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The kinematics of break-thrust folds

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Abstract—The kinematics of asymmetric, open to close, often overturned thrust-related folds are commonly explained with fault-propagation or detachment fold models. Field observations of thrust-related folds exposed in Tennessee, Virginia, Wyoming and Montana that exhibit this geometry indicate that models of fault-propagation and detachment folds do not adequately describe the kinematics of these structures. Existing models of fault-propagation and detachment folding employ migrating, kink-shaped hinges and relate fold geometry entirely to fault geometry, slip and to the thickness of the basal detachment layers. The models exclude the relation between fold shape and amplitude, and they do not predict a correlation between competent-layer thickness and fold wavelength as expected from buckling theory. Thrust-related folds examined in this study exhibit unique distributions of fabrics in the hinges and forelimbs which demonstrate a lack of hinge migration. Furthermore, the ratios of dominant member thickness to fold wavelength agree with those expected for folds controlled by a single competent layer and they are within the expected range for folds with multiple, evenly spaced, harmonically deforming layers. Our analyses suggest these folds evolved from an initial, brief stage of sinusoidal buckling to a later stage of fixed-hinge kinking and thrusting. Thrust-related folds which exhibit a geometry and mesofabric distribution suggesting this type of evolution are defined as break-thrust folds.

INTRODUCTION

Three geometric types of thrust-related folds are recognized in foreland fold and thrust belts: ramp–flat folds, detachment folds and tip-line folds. Ramp–flat folds result from stratigraphic duplication at a thrust ramp where hanging-wall ramps overlie footwall flats (Rich 1934). Detachment folds commonly develop above a detachment that is subparallel to bedding and are cored by incompetent, often disharmonically folded strata (Dahlstrom 1970, Laubscher 1976a). Tip-line folds develop as a result of enhanced compression and shortening above, or in front of the tip line of a blind thrust (Elliott 1976, Williams & Chapman 1983). Ramp–flat folds do not form at blind thrust tips and therefore cannot be tip-line folds. In contrast, detachment folds may form at the tip line of a thrust that is subparallel to bedding and therefore may be tip-line folds (Jamison, 1987).

After conducting centrifuge modeling of thrust structures, Dixon & Tirrul (1991), and Dixon & Liu (in press) proposed that these three thrust-related folds each represent different stages in the evolution of a single thrust-related fold. Model structures initiated as buckle folds which progressively evolved into detachment folds, tip-line folds and finally ramp–flat folds. In contrast, Fischer & Woodward (in press) demonstrate using surface and subsurface cutoff-line data that there is no necessary evolutionary sequence from a tip-line fold into a ramp–flat fold from the center of a thrust sheet towards the lateral thrust tip. Instead we suggested that the particular style of thrust-related folding which develops in an area is controlled by the local kinematics of thrusting.

Asymmetric, open (120°–70° interlimb angle) to close (70°–30° interlimb angle; Ramsay & Huber 1987), often overturned thrust-related folds that verge toward the foreland are commonly suggested to have formed as tip-line folds (Elliott 1976, Dubey & Cobbold 1977, Thompson 1981, Berger & Johnson 1982, Williams & Chapman 1983, Boyer 1986). Previous workers have explained the kinematics of formation of these folds using fault-propagation fold (Suppe & Medwedeff 1984, Suppe 1985, Mosar 1990) or detachment fold (Jamison 1987) models.

A fault-propagation fold is a geometric, kinematic model that explicitly describes the evolution of a tip-line fold using equations relating fold geometry to fault shape and displacement. Detachment folds at thrust tip lines, hereafter referred to as detachment folds, are similarly modeled with equations relating fold amplitude to thickness of a basal detachment layer (Jamison 1987). These models assume that structures evolve as migrating-hinge kink folds deformed only by slip on bedding planes between fold hinges, and imply that cumulative strain is constant and homogeneously distributed in the fold limbs.

This paper assesses the applicability of fault-propagation and detachment folding models to four thrust-related folds in Wyoming, Virginia, Montana and Tennessee. In contrast with model predictions, mesoscopic fabric data from these structures show that they formed by fixed-hinge kinematics. We interpret these structures as break-thrust folds as defined by Willis (1893) because their evolution involves a component of buckle folding prior to faulting. We hypothesize that these folds evolved from an initial stage of sinusoidal buckling to a later stage of fixed-hinge kinking and thrusting.

THRUST-RELATED FOLDING MODELS

There are two main groups of folds that may be used to explain the kinematics of thrust-related folding: kink folds and buckle folds. The distribution of strain expected for folds that evolved by either of these mechanisms may vary significantly.

Models based on kink folding

Numerous researchers have investigated the mechanics and kinematics of microscopic and mesoscopic chevron-style kinks (Dewey 1965, Paterson & Weiss 1966, Ramsay 1967, Donath 1968, Weiss 1968, 1980, Anderson 1974, Johnson & Ellen 1974, Johnson 1977, Williams & Price 1990). Kinks at all scales occur in rocks with at least one set of pervasive slip surfaces. They may initiate by bending or plastic yielding instabilities promoted by local layer perturbations, low-amplitude sinusoidal folding, or any other condition or process which imparts an initial deflection out of the plane of the layering (Johnson 1977, Weiss 1980). Weiss (1980) offered the following properties as characteristics of *ideal* kinks: (1) deformation is by layer-parallel simple shear on discrete slip surfaces between the kink band boundaries; (2) material outside the kink is undeformed and unslipped; (3) layer-perpendicular thickness within the kink remains constant (i.e. no dilatation); and (4) slip surfaces are spaced infinitesimally close and are present in deformed and undeformed material.

