Resolving complexities associated with the timing of macroscopic folds in multiply deformed terrains: The Spring Hill synform, Vermont

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ABSTRACT

Determining the timing of macroscopic folds of bedding in multiply deformed terrains is difficult, especially for rocks that have undergone a succession of overprinting near-orthogonal deformations. The Spring Hill synform in southeast Vermont is an example of such a fold. The origin and timing of this structure has been the subject of several previous studies; understanding its development is crucial to unraveling orogenesis in the Vermont Appalachians. The fold formed during a deformation path that involved a succession of overprinting near-orthogonal deformations that produced matrix fabrics S₁, S₂, and S₃. These foliations developed with subvertical, subhorizontal, and subvertical orientations, respectively, before being rotated by the effects of younger deformations. The Spring Hill synform is generally thought to have formed as a recumbent structure during regional nappe development, S₃ developing as an axial planar foliation. However, we demonstrate that the Spring Hill synform developed as a fold with a steeply dipping axial plane that was overprinted by S₁ and S₂. Although this geometry and overprinting history are consistent with a D₃ time of formation, we can find no change in the asymmetry of pre-S₁ foliations across the fold. We suggest that the synform may have formed at a much earlier stage in the orogen’s history and was subsequently modified and rotated to its present geometry by the long history of west-to-east shortening that dominated the later stages of Acadian orogenesis in southeast Vermont.

Keywords: Acadian, ductile deformation, folding, foliation, orthogonal overprinting, Vermont.

INTRODUCTION

Documentation of the deformation paths responsible for development of structures within orogenic belts is a major goal of structural analysis. However, many ductilely developed structures are the product of overprinting events, and determining the deformation path responsible for the progressive development of even simple structures can be difficult (e.g., Hobbs et al., 1976). Folds are a common product of ductile deformation, and large macroscopic folds of bedding are present in all orogens. The final geometry of many large macroscopic folds of bedding should reflect, to some degree, the cumulative effect of the whole deformation history, and deciphering how such folds develop is an important part of understanding orogenesis in the middle to lower crust (e.g., Sandiford, 1989; Aerden, 1992). Consequently, use of foliation-foliation asymmetry, or bedding (Fig. 1A; Bell, 1981; Duncan, 1985). Cleavage vergence provides a geometric means of determining whether a foliation is subparallel to the axial plane of a macroscopic fold, a relationship generally considered to imply that fold and cleavage formed during the same deformation event (e.g., Ramsay, 1967; Hobbs et al., 1976). However, using cleavage vergence relationships at the micro- and mesoscopic scales to constrain the timing of macroscopic bedding folds has several major limitations.

1. An enveloping bedding surface must be defined at the mesoscopic scale, and in areas of tight folding or extensive bedding transposition, this is difficult without reliable facing direction data.

2. Determining whether a foliation is subparallel to the axial plane of a fold does not necessarily imply a direct genetic relationship between the two structures, particularly for deformation paths where foliations formed with similar orientations, or were rotated into similar orientations. This can be illustrated by comparing cleavage vergence with the related concept of foliation-foliation asymmetry, which describes the asymmetry with which a foliation (or bedding) is crenulated from the microlithon into the folia of an overprinting foliation (Fig. 1B; Duncan, 1985, Bell and Johnson, 1992). A direct genetic relationship between folds in bedding and axial plane crenulation cleavages can be inferred only when the asymmetry with which bedding curves from the microlithon into the cleavage folia reverses across the fold (Fig. 1). However, absence of such a change need not indicate the reverse (boxed area in Fig. 1B; Bell and Johnson, 1992). Consequently, use of foliation-foliation asymmetry or cleavage vergence for timing macroscopic folds can be quite equivocal.

3. To time macroscopic folds relative to episodes of deformation expressed at the mesoscopic scale, geologists must be able to correlate foliations across the macroscopically folded region. Foliations are typically correlated by style, orientation, and overprinting relationships. In multiply deformed terrains this can be difficult, because fabric develop-
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Figure 1. (A) Cleavage vergence and structural facing in rocks deformed by two phases of folding, D<sub>1</sub> and D<sub>2</sub>. A change in S<sub>2</sub> cleavage vergence across a fold hinge implies that it is axial planar to the folds. This is supported by the change in asymmetry with which S<sub>1</sub> and S<sub>2</sub> are crenulated into S<sub>2</sub> folia across the hinge. A reversal in the direction of facing on S<sub>2</sub> implies that there was an earlier phase of D<sub>1</sub> folding. (B) Same as A, but with two additional orthogonal overprinting deformation events, D<sub>3</sub> and D<sub>4</sub>. D<sub>3</sub> produced a weak, subhorizontal cleavage, S<sub>3</sub> (thin dashed lines), but little refolding of S<sub>2</sub> on the scale of the diagram. D<sub>4</sub> produced a subvertical crenulation cleavage, S<sub>4</sub>, which is an axial plane to a large synform in S<sub>3</sub> and a smaller antiform-synform couplet in S<sub>0</sub> (boxed area). S<sub>4</sub> is parallel to S<sub>2</sub> and changes vergence across the D<sub>2</sub> fold, even though it is genetically and temporally unrelated to it. However, the asymmetry with which S<sub>3</sub> and S<sub>0</sub> are crenulated into the S<sub>4</sub> folia does not change (compare i and ii). Interestingly, this asymmetry does change where a D<sub>4</sub> hinge coincides with a D<sub>2</sub> hinge (compare ii and iii), although in this case the former is a synform and the latter an antiform. It is possible to determine fold timing only by comparing the asymmetry with which earlier formed foliations pass from the microlithons into the folia of overprinting axial plane foliations (i–iv).

Figure 2. Location map and regional geology of southeast Vermont showing major lithological units and position of Spring Hill synform. Modified from Doll et al. (1961), Thompson et al. (1990), Ratcliffe et al. (1992), and Ratcliffe and Armstrong (1995, 1996). Yg—Mesoproterozoic basement gneiss of the parautochthonous Green Mountain Massif and the allochthonous Chester and Athens domes; CZh—allochthonous Neoproterozoic to Early Cambrian Hoosac Formation; Cpors—Cambrian Pinney Hollow Formation, Ottauquechee Formation, Rowe Schist; Ordovician and Cambrian Stowe Formation; Omncb—Ordovician Moretown Formation, North River igneous suite, Cram Hill Formation, Ordovician to Silurian Barnard Gneiss; DSnw—Devonian and Silurian Northfield Formation and Waits River Formation. SHS—Spring Hill synform; BHF—Butternut Hill fold; SHF—Star Hill fold. Map coordinates in meters on UTM (universal transverse Mercator) projection (zone 18) using NAD27 datum.

