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Displacement transfer at thrust terminations: the Saltville thrust and Sinking Creek anticline, Virginia, U.S.A.

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Abstract—The Saltville thrust terminates in the core of the Sinking Creek anticline. Changes in the amplitude of the anticline may preserve profile shortening as the thrust displacement decreases towards the fault termination. Consequently, thrust displacement would be transferred into the fold. We combine newly published maps and new strain and mesostructural data from the Tuscarora Sandstone to argue that the Sinking Creek anticline did perform this kinematic role. We propose that the anticline developed as a fault-propagation fold that experienced both décollement and anticlinal breakthrough by the Saltville thrust. Thrust displacement was accommodated by the development of the modified fault-propagation fold and by transfer to a roof flat from the décollement breakthrough. New strain and mesostructural data indicate no fixed pin lines in either the hinge or backlimb throughout folding. Consequently, layer slip occurred through the hinge during folding and the forelimb deformed internally during breakthrough. Towards the plungeout of the Sinking Creek anticline, the displacement on the Saltville thrust is transferred to a floor thrust. We apply this interpretation to the termination of the St. Clair thrust, which has a similar surface geometry where the thrust terminates into an anticline. A testable implication of this proposed interpretation for the St. Clair thrust is that the Appalachian Plateau must absorb over 20 km of thrust displacement as horizontal shortening.

INTRODUCTION

A CLASSIC geometry in foreland thrust systems is a thrust fault terminating into an anticline (Dahlstrom 1970, Rodgers 1970, Gardner & Spang 1973, Brown & Spang 1978, House & Gray 1982). Thrust displacement decreases towards the termination, but overall shortening may be preserved where this translation is transferred to the anticline as an amplitude increase. This kinematic transfer depends on the geometric relationship of the anticline to the thrust. Three end-member geometries result when an anticline is related to either a fault bend, a fault tip or a delaminated piece of hanging wall (Table 1 and Fig. 1). The fault-bend anticline (Rich 1934, Suppe 1983) is a consequence of a change in thrust trajectory and does not accommodate displacement transfer. When displacement on the thrust decreases, typically by slip transfer to a floor thrust, the related anticline loses amplitude (Fig. 1a). A fault-propagation anticline (Gardner & Spang 1973, Brown & Spang 1978, Williams & Chapman 1983, Jamison 1987, Mitra 1990, Suppe & Medwedeff 1990, Fischer *et al.* 1992) does accommodate displacement transfer with an amplitude increase (Fig. 1b). However, the relative amount of accommodation will decrease if the thrust breaks through the anticline after folding (Fig. 1b). An anticline will be produced at a thrust termination by delamination (House & Gray 1982) where a portion of the hanging wall from the thrust is decoupled and inserted into the footwall as a triangular region (Fig. 1c). The thrust does not transfer displacement to another structure, but instead, forms a breakthrust with displacement decreasing to zero at the fold plunge-out. Consequently, the fault-propagation anticline is the only geometry where profile shortening is transferred to the anticline with decreasing displacement toward a thrust termination. In contrast, delamination does not produce a displacement transfer, so that anticlinal amplitude is not related to changing thrust displacement.

A well known example of a major thrust terminating into an anticline is in the southern Appalachians, where the Saltville thrust ends in the Sinking Creek anticline (Rodgers 1970, House & Gray 1982). The anticline has been interpreted to have formed by delamination (Fig. 1c) from analog modeling and mesostructural data (House & Gray 1982). This anticline was the first to be ascribed with this geometry for thrust termination. It was also used to explain, by analogy, the terminations of two other major southern Appalachian faults, the St. Clair and Narrows thrusts (House & Gray 1982).

The purpose of this paper is to re-evaluate the geometric relationship between the termination of the Saltville thrust and the Sinking Creek anticline, using newly published map information with new micro- and mesostructural data. This re-evaluation will show that: (1) the thrust–fold pair developed during fault-propagation folding with breakthrough thrusting and no fixed pin lines; (2) displacement transfer does occur and is achieved via a combination of slip on a floor thrust and the development of the anticline; and (3) this revised geometry may feasibly explain other thrust-to-anticline transitions.

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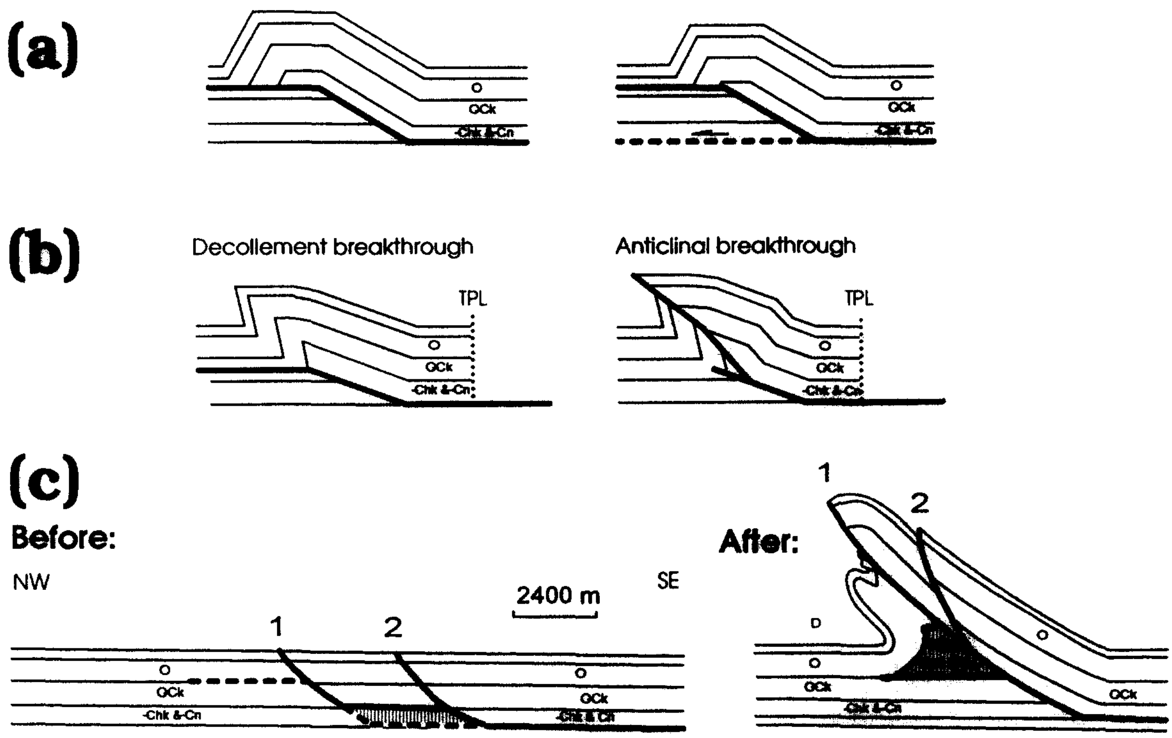

Fig. 1. Possible fold–fault geometries. (a) Fault-bend fold (modified from Suppe 1983) with decreasing amplitude as displacement is transferred to a floor thrust; (b) fault-propagation folds with décollement or anticlinal breakthrough (TPL—trailing pin line) (modified from fig. 11 in Suppe & Medwedeff 1990); and (c) delamination of a portion of the hanging wall (stippled region) into the footwall (modified from House & Gray 1982). D—Devonian; O—Upper and middle Ordovician; OCk—Cambro-Ordovician Knox Group; Chk & Cn—Cambrian Honaker Dolomite and Nolichucky Shale.