Kinks may develop with fixed or migrating kink-band boundaries (i.e. fold axial planes or hinges; Dewey 1965, Anderson 1974) or combinations of these two end-members. In fixed-hinge kinks, shortening occurs by progressive rotation of the limb between kink-band boundaries which maintain a constant spacing measured along bedding (Fig. 1a). Total shortening is limited by the locking angle of the kink, beyond which strata cannot fold without changing stratigraphic thickness or faulting (i.e. *non-ideal* behavior; Dewey 1965, Ramsay 1974). A fixed-hinge kink will lock at a unique angle determined by intrinsic rock properties like interlayer friction, the ratio of competent to incompetent material

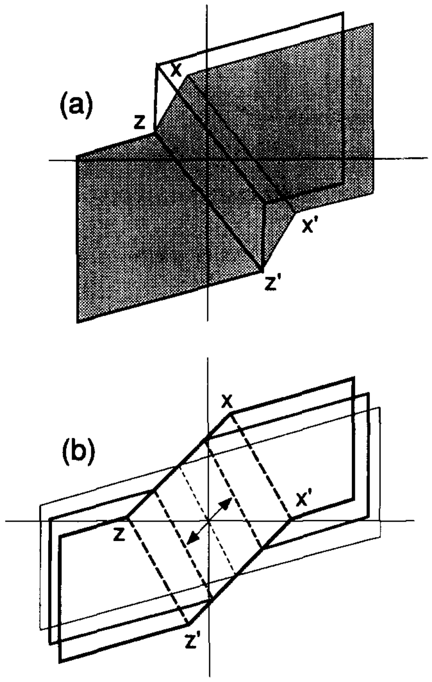


Fig. 1. Two end-members of ideal kink kinematics. (a) Fixed-hinge kink evolves by progressive limb rotation. (b) Migrating-hinge kink evolves by lateral movement of hinges x–x′ and z–z′ as shown by double-headed arrow. Modified from Weiss (1980).

(Ramsay 1974), and the remote stresses during deformation.

During fixed-hinge kinking, material within the kink (panel x–x′–z–z′ of Fig. 1a) undergoes progressive simple shear by slip between beds during rotation (Weiss 1980). At any given moment therefore, cumulative strain is constant throughout this part of the structure, and it continuously increases as material in the kink rotates. Strain and deformation is expected to concentrate in areas of maximum curvature (i.e. fold axial surfaces), which are the locus of plastic yielding (Dieterich & Carter 1969).

In migrating-hinge kinks, shortening occurs by lateral migration of hinges, and total shortening is limited only by the amount of hinge migration (Fig. 1b). A migrating-hinge kink band enlarges volumetrically as strata passing through a hinge is rotated into the kink band through a fixed angle. During migrating-hinge kinking, each volume of rock added to the kink band undergoes the same incremental strain as it passes through the fixed angle at the hinge. Because limbs of a migrating-hinge kink do not rotate with time, the incremental strain equals the cumulative strain in the structure. All strain in the kink band is imparted at kink band boundaries, and deformation should be homogeneously distributed throughout the kink band. Kinks that enlarge by a combination of fixed- and migrating-hinge mechanisms occurring simultaneously or at different times are also possible (Weiss 1980).

Because field studies suggest the geometry of many thrust-related folds closely resembles macroscopic kink bands (e.g. Faill 1969, 1973), and since deformation in foreland fold and thrust belts commonly occurs under conditions favoring a flexural-slip mechanism of folding

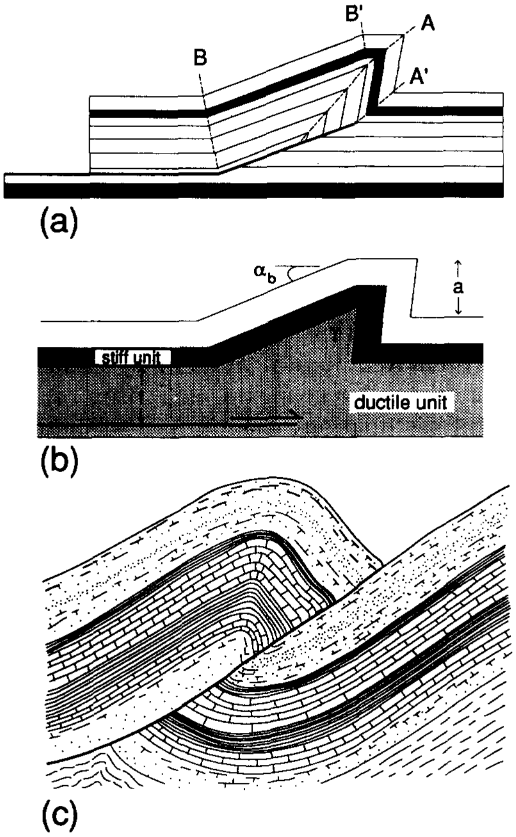


Fig. 2. Thrust-related fold models: (a) fault-propagation fold, (b) detachment fold, (c) break-thrust fold. After Suppe (1985), Jamison (1987) and Willis (1893), respectively.

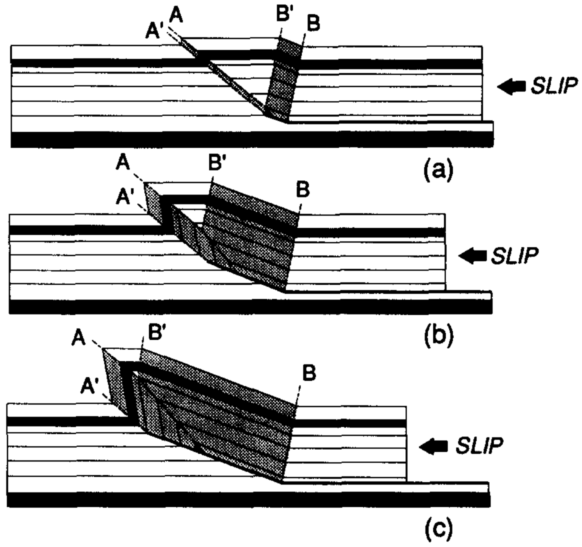


Fig. 3. Evolution of a fault-propagation fold by migrating-hinge kinematics. (a) Intersecting, migrating kinks A–A′ and B–B′ initiate with the first increment of fault slip. (b) With continued slip, hinges A′, B and B′ migrate through strata; the kink bands increase in volume; and fold amplitude increases. (c) Kink bands continue enlarging until fault propagation ceases or fault trajectory changes. Stippled areas show extent of migrating-hinge kinks at each stage of fold growth. After Suppe (1985).

