, increased from $k = 3.86$ at 0% tilt-correction (Fig. 8). The mean direction for the three Red Mountain Formation sites is a southeast and down direction of $D = 150.2^\circ$, $I = 21.7^\circ$, and $\alpha95 = 8.7^\circ$ (Table 3).

5. Discussion

5.1 Age and relative timing of magnetization in the Tennessee salient

The paleomagnetic fold-test was applied to the results from all datasets to test the relative age of magnetization, producing significant results for the Chickamauga Group limestones (Fig. 4) and the Red Mountain Formation red beds (Fig. 8). Since sampling of the limestones is widespread, the tilt-test for this unit is used to infer the relative age of deformation throughout our study area in the fold–thrust belt. At 60% untilting, k is at a maximum, suggesting more than half of the tilting had occurred on the dipping thrust sheets by the time remagnetization took place. Separating the data into two subsets from the foreland and hinterland sides of the Saltville thrust allows us to infer the progression of deformation. The Saltville thrust is a major displacement thrust (~100 km; Hatcher et al., 2007) in the southern Appalachian, separating a zone of major folding toward the hinterland and a zone dominated by imbricate thrusts toward the foreland (Woodward et al., 1988). While the difference is not statistically significant, the two tilt-tests suggest that the hinterland sites were more tilted (k maximum = 30% untilting) during remagnetization than sites located more toward the foreland (k maximum = 70% untilting) (Fig. 9). This is a similar situation to that in the Pennsylvania–Maryland fold–thrust belt, which shows a post- to syn- to-prefolding magnetization from the hinterland to the foreland (Stamatakos et al., 1996). However, since the variation of untilting is not statistically significant, the bulk 60% untilting is used to calculate a paleomagnetic pole for the Chickamauga limestones. Moreover, the difference in paleomagnetic direction between the 60% tilt-correction and the two subsets is minimal (<1°).

To determine an approximate age for these remagnetizations, and thus, deformation, the mean directions for each dataset are compared to the APWP of Laurentia, constructed from published data found in Torsvik et al. (2008; Table 3) and Van der Voo (1993; Table A1). The remagnetizations for all units occurred during a reversed polarity interval. The mean paleomagnetic pole for the tilt-corrected Ordovician Chickamauga limestones clearly lies on the Pennsylvanian segment of the path (Fig. 10; Table 4). The mean paleopole for the Rome Formation is calculated using a similar amount of untilting used for the Chickamauga limestones, despite the tilt-test being insignificant for the Rome. The resulting paleomagnetic pole also corresponds to the Pennsylvanian portion of the APWP and is statistically indistinguishable from the Chickamauga direction, further justifying our tilt correction procedure. Finally, the paleomagnetic pole calculated from the 100% unfolded Red Mountain Formation also lies on this segment of the path (Fig. 10; Table 4).

Based on our analysis of the data, we conclude that remagnetization in the southern Appalachians affected both carbonates and red

Table 4
Paleomagnetic poles from this study along with published paleopoles for North Laurentia for the interval from the Mississippian to the Permian.