Table 1. Displacement transfer from thrust and fold geometry

	Fault bends	Fault propagation	Delamination
Fold cause	Change in fault trajectory	Displacement transfer	Footwall delamination
Thrust location	Beneath anticline	Terminates in core or forelimb of anticline	As a breakthrust that offsets fold core
Displacement transfer	Into floor thrust as thrust displacement	Into anticline as fold amplitude	Into breakthrust as thrust displacement

REGIONAL GEOLOGY

The study area (Figs. 2 and 3) is located in the Valley and Ridge Province at the transition from the southern to the central Appalachians in Virginia and West Virginia. Regional structural trend changes northward from 060° (southern Appalachian) to 030° (central Appalachian). At the transition into the central Appalachians, two major southern Appalachian thrusts, the Saltville and St. Clair thrusts, lose displacement and terminate into anticlines (SaT and SCT, respectively, on Figs. 2 and 3).

These southern Appalachian thrusts (Fig. 3, sections Y and Z) terminate where roof flats in the northward-thickening upper Ordovician and Middle Devonian shales of the central Appalachians are developed (Colton 1970, Rader & Henika 1978, Bartholomew 1987, Kreisa & Springer 1987). Thus, the structural style (Figs. 2 and 3) changes from outcropping thrusts in the southern Appalachians to map-scale folds deforming a roof sequence of Ordovician and younger rocks above blind thrust horses in the central Appalachians (Rodgers 1970, Geiser 1988a,b, Ferrill & Dunne 1989).

THE SINKING CREEK ANTICLINE

The Sinking Creek anticline is rounded and open at its northeastern plunge-out, but to the southwest, the anticline tightens with northwestern vergence (Fig. 4). The southeast limb of the anticline preserves layer thickness and is not affected by map- or outcrop-scale thrusts or parasitic folds. In the overturned northwest limb (Fig. 4b), Middle Ordovician rock units are thickened by smaller folds and cleavage development (House & Gray 1982), and Silurian units, including the Tuscarora Sandstone, vary from simply overturned to disharmonically folded (Bartholomew *et al.* in press) (near sample 12, Fig. 4a).

New geologic maps (Schultz *et al.* 1986, Batholomew *et al.* in press) depict the geometry in the core (between 12 and 2, Fig. 4a) of the Sinking Creek anticline. For the delamination geometry (Fig. 1c) (House & Gray 1982), the core should contain a triangular region of intensely deformed Cambrian rocks beneath the Saltville thrust. This triangular region is absent and instead, a newly mapped thrust (Bartholomew *et al.* in press) branches to the north from the Saltville thrust (Fig. 4). The thrust

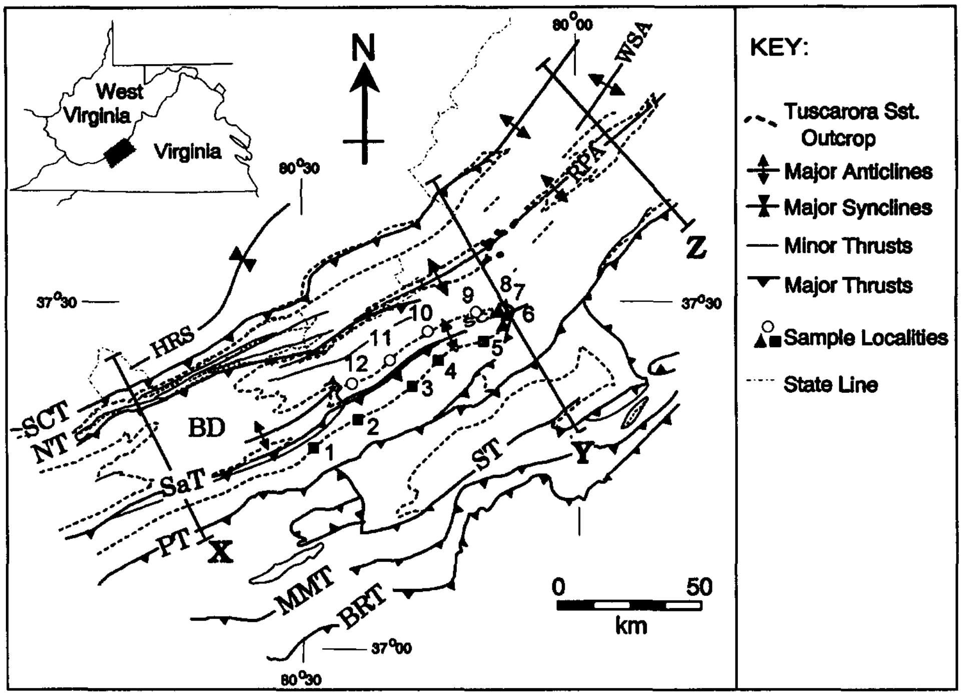

Fig. 2. Map of study area showing major structural features around terminations of Appalachian thrusts and sample locations (1–12) around the Sinking Creek anticline (SCA). Squares denote samples on the southeast limb, triangles denote hinge samples, and circles denote samples on the northwest limb. BD—Bane Dome; BRT—Blue Ridge thrust; HRS—Hurricane Ridge syncline; MMT—Max Meadows thrust; NT—Narrows thrust; PT—Pulaski thrust; RPA—Rich Patch anticline; SaT—Saltville thrust; SCT—St. Clair thrust; ST—Salem thrust; WSA—Warm Springs anticline. Section lines X, Y and Z are in Fig. 3 (modified from Butts 1940, Schultz *et al.* 1986, Bartholomew *et al.* in press).