(i.e. brittle deformation of mechanically anisotropic rocks with a low mean ductility; Donath & Parker 1964), a kink mechanism is often used to explain the kinematics of thrust-related folds.

Fault-propagation and detachment folds. Fault-propagation and detachment fold models have been extensively applied to explain the formation of close-to-open, asymmetric, chevron-shaped, tip-line folds with steep to overturned forelimbs (terminology of Dahlstrom 1970). Fault-propagation folds develop coevally with thrusting and consume slip at the tips of blind thrusts (Fig. 2a) (Suppe & Medwedeff 1984, Suppe 1985, Mosar 1990). As the thrust tip migrates, strata are folded in front of, and are eventually truncated by the thrust. Fault-propagation folds form above footwall ramps, but may be transported onto higher footwall flats with attendant geometric modifications (Jamison 1987).

The fault-propagation fold model assumes migrating-hinge kink kinematics and parallel-fold geometries (Suppe & Medwedeff 1984, Suppe 1985). Models employing non-parallel geometries have also been presented by Jamison (1987) and Mosar (1990). In parallel fault-propagation folds, two constant-angle kink bands A–A′ and B–B′ in Fig. 3(a), initiate at the first instant of fault slip. The constant angle of these kink bands is determined only by the geometry of the underlying fault. With continued slip (Figs. 3b & c), the fold grows in amplitude by lateral migration of kink boundaries A′, B and B′ while boundary A remains fixed to material in the hanging wall. The fold continues growing in this manner until fault propagation ceases or fault trajectory is significantly altered (e.g. development of an upper flat; Suppe 1985).

Jamison's (1987) detachment fold model relates fold interlimb angle (γ) and backlimb dip (α_b) to the ratio of fold amplitude (a) to the undeformed thickness of incompetent strata along the associated detachment (f) (Fig. 2b). Because f is fixed in any given structure, continued shortening always increases a/f and alters γ and α_b. The fold grows in amplitude by a migrating-hinge kink mechanism similar to that in fault-propagation folds.

Models based on buckle folding

Of the four types of thrust faults recognized by Willis (1893, p. 223), the break thrust was suggested to develop "when strata form first an anticline, so conditioned that in process of development folding soon becomes more difficult than breaking, followed by an overthrust on the fracture plane" (Fig. 2c). Willis did not offer a mechanical model for the development of break thrusts, and we infer that he is hypothesizing buckle folding before thrusting. We refer to thrust-related folds which developed by this mechanism as break-thrust folds.

Numerous experimental and theoretical studies have shown that the geometry of buckle folds depends on the rheological properties of the strata involved (Currie *et al.* 1962, Ramberg 1964), total shortening (Johnson & Ellen 1974), and pre-folding structural discontinuities in the rock (Ramberg 1964). Currie *et al.* (1962) showed that the wavelength of buckle folds (λ) is controlled by

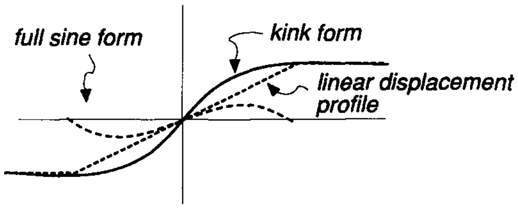


Fig. 4. Kink geometry presented by Johnson (1977). Kink form results from combination of full sine wave and linear displacement profile of a kink formed by plastic yielding. The kink form may be continuous or discontinuous; it forms by buckling followed by incomplete plastic yielding.

the thickness of competent rock units (T) in a stratigraphic section. They found that a thickness to wavelength ratio of 1:27 gave a best-fit to field data from folds controlled by a single competent layer. Multilayered experiments, in which closely-spaced competent layers deformed as a composite layer, show somewhat lower T/λ ratios.

Because many asymmetric, thrust-related folds exhibit large ratios of limb-length to hinge-width, the geometry is best approximated by the kink form. Johnson (1977) noted that an early stage of sinusoidal buckling commonly precedes the formation of kink folds and may be reflected in the kink geometry. The kink form may be expressed mathematically as the sum of a sine wave and the linear displacement profile of a kink formed by plastic yielding (Fig. 4) (Honea & Johnson 1976, Johnson 1977).

As noted by Woodward *et al.* (1985, p. 73), the distribution of strain in flexural-slip or buckle folds is primarily controlled by the position of pin lines in the structure. Axial plane pin lines result in maximum bedding slip at limb inflection points. Backlimb or forelimb pin lines result in maximum bedding slip on the opposite limb. Large bending strains occur near the pin line in all cases.

Determining fold kinematics

Critical data for determining the role of buckle folding and migrating or fixed hinges in thrust-related fold development can be obtained by examining the distribution of deformation in well-exposed folds. Models utilizing migrating-hinge kinks and parallel geometries predict that material outside the kink bands should be undeformed and that all strain in the kink bands should occur at the instant material passes through a hinge (Ramsay 1990). Thrust-related folds which evolved in this manner should have homogeneous strain and an even distribution of deformation features in the forelimb. In contrast, thrust-related folds that formed with fixed-hinges should have deformation concentrated close to pin lines (e.g. axial surfaces) and may have substantial interbed slip in the forelimb (Mitchell & Woodward 1988). The agreement between theoretically estimated and observed T/λ ratios is evidence that a folding instability influences structural geometry. Structures that evolved by combinations of migrating- and fixed-hinges will exhibit unique distributions of deformation, or specific sequences of deformation overprinting, depending on where and when hinge migration occurred.

FIELD EXAMPLES

To document the intensity and distribution of deformation in asymmetric thrust-related folds and thereby test the migrating-hinge model of fold kinematics, we examined mesofabrics in four well-exposed, close to tight, asymmetric, locally overturned anticlines and truncated footwall synclines. Comparison of observed mesofabric distributions with strain distributions predicted by theoretical models of thrust-related kink folding provides a basis for analyzing the kinematics of these structures.