We present a detailed structural analysis of the Spring Hill synform in southeast Vermont (Fig. 2). Previous interpretations of this fold have featured prominently in models for the structural evolution of the Acadian orogen in southeast Vermont (Rosenfeld, 1954, 1968; Doll et al., 1961; Thompson et al., 1968, 1993; Rosenfeld et al., 1988; Ratcliffe et al., 1992, 1997a, 1997b). The classic Acadian nappe and dome style folding model, proposed to explain the development of the Chester and Athens domes, hinges to some degree on the geometry and timing of the Spring Hill synform (Rosenfeld, 1954, 1968, 1970; Thompson et al., 1968, 1993; Rosenfeld et al., 1988). Previous workers have shown that rocks in southeast Vermont preserve evidence for a complex deformation history at the microscopic and mesoscopic scales (e.g., Hayward, 1992; Ratcliffe et al., 1992, 1997a, 1997b; Bell and Hickey, 1997; Bell et al., 1998). However, the Spring Hill synform has a relatively simple geometry in plan (Fig. 3), lacking any large-scale indication of refolding. How does the Spring Hill synform fit into the complex deformation history at the microscopic and mesoscopic scales? Is its simple macroscopic geometry a product of a relatively late timing? Our efforts to answer these questions show that deformation paths expressed at the microscopic and mesoscopic scales can produce structural patterns quite different from those developed at the macroscopic scale. Detailed structural mapping combined with microstructural analysis in
three dimensions reveal that the Spring Hill synform developed as part of a cyclic pattern of overprinting subvertical and subhorizontal foliations.

GEOLOGIC SETTING

Regional Geology

The Appalachian orogen of southeast Vermont can be divided into three main lithotectonic units (Fig. 2). The oldest is composed of Mesoproterozoic basement gneisses (Stanely and Ratcliffe, 1985). These are overlain by Neoproterozoic to Middle Ordovician, or possibly Silurian, calcareous, pelitic, semipelitic, and quartzitic metasedimentary schists interlayered with metavolcanic and intrusive rocks. These two lower lithotectonic units are nonconformably overlain by a third, Silurian-Divonian, sequence of calcareous schists (Fig. 2; Ratcliffe et al., 1997a, 1997b; Thompson et al., 1993, 1997; Ratcliffe and Armstrong, 1995; 1996). The Spring Hill synform is developed within the middle (Neoproterozoic-Silurian) unit, the internal relationships of which have been the subject of recent debate (Thompson et al., 1993, 1997; Ratcliffe et al., 1992, 1997a, 1997b).

Deformation and metamorphism of the Appalachian orogen in southeast Vermont occurred during the Ordovician Taconic and Devonian Acadian orogenic events (Stanely and Ratcliffe, 1985; Armstrong et al., 1992). The Acadian deformation is traditionally thought to have involved an initial stage of regional, westward directed, nappe folding that was overprinted by large domes produced by the diapiric rise of Proterozoic gneisses and contemporaneous subhorizontal east-west shortening (Rosenfeld, 1954, 1968, 1970; Doll et al., 1961; Thompson et al., 1968, 1993; Hepburn et al., 1984). Nappe folding produced a subhorizontal schistosity that Hepburn et al. (1984) called S1. This foliation overprints an earlier foliation, S2, which is axial planar to rare isoclinal folds, and was overprinted by a subvertical crenulation cleavage, S3, during doming (Hepburn et al., 1984). Ratcliffe et al. (1992, 1997a) have suggested that Acadian orogenesis involved the westward reactivation of a Taconic thrust stack and up to five stages of generally upright folding of the whole Proterozoic to Devonian sequence during east-west-directed shortening, rather than the formation of large nappes (Stanley and Ratcliffe, 1985 Pl. 2; Ratcliffe et al., 1992, 1997a).

Figure 3. Geological map of the Spring Hill synform with representative bedding measurements. Main lithological relationships and structural features are those of Ratcliffe and Armstrong (1995, 1996), with some modification based on our own mapping. Field localities are those referred to in text. The lithological units from youngest to oldest are: Yg—Mesoproterozoic metasedimentary, granitic, and amphibolitic basement gneisses; CZh—Hoosac Formation (quartz-mica-plagioclase ± garnet schist and amphibolite [black]); Cr—Rowe Schist (quartz-mica ± plagioclase ± garnet ± chlorite metasedimentary schist and amphibolite); Om—Moretown Formation (laminated quartz-mica-plagioclase, garnet metasedimentary schist, coticule and amphibolite [gray]); Ont—North River igneous suite (trondhjemitic, tonalitic, and amphibolitic intrusive rocks); Och—Cram Hill Formation (hornblende ± garnet amphibolite and biotite-quartz granofels); Ochq—Cram Hill Formation (carbonaceous and noncarbonaceous quartz-mica-garnet ± plagioclase metasedimentary schist and phyllite); Ochfs—Cram Hill Formation (plagioclase-mica ± garnet metasedimentary schist and granofels, and hornblende-magnetite coticule). TT—Townshend thrust. Cross sections A–A’, B–B’ and C–C’ are shown in Figure 14. Map coordinates in meters on UTM (universal transverse Mercator) projection (zone 18) using NAD27 datum.
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Cliffe et al. (1997a). The lithological sequence from the southern end of the Spring Hill synform (sample v437A, Fig. 3). A subvertical, north-south striking crenulation cleavage, Sn, is the youngest fabric developed in this sample and has evolved to stage 3 to 4 of Bell and Rubenach’s (1983) model of crenulation cleavage development. An earlier crenulation cleavage, Sn, is preserved within the Sn microlithons where it has a subhorizontal dip (the orientation of fabrics in this and other samples was determined from the variation in foliation pitch and asymmetry of curvature in as many as eight differently oriented thin sections). Sn is rotated into a steep westerly dip as it passes into the Sn folia. Sn crenulates an earlier foliation, S\lowercase{m}, which in Sn microlithons has a subvertical enveloping dip between spaced Sn folia. Vertical section striking 095 (in this and subsequent photomicrographs the strike direction is shown by half arrow in top right-hand corner) oriented subperpendicular to the intersection of Sn, Sm, and S\lowercase{m}. Plane polarized light. (B) Garnet-mica schist collected from the hinge of a mesoscopic D* fold on the west limb of the Spring Hill synform (sample v450A, Fig. 3). A weakly developed subvertical crenulation cleavage, S\lowercase{a}, symmetrically overprints an earlier crenulation cleavage, S\lowercase{m}, which has a subhorizontal enveloping dip. S\lowercase{a} crenulates an earlier foliation, Sn, which has a subvertical attitude within microlithons between the well-developed Sn folia. In areas unaffected by Sn, Sn is rotated toward a subhorizontal dip as it passes into the Sn folia. Sample v450A. Vertical section (strike given in top right-hand corner) oriented subperpendicular to the intersection of S\lowercase{a}, Sm, and S\lowercase{m}. Plane polarized light.

**Spring Hill Synform**

The Spring Hill synform is a large (3 x 7 km) doubly plunging fold (Fig. 3) on the eastern limb of the Green Mountain Massif west of the saddle between the Chester and Athens domes (Fig. 2). It folds a sequence of pelitic, semipelitic, and quartzitic metasedimentary rocks around the Spring Hill synform (Rosenfeld, 1954; Hayward, 1992; Ratcliffe and Armstrong, 1995, 1996; Ratcliffe et al., 1997a). The lithological sequence.