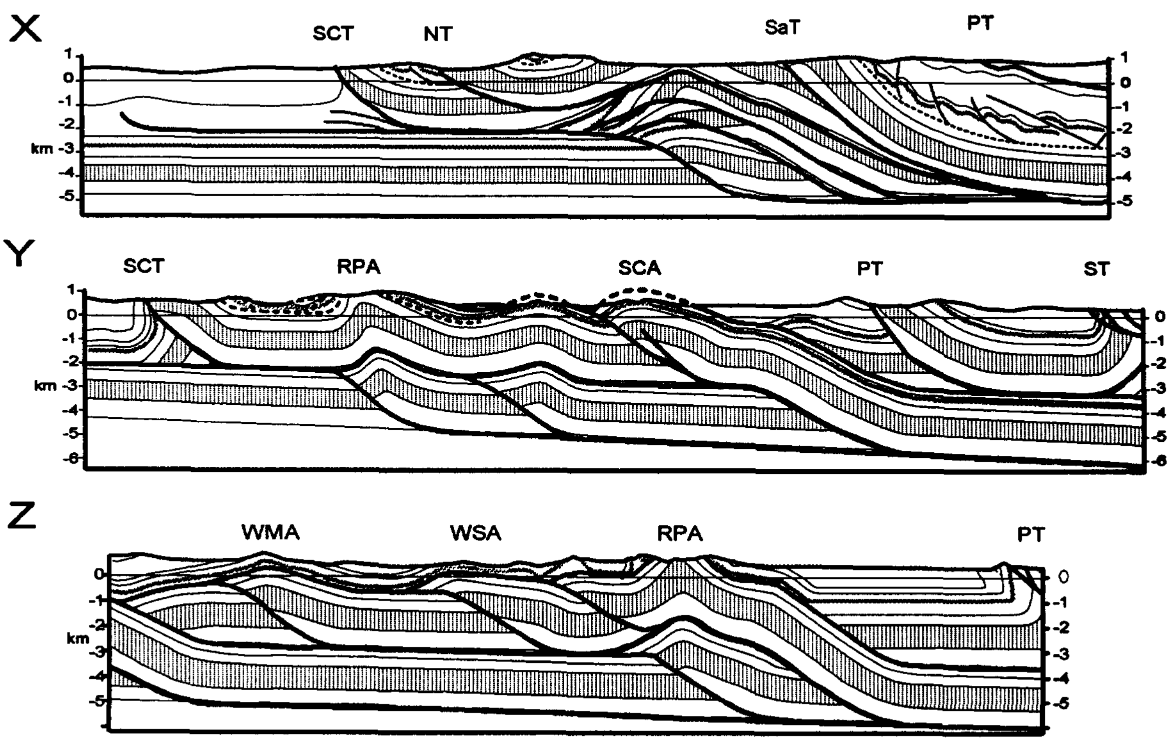

Fig. 3. Three cross-sections across the foreland thrust system in the transition zone between the southern and central Appalachians near the termination of the St. Clair thrust. Locations are shown in Fig. 2. Cross-section X after Kulander & Dean (1986). Cross-section Z after Onasch & Dunne (1993). Cross-section Y shows a proposed geometry where the St. Clair thrust (SCT) has a geometry similar to that inferred for the Saltville thrust. The stippled unit is the Cambro-Ordovician Knox Group and the thin gray unit is the Silurian Tuscarora Sandstone. NT—Narrows thrust; PT—Pulaski thrust; RPA—Rich Patch anticline; SCA—Sinking Creek anticline; SaT—Saltville thrust; ST—Salem thrust; WMA—Wills Mountain anticline; WSA—Warm Springs anticline.

emplaces a hanging wall ramp of the northwest limb of the Sinking Creek anticline over the Clover Hollow anticline (Bartholomew *et al.* in press). Consequently, the geometry of the Sinking Creek anticline is not the result of one thrust (Saltville thrust), but two (Bartholomew *et al.* in press). We infer that this branch ramps into a roof flat in the Devonian shale (dotted line, Fig. 4). A significant fraction of the Saltville thrust displacement is presumably also transferred to the roof thrust. This interpretation is proposed to account for the lack of a mappable trace for the ramp to the north of the Sinking Creek anticline. Such an interpretation is consistent with the role of the Devonian shale in the central Appalachians as a regional décollement (Perry 1978, Mitra 1986). The absence of the triangular region proposed by House & Gray (1982), the existence of the newly mapped thrust, and the inferred existence of the roof flat together necessitate a new interpretation for the geometric relationship between the Saltville thrust and Sinking Creek anticline.

Proposed geometry

A series of seven cross-sections (Figs. 4 and 5) were constructed to illustrate the geometry between the newly mapped thrust (Bartholomew *et al.* in press), the inferred thrust flat, the Saltville thrust and the Sinking Creek anticline. Constraints for section construction were: (1) the surface geology from the new maps (Schultz *et al.* 1986, Bartholomew *et al.* in press); (2) new bedding orientation data (unpublished data and Fig. 4b); (3) stratigraphic thicknesses (Reger & Price 1926, Colton 1970, Amato 1974, Bartholomew & Lowry 1979, Perry *et al.* 1979, Bartholomew 1981, 1987, Chen 1981); (4) depth and dip of basement extrapolated between two positions where the stratigraphy is flatlying (section Y, Figs. 2 and 3—Appalachian plateau to the northwest of St. Clair thrust and Pulaski thrust sheet (PT) where a flat-on-flat geometry exists); (5) down-plunge projection of surface structures into subsurface to the northeast; and (6) the requirement of lateral consistency in structure between adjacent cross-sections. We assumed that the dip of the Saltville thrust ramp mimics the bedding dip of the hanging wall rocks in the southeast limb of the Sinking Creek anticline. In addition, we used the simplest interpretation in terms of least number of faults and simplest folds shapes needed to honor the surface mapping (Schultz *et al.* 1986, Bartholomew *et al.* in press), and subsurface data (Perry *et al.* 1979) available from the adjacent Bane Dome (BD, Fig. 2).

The key results from section construction (Figs. 4 and 5) are: (1) the Sinking Creek anticline is located over a ramp that roots into a floor thrust, which continues northwest as a floor thrust to the St. Clair and Narrows thrusts (section Y, Fig. 3); (2) as mapped, the Saltville thrust branches from near the middle of the ramp and is within the anticlinal core; and (3) the ramp can be successfully inferred to continue into a flat in the Devonian shales.

The maps and cross-sections (Figs. 4 and 5) show that neither of the ideal geometries for fault-bend folding and fault-propagation folding accurately describe the geometric relationship between the Saltville thrust and Sinking Creek anticline. Ideal fault-bend folding is inappropriate because footwall ramp angle is nearly constant at 25–30° through the sections, but the hanging wall ramp (northwest limb of Sinking Creek anticline) changes dip from less than 35°NW to less than 80°SE (overturned). The consistent footwall ramp angle with the fluctuating attitude of the hanging wall ramp does not match model predictions (fig. 7 in Suppe 1983). Ideal fault-propagation folding is also inappropriate because fluctuating attitude of the northwest fold limb vs the consistent dip of the footwall ramp is not predicted (fig. 25 in Suppe & Medwedeff 1990). Simple modification of either model by forelimb thickening does not yield a consistent predicted geometry (figs. 2 and 3 in Jamison 1987) that matches the illustrated geometry.

The inability of ideal models for fault-bend and fault-propagation folding to predict the mapped and proposed geometry should not be surprising because the Sinking Creek anticline involves *two* thrust faults. More complex alternative geometries such as breakthrusting (Willis 1893, Fischer *et al.* 1992), fault-propagation folding with thrust breakthrough (fig. 11 in Suppe & Medwedeff 1990), or displacement of a fault-propagation fold into a fault-bend (Jamison 1987, fig. 15 in Mitra 1990) may be appropriate. However, these geometries involve pin lines and internal strains that cannot be determined from the geometry in the cross-sections alone (fig. 6 in Geiser *et al.* 1988). Outcrop- and microscale data were collected to attempt to determine which alternatives were most appropriate.