Hossfeldt anticline

The Hossfeldt anticline in southwest Montana is an asymmetric, overturned fold in the Sevier fold and thrust belt (Fig. 5) (Mitchell 1987). Mesofabrics including bedding-slip surfaces, tectonic breccias, shear and extension fractures, pressure-solution cleavage, bedding-perpendicular stylolites and wedge faults are heterogeneously distributed throughout the anticline (Fig. 6) (Mitchell & Woodward 1988). The forelimb and hinge regions of the fold, exhibiting prominent cleavage in silty carbonates and brecciation in massive units, are considerably more deformed than the backlimb, with mesofabrics limited to minor wedge faults and local bedding-slip surfaces. Massive calcite veins locally comprise as much as half of the material in the hinge, indicating that the hinge underwent significant brecciation and extension. Laubscher (1976b) modeled just this sort of void formation and room problem for fixed-hinge folds in the Jura. Mitchell & Woodward (1988) suggest the sequence of stylolitization and fracturing observed in the forelimb of the Hossfeldt anticline represents a gradual rotation of bedding through the regional stress field and interpret this fold as a fixed-hinge kink-buckle fold.

Indian Creek syncline

The Indian Creek syncline underlies the St. John thrust in the southern Snake River Range of Wyoming (Fig. 7) (Woodward 1986). The structure was mapped by Jobin (1972) and Albee & Cullens (1975) as a faulted sequence in the Mississippian rather than a folded one, as seen in Fig. 7(c). This high-amplitude syncline is best exposed in Indian Creek in the Mississippian Mission Canyon Formation (Mm) and the Pennsylvanian–Mississippian Amsden Formation (PMa). It is present in rocks as young as the Triassic Thaynes Formation, although the initial amplitude at that stratigraphic level is unknown because only the hinge region is preserved. Beds on both limbs are planar. The preserved Mission Canyon Formation is about 300 m thick and the pre-

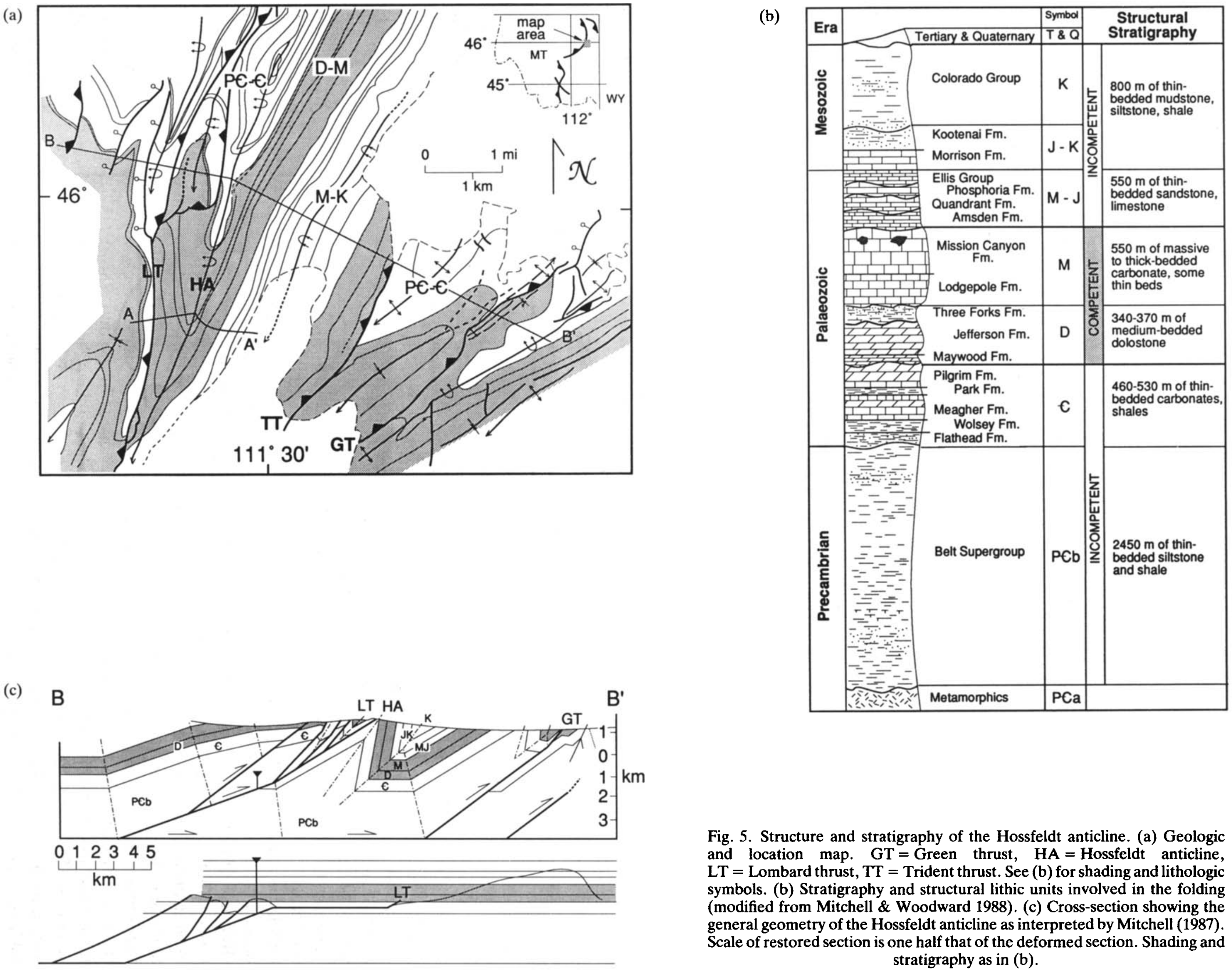


Fig. 5. Structure and stratigraphy of the Hossfeldt anticline. (a) Geologic and location map. GT = Green thrust, HA = Hossfeldt anticline, LT = Lombard thrust, TT = Trident thrust. See (b) for shading and lithologic symbols. (b) Stratigraphy and structural lithic units involved in the folding (modified from Mitchell & Woodward 1988). (c) Cross-section showing the general geometry of the Hossfeldt anticline as interpreted by Mitchell (1987). Scale of restored section is one half that of the deformed section. Shading and stratigraphy as in (b).