Youngs into the core of the fold, indicating that the structure is synclinal in nature (Fig. 3; Rosenfeld, 1954; Doll et al., 1961; Thompson et al., 1990, 1993; Ratcliffe and Armstrong, 1995, 1996). Ratcliffe and Armstrong (1995, 1996) have mapped a series of thrust faults in the upper part of the gneiss domes and the overlying Hoosac, Stowe, and Rowe Schist formations. The thrusts originated during the Taconic orogeny and were subsequently folded around the Spring Hill synform and the steeply southward plunging Butternut Hill fold farther to the west (Fig. 3; Ratcliffe and Armstrong, 1995, 1996; Ratcliffe et al., 1997a).

The macroscopic geometry of the Spring Hill synform is most clearly defined by the trace of a conglomeratic quartzite unit in the Cram Hill Formation (Ochq in Fig. 3). Bedding measurements and outcrop patterns of this unit suggest that it has a moderately west dipping enveloping surface on the east limb and a subvertical dip on the west limb (Fig. 3). There is little evidence for significant large-scale refolding, or repetition of any lithological units, and the synform has a simple “boat-shaped” geometry in plan. Although a lack of distinct marker units in the sequence prevents precise location of the axial surface, the macroscopic distribution of rock types suggests a gross north-south strike.

Rocks around the Spring Hill synform were metamorphosed at amphibolite faces during the Acadian orogeny. Most metasedimentary units have a semipelitic composition and contain assemblages of garnet-biotite-muscovite-plagioclase-quartz ± graphite ± chlorite, with minor ilmenite, rutile, carbonate, and epidote-clinozoisite. Chlorite is a retrograde phase and partially replaces biotite and garnet. Rocks of pelitic composition are less common and typically contain assemblages of garnet-biotite-staurolite-muscovite-quartz ± kyanite ± chloritoid ± graphite ± chlorite ± plagioclase, with minor ilmenite and rutile. Previous work suggests that peak metamorphic conditions in the area were near 550°C and 8.5 kbar (Ratcliffe et al., 1997a).

**ANALYSIS OF MATRIX STRUCTURES ACROSS THE SPRING HILL SYNFORM**

There is extensive microscopic and mesoscopic evidence for multiple deformation events in the matrix of the rocks folded about the Spring Hill synform (Rosenfeld, 1954; Hayward, 1992; Ratcliffe and Armstrong, 1995, 1996; Ratcliffe et al., 1997a). We studied the three-dimensional geometry and relative timing of matrix structures in detail at the mesoscopic and microscopic scale, using multiple spatially oriented thin sections cut from more than 60 oriented samples. We used these thin sections to identify and determine the orientation of the youngest fold phase or foliation (S\lowercase{n}) developed in each sample. The geometry with which older structures (S\lowercase{m}) were folded, or crenulated, into S\lowercase{n} from regions of lower to higher D\lowercase{n} strain were then assessed (e.g., progressively steeper or progressively shallower; whether it passed through the vertical or the horizontal, Fig. 4). The same process was then applied to the next youngest structures (S\lowercase{n-1}), assessing the manner in which they overprinted even earlier structures (Fig. 4). Structures were
Figure 5. (A) Sketch of tight $D_3$ folds of $S_0$ overprinted by open, symmetrical $D_4$ folds. Note subvertical and shallow enveloping dips of $S_3$ and $S_4$, respectively. Structural measurements are given as dip and dip direction. Field locality v227, in the Cambrian Rowe Schist on the east limb of the Spring Hill synform (Fig. 3). (B) Detail of $D_3$ fold hinge overprinted by $D_4$ folds with shallowly dipping axial planes. $D_3$ and $D_4$ axial planes are shown with small and large dashes, respectively. The tight upright folds are identified as $D_3$ because they are overprinted by a set of symmetric folds with shallowly dipping axial planes. In surrounding outcrops, these folds become tighter and develop an intense axial plane foliation, $S_4$, that maintains a relatively consistent dip into areas where it is overprinted by a steeply dipping crenulation cleavage, $S_5$.

Table 1. Correlation of Structural Histories

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correlated from sample to sample and outcrop to outcrop using consistencies that we observed in the orientation and the overprinting style of folds and foliations (Figs. 4 to 6). The main foliation or fold phase developed in any one area was not always of the same generation (Figs. 4 to 7), as is commonly the case in multiply deformed terrains (Johnson, 1992, 1999a; Davis and Forde, 1994; Aerden, 1995; Davis 1995), and it was not always possible to uniquely assign a given structure to a particular deformation event.

Using this approach, we identified five foliation-forming deformation episodes within the matrix of the rocks around the Spring Hill synform, and we attempted to correlate these with previous work (Table 1). We have correlated our foliations with the $S_i$ to $S_8$ fabrics described by Hayward (1992) and have used his structural notation. We found no evidence in the matrix for the remains of a foliation equivalent to Hayward’s $S_i$, although there is evidence for older foliations preserved in porphyroblasts that may correlate with this fabric (see below).

For the purposes of structural correlation, $S_4$...
acts as marker foliation at both the microscopic and mesoscopic scale over much of the study area. It is characteristically overprinted by a steep crenulation cleavage ($S_1$) and is always rotated into a steeper orientation as it passes into $S_2$ folia (Fig. 4). $S_2$ is typically axial planar to tight, near-symmetrical folds of an earlier foliation, $S_0$ (Figs. 4 to 6).

$S_0$ and $S_2$

Thin-bedded to finely laminated units of psammite or quartzite are common in metasedimentary schists around the Spring Hill synform, but tight mesoscopic folding, intense cleavage development, and a lack of facing indicators make it difficult to define an enveloping bedding surface across many outcrops. The earliest deformational fabric preserved in the matrix is a well-developed bedding-parallel foliation, $S_2$, that is folded around tight $D_3$ folds cropping out at one locality on the east limb of the synform (Fig. 5). No folds of bedding associated with $S_2$ were observed in this study.

$D_3$ Structures

$S_3$ in metasedimentary schist generally forms a fully differentiated, penetrative fabric (Figs. 5 to 8). It is tightly crenulated by $D_4$ and, at thin-section scale, is commonly rotated into the developing $S_4$ fabric (Figs. 7B, 8, B and C). At the microscopic scale $S_3$ is generally subparallel to $S_0$ (e.g., Figs. 5 and 8) and no systematic asymmetry of $S_3$ on $S_0$ was observed, although tight symmetrical $D_4$ folding tends to mask the relationship in most rocks. Unequivocal $D_3$ folds were observed at only one locality in the Rowe Schist on the east limb of the Spring Hill synform (Fig. 5). These $D_3$ folds have a tight, upright profile and overprint $S_2$ in a near-orthogonal manner. They fold $S_3$ and $S_2$ and are overprinted at a high angle by open, symmetrical $D_4$ folds with shallowly west-northwest–dipping axial planes (Fig. 5). $L_3$ lineations (formed by the intersection of $S_0$ and $S_3$; terminology after Bell and Duncan, 1978) are northwest-plunging and approximately colinear with $L_3^2$ and $L_3^3$.