MESOSTRUCTURES AND MICROSTRUCTURES

Mesostructural data from the lower Silurian Tuscarora Sandstone, a medium- to fine-grained quartz arenite, were collected at stations covering several hundred square meters and in traverses along strike between sites 7–9 and 10–12 (Fig. 4a). The data included structural type, geometry to bedding, and spacing (Table 2). In the southeast limb of the Sinking Creek anticline, no evidence for bedding-parallel slip or cataclasis was found, and veins were only rarely observed (Fig. 4b and Table 2). In contrast, bedding-parallel slip surfaces are common in both the northwest limb and the hinge (Table 2). The surfaces are ornamented by abundant polished groove slickenlines with less than 1 mm of relief and 2–8 mm of width. In the northwest limb, the slickenlines are parallel to bedding dip-direction, indicating that the beds moved parallel to dip during slip. The only exception is at Station 10 where less common groove slickenlines are parallel to bedding strike and form about a 1 mm thick layer that overprints the older, more abundant dip-parallel slickenlines. In the hinge, the slickenlines are normal to the fold axis.

Veins are abundant in both the northwest limb and the hinge (Fig. 4b and Table 2). The veins contain granular

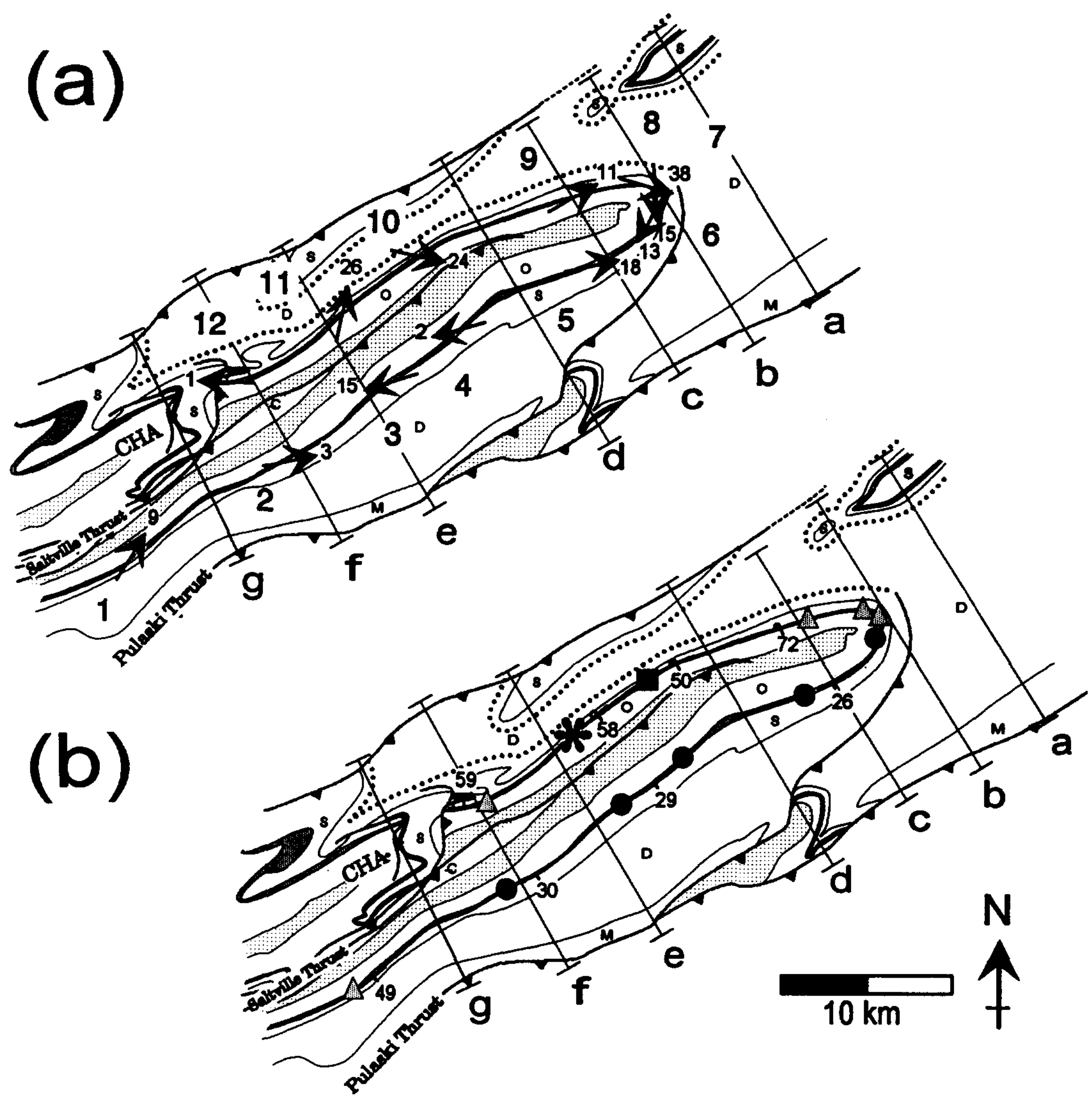

Fig. 4. (a) Map showing the location of cross-sections in Fig. 5 and the orientation of the X axes of measured strains from samples (1–12 in large numbers) of the Tuscarora Sandstone (medium grey). Arrows show trend of ellipsoidal long axes for present-day bedding orientations. Smaller numbers show the amount of X axis plunge. (b) Map depicting bedding orientations of the Tuscarora Sandstone around the anticline and the small-scale structures found at each station. Structural suites: triangles—bedding slickenlines and uncommon bed-perpendicular microveins; asterisk—systematic strike-parallel, bed-perpendicular veins that cut bedding slickenlines; solid square—systematic strike-parallel, bed-perpendicular veins with offset of top-to-the northwest; and dots—no veins or bedding-parallel slip surfaces. In both maps, the lightly stippled regions are outcrop of the Cambro-Ordovician Knox Group and medium gray is outcrop of Tuscarora Sandstone. CHA—Clove Hollow anticline; M—Mississippian rocks; D—Devonian rocks; S—Silurian rocks; O—Ordovician rocks; C—Cambrian rocks. Maps are modified from Bartholomew *et al.* (in press) with the dotted line denoting the inferred thrust flat in the Devonian shales.

quartz that is optically continuous to wall grains in thin section. The veins lack inclusion bands or trails, but many veins transect detrital quartz grains such that pieces of the grains may be identified on both sides of the vein (Fig. 6b). In these cases, displacement is normal to the vein walls in the plane of the section, indicating extensional behavior. In the northwest limb, the majority of the veins are bed-perpendicular and strike-parallel, indicating that they caused dip-parallel extension. They are most abundant where bedding is the most overturned (Station 10). The bed-perpendicular strike-parallel veins at Station 10 are unusual because they have a shear component. They offset bedding, as well as bedding-slip surfaces, parallel to the vein walls, moving top blocks of bedding to the northwest. In the hinge, bed-perpendicular veins are less abundant, have an average spacing of 16 cm rather than 7 cm (Table 2) as compared to the northwest limb, and are oblique to bedding strike.