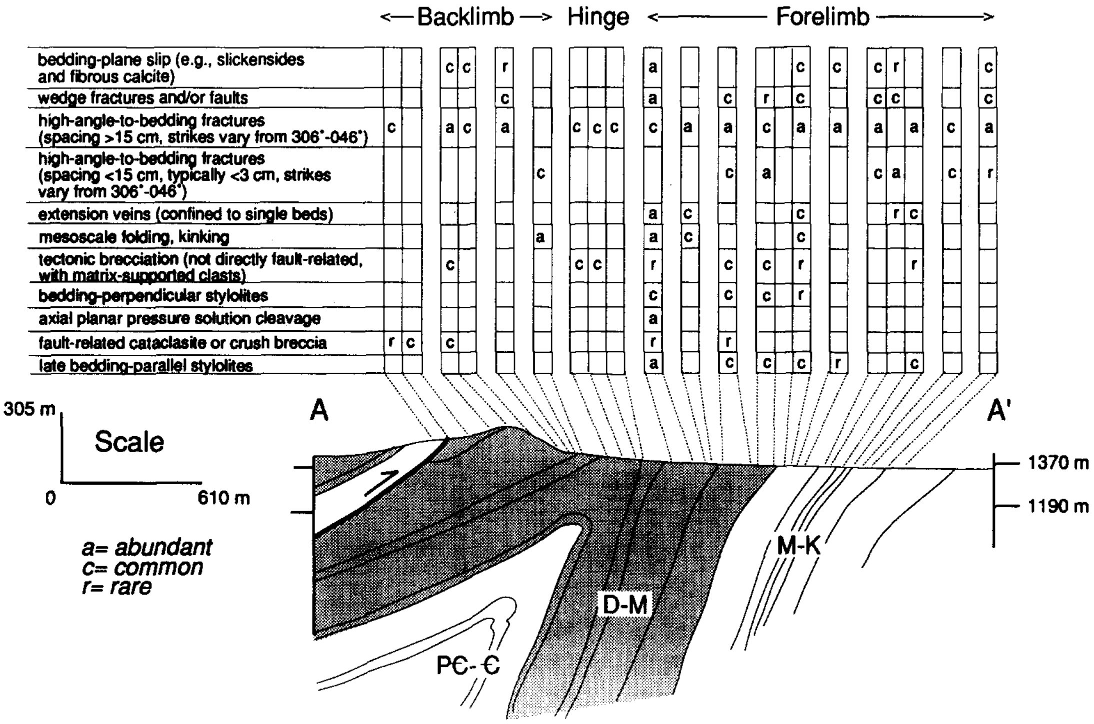


Fig. 6. Cross-section from traverse A–A′ near the southern end of the Hossfeldt anticline showing distribution and abundance of mesofabrics observed. Backlimb deformation is less intense than hinge or forelimb deformation as suggested by the following examples. In the backlimb: (1) displacements on bedding-slip surfaces are less than 10 cm, (2) aperture of extension veins less than 3 mm, (3) all bedding-parallel stylolites are related to sedimentary loading. In the forelimb: (1) extensively developed bedding-slip surfaces with up to 1.5 cm of fibrous calcite locally preserved on the surfaces, (2) aperture of veins may reach 1 cm, (3) bedding-parallel stylolites cut early formed veins and bedding-perpendicular stylolites. See Fig. 5(a) for location of section line, Fig. 5(b) for shading and lithologic symbols. Note that these are semi-quantitative observational data. No attempt was made to factor in the affects of differing lithologies on the intensity of mesofabric development. From Mitchell (1987).

served overturned limb is about 500 m long. Local brecciation in the syncline, thought earlier to indicate faulting (Jobin 1972, Albee & Cullens 1975), is common in the core but absent in the limbs. The lack of mesoscopic structures other than bedding slip surfaces on the overturned limb again argues against a migrating hinge kink mechanism.

Rocky Valley anticline

The Rocky Valley anticline, in the central east Tennessee Valley and Ridge Province, deforms strata of the Cambrian Rome Formation through Middle Ordovician Knox Group for nearly 60 km along the trailing edge of the Rocky Valley thrust system (Figs. 8 and 9). The fold exhibits a complex geometry which varies both along strike and with stratigraphic level (Fig. 10a) (Fischer 1989, Fischer & Woodward in press). Mesofabrics in the Rocky Valley thrust system, including mesoscopic folding, faulting and pressure-solution cleavage, are only developed in the fold hinges or near faults (Fig. 10b). Shale beds exposed in the hinge zone of the Rocky Valley anticline are pervasively deformed into folds with 1–20 cm wavelength and 3–20 cm amplitude, and consequently may be thickened as much as 50%. Similar stratigraphic thickening is observed in hinges of fixed-hinge mesoscopic chevron folds (Ramsay 1974) and thrust-related folds in the Jura (Laubscher 1976b). Shale beds in the limbs of the anticline are relatively undeformed and dip homoclinally away from the hinge. Silty carbonate beds in the hinge exhibit spaced stylolitic cleavage or, locally, a weak, penetrative, pressure-solution cleavage (Fig. 10b). Cleavage intensity is greatest in the core of the anticline at the statigraphic level of the Middle Cambrian (i.e. Rutledge Limestone of the Conasauga Group), and intensity decreases upward in the section. Again the distribution of mesoscopic structures indicates this fold could not have evolved as a migrating-hinge kink.