Unit	P_{lat}	P_{long}	α95	Age	Source
Chickamauga Group	34.7°	126.4°	3.9°	–	
Rome Formation	35.6°	127.2°	8.2°	–	
Red Mountain Formation	35.8°	131.9°	8.7°	–	
Previous results					
Ochoan red beds	55°	119°	15°	252	Torsvik et al. (2008)
Bernal Formation	50°	120°	8°	252	Torsvik et al. (2008)
Basic sill, Prince Edward Island	52°	113°	5°	252	Torsvik et al. (2008)
Dewey Lake Formation	51°	126°	5°	254	Torsvik et al. (2008)
Guadalupian red beds	51°	125	5°	260	Torsvik et al. (2008)
Artinskian Pictou red beds	42°	126°	3.6°	264	Torsvik et al. (2008)
Toroweap Formation	52°	125°	10°	275	Torsvik et al. (2008)
Churchland pluton	34°	126°	16.3°	282	Torsvik et al. (2008)
Elephant Canyon Formation	42°	122°	5°	283	Torsvik et al. (2008)
Cutler Formation	41°	122°	2°	283	Torsvik et al. (2008)
Fountain and Lykins Formations	45°	126°	13.1°	283	Torsvik et al. (2008)
Minturn and Maroon Formations	40°	121°	2.8°	283	Torsvik et al. (2008)
Cutler Formation, Lisbon Valley	41°	128°	7.1°	283	Torsvik et al. (2008)
Cutler Formation	40°	128°	12.3°	283	Torsvik et al. (2008)
Ingelside Formation	43°	128°	2°	283	Torsvik et al. (2008)
Upper Casper Formation	51°	123°	1.5°	283	Torsvik et al. (2008)
Leonardian subset	52°	119°	5°	283	Torsvik et al. (2008)
Abo Formation	47°	125°	2.1°	283	Torsvik et al. (2008)
Prince Edward Island red beds	42°	133°	6°	288	Torsvik et al. (2008)
Prince Edward Island red beds	41°	126°	5.8°	288	Torsvik et al. (2008)
Laborcita Formation	42°	132°	2.1°	290	Torsvik et al. (2008)
Piedmont mafic intrusions	39°	121°	10°	292	Torsvik et al. (2008)
Wescogame Formation (Supai)	44°	125°	3.4°	296	Torsvik et al. (2008)
Hurley Creek Formation	39°	125°	10°	296	Torsvik et al. (2008)
Tormentine Formation	41°	132°	4°	296	Torsvik et al. (2008)
Brush Creek Limestone	36°	124°	4.2°	296	Torsvik et al. (2008)
Lower Casper Formation	46°	129°	1.8°	297	Torsvik et al. (2008)
Morien Group	40°	131°	6°	297	Van der Voo (1993)
Dunkard Formation	44°	123°	3.9°	300	Torsvik et al. (2008)
Bonaventure Formation	38°	133°	10°	305	Van der Voo (1993)
Cumberland Group	36°	125°	5°	306	Van der Voo (1993)
Riversdale Group	36°	122°	6°	310	Torsvik et al. (2008)
Minudie Point	36°	122°	6°	312	Van der Voo (1993)
New Brunswick Volcanics I	21°	135°	10°	316	Van der Voo (1993)
Barachois Group	34°	143°	7°	320	Torsvik et al. (2008)
Shepody Formation	36°	124°	4.6°	320	Torsvik et al. (2008)
Maringouin Formation	32°	121°	4°	323	Torsvik et al. (2008)
Pomquest and Lismore Formations	29°	122°	33°	324	Van der Voo (1993)
New Brunswick Volcanics II	36°	136°	6°	325	Van der Voo (1993)
Liesville Pluton	40°	134°	3°	326	Van der Voo (1993)
Hopewell Group	34°	118°	7°	329	Van der Voo (1993)
Deer Lake Formation	22°	122°	9°	330	Torsvik et al., 2008
Mauch Chunk Formation, south PA	24°	141°	10°	330	Van der Voo (1993)
Mauch Chunk Formation, north PA	26°	143°	9°	330	Van der Voo (1993)
Maringouin and Shepody	36°	122°	3°	331	Van der Voo (1993)
Jeffreys Village Member	27°	131°	8°	333	Torsvik et al. (2008)
Fisset Br. Synfold	20°	139°	5°	341	Van der Voo (1993)
Windsor Group	36°	137°	6°	343	Van der Voo (1993)
Gaspé Dikes and Contacts	11°	148°	10°	344	Van der Voo (1993)
Spout Falls Formation	29°	143°	7°	355	Van der Voo (1993)
Chèverie Formation	24°	152°	6°	356	Van der Voo (1993)
Horton Group	32°	136°	8°	356	Van der Voo (1993)
St. Lawrence Alaskite	12°	120°	10°	360	Van der Voo (1993)
Peekskill Granite	23°	117°	16°	360	Van der Voo (1993)