Mesostructural development also varies between the northwest and southeast limbs of the Sinking Creek anticline in Ordovician units (House & Gray 1982). In the southeast limb, a weak cleavage exists in the mudstones. In contrast, the northwest limb contains: (1) isoclinal folds in the Martinsburg Formation as well as overturned folds in the Middle Ordovician limestones; (2) strongly developed cleavage that is axial planar to overturned folds; and (3) younger contraction and extension faults that displace the folds and cleavage in the Ordovician rocks. The stronger cleavage intensity in the

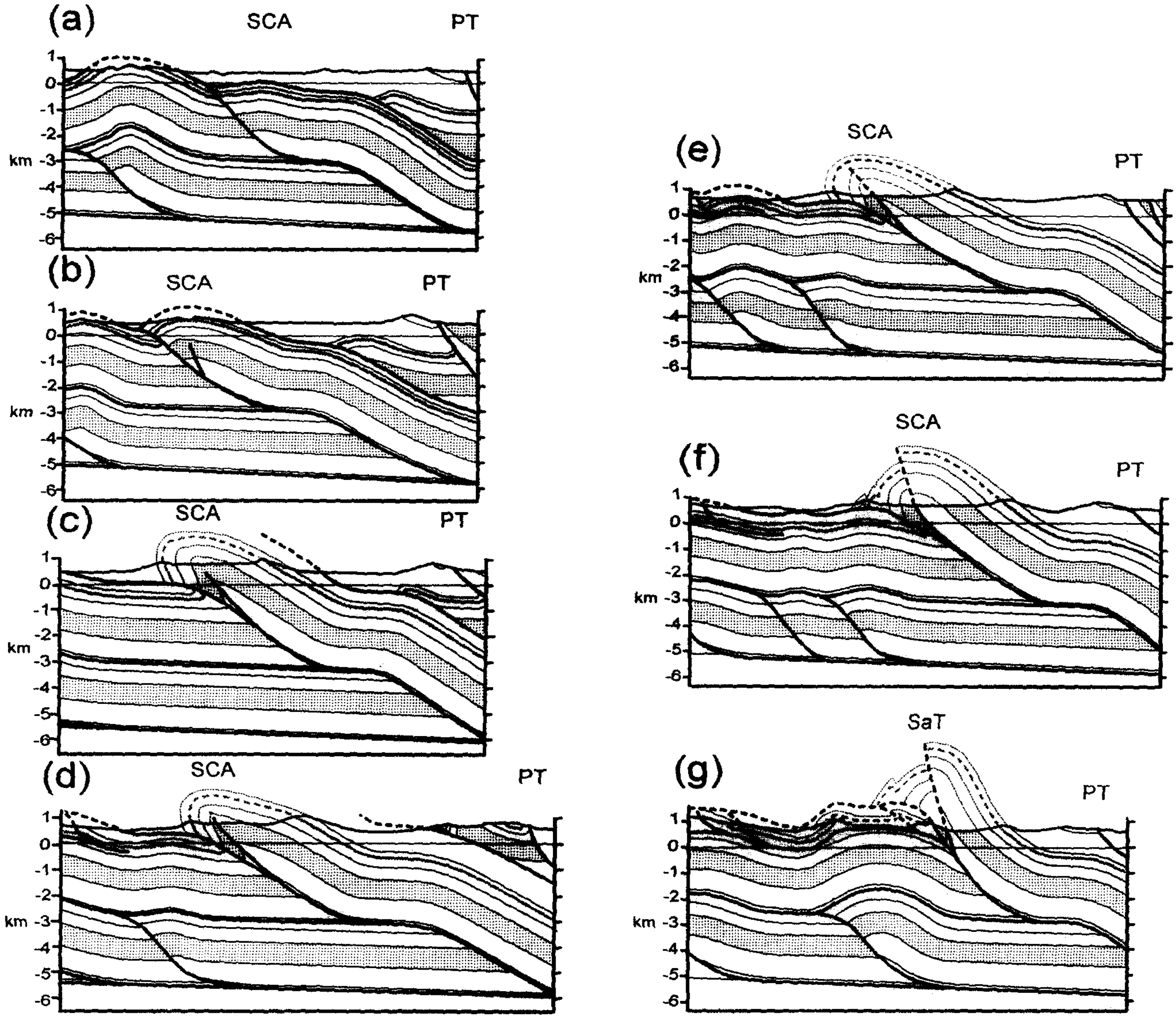

Fig. 5. Set of serial cross-sections perpendicular to strike through the Sinking Creek anticline. Cross-section (a) is the farthest northeast section, and section (g) is the farthest southwest (Fig. 4). Section (b) is a portion of section Y in Fig. 3. Figure 1(c) is a section from House & Gray (1982) that is located between sections (d) and (e). The stippled unit is the Cambro-Ordovician Knox Group and the thin gray unit is the Silurian Tuscarora Sandstone. PT—Pulaski thrust; SaT—Saltville thrust; SCA—Sinking Creek anticline.

northwest limb was attributed to either the greater limb rotation from overturning or the propagation of the Saltville thrust (House & Gray 1982).

Microstructures

Twelve samples were collected from the Tuscarora Sandstone for strain analysis and microstructural occurrence (Figs. 4 and 6). Three mutually perpendicular thin-sections were cut from each sample: bed-parallel, bed-normal along strike and bed-normal along dip. Cathodoluminescence photomicrographs were taken of each thin section because quartz luminescence distinguishes between detrital grains and their optically continuous diagenetic cement or vein fills (Houseknecht 1988, Onasch & Dunne 1993).

Thin sections from the southeast limbs contain about 95% quartz grains with undulatory extinction, and a few deformation bands and lamellae. The grains have sutured grain boundaries from solution during compaction (Houseknecht 1988, Onasch & Dunne 1993) and lack tectonic veins and transgranular solution surfaces (Table 2 and Fig. 6a). The microstructural suite seen in samples from the southeast limb is also present in samples from the northwest limb. In addition, the samples (9–11) in the overturned portion of the northwest limb contain younger bed-perpendicular, strike-parallel microveins that offset other microstructures (Table 2, Figs. 4b and 6b). These microveins are parallel to outcrop veins and have the same optically continuous quartz fill. They are most abundant (Table 2) in sample 10 where the bedding is most overturned by folding.

Strain data

The quartz grains are viable strain markers (Dunne *et al.* 1990) because their original centers can be determined from the cathodoluminescence images (Fig. 6).