$D_4$ Structures

$S_4$ is a heterogeneously developed crenulation cleavage that has generally evolved to stage 3 or 4 of Bell and Rubenach’s (1983) model of cleavage differentiation (Fig. 7, A and B), but which has, in places, differentiated to produce a continuous foliation at stages 5 or 6 (Fig. 7C). At the mesoscopic scale, $S_4$ has a gentle to moderate northwest dip across much of the Spring Hill synform, although a zone of steeper west-northwest–east-southeast to east-west dips is developed on its western limb (Fig. 9A). $S_4$ also has a locally steep dip around the nose of the Butternut Hill fold, west of the Spring Hill synform, where it is folded by a macroscopic $D_5$ synform. The intersection lineations $L_4^2$ and $L_4^3$ within the core of the synform are similarly oriented to $L_3^4$ trending to plunge south at the north end of the synform and north at its southern end (Fig. 9B). However, $L_4^2$ and $L_4^3$ are locally oblique to $L_4^4$, tending to have more westerly plunges, and at some outcrops in the opposing direction (Fig. 9B). Near the Proterozoic gneiss of Chester Dome, $L_4^2$ and $L_4^3$ axes tend to have a more northwest to west-northwest plunge, locally approaching a down-dip pitch on $S_4$ (Fig. 9B). In the area of steeper dipping $S_4$ on the west limb of the Spring Hill synform, $L_4^4$ locally varies in plunge in a single outcrop, reflecting some earlier phase of folding or heterogeneous strain in $D_4$ and/or $D_5$.

Microscopic and mesoscopic $D_4$ folds of bedding and $S_4$ are perversely developed across the Spring Hill synform. They typically...
Figure 8. (A) Hinge of a small D₄ fold showing axial plane D₄ crenulations overprinting well-developed S₃ foliation subparallel to S₀. Sample v452B on the west limb of the Spring Hill synform (Fig. 3). Vertical section; strike indicated. Plane polarized light. (B) Inclined isoclinal D₄ fold of S₀ and S₃ overprinted by a steeply dipping S₅ crenulation cleavage with a synform-to-west asymmetry. Sample v443A from the west limb of a mesoscopic D₅ fold on the west limb of the Spring Hill synform (Fig. 3). Vertical section; strike indicated. Plane polarized light. (C) Subhorizontal isoclinal folds of S₀ and S₃ overprinted by D₅ crenulations with steeply dipping axial planes in a carbonaceous phyllite. Sample v262 west of the Spring Hill synform (Fig. 3). Vertical section; strike indicated. Plane polarized light.

Figure 9. (A) Map of S₄ and S₅ (matrix foliation of unknown age, but in most cases likely to represent fully differentiated S₄). S₄ typically has a moderate west to northwest dip across the Spring Hill synform. Farther west near the nose of the Butternut Hill synform, S₄ has a moderate to steep northeast dip. (B) Map of S₅ intersection lineations with S₀ and S₃. Note reversal of plunge along the Spring Hill synform and the presence of a more westward plunge direction on its eastern limb.

D₅ Structures

S₅ is a steeply dipping to subvertical (≥60°), north to northeast striking, crenulation cleavage (Fig. 11) that is best developed in phyllite and schist. S₅ is axial planar to mesoscopic D₅ folds and has typically evolved to stage 3 or 4 of cleavage development (Figs. 4 and 12). S₅ is heterogeneously developed, being most intense in metasedimentary units of the Cram Hill Formation on the west limb of the synform, and in Moretown rocks south of
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Figure 10. Approximate surface trace of $S_4$ across topography superimposed on the surface geology shown in Figure 3. $S_4$ transects the southern half of the Spring Hill synform, suggesting that it is a pre-$D_4$ structure. The asymmetry of mesoscopic $D_4$ folds observed in this study is also shown, as is the trace of a large $D_0$ synform that overprints the Butternut Hill fold west of the Spring Hill synform (a smaller $D_4$ fold is also developed at the southwest end of the Spring Hill synform). Although small macroscopic folds can be delineated on the basis of switching fold asymmetry, similar folds are not developed on the scale of the Spring Hill synform where $D_4$ folds appear to have an overall near-symmetric geometry. The approximate trace of the axial plane to the Spring Hill synform is based on its interpreted pre-$D_4$ timing and the distribution of lithological units. Tight $D_4$ folding precludes a more accurate determination of its position.

The Butternut Hill fold. $D_5$ crenulations are only locally developed in units below the Cram Hill Formation on the eastern limb of the synform, where $S_4$ has a moderate west-dipping enveloping surface (Figs. 7C and 11A). Microscopically, $S_5$ commonly overprints $S_4$ in a near-orthogonal fashion (Figs. 4, 6, and 8C), particularly in the hinge regions of $D_5$ folds (Fig. 4B). On the limbs of some $D_5$ folds, $S_4$ is only sporadically developed, forming discontinuous crenulations overprinting moderate to steep dipping $S_4$ (Fig. 12B).

$L_4^\perp$ intersection lineations are generally shallowly plunging from north-northwest–south-northwest to northeast-southwest and are mainly subparallel to $L_3^\perp$ (Fig. 11B). $L_5^\perp$ and $L_4^\perp$ reverse plunge along the synform (Fig. 11B), but they are slightly oblique and shallower plunging than $D_5$ intersection lineations (Fig. 9B). These findings suggest that the doubly plunging nature of folded bedding, though partially a consequence of heterogeneous $D_5$ strain, originated during, or before, $D_5$. A large macroscopic $D_5$ synform in $S_5$ is developed near the trace of the Butternut Hill fold (Fig. 10). $S_6$ in this area has an enveloping surface with a northeast dip on the west side of the fold, a northward dip near the nose, and a northwest dip on the east side (Fig. 9A). We identified no other large macroscopic $D_5$ folds, $D_5$ structures having a mainly synform-to-west geometry across the study area (Fig. 11A).

$S_6$ and the Matrix Foliation, $S_m$

At several localities across the Spring Hill synform (Fig. 13), we observed weak, shallowly dipping crenulation cleavages that overprint $S_6$, especially on the margins of garnet, staurolite, and plagioclase porphyroblasts. Similar weak crenulations with moderately inclined axial planes (traces in vertical thin sections pitching up to 45°) overprinting $S_6$ were also observed in some samples. In the absence of clear overprinting relationships, these post-$D_4$ crenulations have all been called $S_6$. At the mesoscopic and macroscopic scale, the Spring Hill synform and the $S_5$–$S_6$ foliations appear little affected by post-$D_4$ deformation.

At several localities within units of quartz-mica schist or amphibolite, there is a single well-developed matrix schistosity, $S_m$ (Fig. 9A). This fabric generally lacks evidence of overprinting crenulations and is commonly subparallel to lithological layering in outcrop. $S_m$ probably represents highly differentiated $S_5$, or well-developed $S_6$, strongly reactivated during $D_5$ and/or $D_6$.

