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Remagnetization of the Tonoloway Formation and the Helderberg Group in the Central Appalachians: testing the origin of syntilting magnetizations

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SUMMARY

Palaeomagnetic, rock magnetic, geochemical and strain studies of the Helderberg Group and the Tonoloway Formation in the Valley and Ridge province of West Virginia were performed to test the origin of syntilting magnetizations and to test the mechanisms of chemical remanent magnetization (CRM) acquisition. The test for a connection between strain and remagnetization was performed by comparing the types and levels of strain with the magnetic properties between the generally coarse-grained, thickly bedded Helderberg and the thinly bedded and finer-grained Tonoloway. Standard tilt tests as well as optimal differential untilting from two transects on the Wills Mountain anticline indicate that the Helderberg contains a pervasive late syntilting (~30 per cent untilting) characteristic remanent magnetization (ChRM) whereas the Tonoloway contains a well defined early syntilting ChRM-1 (~76 per cent untilting) as well as a ChRM-2, which is similar to the ChRM in the Helderberg. The ChRMs reside in magnetite. The rock magnetic results from the two units are similar although the Helderberg samples have a finer apparent grain size, perhaps as a result of magnetic hardening. Strain data reveal an apparent correlation between the syntilting magnetizations and types/degrees of pressure solution strain. Pressure solution strain is higher in the Helderberg and lower in the Tonoloway. Strain may have caused rotation of magnetic minerals, but it not clear that the differences in strain between the units were high enough to cause the rotations that are needed to explain the tilt test results. Several other viable hypotheses were also investigated. One hypothesis is a strain-enhanced chemical process that caused dissolution and precipitation of new magnetite in solution structures during folding. A preliminary test of this hypothesis produced inconclusive results. Another hypothesis, consistent with some of the characteristics of the magnetizations in the Helderberg and Tonoloway units, is that the rocks were partially to completely remagnetized by a piezoremanent remagnetization process. Geochemical results show that origin of the remanence carrying grains cannot be attributed to orogenic type fluids but were probably caused by a burial diagenetic process.

Key words: deformation, folding, palaeomagnetism, remagnetization.

INTRODUCTION

Pervasive syntilting magnetizations, interpreted as chemical remanent magnetizations (CRMs), are common in many carbonate units (e.g. McCabe & Elmore 1989). Despite considerable progress in understanding remagnetization processes in the last 20 yr, two issues regarding the origin of these CRMs remain unresolved. First, although the growth of new magnetic minerals during folding is certainly possible, the syntilting character of some CRMs is open to question. The suspicion exists that some CRMs are not truly syntilting (e.g. Hudson *et al.* 1989), instead being the result of modification of a pre-tilting CRM by strain (e.g. Kligfield *et al.* 1983; Hirt *et al.* 1986; Cogne & Perroud 1987; van der Pluijm 1987; Kodama 1988; Stamatakos & Hirt 1994; Stamatakos & Kodama 1991a,b; Lewchuk *et al.* 2003) or stress (e.g. Borradaile 1997) during the folding process. If this is the case, then the magnetization did not behave as a passive marker during folding. Resolution of this issue is important in order to reliably apply tilt test data to resolve issues such as block rotations (e.g. Aubourg & Chabert-Pelline 1999; Grabowski & Nawrocki 2001), plate migration (e.g. Van der Voo 1993), timing of folding (e.g. Stamatakos *et al.* 1996), and oroclinal bending (e.g. Kent & Opdyke 1985; Miller & Kent 1986; Kent 1988; Van der Voo *et al.* 1997). The true origin and timing of the remagnetization also needs to be understood when using palaeomagnetism to date diagenetic events (e.g. Elmore *et al.* 1993; Banerjee *et al.* 1997). In addition, understanding of the processes involved in causing syntilting remagnetization may lead to a way of correcting for the syntilting component.

The second issue relates to the mechanism for acquisition of the CRM. Many CRMs are interpreted to form as a result of migration of externally derived fluids such as 'orogenic fluids' (Oliver 1986; McCabe & Elmore 1989; McCabe *et al.* 1989) although burial diagenetic processes have been suggested for some pervasive CRMs (Katz *et al.* 2000), including some that are syntilting (Elmore *et al.* 1993; Banerjee *et al.* 1997; Elmore *et al.* 2001). Determination of which mechanisms operate in different situations is important because if CRMs are to be used to date diagenetic events it is important to know what event is being dated.

In this study, results from the Silurian Tonoloway Formation and the Devonian Helderberg Group in the Valley and Ridge province of West Virginia will be used to investigate the origin of CRMs in folded carbonate rocks. The test for a connection between syntilting remagnetization and deformation was performed by comparing palaeomagnetic, rock magnetic and strain data from the generally coarser-grained, thick-bedded Helderberg with the finer-grained, thin-bedded Tonoloway. We hypothesize that the differences in the lithologies between the two units could result in a differential response to deformation that could cause or influence the syntilting character of the magnetizations. Rock magnetic studies were performed to compare the magnetic characteristics of the two units. Both units have similar diagenetic and deformational histories, and both are aquitards (Evans & Battles 1999). Comparing the palaeomagnetic with the geochemical results will test chemical models for CRM acquisition.

GEOLOGIC SETTING

The fold and thrust belt of the central Appalachian Valley and Ridge province developed during the Late Palaeozoic Alleghanian Orogeny (Gwinn 1964; Perry 1978; Evans & Battles 1999). This area contains a series of blindfold and thrust sequences (Gwinn 1964) and several doubly plunging anticlines and synclines with a consistent trend of about 30° to the northeast (Jacobeen & Kanes 1975) (Fig. 1). The fold and thrust belt was formed by the westward ramping of the Broadtop thrust sheet (Jacobeen & Kanes 1975; Kulander & Dean 1986). The study area is the Wills Mountain anticline, which is the westernmost anticline in the Valley and Ridge province. It is bounded to the west by the Appalachian structural front (Perry 1978; Avary 1986) and to the east by the Patterson Creek and Broadtop anticlines.

Wills Mountain is a large amplitude asymmetrical anticline that varies in width from 2 to 5.6 km and has a northwestern limb that is vertical to slightly overturned (Perry 1978). Minor folds are present on the northwestern limb (Fig. 1). Two transects perpendicular to strike were studied: the northern Antioch transect in the U.S.G.S. Keyser quadrangle and the southern Mays Gap transect in the Greenland Gap and Maysville quadrangles (Fig. 1). The plunge on the anticline is 1° or 2° to the northeast.

This study will focus on a detailed analysis of the Upper Silurian Tonoloway Formation and the conformably overlying Lower Devonian Helderberg Group. In the study area, the thinly bedded Tonoloway Formation ranges in thickness from about 130 to 180 m and is composed of limestone, dolostone and calcareous shale (Dorobek & Read 1986; Dorobek 1987; Meyer & Dunne 1990). The Tonoloway Formation lithologies are predominantly fine grained, such as carbonate mudstone, but the unit also contains coarser-grained wackestones, packstones and grainstones. In comparison, the Helderberg Group ranges in thickness from 80 to 120 m (Head 1974) and it contains grainstones, packstones, wackestones and carbonate mudstones, but it is predominantly composed of coarse-grained lithologies (Dorobek & Read 1986; Dorobek 1987; Meyer & Dunne 1990). These two units have experienced the same deformation history, the same pressure-temperature-fluid conditions (Evans & Battles 1999) and were both remagnetized (Elmore *et al.* 2001; Lewchuk *et al.* 2003) during the Late Palaeozoic Superchron.

A eustatic rise in sea level during the Late Silurian, following the Taconic Orogeny during the Middle to Late Ordovician, allowed for the deposition of the Tonoloway limestone (Dennison 1970). The Early Devonian was marked by a rise in sea level and extensive deposits of the Keyser Formation at the base of the Helderberg Group, which conformably overlie the Tonoloway within the study area. Both units were deposited in shallow water carbonate environments on the eastern side of the central Appalachian foreland basin during a time of tectonic quiescence (e.g. Dorobek & Read 1986). Carbonate activity ceased with rising relative sea level, widespread deposition of deep-water marine shales, and the onset of the Acadian Orogeny late in the Devonian (Dorobek & Read 1986).

Evans & Battles (1999) described the Palaeozoic stratigraphic succession in the study area as a regional hydrologic system that was connected at the formation level during the Alleghanian Orogeny. They found that groups of formations were chemically and isotopically isolated from adjacent units. For example, the Middle Ordovician Trenton through Lower Devonian Helderberg was interpreted to be a regional aquitard, containing mostly *in situ* fluids with fluid inclusion trapping temperatures ranging from 60° to 160°C. The overlying Oriskany through Upper Devonian Chemung formations contain higher trapping temperatures ranging from 155° to 230°C. This interval was interpreted to be a regional aquifer system with the increase in temperature due to advected heat.

A previous study of the Helderberg Group and Tonoloway Formation on the adjacent Patterson Creek anticline by Lewchuk *et al.* (2003) reported that both units have similar CRMs that reside in magnetite, but fold test results suggest differences between the two units. The CRMs are syntilting in the Helderberg and early syntilting to pre-tilting in the Tonoloway. The early syntilting sites exhibit less pressure solution strain compared to the syntilting sites. Apparently identical magnetizations from adjacent sites may have very different histories and/or responses to deformation. Lewchuk *et al.* (2003) suggest that their results may indicate a relationship between deformation and alteration of the magnetization.