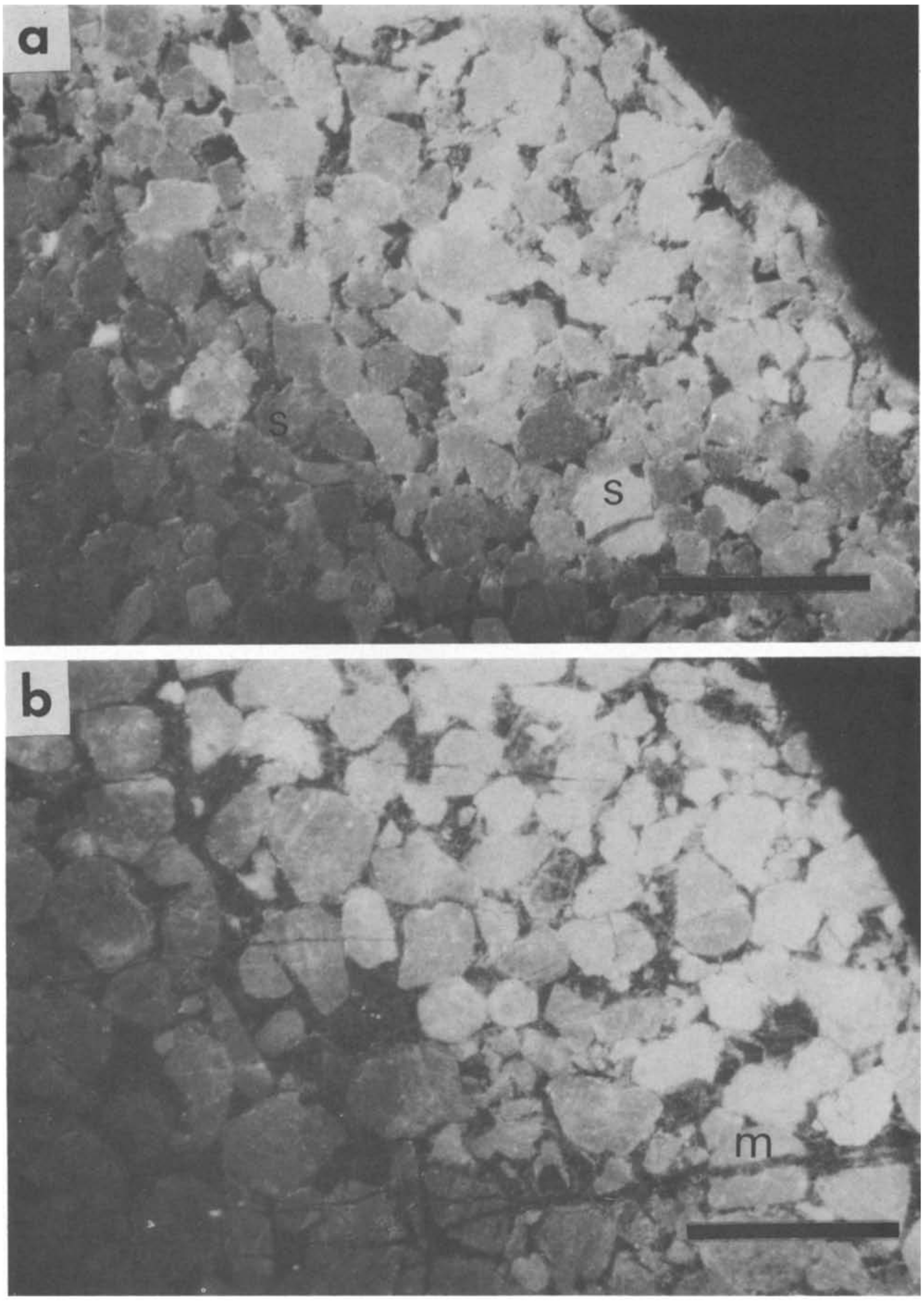

Fig. 6. (a) Bedding-parallel photomicrograph of sample 4 from the southeast limb showing only compactional microstructures (s—sutured grains). (b) Bedding-parallel photomicrograph of sample 11 from the northwest limb showing microveins (m).

Table 2. Locations, geometries and spacing of meso- and microstructures in Tuscarora Sandstone

Location	Station	Structure	Geometry to bedding	Spacing
Southeast limb	1	Microveins (thin-section only)	Bed-perpendicular, strike-parallel	Rare
	2–6	None		
Hinge	7	Bedding slip surfaces with lineation perpendicular to fold axis	Bed-parallel	2–5 m spacing
		Veins with lineation perpendicular to fold axis	Bed-perpendicular	Common (average spacing 16 cm)
		Conjugate veins that offset bedding down-to-the-north	Bed-perpendicular and 60° to bedding	Rare
Northwest limb	8	None		
	9	Microveins	Bed-perpendicular, strike-parallel	Less than 25 cm
	10	Bedding slip surfaces with dip-parallel overprinted by rare strike-parallel lineations	Bed-parallel	2–3 m spacing
		Microveins that offset bedding (and slip surfaces) top-to-the-north	Bed-perpendicular, strike-parallel	Common (average spacing 7 cm)
		Microveins without offset (in thin-section)	Bed-perpendicular, strike-parallel	Common (1–2 mm spacing)
	11	Bedding-slip surfaces with dip-parallel lineations (perp. to fold axis)	Bed-parallel	2–5 m spacing
		Microveins (no offset)	Bed-perpendicular, strike-parallel	Rare (Average 7 cm spacing)
	12	Bedding-slip surfaces with dip-parallel lineations (perp. to fold axis)	Bed-parallel	1–3 m spacing
		Slip-surfaces with dip-parallel lineations	Bed-perpendicular, dip-parallel	5–10 m spacing

The shapes and positions of 200 quartz detrital grains were digitalized in each thin-section, centers were calculated for each digitized grain, and strain determined using the normalized Fry method (Fry 1979, Erslev 1988). Strain ellipsoids (Fig. 4a and Table 3) were calculated from the three mutually perpendicular ellipses for each sample using the TRIAX program (Gendzwill & Stauffer 1981).

Because most samples have X (maximum principal strain) axes for strain ellipsoids that are nearly parallel to local bedding strike, the ellipsoidal axes were plotted in equal-area stereonets to emphasize this characteristic (Fig. 7). Bedding was rotated to horizontal by removing fold plunge and the remaining bedding dip, and then, rotated about a vertical axis so that all local strikes were parallel or normalized. All samples have Z axes that are bed-normal, which have been interpreted to represent deformation during diagenetic compaction being greater than subsequent tectonic strains (Couzens *et al.* 1993). Unlike other samples, samples 10 and 11 (Fig. 7) have X axes oblique to strike and approaching dip-parallel for sample 10. Also, the X axes for hinge samples (samples 6, 7 and 8) are parallel to local strike (Fig. 7), so they 'wrap around' the hinge (Fig. 4a), rather than being parallel to regional strike and the axis of the Sinking Creek anticline.