Rye Cove syncline

The Rye Cove syncline is a major fold in the Hunter Valley thrust sheet of southwestern Virginia (Fig. 8). The syncline is well exposed just south of Duffield, Virginia, where it deforms strata of the Knox and Conasauga Groups. In that area the Clinchport thrust dips steeply southeastward above the overturned limb of the syncline (Fig. 11). Knox Group strata in the core of the syncline show brecciation within layering, but no significant faults have been observed in the hinge (Harris & Miller 1958). The overturned limb of the Rye Cove syncline shows less evidence of bedding slip or other deformation than does the gently SE-dipping upright limb (Wojtal 1989). There is some limited disruption of bedding suggestive of NW-verging bedding slip on the upright limb (Diegel & Wojtal 1985). Massive carbonates in the overturned limb have rotated passively with-

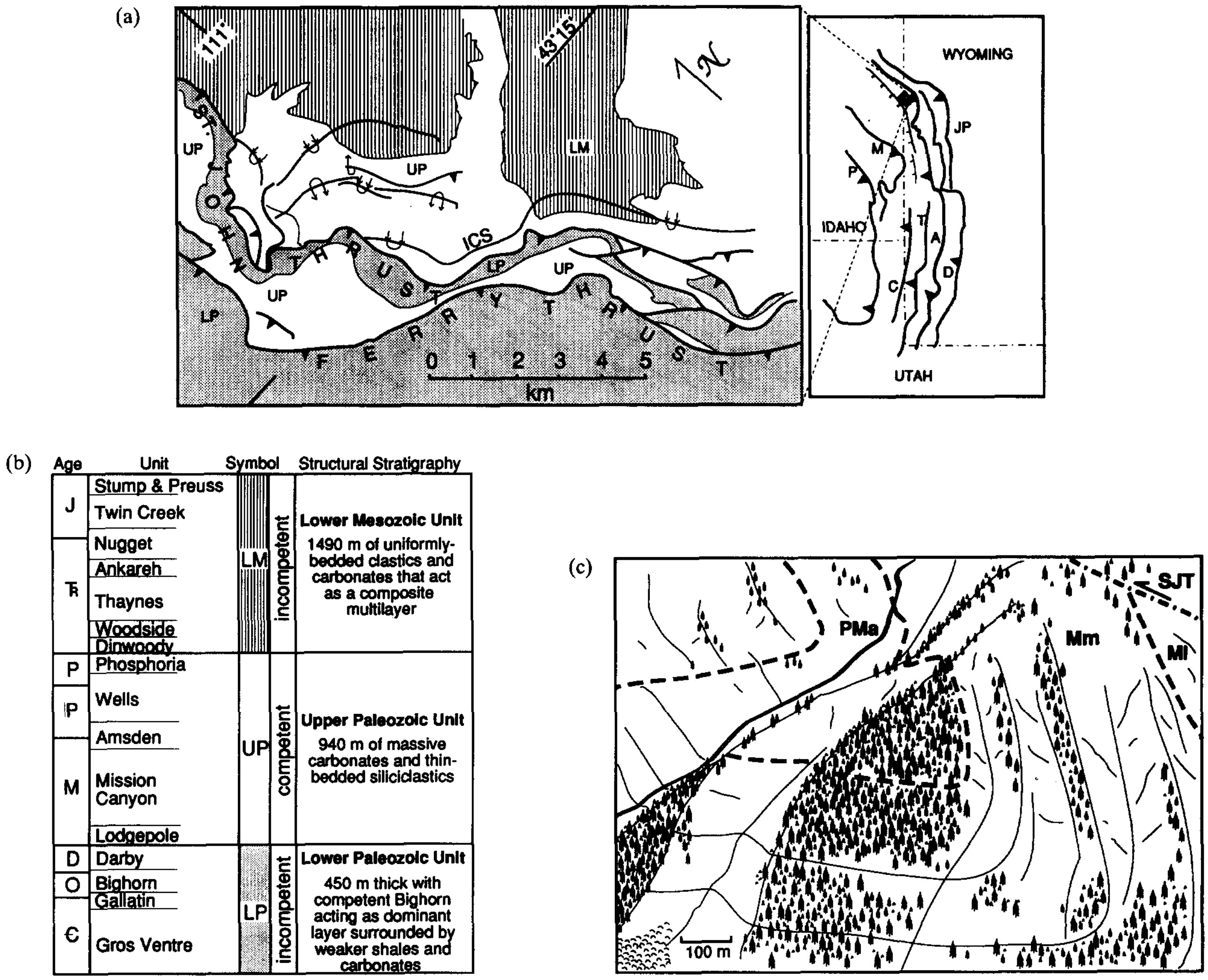


Fig. 7. Generalized geologic and location map of the area around the Indian Creek syncline. Symbols on small-scale map: A = Absaroka thrust, C = Crawford thrust, D = Darby thrust, JP = Jackson–Prospect thrust, M = Meade thrust, P = Paris thrust, T = Tunp thrust. See (b) for lithologic symbols (modified from Woodward 1981, 1986). (b) Stratigraphy and structural lithic units involved in the Indian Creek syncline. (c) Field sketch showing southeastward view of the Indian Creek syncline as exposed in the footwall of the St. John thrust. Coarse dashed line = formation contacts, dot–dash line = thrust fault, PMa = Amsden Formation, Mm = Mission Canyon Formation, Ml = Lodgepole Formation, SJT = St. John thrust.

out passing through an angular hinge. Brent (1985) interpreted the Rye Cove syncline as a break-thrust fold that formed by folding preceding thrusting.

SUMMARY

Although existing models of fault-propagation and detachment folding approximate the geometry of many thrust-related folds accurately and utilize a layer-parallel slip deformation mechanism thought to be dominant in many foreland structures (Laubscher 1976b, Wiltschko *et al.* 1985), the general kinematics of these models are not compatible with our field observations. These commonly employed models of asymmetric thrust-related folds explain neither the concentration of mesofabrics in fold hinges nor the dominant member thickness/wavelength co-ordination observed in many of these structures. Neither fault-propagation nor detachment fold theory predicts any relationship between fold wavelength and the thickness of competent layering, but instead predict a large range of wavelengths that depend on how far a fault-propagation or detachment fold has evolved.