METHODS

Specimens were collected in the field by using a gasoline-powered portable drill. Five to twelve 2.5 cm diameter cores were drilled at 21 sites and were oriented *in situ* with an inclinometer and a Brunton compass. All cores were drilled in the same bed within 1 m of each other along strike. The sites include both limbs of the Wills Mountain anticline along two road transects, Antioch and Mays Gap (Fig. 1). Along the Antioch transect, eight sites were located in the Helderberg and six sites were in the Tonoloway. Five of the Helderberg sites along the Antioch transect were collected on a small

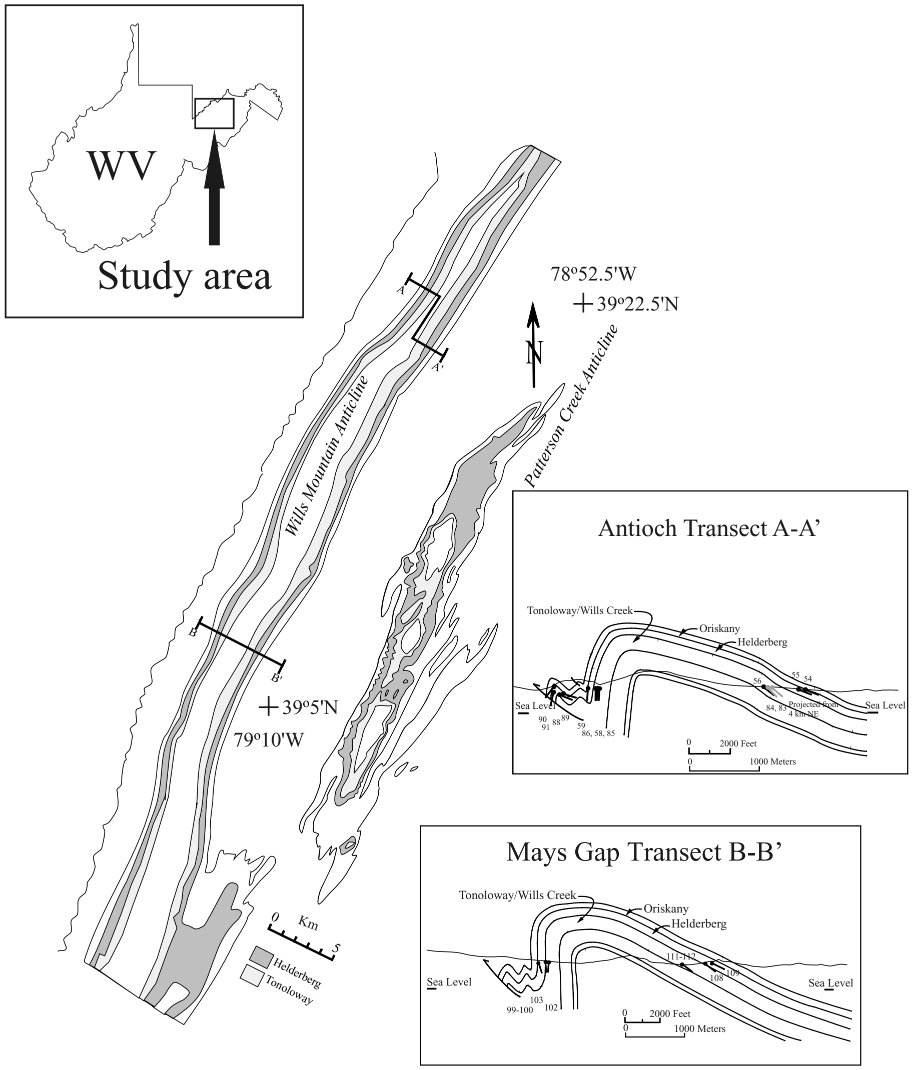

Figure 1. Map of the Wills Mountain study area in the Valley and Ridge province of the central Appalachians. Outlines of the units examined in this study are shown along with the Antioch transect (A-A′) and the Mays Gap transect (B-B′). Inset map shows the study location in West Virginia. Cross sections show the site locations from the Antioch (A-A′, and Mays Gap (B-B′) transects. The bars by the sites show the dip direction and dip amount.

fold (Antioch West fold) to the west of the Wills Mountain anticline. Approximately 27 km south of the Antioch transect is the Mays Gap transect, four sites were collected in the Helderberg and four in the Tonoloway.

Specimens were cut to 2.2 cm in length and the natural remanent magnetization (NRM) was measured on a 2G Enterprises three-axis cryogenic magnetometer housed in a magnetically shielded room. All samples underwent stepwise demagnetization by heating up to 600°C in a shielded Schonstedt TSD-1 oven. The heating steps were generally by 20°C above 300°C. Alternating field (AF) demagnetization resulted in curved demagnetization paths on orthogonal projections, suggesting vector addition of two components. Therefore, thermal demagnetization was used to better resolve components. The decay pattern was displayed using orthogonal projections (Zijderveld 1967), and principle component analysis (Kirschvink 1980) was performed on line segments with maximum angular deviations (MAD) of less than 10° to calculate the specimen directions. Fisher (1953) statistics were used to calculate mean site directions.

Low-temperature demagnetization (LTD; Dunlop & Ozdemir 1997) was performed on a representative set of specimens to assess the possibility that the characteristic remanent magnetization (ChRM) was contaminated by overlap with a resistant Modern viscous remanent magnetization (VRM). After measuring the NRM, representative specimens were submerged in liquid nitrogen and subjected to temperatures below −196°C for 30 min. The specimens were warmed to room temperature in a shield, and the NRM was remeasured. Most of the specimens were subjected to one or in some cases two cycles of LTD prior to thermal demagnetization.

The specimen directions in geographic coordinates were geometrically restored to horizontal (stratigraphic coordinates) in the tilt tests. In particular, the parameter tilt test formulated by Watson & Enkin (1993) was performed using site means to test for the best grouping of untilting from −50 to 150 per cent (in 10 per cent increments). Tilt tests were conducted for each unit along both transects. In addition, a tilt test was performed on the small secondary fold to the west of the Antioch fold and specimen directions were also used for an incremental tilt test on one site at the hinge of this small fold. A regional tilt test was also performed on all sites from each unit. Fold plunges are minimal and were not considered in the tilt tests. Small circle analysis (Shipunov 1997), using the optimal differential untilting (ODU) function of PMSTAT (R. Enkin, as modified 2004, Geological Survey of Canada, personal communication, 2004), was performed on the folds with at least four sites to determine to what extent individual site means shared a common direction during untilting. The advantage of this test is that it untilts each site individually at differing rates to derive a common direction from the intersection of their small circle paths from geographic to stratigraphic coordinates, rather than untilting each limb symmetrically to the best grouping of site directions. The result yields a set of untilting percentages for each site at this shared direction. A regional ODU tilt test was also performed for each unit.

Rock magnetic analysis was performed on one representative sample from each site of the Helderberg and Tonoloway from the Antioch and Mays Gap transects to characterize the magnetizations and determine the magnetic mineralogy. An impulse magnetizer was used to acquire isothermal remanent magnetizations (IRMs). Thermal demagnetization of three perpendicular IRMs with fields of 120, 500 and 2500 mT was also performed (Lowrie 1990).

A representative suite of samples (26) from the Helderberg and Tonoloway sites at the Wills Mountain anticline were analysed in a Vibrating Sample Magnetometer (Micro VSM) at the Institute for Rock Magnetism, University of Minnesota to determine the hysteresis parameters, coercivity of remanence (Hcr), coercive force (Hc), saturation remanence (Mrs), and saturation magnetization (Ms). To further evaluate the rock magnetic characteristics of the units, the thermal demagnetization patterns (zero field warming) of low-temperature saturation IRMs (2.5 T) acquired at 10 K were measured for representative untreated samples (13) on a Magnetic Property Measurement System (MPMS) at the Institute for Rock Magnetism.

Four Helderberg and 8 Tonoloway representative samples were selected for ^{87}Sr/^{86}Sr analysis. Only four Helderberg samples were chosen because some results from the Helderberg on the nearby Broadtop anticline were reported in a previous study (Elmore *et al.* 2001). Micrites were selectively sampled for the analyses. The Sr isotope ratio values were calculated and normalized following standard procedures (see Elmore *et al.* 2001). The values for each lithologic unit were compared to the coeval seawater values for the Silurian and Devonian (e.g. Denison *et al.* 1997).

Strain data from 10 sites was reproduced from Evans *et al.* (2003) and gathered for an additional three sites (102, 103 and 108) following the techniques described in Lewchuk *et al.* (2003) and Evans *et al.* (2003). Specimens were tested for amounts of compaction pressure solution, grain boundary sliding, tectonic pressure solution and twinning strain to determine a percentage of shortening. The solution structures were examined by optical reflectance microscopy and scanning electron microscopy–energy dispersive analysis (SEM–EDA).

RESULTS AND INTERPRETATIONS

A low-temperature (NRM to 300°–325°C) VRM with northerly declinations and steep down inclinations was removed from the Helderberg and Tonoloway specimens during thermal demagnetization (Figs 2a and c). This VRM is commonly stronger in intensity than the ChRM (e.g. Figs 2a and c). Representative specimens from 9 sites were subjected to low-temperature treatment prior to thermal demagnetization. In most specimens, the LTD did not significantly change the NRM intensities. The directions after thermal demagnetization for the LTD specimens generally exhibited only minor changes compared to the untreated specimens. If the changes were greater than 10° they did not follow a consistent pattern. Specimens from only one site exhibited a change in inclination that is consistent with removal of a resistant Modern VRM that has a high-temperature tail.

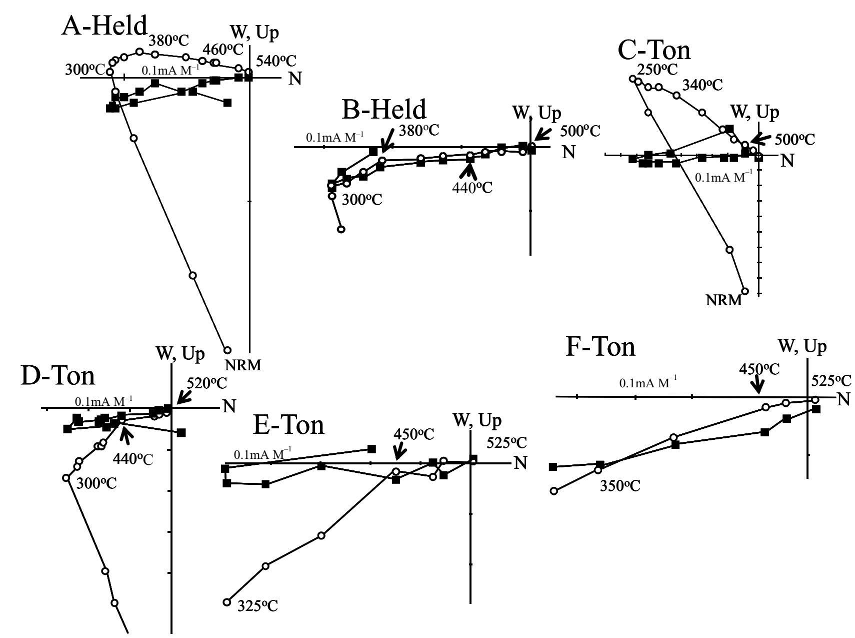

Figure 2. Orthogonal projections of representative specimens from Wills Mountain. (a) Helderberg sample with the VRM and one ancient ChRM. (b) Helderberg with the ChRM and a possible second component between 320°–380°C. (c) Tonoloway specimen with a VRM and ancient ChRM-1. (d) Tonoloway with two possible components: ChRM-1 between 325°–450°C and a noisy ChRM-2 above 450°C. (e) Tonoloway with ChRM-1 (300°–440°C) and ChRM-2 (440°–520°C). (f) Tonoloway with vertical component that is curved (moderate to shallow) as temperature increases. The horizontal projections have solid points and apparent vertical projections have open points. The NRM step and some low-temperature demagnetization steps were removed from B, D, E, and F to more clearly show the behaviour at higher temperatures. All projections are in geographic coordinates.