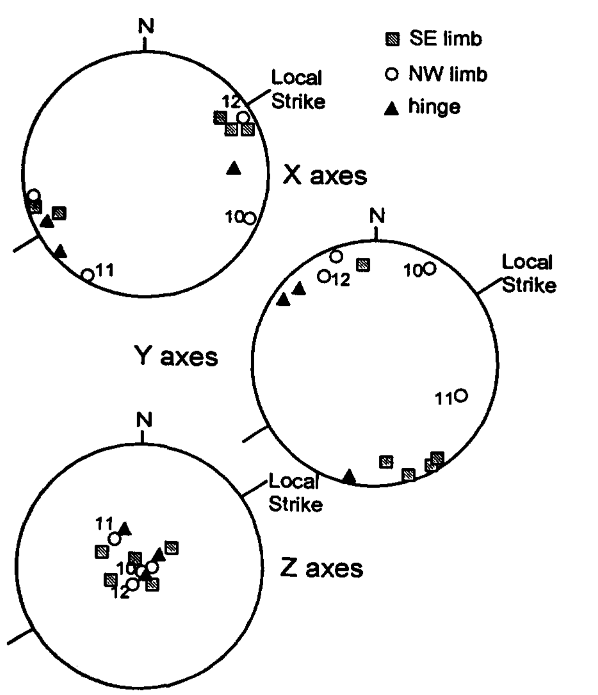

Fig. 7. Equal-area lower-hemisphere stereonets depicting the orientation of strain ellipsoid axes ($X > Y > Z$) in a common reference frame where all samples have been rotated to the horizontal and *normalized to a common strike* (symbols are the same as for stations in Fig. 2).

Table 3. Strain ratios for samples from Tuscarora Sandstone

Sample	X/Y	Y/Z	X/Z
1	1.09	1.25	1.36
2	1.22	1.06	1.29
3	1.08	1.18	1.27
4	1.16	1.16	1.34
5	1.04	1.26	1.31
6	1.08	1.11	1.19
7	1.14	1.32	1.50
8	1.19	1.08	1.29
9	1.15	1.15	1.32
10	1.02	1.20	1.22
11	1.18	1.25	1.47
12	1.18	1.13	1.32

DEVELOPMENT OF THE SINKING CREEK ANTICLINE

These mesostructural and microstructural data may be used to consider more complex geometric relationships for anticlinal development. For example, breakthrusting requires a hinge fixed with a pin line (Fischer *et al.* 1992) This kinematic behavior produces no slip on bedding in the hinge and significant shear/slip parallel to bedding in both fold limbs (Geiser *et al.* 1988). The hinge of the Sinking Creek anticline, however, contains prominent bedding-parallel slip surfaces in the Tuscarora Sandstone. Also, the southeast fold limb lacks deformation related to layer-parallel shear in both the Tuscarora Sandstone and underlying Ordovician units. Therefore, the mesostructural and microstructural data eliminate breakthrusting as a cause for the formation of the Sinking Creek anticline and Saltville thrust.

Bedding slip in the hinge and lack of deformation in the southeast limb are consistent with fault-propagation folding and a trailing pin line in or behind the southeast fold limb (Geiser *et al.* 1988, Suppe & Medwedeff 1990). For fault-propagation fold kinematics, the existence of a ramp and a splay thrust in the anticlinal core as well as the mapped cutoff of the northwest limb suggests a combination of décollement and anticlinal breakthrough (Suppe & Medwedeff 1990) (Fig. 1b). Breakthrough, however, does not alter bed-thickness or bed-dip in the northwest limb (Suppe & Medwedeff 1990) (Fig. 1b). This lack of deformation is inconsistent with several observed features of the Sinking Creek anticline: (1) the variable geometry of the hanging wall ramp along strike; (2) the intense deformation and thickening of Ordovician units in the northwest limb; (3) the veining in the Tuscarora Sandstone with dip-parallel extension and offset across bedding in the northwest limb; and (4) the deviation of X axes for strain ellipsoids from a regional strike parallel attitude towards the dip direction in the northwest limb. Also, the degree of overturning is greater in the northwest limb than is predicted by the breakthrough models (Suppe & Medwedeff 1990). These features indicate that the northwest limb underwent an internal deformation. The deformation is likely to be late since features such as veins offset the structures for bedding-parallel slip. It could have occurred during anticlinal breakthrough, which was late (House & Gray 1982), or during translation on the décollement (Mitra 1990). In either case, the deformation would occur in the absence of a trailing pin line (Mitra 1990), allowing internal deformation in the northwest limb. The absence of shear deformation in the southeast limb also suggests that the deformation was late and relatively small. In summary, the fold–thrust geometry, structural suites and strains are consistent with the Sinking Creek anticline having formed as a fault-propagation fold that involved a combination of décollement and anticlinal thrust breakthrough probably without fixed pin lines.

Role of Sinking Creek anticline in displacement transfer

As the Saltville thrust terminates into the plungeout of the Sinking Creek anticline (Figs. 4 and 5), it is interpreted to transfer about 3 km of displacement from the ramp into the floor thrust that connects the Saltville thrust to the Narrows and St. Clair thrusts (section Y in Figs. 3 and 5). The change in amplitude of the Sinking Creek anticline does have a role in accommodating the remaining thrust displacement before the termination of the Saltville thrust. This role can be quantified by measuring the change in displacement between the Tuscarora Sandstone and the base of the Cambro-Ordovician Knox Group along the imbricate thrusts in a particular cross-section (Fig. 5). These measurements show that the amount of displacement along the thrusts decreases upwards from the Knox Group to the Tuscarora Sandstone, which is consistent with the increase in anticlinal amplitude from the Knox Group to the Tuscarora Sandstone. The proportion of the remaining displacement that is accommodated by anticlinal amplitude increases from 43 (Fig. 5e) to 68% (Fig. 5b) towards the thrust termination. The remainder of thrust displacement is transferred to the inferred roof flat in the Devonian shales (Figs. 5 and 8).

IMPLICATIONS FOR OTHER THRUST TERMINATIONS

Another major southern Appalachian thrust fault, the St. Clair thrust, terminates into the core of a NW-verging anticline at the transition to the central Appalachians. The similarity in surface geometry (Fig. 2) of the Saltville and St. Clair thrusts suggests that the two faults terminate in a similar subsurface geometry. Several cross-sections containing these two structures have been published (Woodward 1985, Kulander & Dean 1986, Hatcher *et al.* 1989). Both surface geology and well data around a structural high (Perry *et al.* 1979, Woodward 1985, Kulander & Dean 1986, Schultz *et al.* 1986), the Bane dome (BD, Fig. 2), indicate that the Saltville and St. Clair thrusts are connected by a floor thrust that completely doubles the Cambro-Ordovician stratigraphy by a flat-on-flat geometry (X in Fig. 3). This geometry locates the footwall ramp of the St. Clair thrust to the southeast of the Bane dome and requires more than 25 km of displacement along the thrust. Previously, the displacement from the flat-on-flat geometry has been interpreted to be taken up on the emergent St. Clair thrust (Woodward 1985, Kulander & Dean 1986, Bartholomew personal communication).