Figure 12 shows the dominant member thickness (T)/wavelength (λ) relations for the four thrust-related folds discussed in this paper. Fold wavelengths were measured along the centers of competent members in the forelimbs of anticlines and along the overturned limbs of synclines depicted in cross-sections through each structure. These limb lengths are taken to represent approximately one half of the initial fold wavelength. Wavelength measurements of folds with the limbs eroded or truncated by thrust faults are taken as minimum estimates. Measurements of backlimb lengths were not used because these values most likely represent the length of underlying footwall ramps rather than a buckling wavelength. Estimates of thickness of the dominant members, including simple and composite units, are based on previous interpretations of regionally

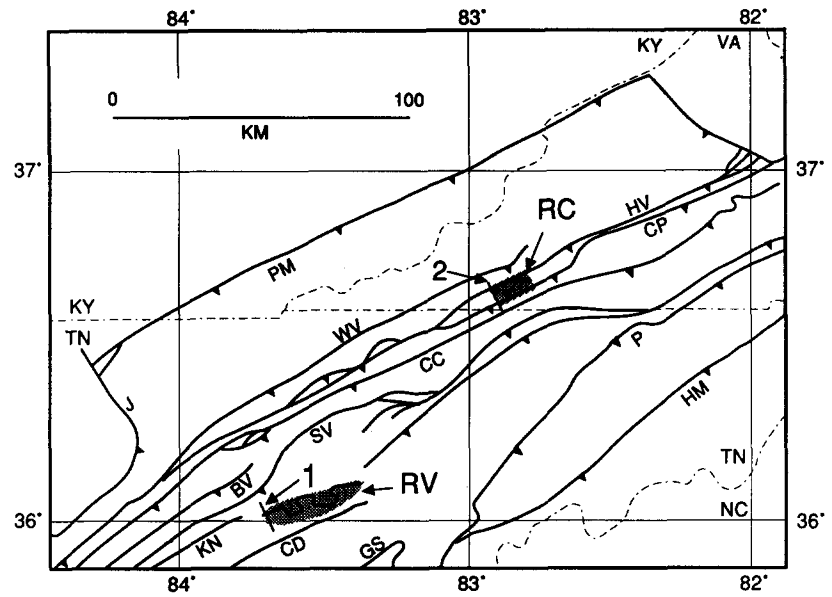


Fig. 8. Principal thrust faults in the east Tennessee Valley and Ridge. Stippled areas show locations of the Rocky Valley anticline (RV) and Rye Cove syncline (RC). Lines 1 and 2 show locations of cross-sections through these structures. BV = Beaver Valley thrust, CC = Copper Creek thrust, CD = Chestuee–Dumplin Valley fault zone, CP = Clinchport thrust, GS = Great Smoky thrust, HM = Hunter Mountain thrust, HV = Hunter Valley thrust, J = Jacksboro fault, KI = Kingston thrust, KN = Knoxville thrust, P = Pulaski thrust, PM = Pine Mountain thrust, SV = Saltville thrust, WV = Wallen Valley thrust. Modified from Woodward *et al.* (1988).

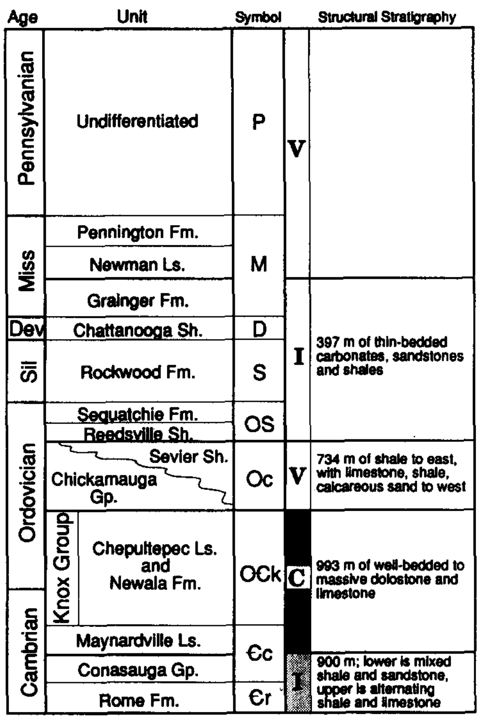
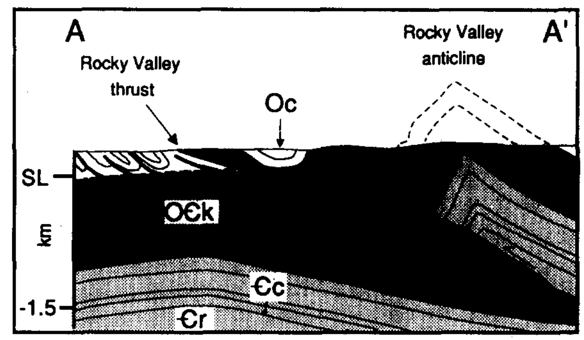


Fig. 9. Stratigraphy and structural lithic units in the Rocky Valley and Rye Cove structures. I = incompetent, C = competent and V = variable competency units. Chickamauga–Sevier unit typically serves as a thrust ramp to the west and a flat to the east. From Woodward & Rutherford (1989).

(a)



(b)

STRATIGRAPHIC LEVEL		FORELIMB	HINGE ZONE
Oc	Ottosee Sh.	1	2, 3
	Holston Ls.		1
	Lenoir Ls.	2	2
OЄk	Mascot Dol.		1
	Longview Dol.		4
	Kingsport Fm.		4
	Chepultepec Dol.	not exposed	
	Copper Ridge Dol.	5	not exposed
Єc	Maynardville Ls.		3
	Nolichucky Sh.	3	2, 3, 5
	Maryville Ls.	3	3, 4
	Rogersville Sh.	3	
	Rutledge Ls.		1
	Pumpkin Valley Sh		2, 4

Fig. 10. (a) Cross-section showing the general geometry of the Rocky Valley anticline. Horizontal and vertical scales are equal. See Fig. 8 for location and Fig. 9 for stratigraphic symbols. Modified from Fischer (1989). (b) Composite distribution of consistently developed mesofabrics in the Rocky Valley anticline based on traverses across the fold at different locations along strike. 1 = Spaced pressure-solution cleavage, 2 = penetrative pressure-solution cleavage, 3 = mesoscopic folding, 4 = strike-parallel extension veins (10–50 cm spacing), 5 = mesoscale faulting. Blanks indicate none of these fabrics were consistently developed.