FOLIATION OVERPRINTING RELATIONSHIPS IN THE MATRIX

Patterns of Overprinting

Matrix foliation development in rocks across the Spring Hill synform has produced several foliations with nearly orthogonal overprinting geometries (Figs. 4 to 8, 13). To constrain the timing of the development of the Spring Hill synform, it is important to know whether this near-orthogonal pattern reflects a primary overprinting geometry or whether it is the finite product of progressive deformation.

We have insufficient data to assess the relationship of $D_5$ on $S_6$. However, it seems likely that $S_5$ overprinted $S_6$ in a near-orthogonal fashion, because the asymmetry with which $S_6$ rotates out of $D_6$ microlithons into $S_6$ folia reverses across the axial trace of $D_5$ folds, and $D_5$ folds appear to be mainly symmetric at the mesoscopic scale (Fig. 10). $S_6$ is subvertical (dip >60°) across the Spring Hill synform (Fig. 11). Because $S_6$ is only weakly developed across the area, it seems likely that $S_6$ developed with this steep orientation. Assuming that $S_6$ formed as a relatively planar fabric,
Figure 11. (A) Map of $S_5$. The surface trace of $S_5$ across topography has been superimposed on the surface geology shown in Figure 3. Direction to $D_5$ synform was determined from asymmetry with which $S_4$ curves into $S_5$ folia. Late, steep crenulation cleavages mapped by the U.S. Geological Survey (Ratcliffe and Armstrong, 1995, 1996) and thought to be equivalent to $S_5$ in this study, are also shown. $D_5$ structures have a predominantly synform-to-west asymmetry across the Spring Hill synform. (B) $D_5$ intersection lineations across study area. Note reversal of $L_5$ and $L_5'$ plunge direction along the synform.

The $S_5/S_4$ overprinting relationships described above could have developed in one of two ways. (1) $S_4$ formed with a subhorizontal orientation, and was progressively rotated to a steeper enveloping dip during $D_5$ (Fig. 14A). Shortening in the limbs of $D_5$ folds was accommodated by the development of the $S_5$ crenulation cleavage (Fig. 14B) and, locally at least, by shear along $S_4$ (reactivation, Fig. 14B). (2) $S_4$ formed with a moderate to steep westerly dip and was locally rotated into a subhorizontal orientation during $D_5$. We believe the latter alternative is less likely, as evidenced by the fact that $S_4$ is progressively rotated toward a steep dip as it passes out of $D_5$ microthlons into the steeply dipping $S_5$ folia.

Figure 12. (A) Steep $S_5$ at stage 3 of crenulation cleavage development overprinting $S_4$ at stage 5. Note synform-to-west asymmetry with which $S_5$ overprints $S_4$. Sample v204 on the east limb of the Spring Hill synform. Vertical section; strike indicated. Plane polarized light. (B) Relatively weak $S_5$ that overprints a well-developed $S_4$ foliation, which has a moderate to steep enveloping dip to the west. Individual $S_5$ folia are discontinuous, curving into the $S_4$ foliation in a manner suggesting that $D_5$ shortening was accommodated primarily by the reactivation, rather than the crenulation, of $S_4$ (e.g., Bell, 1986; Fig. 14 here). Sample v443A from the west limb of a mesoscopic $D_5$ fold on the west limb of the Spring Hill synform (Fig. 3). Vertical section; strike indicated. Plane polarized light.
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Figure 13. The overprinting effects on a pervasive S₅ foliation of local weak D₆ crenulations with subhorizontal axial planes and top-to-the-east asymmetry. Note that the shallow-dipping (in three dimensions) inclusion trails in the two garnet porphyroblasts are truncated by the matrix, S₅. Sample v436A from the east limb of the Spring Hill synform. Vertical section; strike indicated. Plane polarized light.

Figure 14. (A) Initially subhorizontal S₄ rotated into a steep enveloping dip on the limbs of a D₅ fold. (B) Detail of fold limb illustrating how the crenulation or reactivation of S₄ can accommodate D₅ shortening. In the reactivated zones, shortening and limb rotation are accommodated by shear along a preexisting anisotropy, S₄. Zones of such reactivated shear pass laterally and vertically into zones where D₅ shortening and limb rotation are accommodated by the development of the S₅ crenulation cleavage (see Bell, 1986; Davis and Forde, 1994). In the latter regions, S₄ maintains a subhorizontal orientation in the microlithons between the S₅ folia. One-sided arrows show decreasing contribution of S₄-parallel shear outward from the zones of reactivation.

Colinear Orthogonal Overprinting Foliations S₂±S₆

We argue that matrix deformation in the area around the Spring Hill synform involved the progressive development of a series of near-orthogonal overprinting foliations (Fig. 15). Each episode of deformation rotated preceding fabrics away from their initial steeply and shallowly dipping orientations by a combination of crenulation and reactivation of pre-existing fabrics (Figs. 14 and 15). D₅ reactivation rather than crenulation of S₄ appears to have been particularly prevalent in coarse-grained schist below the Cram Hill Formation on the east limb of the synform. The near parallelism of Lₓ and Lᵧ over much of the study area (Figs. 9B and 11B) suggests that subvertical S₄ and S₅ developed with similar north-northeast–south-southwest strikes and that the horizontal component of bulk shortening during D₅ to D₆ was oriented approximately east-southeast–west-southwest.

PRE-D₅ FOLIATIONS IN PORPHYROBLASTS

Inclusion trails in garnet porphyroblasts around the Spring Hill synform are not generally continuous with the S₄–S₅ matrix foliations (Fig. 13; Bell and Hickey, 1997; Bell et al., 1998). This makes it difficult to unequivocally constrain the timing of inclusion trails in individual porphyroblasts relative to the matrix deformation history and the development of the Spring Hill synform. However, Bell et al. (1998) assessed the relative timing of these inclusion trails using axes to inclusion trail curvature in samples collected across the synform. These axes, which have been termed foliation inflexion or intersection axes in porphyroblasts (FIAs; Bell et al., 1998), can be separated into four populations, on the basis of their trend and the relative timing with which those trends developed in porphyroblasts, where the axis of curvature changes orientation from core to rim (for details on methodology, see Bell et al., 1998). From oldest to youngest, the four populations (sets 1–4) have modal peaks trending southwest–northeast, west–east, north-northeast–south–southwest, and south–southwest–north–northeast (Fig. 16). All four FIA populations maintain a consistent trend and timing across numerous mesoscopic and macroscopic folds, including the Spring Hill synform (Fig. 16). FIAs of the youngest population, set 4, are subparallel to D₅–D₆ fold
axes and intersection lineations (Figs. 9B, 11B, 16C) and are defined by inclusion trails that are typically continuous with foliations in the matrix, mainly S_3 and S_4 (Bell and Hickey, 1997; Bell et al., 1998). This suggests that inclusion trails defining set 4 FIAs represent pre-D_3 to syn-D_6 foliations that had fold axes subparallel to those of the D_3 to D_6 matrix deformations. FIAs of sets 1–3 have a shallow plunge (∼30°), oblique to the majority of D_3–D_6 fold axes and intersection lineations in the same outcrops (e.g., Figs. 9B, 11B, 16C) and are defined by inclusion trails that are typically truncated by matrix foliations (Bell et al., 1998). This suggests that the inclusion trails defining set 1–3 FIAs represent foliations that formed prior to matrix fabrics S_3–S_6 and prior to foliations defining the set 4 FIAs.