Table 1. Site mean statistics.

Site	Unit	Lith	N/N$_0$	Strike	Dip	GDec	Ginc	k	α_{95}	TDec	TInc	k	α_{95}	ODU
							Antioch							
33	Held-W	p	8/8	217	85	173.3°	−29.8°	259	3.2°	175.9°	33.6°	261.5	3.2°	21/40
9	Held-E	p	8/8	217	90	166.3°	−19.2°	374.3	2.9°	188.2°	47.0°	374.3	2.9°	21/20
91	Held-W	p	6/6	227	60	180.9°	−23.6°	81.8	7.5°	180.2°	21.8°	83.2	7.4°	21/40
54	Held-E	p	7/10	18	22	165.9°	−6.8°	392.8	3.0°	170.1°	−17.9°	434.5	2.9°	0/0
55	Held-E	p	7/8	18	22	164.7°	10.2°	368.7	3.1°	163.4°	−2.2°	368.7	2.9°	100/100
88	Held-W	p	8/8	25	30	168.9°	−0.4°	549.9	2.4°	172.9°	−17.5°	598.4	2.9°	87/25
89	Held-W	p	8/8	17	24	167.0°	−3.9°	120.9	5.1°	170.6°	−15.4°	120.6	2.9°	100/34
58	Ton	w	13/13	222	84	188.3°	−41.8°	656.7	1.6°	173.3°	20.0°	653.8	1.6°	89/88
85	Ton	g	9/9	222	83	198.9°	−36.6°	46.8	7.6°	181.8°	13.9°	46.8	7.6°	95/95
86	Ton	p	8/8	222	90	205.0°	−48.1°	110.2	5.3°	172.6°	11.3°	106.7	5.4°	100/100
56	Ton	w	8/8	30	38	164.6°	27.4°	3329.5	1.0°	158.6°	−1.5°	3329.5	1.0°	44/44
83	Ton	m	10/10	36	40	172.3°	32.8°	390.1	2.4°	163.5°	2.4°	387.7	2.6°	64/69
84	Ton	m	6/9	31	45	167.7°	23.6°	314.2	3.8°	163.5°	−9.3°	321.1	3.7°	30/31
83*	Ton	m	7/9	31	25	169.0	5.2	17.5	14.8	173.8	−23.5	17.5	14.8	–
							Mays Gap							
99	Held	p	5/9	207	62OT	172.3°	−17.9°	117.7	7.1°	205.8°	38.5°	145.6	6.4°	23/19
100	Held	p	7/7	207	64OT	181.9°	−24.9°	154.3	4.9°	192.7°	32°	165.3	4.7°	39/34
108	Held	w	7/8	25	35	167.7°	7.9°	522.3	2.6°	169.1°	−13.4°	539.9	2.6°	44/61
109	Held	p	8/8	47	25	168.0°	−1.6°	374.9	2.9°	170.9°	−22.8°	374.9	2.9°	0/19
102	Ton	m	7/8	207	90	190.0°	−35.2°	146.0	3.9	170.6°	13.8°	242.6	3.9	82/97
103	Ton	m	7/7	207	75	180.2°	−32.7°	1138.1	1.8°	167.5°	13.1°	1139.1	1.8°	81/98
111	Ton	w	7/7	34	39	165.6°	11.5°	71.1	7.2°	167.1°	−17.8°	72.0	7.2°	25/0
112	Ton	w	6/6	30	36	174.4°	23.4°	40.6	10.6°	168.3°	0.4	41.4	10.5°	86/47

Notes: The mean palaeomagnetic results are listed for all sites per transect and lithologic unit. All data are from the ChRM from each unit except for 83* which is for Tonoloway ChRM-2. W and E indicate the west or east fold from the Antioch transect. N/N$_0$ is the number of specimens used for this study versus the number of demagnetized specimens. GDec. is geographic declination, GInc. is geographic inclination, TDec. is tilted declination, TInc. is tilted inclination, k is a precision parameter, α_{95} is the 95 per cent cone of confidence. Lith is Lithology; p, packstone; g, grainstone; w, wackestone; m, mudstone (Dunham 1962). OT, overturned beds. ODU refers to the optimal differential untilting function of PMSTAT (Enkin, as modified 2004, Geological Survey of Canada). The first number is the ODU value for the individual transect tilt test and the second number is for the regional tilt test. The ODU values for the individual sites on the Antioch East fold are shown, but the best grouping results are not shown on Table 2 because there were only three sites.

Palaeomagnetism-Helderberg Group

At temperatures between 360°–380°C and 500°–525°C, a ChRM with southerly declinations and shallow inclinations is removed (Fig. 2a). In many specimens, the change from the VRM to the ChRM is curved in the 300°–400°C temperature range on the orthogonal projections (Fig. 2a) whereas in other specimens the demagnetization trajectory shows an abrupt change. In a few specimens another possible component is found in the 300°–380°C temperature range (Fig. 2b). The site mean directions produce a very tight cluster of data points with many k-values greater than 100 (Table 1).

Three incremental tilt tests were performed on the Helderberg sites: the Antioch east transect, the Antioch west fold, and the Mays Gap transect. We did not remove strain when performing the tilt tests. The Helderberg tilt tests show that the directions cross during untilting, suggesting that the ChRM is syntilting (Fig. 3a; Table 2). The incremental tilt tests indicate that the best grouping occurs at 36 per cent untilting for the Antioch west fold (Fig. 3c) and 25 per cent untilting for the three sites on the Antioch east transect (Table 2). The Mays Gap fold has a best grouping at 29 per cent untilting (Fig. 3c; Table 2). A regional tilt test with all Helderberg sites produced a similar result (Table 2).

Optimal differential untilting/small circle analysis was performed on data from the transects with four or more sites (Tables 1 and 2). For the Helderberg on the Antioch West fold, the ODU site results (Table 1) from one limb are near 20 per cent untilting and close to pre-tilting (87–100 per cent) from the other limb. This is consistent with a syntilting magnetization. The Helderberg sites at Mays Gap vary from 0–44 per cent untilting which is also consistent with a syntilting component. The distribution of the ODU site means is approximately circular (Fig. 4a). The mean directions from the ODU tilt tests are in general agreement with the Watson & Enkin (1993) tilt test results (Table 2). A regional ODU tilt test also produced a similar result to the standard tilt test (Table 2).

Site 90 lies in the hinge of the west fold of the Antioch transect with individual samples collected around the hinge within one bed. A tilt test performed on specimen directions from this site indicates maximum grouping at 30 per cent untilting (Table 2). The results are consistent with the other Helderberg tilt tests.

Tonoloway Formation

After removal of the Modern VRM, a ChRM that decays in a linear fashion to the origin with southerly declinations and shallow to moderate inclinations (Fig. 2c) is removed at higher temperatures (325° to 440°–525°C) in most specimens. In some specimens, however, closely spaced demagnetization steps revealed two ancient components at temperatures above 300°C (Fig. 2d). One component (ChRM-1) with steeper inclinations is removed at moderate temperatures (325–440°C) and a second component (ChRM-2) with shallower inclinations is removed at higher temperatures (440–520°C; Figs 2d and e). In some specimens, however, the vertical component demagnetization trajectory is curved between 325–500°C (Fig. 2f), and the magnetization never decays in a linear trajectory. These results suggest that the Tonoloway specimens may contain two ancient components.

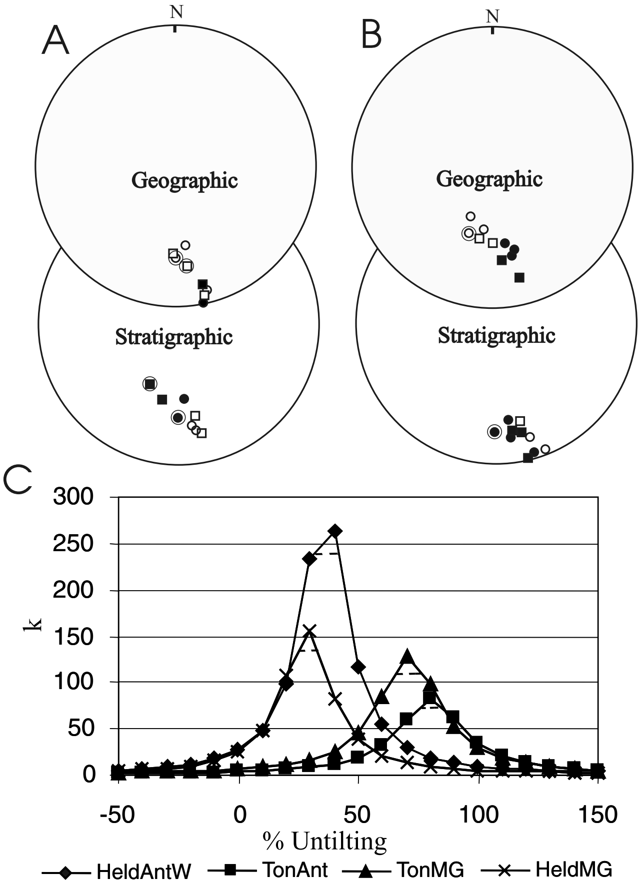

Figure 3. Stereonet projections in both geographic and stratigraphic coordinates (open symbols represent negative inclinations and closed symbols represent positive inclinations) for the (a) Helderberg sites from the Antioch west (circles) and Mays Gap (squares) transects and (b) the Tonoloway sites from the Antioch and Mays Gap transects. The α_{95} circles of confidence around the site means are shown except where the circles are less than or equal to the size of the symbols. (c) Incremental tilt test results (k, precision parameter versus per cent untilting) for the four tilt tests. The dashed horizontal lines show the error bars for the tilt test results. HeldAntW, Helderberg-Antioch West; HeldMG, Helderberg-Mays Gap; TonMG, Tonoloway-Mays Gap; TonAnt, Tonoloway-Antioch.