Taken from Van der Voo (1993; Table A1) and Torsvik et al. (2008; Table 3), these poles were used to construct the APWP in Fig. 10. P_{lat} and P_{long} indicate paleolatitude and paleolongitude, respectively. All poles are for normal polarity. Ages given in Ma.

beds, and occurred during the Pennsylvanian. Previous studies of other units in the region show a similar remagnetization (Watts and Van der Voo, 1979; Bachtadse et al., 1987; McCabe and Elmore, 1989), implying that the bulk of the sedimentary package had experienced a major remagnetization event during the Pennsylvanian. Because the remagnetizations are carried by both hematite and magnetite, it is likely that the remagnetization is chemical in origin and due to orogenic brines that permeated the stratigraphy during deformation (Oliver, 1986; Bethke and Marshak, 1990), affecting various lithologies in different ways. The Pennsylvanian age of magnetization is slightly older than the Permian remagnetization that is pervasive in the central Appalachians and may be due to the diachronous nature of deformation along the trace of the Appalachians (Miller and Kent, 1988).

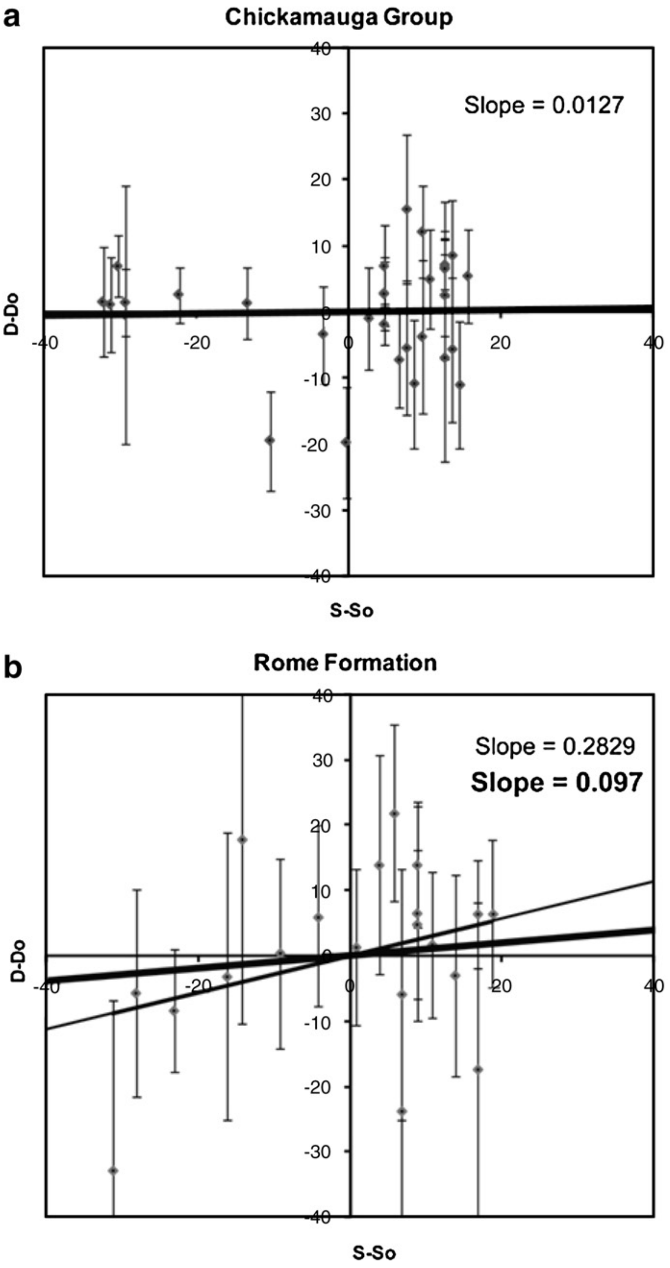

Fig. 11. (a) Declination vs. strike plot for the Chickamauga limestones. Best-fit line through the raw data has a near-zero slope (0.0127). (b) Declination vs. strike plot for the Rome red beds. Declinations are more scattered than in the limestones. Slope of best fit line through moving average of $n=3$ data (heavier line) is also near-zero.