Although the FIA data presented by Bell et al. (1998) provides evidence for foliations older than those preserved in the matrix, it is generally not possible to correlate individual inclusion trails from sample to sample, or even porphyroblast to porphyroblast. This caveat arises because we do not know whether all inclusion trails defining a given FIA set necessarily developed during the same foliation-forming events (Bell and Mares, 1999). This is especially so in cases where inclusion trails are not continuous with matrix foliations or inclusion trails in different parts of a porphyroblast (e.g., across inclusion trail truncation surfaces; Hayward, 1992). Consequently, we cannot directly relate foliations preserved as inclusion trails to the D_3–D_6 deformation history preserved in the matrix.

We found no evidence in the matrix for foliations that formed during the development of FIA sets 1–3, and we suggest that syn deformational recrystallization and grain growth associated with progressive foliation development and prograde metamorphism were responsible for this (Bell and Rubenach, 1983; Hickey and Bell, 1996). In addition, foliations that formed earlier may never have developed fully, the deformation being accommodated by shear on preexisting fabrics (Fig. 14B).

**INTERPRETED TIMING OF THE SPRING HILL SYNFORM**

**Overprinting Matrix Foliation Asymmetry**

Near parallelism of the Spring Hill synform to D_3–D_6 intersection axes (Figs. 9B, 11B), suggests that it formed at some time during their development. However, this similarity in trend makes it difficult to constrain the timing of fold development using orientation alone, because it could have formed at any time and been rotated to its present geometry by the effects of subsequent deformations.

One way to determine that a deformation event formed a fold is to find a foliation whose overprinting asymmetry on the folded fabric (asymmetry with which the folded fabric curves from the microlithion into the overprinting cleavage folia) changes across the axial trace of the larger structure (Fig. 1; Duncan, 1985). No change in asymmetry is evident for S_4 or S_5 across the Spring Hill synform. Rather, D_3 crenulations and folds overprint S_3 with a predominantly synform-to-west asymmetry across the fold (Fig. 11A), and D_4 crenulations of S_3 remain essentially symmetrical on both its limbs (Fig. 10). A change in the asymmetry of S_4 on S_3 across the fold could not be determined because a pre-S_3 foliation was only rarely observed (Fig. 5).

Therefore, we are not able to unequivocally constrain the timing of the Spring Hill synform by means of matrix foliation asymmetry.

**Foliation Geometry at the Macroscopic Scale**

The only avenue left for determining the timing of the Spring Hill synform relative to...
the matrix foliations is to assess the relationship between the matrix foliations and the macroscopic fold geometry. This will determine the youngest fabric that could be associated with fold formation, but it does not preclude the possibility that the fold formed earlier and was subsequently rotated to its present geometry.

The Spring Hill synform is considered to be a pre-D3 structure, because the surface trace of S5 slightly transects the fold (Fig. 11A) and S4 is not, as noted above, folded across it. S5 appears a likely candidate for the axial plane of the Spring Hill synform, for several reasons. First, it is associated with a period of extensive folding at the microscopic and mesoscopic scale. Second, it is axial planar to large mesoscopic folds developed at each end of the synform (Fig. 3, localities v641 and v693). Finally, there are mesoscopic D3 folds of S0 with a synform-to-west and synform-to-east asymmetry locally developed on the eastern and western limbs, respectively, of the synform (Fig. 10). Consequently, we initially suggested that the Spring Hill synform was a D3 structure (Bell and Hickey, 1997; Bell et al., 1998). However, further mapping and sampling suggest that the synform is unlikely to be a D3 structure, for two reasons. (1) The surface trace of S4 across topography transects the axial trace of the Spring Hill synform in the southern half of the fold (Fig. 10) without a reversal in the plunge of L4S (Fig. 9B). (2) Ratcliffe and Armstrong (1995, 1996) mapped several macroscopic S-shaped folds of the Townshend thrust on the east limb of the Spring Hill synform (north of locality v227 in Fig. 3). These folds are oblique to S4 (Fig. 12A), with an axial trace approximately parallel to S4 (Fig. 10). Mesoscopic D3 folds of S4 and S5 are common in the same area, and the large macroscopic folds of the Townshend thrust are also thought to be D3 structures. L4S and L4S lineations measured on mesoscopic D3 folds in the same area plunge northwest to west-northwest (Fig. 9B), suggesting that the macroscopic folds have a synform-to-east asymmetry (if the thrust is subparallel to S4) and cannot be minor folds on the east limb of the Spring Hill synform.

The above points suggest that the Spring Hill synform developed prior to D4, making D4 the youngest deformation that could have produced this fold. Analysis of foliation overprinting patterns suggests that D3 folds developed with steeply dipping axial planes having a general north-south to north-northeast/south-southwest strike. The large Butternut Hill fold to the west of the Spring Hill synform is also partly transected by S4 (Figs. 9B, 10) and, therefore, also formed before or during D3. It may have formed at the same time as the Spring Hill synform, because they have not been folded around one another and there are no other large macroscopic folds in bedding developed between them (Thompson et al., 1993; Ratcliffe and Armstrong, 1995, 1996; Ratcliffe et al., 1997a). If these two folds formed as a couplet, then an originally upright geometry for the Spring Hill synform is suggested by the steep dip of the axial plane of the regionally developed Butternut Hill fold. Consequently, as a basis for constructing the cross sections across the Spring Hill synform, these two macroscopic folds have been shown as pre-D3 structures with steeply dipping axial plane surfaces (Fig. 17). In this interpretation, mesoscopic D4 folds with a synform-to-west asymmetry on the east limb of the synform (Fig. 10) must reflect strain on the short limb of larger D3 structures that were nearly symmetrical, or had the opposite asymmetry. This is supported by the observation that D4 folds on this limb of the synform are symmetric in many other outcrops (Fig. 10). S5 is thus inferred to transect the Spring Hill synform in section as it does in plan view (Figs. 11, 17).