Most Tonoloway specimens contain ChRM-1. The site mean directions generally have a tight cluster of data points with relatively high *k*-values (Table 1). The site mean directions for ChRM-1 cross during untilting (Fig. 3b) and the two incremental tilt tests show that the Tonoloway ChRM is early syntilting with the best grouping at 81 per cent untilting for the Antioch transect and 71 per cent untilting for the Mays Gap transect (Fig. 3c; Table 2). A regional tilt test with all Tonoloway sites produced a similar result (Table 2).

The ChRM-2 has only been clearly identified in one site (site 83; Table 1), but it can be inferred to be present in other specimens based on the curved demagnetization trajectories. In addition, the specimen directions in several sites (e.g. sites 86 and 112) have a streaked distribution between a moderate down inclination like ChRM-1 and a shallow inclination like ChRM-2 (Fig. 4b). Compared to ChRM-1, ChRM-2 has shallower inclinations and is more similar to the results for the Helderberg ChRM (Table 1). The component appears to be most common on the SE limb of the anticline. A tilt test for this component was not possible because it is only well defined on one limb. A tilt test with ChRM-2 from the Tonoloway SE limb and Helderberg results from the NW limb produces a syntilting result.

The ODU/small circle analysis of the Tonoloway Antioch sites from the transects produced generally consistent site untilting percentages from the northwest limb (89–100 per cent; Table 1), although the results from the southeast limb (30–64 per cent; Table 1) are more variable. This could be because the syntilting ChRM-2 appears to be most common on the SE limb. The Mays Gap site untilting percentages are consistent with an early syntilting component except for one site (site 111; Table 1). The distribution of the ODU site means is approximately circular (Fig. 4c) and the mean directions are in general agreement with the standard tilt test results (Table 2). The regional ODU tilt test produced a similar, although slightly steeper result compared to the standard tilt test (Table 2).

The palaeomagnetic pole positions for the Helderberg and Tonoloway plot near each other on the Late Permian part of the apparent polar wander path (APWP) for North America (Fig. 5; Table 2). Although the Tonoloway pole has a lower latitude, suggesting that it could be older than the Helderberg pole, the circles of confidence overlap the poles.

Rock magnetism

An IRM acquisition plot for a representative Helderberg sample shows a rapid acquisition of magnetic intensity below 200 mT with a slight increase above 300–400 mT (Fig. 6a), suggesting that the Helderberg contains predominantly low-coercivity minerals. The thermal decay plot (Fig. 6b) shows that the magnetization in the low-coercivity axis has the highest intensity and that it, along with the other axes, completely decay by 580°C. This suggests that the magnetization resides in magnetite and is consistent with the demagnetization data as well as previous studies (Kent 1985; Evans *et al.* 2000; Elmore *et al.* 2001; Lewchuk *et al.* 2003).

An IRM acquisition plot for a representative Tonoloway sample is similar to the Helderberg plot as it shows a rapid acquisition of magnetic intensity and saturation near 300–400 mT, suggesting that the Tonoloway contains predominantly low-coercivity minerals (Fig. 6c). The thermal decay plot shows that the low-coercivity axis has the highest intensity, and it completely decays by 580°C (Fig. 6d), suggesting that the magnetization also resides in magnetite.

Hysteresis loops for both the Helderberg and Tonoloway samples are similar (Figs 7a–d) and are consistent with magnetite being the dominant carrier of the magnetization in the samples. All of the samples are wasp-waisted, which is interpreted to reflect the presence of a range of magnetite grain sizes and/or other magnetic minerals (e.g. Jackson 1990; Roberts *et al.* 1995). The fact that the loops do not close below 300 mT suggests that hematite may contribute to the wasp-waistedness of the loops (e.g. Roberts *et al.* 1995).

Coercivity (Hcr/Hc) and remanence (Mrs/Ms) ratios for samples from both units (Fig. 8a) are close to those previously interpreted to be characteristic of chemical remagnetization (e.g. Jackson 1990; McCabe & Channel 1994). A plot of Hc versus Mrs/Ms shows some overlap, but the values are higher for the Helderberg than the Tonoloway (Fig. 8b). This suggests that the magnetic grains in the Helderberg are finer because Hc and Mrs/Ms increase as particle size decreases (e.g. Dunlop 1986; Suk & Halgedahl 1996). Another possibility, however, is that the difference is due to magnetic hardening, which occurs because deformation can change the hysteresis properties of magnetite grains to those of a smaller grain size (Borradaile 1991; Jackson *et al.* 1993).

Table 2. Summary of tilt test results.

	Location	N/N_0	Per cent untilting	*In situ* Dec.	*In situ* Inc.	*k*	α_{95}	Pole	*dp*/*dm*	β_{95}
HELDERBERG	Antioch East Fold	3/3	25.1 per cent ± 3.0	164.8°	−1.3°	89.6	13.6°	49.1°N, 124.4°E	6.8/13.6	9.6°
	Antioch West Fold	4/4	35.8 per cent ± 4.3	170.1°	−7.4°	296.5	5.7°	53.5°N, 117.6°E	2.9/5.7	4.1°
	ODU	4/4		172.1°	−15.5°	370.4	4.8°	58.0°N, 115.7°E	2.5/4.9	3.5°
	Mays Gap	4/4	28.6 per cent ± 3.6	169.2°	−2.9°	159.2	7.4°	51.1°N, 118.2°E	3.7/7.4	5.2°
	ODU	4/4		168.9	−1.6°	1254.9	2.6°	50.4°N, 118.4°E	1.3/2.6	2.0°
	Regional Tilt	11/11	30 per cent ± 2.4	168.4	−5.2°	401.9	2.3°	51.4°N, 119.3°E	2.1/4.2	3.0°
	Regional ODU	11/11		168.4	−4.2°	119.2	4.2°	51.9°N, 119.5°E	1.2/2.3	1.7°
	Site 90	11/11	30.0 per cent	169°	−9.7°	64.0	5.8°	54.3°N, 119.9°E	3.0/5.9	4.2°
TONOLOWAY	Antioch	6/6	80.6 per cent ± 2.5	169.9°	3.1°	82.6	7.4°	47.9°N, 116.2°E	3.7/7.4	5.2°
	ODU	6/6		169.1°	13.1°	120.0	6.1°	42.8°N, 115.9°E	3.2/6.2	4.5°
	Mays Gap	4/4	71.2 per cent ± 6.2	167.1°	−1.3°	130.1	8.1°	49.5°N, 121.1°E	4.1/8.1	5.8°
	ODU	4/4		166.9°	3.9°	1807.9	2.2°	46.9°N, 120.4°E	1.6/3.2	2.3°
	Regional Tilt	10/10	77.7 per cent ± 2.8	167.6°	1.4°	96.6	5.0°	48.5°N, 119.4°E	2.5/5.0	3.5°
	Regional ODU	10/10		168.7°	12.5°	201.4	3.4°	43.3°N, 116.0°E	1.8/3.5	2.5°

Notes: Per cent untilting and confidence interval from Watson & Enkin (1993); *dp*/*dm* is the semi minor and semi major axis, respectively, of the 95 per cent error ellipse, β_{95}, oval of 95 per cent confidence about the pole. ODU, optimal differential untilting function of PMSTAT (Enkin, as modified 2004, Geological Survey of Canada).

Low-temperature demagnetization curves for samples from both units are similar with no consistent differences (Fig. 9). The samples do not generally show the Verwey transition for magnetite at about 110 K, which may be due to partial oxidation (e.g. Ozdemir *et al.* 1993).

Geochemical and petrographic analysis

The $^{87}Sr/^{86}Sr$ analysis of representative Helderberg and Tonoloway samples reveals that the ratio values for all samples from both units are within the coeval seawater range (0.70850–0.70880) for the Silurian and Devonian (Denison *et al.* 1997). The mean value for the Tonoloway is 0.708637 (standard deviation [std] = 0.000022, $N =$ 8). The mean for the Helderberg is 0.708704 (std. = 0.000049, $N =$ 4). The results from the Helderberg are consistent with that found in a previous study (Elmore *et al.* 2001). These results suggest that externally derived fluids did not alter the units. This interpretation is consistent with other studies of the units that suggest that they were affected by burial diagenetic processes and only locally altered by externally derived fluids (Dorobek 1987; Evans & Battles 1999; Elmore *et al.* 2001).

Strain partitioning

Strain partitioning studies (for a review see Evans *et al.* 2003) were conducted to test for a relationship between the magnitude and type of deformation and the magnetic response. The strain was measured in terms of:

(1) compaction pressure solution (CPS) in the form of macroscopic bed-parallel stylolites and/or grain-to-grain penetration with shortening normal to bedding;
(2) grain boundary sliding (GBS) determined in fine-grained rocks where passive markers exist such as pellet outlines;
(3) tectonic pressure solution (TPS) manifested as bed-normal stylolites with shortening sub parallel to bedding, and calcite twinning strain (TW) determined by the calcite strain gauge technique (Groshong 1972, 1974; Evans & Groshong 1994).