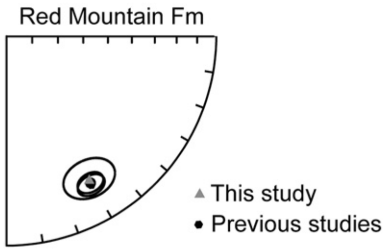

Fig. 12. Comparison of the Red Mountain Formation results from the southern limb of the Tennessee salient (triangle) with results from previous studies (Perroud and Van der Voo, 1984; Hnat et al., 2008) in Alabama (circles).

5.2. Assessment of the nature of curvature in the Tennessee salient

Using the method of Eldredge et al. (1985) to determine whether units show any trace of secondary curvature, site–mean declinations of syn-tilting magnetizations for the Chickamauga and Rome sites are plotted against the regional strike. Regional orogenic strike is used to limit the effect of local strike variations. The slope of the best-fit line through the data indicates the approximate degree to which a curved belt experienced rotations. A slope of zero represents primary curvature and a slope of one reflects a pure orocline, while intermediate correlations indicate some amount of secondary curvature.

The thirty-two Chickamauga sites are plotted with the site–mean $\alpha95'$s as error bars in declination space (Fig. 11a). Whereas the data are primarily clustered into two strike groups (with a large cluster from the northern limb), the lack of correlation is apparent, with the slope of the best-fit line being essentially zero (0.01). Also plotted are the twenty sites of the Rome Formation (Fig. 11b). The Rome data show much more scatter and result in high residuals to the trendline, which requires a moving average analysis to properly evaluate. Using a window of $n=3$ significantly reduces the scatter and reinforces the lack of correlation between strike and declination. As with the limestone results, the slope of the best-fit line is near-zero (0.01).

Because Silurian red beds are not exposed through much of the Tennessee fold–thrust belt, the Red Mountain Formation results cannot provide a test for the overall curvature of the Tennessee salient. However, we can compare our sites from the nearly north–south trending southern limb of the Tennessee salient with previously published results from the northeast-trending Alabama fold–thrust belt, thus allowing a test of the rotational history of the southern limb. Mean directions from Perroud and Van der Voo (1984) and Hnat et al. (2008) from the Red Mountain Formation in Alabama, with a regional strike of ~50°, are statistically indistinguishable from our mean direction, where the average strike is ~15° (Fig. 12; Table 3). This indicates collectively that the southern limb of the Tennessee salient was not rotated relative to the Alabama trend.

Both red beds of the Rome Formation and limestones of the Chickamauga Group show no correlation between regional strike and magnetic declination, indicating that the Tennessee salient possessed its curvature already in the Pennsylvanian when the magnetizations were acquired. The Red Mountain Formation also shows no difference in paleomagnetic direction from sites with different regional strikes, further supporting this finding.

6. Conclusions

Paleomagnetism of red beds and limestones from the Tennessee salient displays late Paleozoic remagnetization, similar to rocks from other areas in the Appalachians. Paleomagnetic analysis of the Ordovician Chickamauga Group limestones reveals a syn-tilting magnetization. The Cambrian Rome Formation red beds display a similar remagnetization. Complementing these findings, the pre-folding paleomagnetic results from three sites in the Silurian Red Mountain Formation on the N–S striking southern limb of the

Tennessee salient display an indistinguishable direction from previous results in Alabama. Comparison of these directions with the North American APWP shows that the regional remagnetization occurred during the Pennsylvanian, thus demonstrating that deformation (tilting) was partly completed by this time in the southern Appalachian fold–thrust belt. This timing is earlier than deformation in the central Appalachians, where syn-folding remagnetizations occurred during the Permian. The absence of correlation between orogenic strike and declination for both the Rome and Chickamauga results demonstrates that curvature in the Tennessee salient was either of primary origin or that secondary curvature was achieved before the Late Pennsylvanian. Although our results do not allow us to resolve the complete nature of curvature in the Tennessee salient, we can constrain the timing of any curvature development to Early Pennsylvanian to Mississippian.

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