Foliations in Porphyroblasts

Matrix data on the relationship of S4 to S5 or S6 across the study area are insufficient to determine if the Spring Hill synform developed prior to D5. However, the symmetry of inclusion trail curvature in garnet porphyroblasts provides a possible means for determining if the fold formed prior to D5. Porphyroblasts that grew during development of the synform should have mainly clockwise asymmetries (looking north) on the western limb and counterclockwise asymmetries (looking north) on the eastern one (Fig. 18A). The distribution of inclusion trail asymmetry across the synform for each of the four FIA sets recognized by Bell et al. (1998; summarized in Fig. 18), suggests that there is no genetic relationship between the synform and inclusion trails in garnet porphyroblasts. Consequently, the Spring Hill synform must have formed during D5, or very early in the structural history prior to the set 1 FIA. In the latter case, it may have been rotated to its present orien-

Figure 16. Maps showing the trend (and plunge where measured) of foliation inflexion or intersection axes (FIAs) in porphyroblasts determined from samples collected across the Spring Hill synform (Bell et al., 1998). Geometrically, an FIA is the axis of inclusion trail curvature within a porphyroblast. Most porphyroblasts around the Spring Hill synform have inclusion trail curvature that is described by a single, constantly oriented axis. However, in many garnets, the axis of curvature (i.e., the FIA) changes orientation outward from the core to the rim of the porphyroblast (multi-FIA porphyroblasts). Bell et al. (1998) found that there was a consistent pattern to the relative timing (from core to rim) with which FIA trends formed in multi-FIA porphyroblasts, and this enabled them to differentiate four populations of differently oriented FIAs, which they called FIA sets 1–4. The distribution of set 1 (solid line) and 2 (dashed line) FIAs across the Spring Hill synform is shown in A. FIAs from sets 3 and 4 are shown in B and C, respectively. Note that the FIAs maintain a consistent orientation across the synform. See text for discussion.
suggested that the Spring Hill synform formed as a subhorizontal nappe fold (Fig. 19, A and B) that was rotated into its present orientation by later doming (Fig. 19C). The synform was thought to be an extension of the Star Hill fold, a synclinal antiform between the Butternut Hill fold and the Chester dome, north of our study area (Fig. 19, A and B). Rosenfeld (1968, 1972) suggested that the synformal nature of the Spring Hill structure was a product of large-scale, syn-nappe detachment (megaboudinage) of the Cram Hill–Hawley units in the core of the Star Hill fold (Fig. 19B). Such a detachment must have occurred on a tongue-like protrusion of Cram Hill–Hawley units (Fig. 20, A–C) that were steepened around a north-south axis during later doming and subhorizontal east-west shortening (Fig. 20D). This rotation should have caused S3 to dip more steeply toward the core of the synform (Fig. 20E), but we did not observe that in this study. Folds and intersection lineations in S3 shallow progressively into the core of the synform, passing through the horizontal to produce its double-plunging character (Figs. 9B, 11B; Ratcliffe et al., 1997a). Rosenfeld et al. (1988) recognized the problematic origin of this fold, stating “it is not at all clear how it (the Spring Hill syn-

**Figure 17.** East-west cross sections constructed along the lines A–A’, B–B’, and C–C’ in Figure 3. Both the Spring Hill synform and the Butternut Hill fold are shown as steeply dipping structures overprinted by the D4 and D5 deformations. Note zone of relatively higher D5 strain between the two folds, where S4 has a steep, enveloping dip to the west. Analysis of foliation overprinting asymmetries suggests that the Spring Hill synform is not folded around any large macroscopic D4 or D5 structures and that it has a steep enveloping dip almost due east. The synform amplitude has been extensively flattened at the mesoscopic scale by tight D4 folds that transect the synform. Although mesoscopic D4 folds of bedding appear to be nearly symmetrical across most outcrops, the macroscopic geometry suggests that they should have an overall reversal in asymmetry across the Spring Hill synform as a consequence of the pre-D4 fold geometry. The large D4 folds in the Townshend thrust on the east limb of the synform (Fig. 10) owe their synform-to-east asymmetry to this same pre-D4 geometry. The Butternut Hill fold has a macroscopic geometry similar to that of the Spring Hill synform, but it has been partially overprinted by a steeply dipping D3 synform near to its axial plane. Lithological units as for Figure 3 (units in the Cram Hill formation, Och, have not been differentiated by name except for Ochmc and Ochq). The prominent variation in thickness of the North River igneous suite (Ont) along and across the Spring Hill synform is considered to be a primary intrusive feature. Positions for the structural relationships shown in Figures 4 to 8, 12, and 13 are also shown.
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Figure 18. (A) Porphyroblasts that grew during the development of a synform should have a predominance of clockwise asymmetries on the western limb and counterclockwise asymmetries on the eastern one. The actual distribution of inclusion trail asymmetry across the Spring Hill synform for each of the four FIA sets is shown in A and B. FIA sets 1, 3, and 4 have trends at a moderate to low angle to the synform, and asymmetries are given looking north. FIAs from sets 1 and 4 show no significant difference in the distributions of asymmetries across the fold. Set 3 FIAs show a change in the relative proportions of each asymmetry across the synform, but they have the opposite sense to that shown in A. These results suggest there is no genetic relationship between the fold and inclusion trails defining FIA sets 1, 3, and 4. Set 2 FIAs have a predominantly counterclockwise asymmetry (looking west) on the west limb of the fold, and an equal number of both asymmetries on the east limb. We consider it unlikely that the Spring Hill synform formed at the same time as the set 2 FIAs, because it would have developed with a west-east trend, and the regional fold geometry shows no evidence for the large-scale refolding necessary to produce its present geometry.

Figure 19. Nappe- and dome-style fold model for the formation of the Spring Hill synform and the Chester and Athen domes presented by Rosenfeld (1968). See text for description. SHS—Spring Hill synform; BHF—Butternut Hill fold; SHF—Star Hill fold. Adapted from Rosenfeld (1968) and Rosenfeld et al. (1988). (Note: Section D–D’ in Fig. 14–1 of Rosenfeld [1968] appears to have been drawn incorrectly; it shows the Spring Hill synform folded around the Star Hill fold, in contradiction to Rosenfeld’s interpretation [1968, p. 195] that the synform is a detached hinge of the Star Hill fold.)

New Model for the Development of the Spring Hill Synform

We suggest that the Spring Hill synform developed with a steep axial plane during \( D_4 \), or was rotated into this orientation during or prior to \( D_5 \) (Fig. 21A). Subvertical bulk shortening during \( D_4 \) produced subhorizontal \( S_4 \) and numerous, tight, microscopic and mesoscopic \( D_4 \) folds, but no macroscopic folds (Fig. 21B). The gross geometry of the Spring Hill synform was maintained, but its amplitude was reduced. Intersection lineations and fold axes in rocks close to the gneiss units of the Chester dome were rotated toward an east-west to east-southeast–west-southwest stretching direction during \( D_4 \) or \( D_5 \) reactivation of \( S_4 \). During \( D_5 \), the Spring Hill synform was bulk shortened in a subhorizontal east-southeast–west-southwest direction. A macroscopic \( D_5 \) synform formed near the Butternut Hill fold (Figs 10, 17), and \( S_4 \) was rotated to a general west to northwest dip across the Spring Hill synform (Fig 21C). A zone of higher \( D_5 \) strain developed on the west limb of the Spring Hill synform, locally rotating \( S_4 \).
of the synform began before or during D4 and microscopic D5 folds developed. The double plunge was accentuated during D5.

Matrix foliations S2±S6 are broadly synchronous with or later than the set 4 FIAs (see above), the matrix structures preserved in rocks across the Spring Hill synform are also considered to be products of the Acadian orogeny.