Strain data was organized by rock unit as shown in Figure 10. The pattern that emerges from the Helderberg data is that each Helderberg site has 7.3–10.3 per cent shortening due to CPS, no evidence of GBS, and varying degrees of the other strain mechanisms that contribute to the overall total strain. In contrast, the Tonoloway generally exhibits 3.1–5.0 per cent shortening due to CPS strain with up to 9 per cent shortening due to GBS strain. In addition, the compaction strain in the Tonoloway is consistently higher than tectonic strain, and the Helderberg has higher percentages of combined CPS and TPS strain than the Tonoloway (Table 3). The strain partitioning results from the neighbouring Patterson Creek anticline (Lewchuk *et al.* 2003) are similar (Table 3).

Evans & Elmore (2006) investigated the morphology and behaviour of iron oxide minerals occurring within pressure solution structures. They found that iron oxide grains interpreted to be magnetite exhibited multiple forms that behaved differently during solution structure formation. Subcubic to irregular grains and framboids composed of microcrysts that are <1 μm in diameter are interpreted to be altered from pre-existing pyrite as they were concentrated in the solution structures. They occasionally exhibit grain-to-grain dissolution (Fig. 11a). Irregular aggregates of individual, euhedral, 0.05 to 1.0 μm crystals are commonly found within, and strung out along the clay folia of the solution structures and are interpreted to be authigenic (Fig. 11b).

DISCUSSION

The maximum temperature during burial of the two units was around 150°C (Evans & Battles 1999). Given these burial temperatures, a thermo-viscous remanent magnetization (TVRM) can be ruled out as the origin of the ChRMs in both units since the maximum unblocking temperatures of 500°–525°C are too high based on the time-temperature-unblocking relationship of Pullaiah *et al.* (1975) and the experimental evidence from Kent (1985). The ChRMs in both units, therefore, could be interpreted as CRMs. As will be discussed below, however, other explanations for the origin of the remagnetizations are also possible.

The tilt test results from the Wills Mountain anticline indicate that the ChRMs in both units are syntilting but the Tonoloway ChRM-1 is early syntilting compared to the Helderberg ChRM which is late syntilting. As previously stated, Lewchuk *et al.* (2003) reported that a CRM in the Tonoloway on the adjacent Patterson Creek anticline was biased toward pre-tilting compared to a Helderberg CRM. Some Tonoloway specimens from the Wills Mountain anticline also

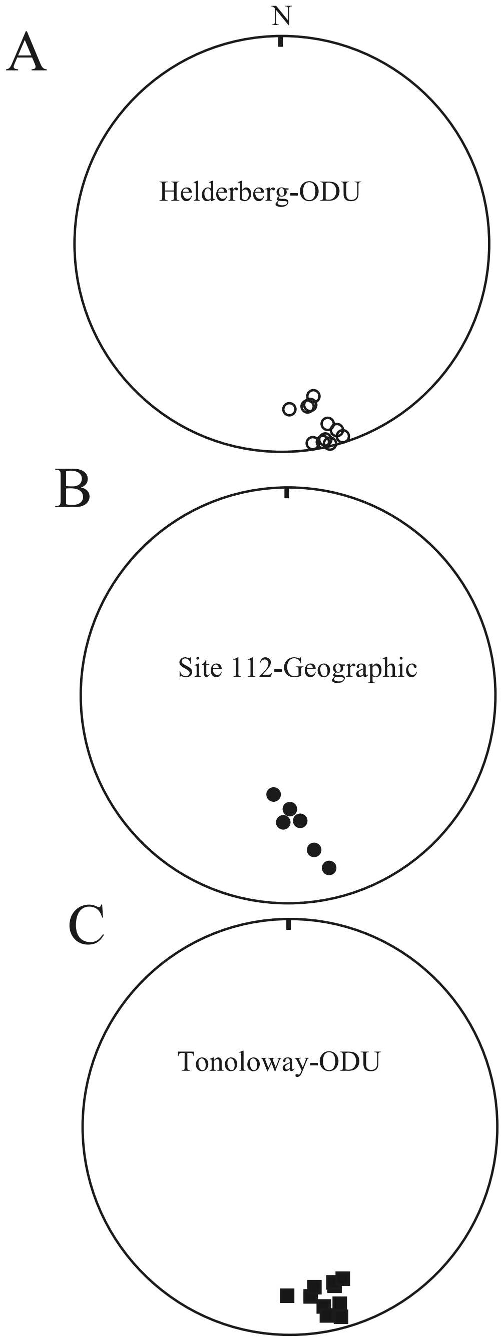

Figure 4. Stereonet projections showing (a) the ODU grouping of the Helderberg site means, (b) the specimen directions from the Tonoloway site 112 that have a streaked distribution from shallow to moderate inclinations (geographic coordinates), and (C) the ODU Tonoloway site means.

contain ChRM-2 that has shallower inclinations in geographic coordinates and is present at higher demagnetization temperatures than ChRM-1. It is similar to the ChRM in the Helderberg and is probably more syntilting than early syntilting in character. It is also interesting to note that a few specimens of the Helderberg may contain a component that is similar to the ChRM-1 in the Tonoloway (e.g. Fig. 2b).

The difference in the tilt test results is an important issue because the two units contain such similar ChRMs in terms of demagnetization and rock magnetic characteristics, as well as apparent age. There are several possible explanations for the difference in the tilt

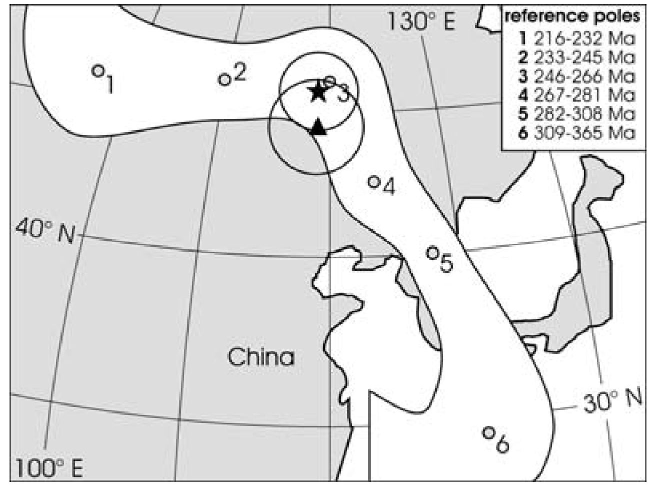

Figure 5. North American apparent polar wander curve (Van der Voo 1993) plotted with Tonoloway and Helderberg poles for the maximum untilting directions in the regional tilt test along with the β_{95}ovals of 95 per cent confidence. The poles plot along the Permian part of the curve. Helderberg: star; Tonoloway: triangle.

test results between the Helderberg and Tonoloway: (1) Because the 'best grouping' direction of a syntilting component is not unique, the different results from the two units could be only apparent, (2) the syntilting ChRMs have been differentially contaminated by the vector addition of components, (3) there were two distinct remagnetization events and (4) the ChRMs were influenced by strain and/or stress during folding.

Are the differences in the tilt test results real?

The best grouping of directions in the standard tilt test is not unique because the incremental tilt test symmetrically unfolds the data, and symmetrical folding is an assumption. It is possible, therefore, that the differences in the tilt test results between the two units are only apparent. This is not considered likely, however, because the inclination, in geographic coordinates, of ChRM-1 in the Tonoloway is steeper than in the ChRM in the Helderberg on a given limb and similar tilt corrections are applied to each unit. The ODU/small circle analysis also produced different results for the two units with the ODU values for the Tonoloway generally higher than for the Helderberg (Table 1).

Interpreting some of the ODU results, however, is not straightforward. For example, a comparison of the ODU values from the transects and regional tilt tests shows that most are similar but a few show significant changes (Table 1). The strikes on the Wills Mountain fold are close to subparallel, particularly for the Mays Gap transect, and as a result, the small circles untilting paths are near parallel and most do not intersect. This limits the value of the ODU technique and may explain some of the differences between the transect and regional tilt tests.

Were the ChRMs contaminated?

The ChRMs could be differentially contaminated by a resistant VRM. The curved demagnetization trajectories and the streaked specimen directions from some sites suggest that contamination could be a factor in the Tonoloway specimens. For example, ChRM-1 may not be a real component but the vector addition of a resistant

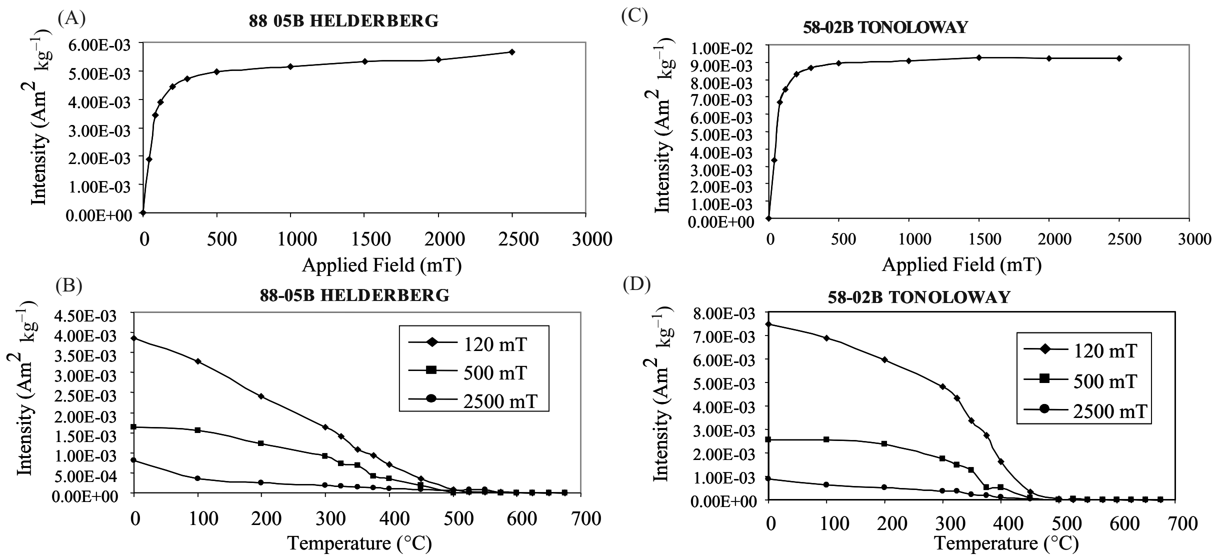

Figure 6. (a) Representative IRM acquisition plot of a Helderberg specimen, (b) triaxial thermal decay plot of a Helderberg specimen, (c) representative IRM acquisition plot of a Tonoloway specimen and (d) triaxial thermal decay plot of a Tonoloway specimen.