significant, competent, structural lithic units (Figs. 5b, 7b and 9) (Mitchell & Woodward 1988, Woodward & Rutherford 1989). The T/λ ratios for the four thrust-related folds are close to the 1:27 ratio found by Currie *et al.* (1962) for folds controlled by a single, competent layer. The modest agreement is expected for complex composite layers. Although this is insufficient evidence

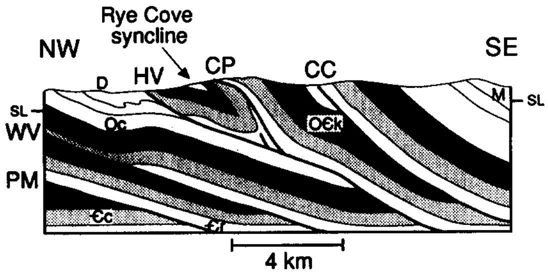


Fig. 11. Cross-section through the Rye Cove syncline derived from a down-plunge projection of the structure near Duffield, Virginia. Thrusts as in Fig. 8; stratigraphy and shading as in Fig. 9. Horizontal and vertical scales are equal. See Fig. 8 for location. Modified from Diegel & Wojtal (1985) and Wojtal (1989).

to prove these structures formed entirely as buckle folds, it suggests an influence of stratigraphic competency contrasts on the fold wavelength.

The distribution of deformation as represented by mesofabrics in the Hossfeldt and Rocky Valley anticlines and the Rye Cove and Indian Creek synclines indicates these structures evolved with insignificant migration of fold axial surfaces. Instead, the concentration of mesofabrics and stratigraphic thickening in fold hinge zones implies these folds developed by some form of fixed-hinge kinking or buckling wherein shortening occurred by progressive limb rotation. Moreover, the consistent ratio of competent member thickness to fold wavelength observed in these structures suggests local stratigraphy influenced the evolution of the folds. But, the kink form geometry of the folds indicates they could not have formed purely by buckling.

We suggest that these structures are break-thrust folds in the original sense defined by Willis (1893). We interpret that the mesofabric distributions and T/λ ratios observed in these thrust-related folds resulted from a sequence of fixed-hinge kinking following an early stage of buckling similar to that suggested for mesoscale kinks (Johnson 1977).

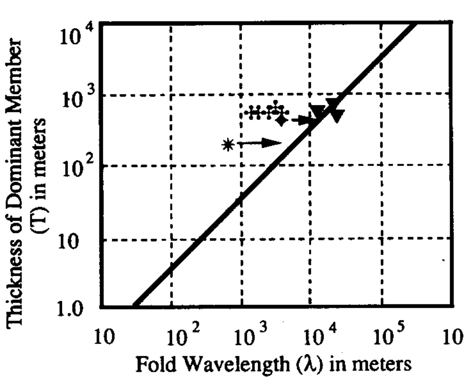


Fig. 12. Fold wavelength (λ) vs dominant member thickness (T) for structures presented in this study. Solid black line is the curve with T/λ equal to 1:27, suggested by Currie *et al.* (1962) to be the best-fit for folds in which the wavelength is controlled by a single competent layer. Wavelengths of the Rye Cove and Indian Creek structures (with arrows pointing to the right) are minimum estimates because of incomplete preservation of the folds. ▼ = Hossfeldt anticline, * = Indian Creek syncline, ✠ = Rocky Valley anticline, ◆ = Rye Cove syncline. Wavelength measurements for Rocky Valley anticline made at different locations along strike. Note Rye Cove syncline and Rocky Valley anticline deform the same stratigraphy and therefore have similar T values.

Because the break-thrust folds we examined exhibit the general geometry of incompletely-yielded kinks (i.e. hinges not perfectly angular; Johnson 1977) and display ratios of dominant member thickness to fold wavelength similar to those of buckle folds controlled by a single competent layer as observed by Currie *et al.* (1962), we believe they initiated as buckle folds. As noted by Johnson (1977), kinks should not ideally form in multilayers where the principal compressive stress is subparallel to layering because the resulting shear stress resolved between layers is insufficient to initiate layer-parallel slip. Consequently, we suggest break-thrust folds begin as low-amplitude sinusoidal buckle folds in which the wavelength is controlled by local stratigraphy. The amplitude of these folds increases until the shear stresses resolved along the limbs is sufficient to overcome the contact strength between layers, after which deformation is by layer-parallel slip between pinned fold hinges. Bedding-slip surfaces and mesofabrics outside the kink-band boundaries are probably relics preserved from this initial buckling stage. Because shear stress required to initiate slip is determined by stratigraphy, the amplitude of early buckling that precedes thrusting (and perhaps the final angularity of fold hinges) is likewise expected to depend on stratigraphy. The modest agreement between ideal and observed T/λ ratios is expected for a composite layer and probably reflects the influence of a complex multilayer rather than one competent layer in the stratigraphic section. Buckling ceases once layer-parallel slip is initiated, but the break-thrust fold continues to grow as a kink by progressive limb rotation about fixed anticlinal and/or synclinal hinges. The gentle curvature imparted to fold limbs during the initial buckling is now removed and deformation concentrates in hinge zones as interlimb angles tighten. Finally, as observed by Dixon & Tirrul (1991) and Dixon & Liu (in press), a thrust propagates through the rotated fold limb where strain and dilation have probably weakened the rock. An asymmetric break-thrust fold cannot, however, evolve into a ramp–flat fold as some models suggest.

Willis (1893) recognized a fundamental difference in the way different thrust-related structures originate. One of his major categories, break-thrust fold, has been seriously neglected in the current revival of thrust system analysis. Our conclusion is that this is a valid name that is applicable to far more structures than presented in this study. Break-thrust folding is another mechanism by which asymmetric tip-line folds evolve and fixed-hinge buckling and kinking may be a mechanism by which other thrust-related folds develop. Mesofabric analyses of the type presented in this paper are valuable tools in determining the kinematics of deformation in thrust-related folds and may provide a framework by which we can assess the applicability of other models of thrust-related folding.

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