DISCUSSION AND IMPLICATIONS

Absence of Macroscopic Refolds

The relatively simple geometry of the Spring Hill synform at the macroscopic scale could be misconstrued as being evidence for the synform having formed late in the deformation history, or that the subsequent history was a simple one. However, this is not so; microscopic and mesoscopic D4 and D5 folds have extensively overprinted the synform, and its simple macroscopic geometry reflects a lack of refolding at a macroscopic scale similar to that at which it formed (Figs. 3, 17). For a given rate of shortening, the wavelength and relative amplitude of folds is a function of the rheological heterogeneity within the sequence of rocks being deformed (e.g., Biot, 1961; Ramberg, 1964, 1970a, 1970b; Hudson, 1973). D5 in this region was a product of subvertical shortening. At the microscopic and mesoscopic scale, there was sufficient rheological contrast for inhomogeneous flow to develop and instigate folding and foliation development. However, the lack of large macroscopic refolds of S0 suggests that there was insufficient rheological heterogeneity developed at that scale for folding to begin at larger wavelengths. Alternatively, the presence of competent gneiss in the core of the Green Mountain and Chester-Athens anticlinoriums, to the west and east, respectively, inhibited lateral extrusion, preventing the development of macroscopic folds with subhorizontal axial planes. In either case, D5 shortening at the macroscopic scale was accommodated by nearly homogeneously distributed mesoscopic folding and foliation development, suggesting that the general perception in the geological literature that multiply deformed rocks have a relatively scale invariant pattern of overprinting structures (e.g., Hobbs et al., 1976) is not necessarily correct.

D4 did not produce large macroscopic refolds of S0, although such folds are developed in S4 (Fig. 10). This lack of D4 folds arose because D4 did not strongly reorient S0 at the macroscopic scale. Reorientation of largescale folds into subhorizontal structures with zones of mainly flat S0 is needed to produce macroscopic refolds during younger deformations with subvertical axial planes (e.g., Bell and Hickey, 1998). Otherwise, as is the case with the Spring Hill synform, an overprinting period of similarly directed subhorizontal shortening will tend to tighten early upper-right folds rather than refold them (Type-0 fold interference pattern of Ramsay, 1967), making it difficult to distinguish fold timing at the macroscopic scale. The general lack of large-scale refolds in plan view in many orogens may reflect a tendency for early-formed folds to simply be reused and reoriented in trend rather than be refolded, if the direction of bulk shortening shifts.

Orthogonal Overprinting of Steeply and Shallowly Dipping Foliations

Deformation of rocks across the Spring Hill synform involved near-orthogonal overprinting of subvertical (S4 and S5) and subhorizontal (S2 and locally S4 and S5) crenulation cleavages (Fig. 15). Near-orthogonal overprinting foliations and inclusion trails are documented from several orogenic belts around the world (Helmstaedt and Dixon, 1980; Hay-

Figure 20. Sketches illustrating how the Spring Hill synform must have developed if it originated by means of boudination of the Star Hill fold (Fig. 19). (A–C) Plan view of the Star Hill fold hinge. The Spring Hill synform developed from a tongue-like protrusion (A and B) of Cram Hill–Hawley rocks (gray) that became detached (C) during subhorizontal nappe formation. During dome-stage folding, the Spring Hill synform was rotated to a steeper orientation (D, adapted from Rosenfeld, 1968). This steepening should have caused folds and intersection lineations in bedding to have progressively steeper plunges into the core of the fold in a north-south longitudinal section (E). The latter geometry is not observed along the Spring Hill synform; see Figures 9B and 11B. SHS—Spring Hill synform; BHF—Butternut Hill fold; SHF—Star Hill fold.
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Figure 21. Sketch illustrating the progressive development of the Butternut Hill and Spring Hill folds in an east-west section, looking north. (A) Folds at the end of D5 time shown as tight upright structures with S5 parallel to their subvertical axial planes. Note, however, that as shown in Figure 1B, D5 need not have formed the fold couplet. The east limb of the Spring Hill synform had a shallower dip than the west limb did. (B) During D4, both folds were overprinted by pervasive microscopic and mesoscopic folding during subvertical bulk shortening without development of large macroscopic D5 folds on the same scale as the Spring Hill synform. (C) Subsequent east-west-directed subhorizontal bulk shortening during D4 produced tight mesoscopic folding and crenulation cleavage development (S5). At the macroscopic scale, D5 rotated the S4 reference surface to a moderate west-northwest dip across the Spring Hill synform, a zone of relatively higher strain developing on its west limb. A large macroscopic D5 synform in S4 developed immediately east of the Butternut Hill fold. Note that D5 lineations reverse plunge along the synform (Fig. 11B), but are slightly oblique and are shallower plunging than D4 intersection lineations (Fig. 9B). This suggests that the doubly plunging nature of folded bedding, though partially a consequence of heterogeneous D5 strain, originated during or before D5. Och—Cram Hill Formation.

Timing Folds in Complexly Deformed Terrains

Establishing the timing of the development of macroscopic folds in bedding in terrains that have undergone a long and complex deformation history is potentially difficult (Fig. 1B). If a succession of alternate deformations can form with similarly oriented axial plane foliations, how can one geometrically distinguish the timing of a fold (e.g., Fig. 1B)? Foliation-foliation asymmetry may identify a fold in a foliation (Fig. 1A), but it does not necessarily time a fold in bedding if a later fold developed directly over the top of an earlier one with the same axial plane orientation (Figs. 1B, 21). Timing the development of macroscopic folds is further complicated if deformation does not produce structures on similar scales, as has been the case with D2 and D4 across the Spring Hill synform. D5 did not produce large areas of flat-lying bedding at a macroscopic scale, preventing D5 from producing large-scale refolds of the Spring Hill synform. A lack of such refolds makes it difficult to time fold development. Clearly, any approach to timing macroscopic fold development in terrains with multiple overprinting foliations and folds must incorporate a detailed analysis of the deformation history and the pattern of structural overprinting at the microscopic and mesoscopic scale.

ACKNOWLEDGMENTS

We thank Tom Armstrong, Nick Ratcliffe, and Greg Walsh, U.S. Geological Survey, for showing us the results of their mapping of southeast Vermont during excellent field trips, and for much discussion and interaction; John Rosenfeld and Jim Thompson for discussion on the geology of the Spring Hill area during the 1997 New England Intercollegiate Geology Conference; Mike Williams, Tom Armstrong, Paul Williams, and Cameron Davidson for their thorough and thoughtful reviews of earlier drafts of this paper; the Australian Research Council for providing the research grant that made this work possible; and the Departments of Geosciences at Weber State University and the University of Massachusetts, where an earlier version of this paper was written, for providing assistance and facilities.

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MANUSCRIPT RECEIVED BY THE SOCIETY APRIL 3, 2000
REVISED MANUSCRIPT RECEIVED DECEMBER 26, 2000
MANUSCRIPT ACCEPTED MARCH 5, 2001

Hickey and Bell