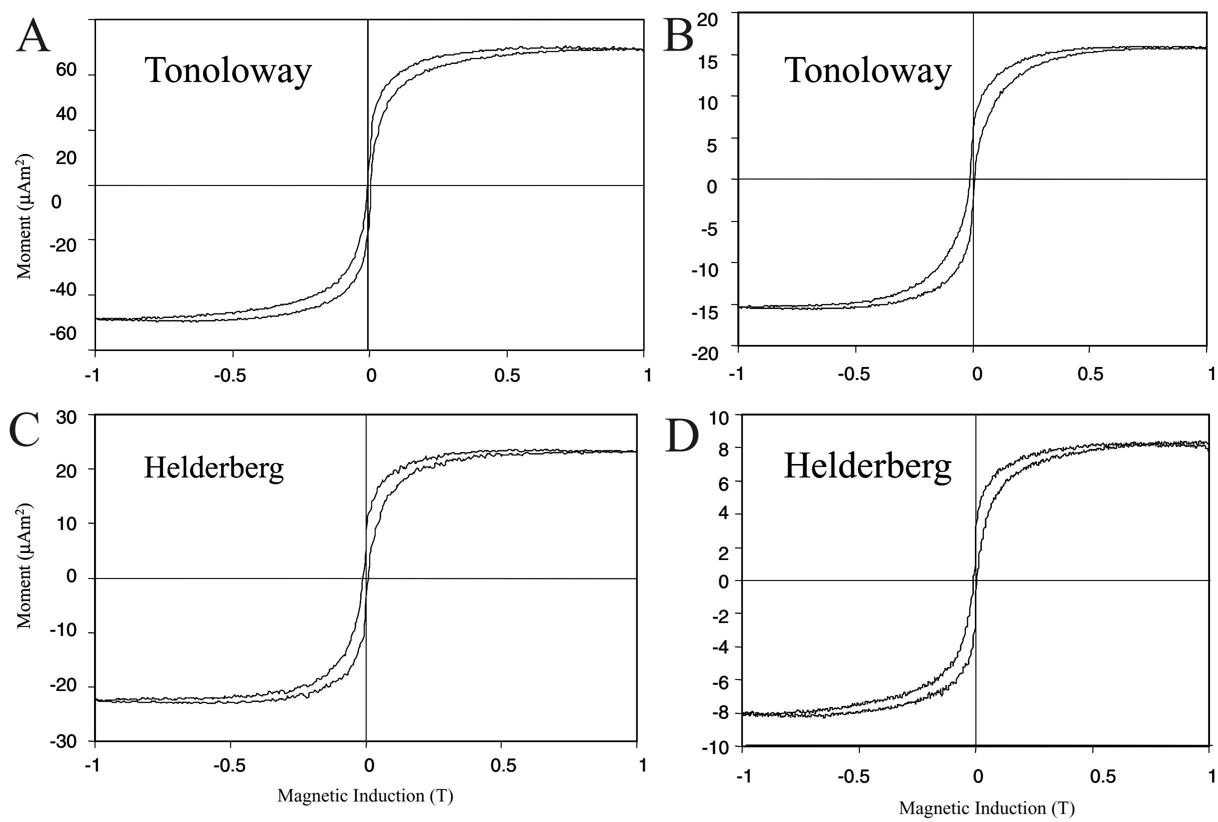

Figure 7. Representative hysteresis loops of samples from the Tonoloway Formation (a and b) and Helderberg Group (c and d). The loops are corrected for paramagnetic slope. The loops are wasp-waisted.

post-folding VRM residing in multidomain (MD) grains (e.g. Dunlop & Ozdemir 1997) and the ChRM-2. The LTD results, however, do not indicate that a resistant VRM is common in the specimens.

The geometric relationships between the two components suggest that contamination by a resistant VRM cannot explain the syntilting character of the Helderberg compared to the early-syntilting Tonoloway (e.g. Lewchuk *et al.* 2003). The Helderberg syntilting CRM has a similar declination but a more negative inclination than the Tonoloway ChRM-1. If the Helderberg were more contaminated by a Modern VRM it is not clear why it has a direction that is further from the present field direction.

Another possibility is that ChRM-1 could be pre-tilting and contaminated by ChRM-2 into a syntilting configuration. This possibility will be discussed below.

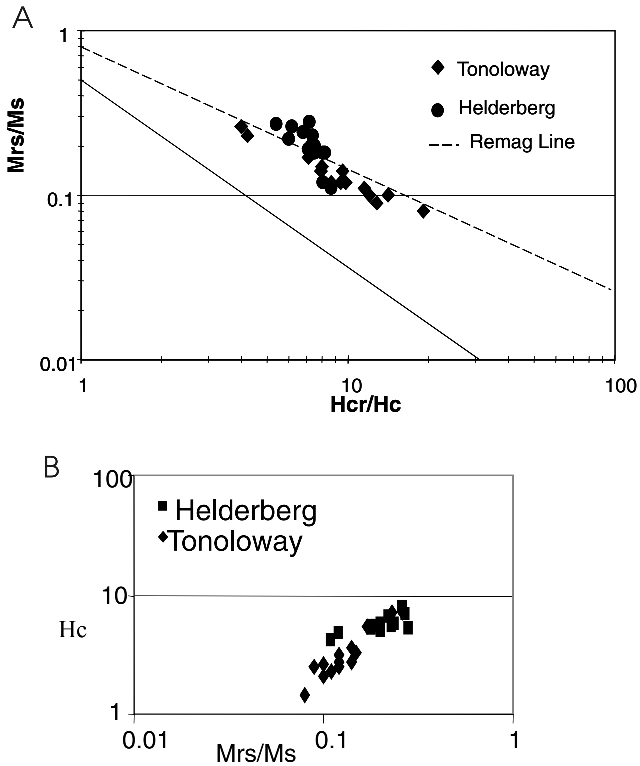

Figure 8. (a) Representation of coercivity ratios versus magnetization ratios on double logarithmic axes of samples from both units. The data from the Helderberg Group and Tonoloway Formation plot along the remagnetization line (e.g. McCabe & Channel 1994). Solid line is the trend for a single domain and MD mixture from Parry (1982). (Mrs, saturation remanence; Ms, saturation magnetization; Hcr, coercivity of remanence; Hc, coercive force) (b) Plot of Hc versus Mrs/Ms. The Hc and Mrs/Ms values are higher for the Helderberg than the Tonoloway, suggesting an apparent finer grain size in the Helderberg.

Were the ChRMs acquired at different times or over a long time interval?

The differences in the tilt tests results could be explained by acquisition of two different CRMs. This does not seem likely because the characteristics of the ChRMs are similar in terms of demagnetization, and they have the same apparent age within the resolution of the pole positions. The rock magnetic characteristics are also similar although with slight differences in the hysteresis properties. The geochemical characteristics of the rocks are also similar. As discussed by Lewchuk *et al.* (2003), it is not likely that one of the possible chemical remagnetization mechanisms (e.g. burial diagenesis or fluids) would have only affected one unit and not the other.

A syntilting magnetization could also be produced if the time of remagnetization was long relative to the folding. The remagnetization process was probably not extremely short because the ChRMs apparently record a long-term dipole field direction. The ChRMs in the Helderberg Group and Tonoloway Formation are single polarity, but this does not provide much information in terms of time constraints because they were acquired during the Late Palaeozoic Superchron. Many similar magnetizations, other than those acquired during the Late Palaeozoic Superchron or the Mid-Cretaceous Superchron, are single polarity, which suggests that remagnetization occurred within less than 1 Myr. The duration of deformation is also unknown although it was probably at least several million years. The issue of remagnetization versus deformation duration is difficult to evaluate because the timing for each process is unknown. Although a long remagnetization time relative to folding is not considered likely, it is a possibility that cannot be discounted. In any case, it cannot explain the differences in the tilt test results.

Were the remagnetizations altered by strain and/or stress?

A comparison of the strain partitioning and palaeomagnetic data suggests a possible connection between the type of strain and the degree of syntitling character (Table 3). Lewchuk *et al.* (2003) also report a correlation between deformation and possible alteration of the magnetization. The Helderberg, which has a higher-pressure solution strain (CPS and TPS), has a syntilting ChRM acquired at 25–36 per cent untilting and at lower untilting percentages in the ODU analysis. In contrast, the Tonoloway exhibits less pressure solution, and has an early syntilting ChRM that was acquired at 71–81 per cent untilting and at higher untilting percentages in the ODU analysis. The differences in the tilt test results and strain levels and types in the two units are consistent with the hypothesis that strain may have altered the ChRM in the Helderberg more than the ChRM-1 in the Tonoloway.

Several mechanisms for strain alteration of the ChRM are possible. For example, remanence-carrying iron oxide grains may rotate (e.g. van der Pluijm 1987; Kodama 1988; Stamatakos & Kodama 1991a,b), which would produce a new magnetic direction that would

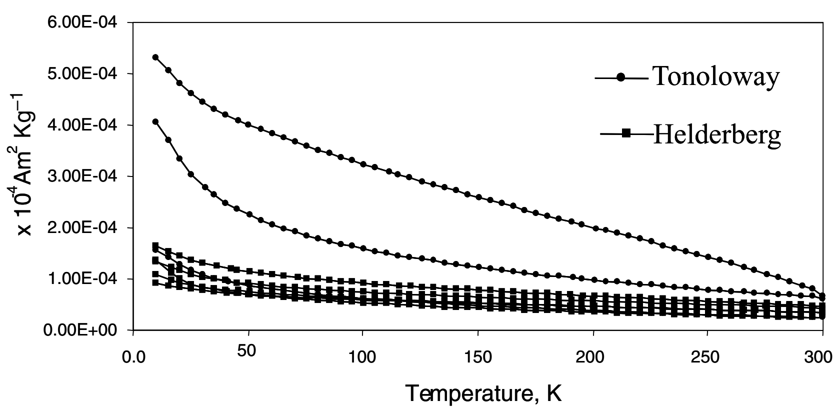

Figure 9. Representative thermal decay curves of saturation IRMs (2.5 T) acquired at 10 K for samples from the Helderberg and Tonoloway samples.