Removal of the displacement from the flat-on-flat geometry through the St. Clair thrust has two problems that are related to its mapped surface termination. First, the cross-section through the Bane dome (section X in Fig. 3) with 26 km of displacement on the St. Clair thrust is about 100 km along strike from the surface termination of the St. Clair thrust. If the termination is the end of the St. Clair thrust, the footwall ramp of the St. Clair thrust must migrate into the foreland over 20 km to meet the St. Clair hanging wall ramp at that termination. The geometric result would be an oblique ramp from behind the Bane dome to the termination that strikes at about 030°. An oblique fault-bend fold should exist above such a ramp, but no such structure is present (Butts 1940, Schultz *et al.* 1986, Bartholomew *et al.* in press) (Fig. 2).

Second, to the northeast in the central Appalachians, Cambro-Ordovician stratigraphy is also doubled (section Z in Fig. 3) by a major flat-on-flat duplex (Jacobeen & Kanes 1974, Wilson 1989, Wilson & Shumaker 1992). As flat-on-flat duplexes with over 20 km of displacement exist along strike to both the northeast and southwest of the termination for the St. Clair thrust, maintenance of lateral continuity would suggest a similar flat-on-flat geometry at the termination. Also, preservation of lateral continuity for the flat-on-flat duplex would negate the need for the oblique ramp that lacks support from geologic map data. Yet, the existence of a surface thrust termination and a subsurface flat-on-flat duplex with over 20 km of displacement must be reconciled.

We propose a solution that has a structure comparable to the geometry of the Saltville thrust–Sinking Creek anticline (Y in Fig. 3 and Fig. 5). The solution requires a small displacement on the St. Clair thrust with the majority of displacement from the flat-on-flat duplex transferred to a flat beneath the Appalachian Plateau (Y in Fig. 3). In this solution, the anticline at the termination of the St. Clair thrust (Fig. 3) is a fault-propagation fold that has been displaced over 20 km along a flat and is cut by the St. Clair thrust as a breakthrough thrust. Similarly, the Sinking Creek anticline is a fault-propagation fold with the Saltville thrust as a breakthrough thrust. Both anticlines have steeply dipping to overturned northwest forelimbs above roof flats. In this solution, the St. Clair thrust only has about 2 km of displacement, so a major oblique ramp is not required at its termination. The interpretation does, however, pose a new problem: what happens to the 25+ km of displacement transferred to the Appalachian Plateau?

To the northeast of the thrust terminations, 20+ km of displacement is interpreted to be transferred by some workers (Jacobeen & Kanes 1974, Wilson 1989, Wilson & Shumaker 1992) along a roof flat into the Appalachian Plateau from flat-on-flat duplexes of the Cambro-Ordovician carbonates. This displacement is absorbed by macroscale folding and bulk strain in Plateau rocks (Wiltschko & Chapple 1977, Engelder & Geiser 1979, Geiser 1988a,b, Craddock & van der Pluijm 1989). In the Appalachian Plateau to the northwest of our study area, map-scale folds account for, at best, 2 km of arc length shortening. Hence, most of the 25 km of shortening that would be transferred into a flat beneath the Plateau must be distributed through the rocks as strain. Allowing the strain to be distributed over 390 km in front of the St. Clair thrust, across a region from Bluefield,

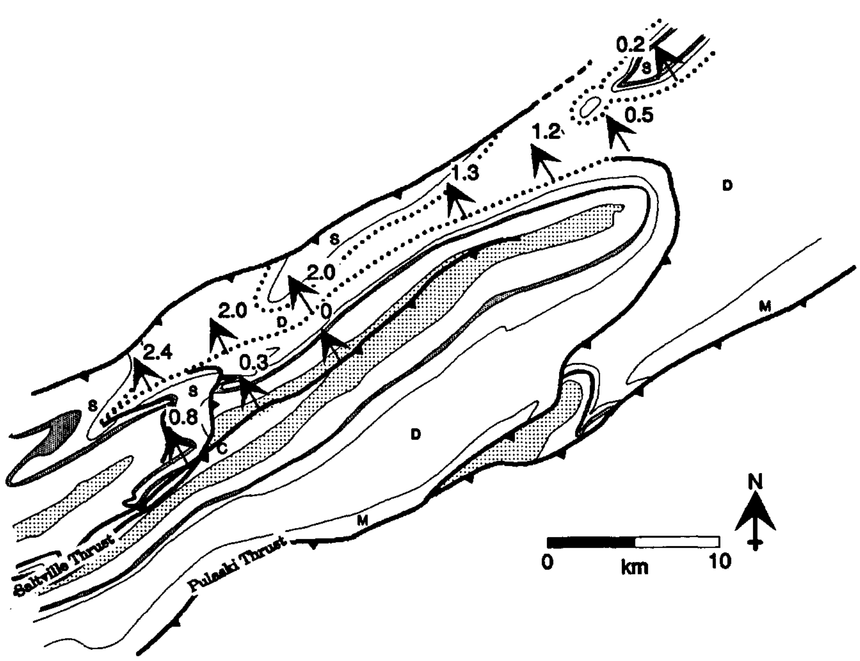

Fig. 8. Map showing the inferred displacement of the Tuscarora Sandstone along the roof flat in Devonian shale (dotted line) and along the Saltville thrust as measured from cross-sections in Fig. 5. Displacement amount is shown in kilometers next to the arrow. The stippled regions represent outcrop of the Cambro–Ordovician Knox Group, the medium gray unit is the Silurian Tuscarora Sandstone. M—Mississippian rocks; D—Devonian rocks; S—Silurian rocks; O—Ordovician rocks; C—Cambrian rocks. Map is modified from Bartholomew *et al* (in press).

West Virginia, to Columbus, Ohio, would require an average contractional strain of 6.4%. Twin strains in limestones of central Ohio record only 1–2% shortening from just one deformation mechanism (Craddock & van der Pluijm 1989). Thus, the strain in the Plateau rocks, instead of being evenly distributed, would have to be greater near the St. Clair thrust. This possibility is supported by field observations in the Appalachian Plateau of strongly cleaved Greenbrier Limestone in the vicinity of the St. Clair thrust (Dean *et al.* 1988), whereas limestones in Ohio are weakly strained (Craddock & van der Pluijm 1989). The actual strain distribution in the Plateau has yet to be determined, so the viability of the proposed solution for the geometry at the termination of the St. Clair thrust has yet to be demonstrated.

CONCLUSIONS

(1) Where the Saltville thrust terminates, displacement is primarily transferred into an underlying floor thrust. Towards the termination, remaining displacement is transferred to a roof flat and absorbed by the development of the Sinking Creek anticline. A greater proportion of this remaining displacement is accommodated by the anticline than the roof flat.

(2) The Sinking Creek anticline is interpreted to be a fault-propagation fold subjected to both décollement and anticline thrust breakthrough. The anticlinal breakthrough was achieved by the Saltville thrust. Meso- and microstructural data indicate that folding did not involve fixed pin lines in either the hinge or backlimb.

(3) The anticlinal termination of the St. Clair thrust has a similar surface geometry to the Sinking Creek anticline and is therefore interpreted to be of similar origin. The St. Clair thrust would be an anticlinal breakthrough to a fault-propagation fold that has been transported over 20 km along a thrust flat. The majority of this displacement would be transferred into the Appalachian Plateau along a thrust flat where it causes horizontal shortening.

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