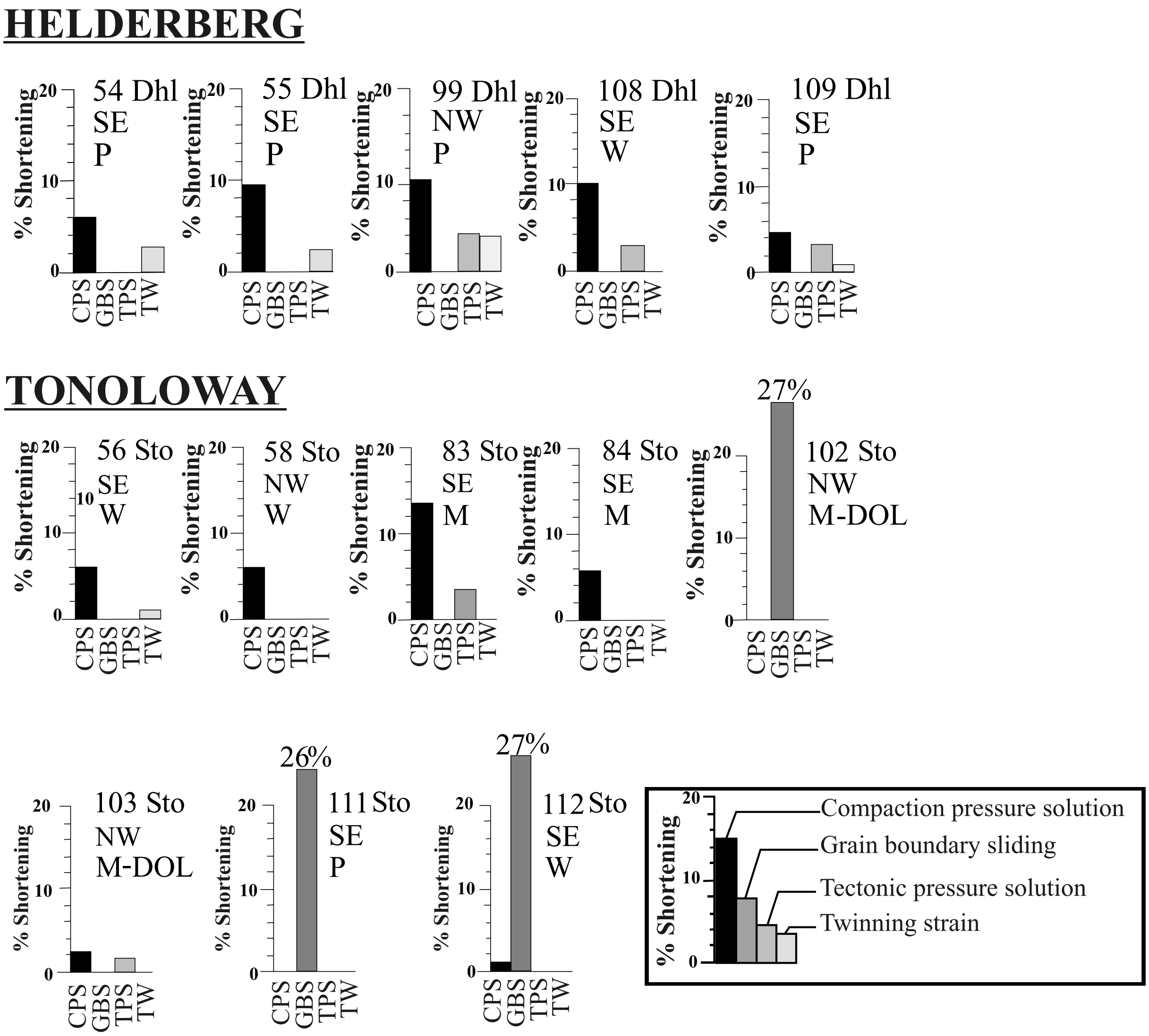

Figure 10. Strain data for Helderberg (Dhl) and Tonoloway (Sto) sites. Each graph contains the site number, rock unit, limb of fold, and lithology. DOL = dolomite, M = mudstone, P = packstone, W = wackestone.

relate to the sense of rotation and not to the ambient field at the time of deformation. Kodama (1988), based on numerical modelling of the effects of strain on simple folding, suggested that shear strain associated with flexural flow folding could rotate a pre-folding magnetization into a syntilting result. Strain and remanence studies also indicate that the amount of strain could account for the synfolding characteristics in clastic units such as the Mauch Chunk Formation (Stamatakos & Kodama 1991a; Stamatakos & Hirt 1994) and Bloomsburg Formation (Stamatakos & Kodama 1991b) but not in the Allentown Dolomite (Kodama 1988). If the rotation occurred preferentially in the pressure solution zones in the Helderberg Group and Tonoloway Formation, then it could explain the tilt test differences because more pressure solution in the Helderberg would have caused more rotation. It is not clear, however, that the differences in the strain types between the two units are high enough to account for the required differences in rotation.

Strain-enhanced CRM

Another possibility is that a strain-enhanced chemical process may have caused dissolution of remanence and other iron-bearing grains, thereby placing iron in solution to be reprecipitated elsewhere during folding. There is direct evidence for dissolution of non-remanence carrying magnetite pseudoframboids (Fig. 11a), and dissolution of smaller remanence carrying grains is also possible. Based on the amplitudes of the solution structures, up to 34 per cent of the rock volume has been removed by dissolution. If the solution structures were sites of new magnetic grain growth as evidenced by the presence of submicron-size iron oxide grains, these grains would contain remanence directions that reflect the time of grain formation (i.e. during folding). Depending on the abundance of the new grains, either whole-rock remanence could be altered to a value intermediate between the original and the new directions; or the new direction could overwhelm any older magnetization.

In this model, the Helderberg ChRM and the Tonoloway ChRM-2 would be strain-enhanced CRMs. The Helderberg only contains one component because the higher levels of pressure solution strain caused complete or almost complete remagnetization (e.g. Fig. 2b). The lower pressure solution strain in the Tonoloway would not have produced the same level of solution-reprecipitation and syntilting remagnetization as was reached in the Helderberg. As a result, a

Table 3. Averages of strain per limb and lithology.

	(Per cent shortening)			
	Compaction		Tectonic	
	CPS	GBS	TPS	TW
	Wills Mountain Anticline SE Limb			
Helderberg	7.3	0	1.6	1.3
Tonoloway	5.0	0.7	0.7	0.2
	NW Limb			
Helderberg	10.3	0	4.3	4.0
Tonoloway	3.1	9.0	0.6	0
	Patterson Creek Anticline SE Limb			
Helderberg	17.7	0	7.1	1.8
Tonoloway	9.4	2.1	1.8	0.7
	NW Limb			
Helderberg	16.1	0	5.4	2.5
Tonoloway	6.1	0	1.5	1.2

Table 3 Notes: The averages of strain are similar for the two anticlines, showing higher amounts of compaction pressure solution (CPS) and tectonic pressure solution (TPS) strain for each lithological unit, limb, and anticline. GBS = grain boundary sliding, TW = twinning strain.

pre-tilting magnetization may have been modified by ChRM-2 into the early syntilting ChRM-1 in the Tonoloway.

This model was tested by determining if there is more magnetic material in solution zones compared to the host carbonate. If the solution structures contain a syntilting remanence, then they might also contain more magnetic material than the host rock. Of course, more magnetic material should be concentrated in the solution structures as a result of dissolution but this could be accounted for by considering the volume loss as a result of dissolution. In any case, based on measurements of several large stylolites and unstylolized rocks, there are no differences in magnetic intensity. It is worth noting, however, that this model is difficult to test because there are many small solution structures in the units and out of necessity our tests focused on large stylolites. It may be that the solution structures are so pervasive in the units that it is not really possible to compare rocks with different levels of solution strain. The results of this test are interpreted as inconclusive. In a recent rock magnetic study, the hypothesis that remagnetization can cause a change in the magnetic content of deformed and undeformed rocks was tested but the results were also inconclusive (Uricia 2003). A recent laboratory study reported significant increases (3000 per cent) in magnetization after simulating burial depths of ~3 km (100 MPa) and heating at 180°C in some preliminary experiments (Moreau *et al.* 2005). Subsequent experiments showed increases, but there were no differences between samples subjected to burial pressures and those subjected to just atmospheric conditions.

In a previous study, Evans *et al.* (2003) tested for a connection between deformation mechanisms and Anisotropy of Magnetic Susceptibility (AMS) and Anisotropy of Anhysteretic Remanent Magnetization (AARM) fabrics. The AMS fabrics were found to be the result of interaction between lithology, deformation mechanisms, and strain magnitude. Different rock lithologies may have different AMS fabrics even though the rocks have undergone a similar deformation history. The AARM analyses show a correlation to the AMS ellipsoid orientations (Evans *et al.* 2003). The AMS fabric is controlled primarily by the chlorite in the solution zones and the ferroan calcite of the rock matrix. In samples where compactional pressure solution dominates the strain, the AMS fabric shows a scattering of intermediate and maximum values along the bedding plane. The AARM values follow a similar pattern. This suggests that magnetite is oriented with its long axis in the plane of flattening. Both the AARM and the AMS ellipsoids show a tectonic component indicating that magnetite in the limestones has a preferential tectonic orientation that is superimposed on the compaction fabric. For example, the long axes of the ellipsoids are generally parallel to strike while the minimum axes are usually normal to bedding.

The question is 'what is the mode of this preferential orientation?' With only 1.3 to 9.0 per cent bulk-rock shortening due to GBS and TW, there is clearly not enough strain to significantly rotate any pre-existing magnetite in the rocks. Alternatively, the solution structures offer a mechanism to either rotate pre-existing magnetite and/or grow new magnetite. Evans and Elmore found no evidence for grain rotation within solution structures. Therefore, we suggest that the AMS and AARM fabrics are related to the growth of new submicron magnetite in a stress field during the formation of the solution structures.

Piezoremanent magnetization

Another possibility is that stress and/or strain may have caused acquisition of a piezoremanent magnetization (PRM), which forms due to internal grain stresses within the magnetic grains that may move dislocations and domain boundaries during folding (e.g. Hudson *et al.* 1989). This PRM, acquired in the Earth's magnetic field direction during the folding, would remagnetize the original remanence directions. Some of the magnetic characteristics described above can be interpreted as consistent with acquisition of a PRM. For example, studies by Borradaile (1997) indicate that acquisition of a PRM can produce a smear of directions between the original

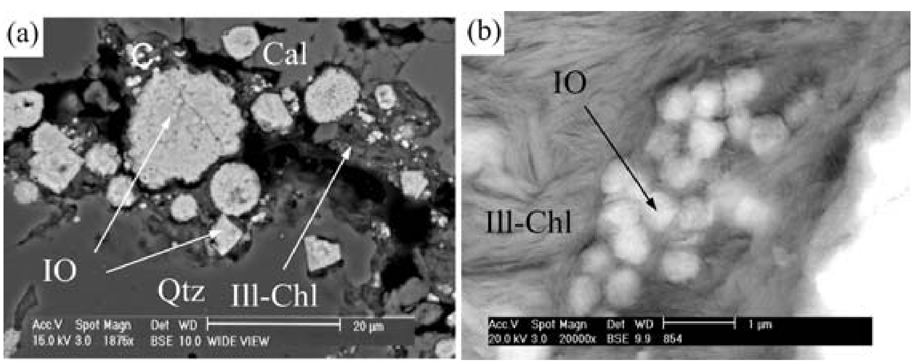

Figure 11. Backscatter SEM images of (a) stylolite containing pressure solved pseudoframboids and altered pyrite grains, and (b) stylolite with euhedral submicron-size iron oxide interpreted to be magnetite. Ill/Chl = illite-chlorite. IO = iron oxide (magnetite). Qtz = quartz. Cal = calcite.

magnetization and the PRM. This could be the explanation of the curved demagnetization trajectories and the streaked specimen directions between ChRM-1 and ChRM-2. Following this model, the magnetizations were originally CRMs but the Helderberg was completely remagnetized and the Tonoloway specimens partially remagnetized by a PRM as a result of differential stress during folding. The ChRM-1 in the Tonoloway could be interpreted as a pre-tilting CRM that has been modified by the PRM (ChRM-2) into an early syntilting configuration. The results from the one Tonoloway site (site 83) where most of the specimens contain ChRM-2 are consistent with the model because this site has higher compactional and tectonic pressure solution strains than the other Tonoloway sites and the values are similar to the strains in the Helderberg (Fig. 10). The finer grain size of the Helderberg samples, perhaps as a result of magnetic hardening due to stress (e.g. Borradaile 1991; Jackson *et al.* 1993), is also consistent with this model.

The interpretation that the Helderberg ChRM and Tonoloway ChRM-2 are PRMs is heavily based on the experimental studies of Borradaile who pointed out that his results should only be extended to natural cases with caution (Borradaile 1997). With the exception of the time factor, however, the experimental conditions (finite strains, differential stresses) were set to reflect nature (Borradaile 1997). Borradaile (1994, 1996) found that a PRM was partially reversible and had the greatest effect on the low-coercivity phases. Some experiments, however, show that a PRM can remagnetize harder components (>60 mT) (Borradaile 1997). The PRM process may have been enhanced by the long-term effects of stress during the deformation as well as moderately elevated burial temperatures (e.g. Hudson *et al.* 1989).

Another issue is how the strain would be accommodated in small magnetic grains, which are much smaller than the calcite matrix. Except for within the solution structures, we assume that remanence-carrying magnetite is evenly disseminated throughout the rock matrix, and that deformation occurred after porosity reduction. Evans *et al.* (2003) discuss the possible mechanical effects of deformation on these grains within the rock matrix.

The PRM hypothesis assumes that there were higher stresses in the Helderberg compared to most of the Tonoloway. Although the Helderberg Group may exhibit higher strains compared to the Tonoloway Formation, this does not necessarily correspond to higher stresses. The key issue is the nature of the grain-to-grain stresses which is difficult to determine. To evaluate this issue, the differential stress during deformation in selected limestone samples was estimated using the calcite twinning method (Jamison & Spang 1976; Ferrill 1998). The differential stress values in the Wills Mountain anticline samples ranged from 143 to 153 MPa for several samples. The stresses are high enough to cause a PRM based on a comparison with Borradaile's work (Borradaile 1997), but the values are similar between the Tonoloway and Helderberg limestones. A PRM may be possible, therefore, but it is not clear that the stress differences between the units could explain the tilt test results.

Based on our current knowledge of the piezoremanent remagnetization process and the characteristics of the magnetizations in the Helderberg and Tonoloway units, a PRM is a viable hypothesis for the ChRM in the Helderberg and the ChRM-2 in the Tonoloway. Additional studies are clearly needed to test this hypothesis.

Another hypothesis for the origin of the ChRM in the Helderberg and ChRM-2 in the Tonoloway is a strain modified transdomain remanence. This type of remanence forms when there is a change in the number of domains (e.g. Moon & Merrill 1986). A transdomain CRM can form as a result of grain volume increases (Merrill & Halgedahl 1995). It is also possible that strain and/or stress could cause domain walls to nucleate or denucleate, thereby creating a transdomain CRM. It is not clear, however, how a transdomain CRM could account for the differences between the two units.

Interpreting the origin of syntilting magnetizations is also complicated by a number of factors. For example, considering the apparent relationship between solution strain and syntilting character, the fact that the distribution of solution strain is not homogeneous throughout the folds studied, and even with a single formation, is a complication. Factors such as fold geometry and position of the rocks in the fold, variations in rock lithology, fold kinematic history, overlapping components and local formation fluid chemistry may also come into play. It is also possible that a combination of factors may account for the differences in the tilt test results from the two units.

Origin of remanence carrying grains

Although the origin of the ChRMs in the Helderberg may be unresolved, the origin of the remanence carrying grains is another question. They could be detrital or diagenetic in origin. The hysteresis properties suggest that they are diagenetic in origin. The mechanism that accounts for precipitation of the inferred diagenetic magnetite, however, is also open to question. Many Palaeozoic carbonates contain similar pervasive magnetizations interpreted as CRMs that form as a result of the migration of orogenic fluids (e.g. McCabe & Elmore 1989). However, externally derived fluids such as orogenic fluids are not a likely mechanism for the ChRMs in the Helderberg and the Tonoloway since these units were aquitards. Geochemical evidence, including stable carbon and oxygen isotopic data (Evans & Battles 1999), fluid inclusion data (Evans & Battles 1999), and the $^{87}Sr/^{86}Sr$ results from this study suggest that externally derived fluids did not pervasively alter these units. In addition, previous diagenetic studies indicate that the Helderberg Group was affected by burial diagenetic processes (Dorobek 1987) and only locally altered by externally derived fluids (Dorobek 1989). A burial diagenetic process in which the rocks 'cooked in their own juices', is a likely candidate for the chemical remagnetization mechanism(s) in the Helderberg and Tonoloway units. Possible mechanisms include the smectite-to-illite transformation (Katz *et al.* 1998, 2000) and maturation of organic matter (Banerjee *et al.* 1997; Blumstein *et al.* 2004). Some simulation studies have shown that magnetite can be created during burial diagenetic processes (Brothers *et al.* 1996). In addition, a recent laboratory study of natural argillaceous samples demonstrated that a magnetite CRM can form at temperatures and pressures that commonly occur in sedimentary basins by *in situ* fluids (Moreau *et al.* 2005). Testing specific burial mechanisms is difficult in the Helderberg and Tonoloway units since all the smectite and organic matter has been altered in these Palaeozoic units and presence/absence tests are not possible.

The results from this study also have implications for the hypothesized regional trends in remagnetization ages perpendicular to the trend of the orogenic belt. For example, Stamatakos *et al.* (1996) presented results from both limestone and sandstone units in the Appalachians, which suggest that there is a trend from post-tilting magnetizations in the hinterland, syntilting magnetizations in the central part of the orogen, and pre-tilting magnetizations in the foreland of the Appalachians. Enkin *et al.* (2000) reported results from carbonates in the western Canadian Rocky Mountains that indicate a trend from a pre-folding to synfolding CRM in the centre of the orogen to a post-folding TVRM in the foreland. The results of this study, as well as the results in Lewchuk *et al.* (2003), suggest that fold test results within one fold can vary and that inferences on regional trends should be treated with caution.

CONCLUSIONS

The Helderberg Group and Tonoloway Formation of the Wills Mountain anticline contain syntilting ChRMs acquired in the Permian. The tilt test results indicate that the ChRM in the Helderberg has a late syntilting character whereas the Tonoloway contains a well defined early syntilting ChRM-1 as well as a possible syntilting ChRM-2. Geochemical results show that these ChRMs cannot be attributed to orogenic type fluids but were probably caused by a burial diagenetic process.

The strain data reveal an apparent correlation between the syntilting magnetizations and types/degrees of pressure solution strain. Pressure solution strain is higher in the Helderberg and lower in the Tonoloway. Rotation of magnetic grains as a result of strain is possible, but it is not clear that differences in the strain values and types between the units would be enough to account for the required differences in rotation. Although the reason for the differences in the tilt test results remains elusive, there are several viable hypotheses. For example, one hypothesis is a strain-enhanced chemical process that caused dissolution and precipitation of new magnetite in solution structures during folding. Another hypothesis, consistent with our current knowledge of the piezoremanent remagnetization process and the characteristics of the magnetizations in the Helderberg and Tonoloway units, is that the rocks were partially to completely remagnetized by a PRM during deformation. It is also possible that a combination of processes may explain the differences in the tilt test results. Additional work is clearly warranted to better understand the reasons for the differences in the tilt test results, and to test the stress and strain-enhanced models for acquisition of syntilting remanence.

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