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Role of basement fabric and cover-rock lithology on the geometry and kinematics of twelve folds in the Rocky Mountain foreland

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ABSTRACT

Detailed field studies of 12 small basement-cored folds in the Rocky Mountain foreland from southwestern Montana to northern New Mexico indicate that there was considerable variation in the degree of deformation of the basement rocks during Late Cretaceous and Paleocene folding. This variation may be characterized by two end-member styles of basement behavior (mode 1 and mode 2). In mode 1 folds basement deformation is confined to a narrow zone of cataclasis adjacent to a single fault, the cover rocks are significantly thinned on the forelimb of the fold and have a small carbonate to clastic rock ratio (<0.2) in the lower 300 m (1000 ft) of section, the basement-cover contact on the forelimb is a fault, and the interlimb angle is 60° or less.

In mode 2 folds basement deformation occurs in a broad zone between the principal fault and the anticlinal hinge surface, which is a fault in several structures. The basement deformation occurs as slip on sets of closely-spaced fractures, as flexural slip on preexisting foliation oriented subparallel to bedding, as axial surface-parallel slip on foliation, or as pervasive cataclasis. The cover rocks in mode 2 structures maintain nearly constant thickness through the fold, have a carbonate to clastic rock ratio that is relatively high in the lower 300 m (1000 ft) of section (>0.4), and are in stratigraphic (as opposed to fault) contact with the basement on the forelimb. The axial surface penetrates the basement, the interlimb angle is >90°, and backthrusts are common.

Most existing folds will have characteristics of mode 1 and mode 2 to varying degrees; for example, a basement-cover interface that is part fault and part stratigraphic contact on the forelimb, an intermediate interlimb angle (60°–90°), moderate thinning of cover rocks on the forelimb, and deformed forelimb basement with an intermediate thickness.

The style of basement-cored folds depends partly on the nature and orientation of prefolding basement fabric and the competence of the cover rocks. Well-foliated basement rocks that have foliation oriented subparallel to bedding or that have foliation in a "favorable" orientation for hinge-surface-parallel slip produce mode 2 folds, as do cover-rock sections with high carbonate to clastic rock ratios. Relatively isotropic basement rocks with low carbonate to clastic ratios produce mode 1 folds. Other factors that probably control the style are degree of influence of earlier faulting and the taper of the hanging-wall basement wedge; however, observations of the 12 folds in this study are inconclusive regarding the importance of these factors. Confining pressure and tempera-

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ture are important only insofar as they determine the overall mechanical behavior of the basement and the cover rocks. Total variation in overburden (2.5–5 km) during initial deformation has not permitted basement behavior to deviate from the brittle field.

In progressive deformation of mode 1 structures, a relatively competent basement block is forced into relatively incompetent cover, resulting in no significant basement deformation. In mode 2 structures a relatively incompetent basement block is forced against a relatively competent cover. The basement deforms by generation of an anticlinal hinge surface that migrates away from the fault. Faults can propagate into the cover along the synclinal hinge, across the forelimb, or along the anticlinal hinge surface. In the latter two cases fault-dip changes can produce backthrusts.

INTRODUCTION

This chapter focuses on the way basement rocks have deformed in fault-related folds in the Rocky Mountain foreland. As stated in the preface, in spite of a considerable amount of field work, techniques for balancing cross sections, and a variety of new model studies, there is still no consensus about how the basement has behaved during folding and faulting to produce the well-known folds in the Phanerozoic cover rocks in the Rocky Mountains. The hypotheses range from the suggestion that folds are produced by slip on a single basement fault (e.g., Blackstone, 1940; Stone, 1984; Erslev, 1986) to simple shear along a series of parallel faults, producing a wide zone of deformation that includes both the anticlinal and synclinal hinge surfaces (Spang and others, 1985; McConnell and Wilson, this volume).

In addition to different hypotheses about fault-zone width, other hypotheses (based on experimental studies, field observations, and implications from balanced cross sections) vary in their interpretation of the degree of basement cataclasis during faulting and folding. Erslev (1986) suggested that significant cataclasis was limited to a subthrust basement wedge broken off from the tip of the hanging wall during deformation. Cook (1988) visualized brecciation and cataclastic flow across a broad zone between the hanging-wall and footwall basement blocks, leading to a wide downward-tapering wedge of fractured basement on both sides of the master fault. Several authors who represented the basement-cover contact as smoothly curved arcs on both the hanging-wall anticline and footwall syncline suggested that fracture surfaces in the basement, developed during earlier deformation, were operative during the later deformation to produce a folded shape at the basement-cover contact (Hudson, 1955; Hodgsen, 1965; Blackstone, 1983). Others suggested that, where foliation in the basement rocks is parallel to or nearly parallel to the cover rocks, folding of the entire package occurred by flexural slip (Schmidt and Garihan, 1983; Chase, 1985; Miller and Lageson, this volume).

Another problem associated with basement-cored folds in the Rocky Mountain foreland is the nature of the surface between the basement and the overlying cover rocks. In most places this is an angular unconformity. However, in the steeply-dipping forelimb region this surface has been shown as a fault by some (e.g., Erslev, 1986), and a rotated unconformity by others (e.g., Brown, 1988). The Elk Mountain anticline, in southern Wyoming, is a good example in which the basement-cover contact (in this case Madison Limestone on Archean granite) was interpreted as a rotated unconformity on the steep limb (Blackstone, 1980) and also as a fault (McClurg and Matthews, 1978). Although the basement-cover contact is rarely exposed on the steep limbs of basement-cored folds, its depiction in cross section is important to the kinematic interpretation.

With few exceptions, studies of basement-cored folds in the Rocky Mountain foreland have not included a detailed look at the basement rocks in those folds. This is partly because of lack of sufficient exposure within the basement, particularly at the basement-cover contact, to document the nature of basement behavior. However, there are a fair number of small folds that have enough exposure to allow reasonably detailed studies on how the basement rocks behaved below the cover rocks to give the upper basement surface a curved shape. This chapter summarizes the results of mapping and examining the basement fabric in 12 such folds in New Mexico, Colorado, Wyoming, and Montana (Fig. 1). These are described briefly below, and much of the pertinent data are presented in tabular form (Table 1) and as geologic maps and cross sections. We tried to limit our study to well-exposed folds that are all about the same size. Half wavelengths vary from 0.8 km (LaPrele anticline in east-central Wyoming) to 4.5 km (Brooks Creek anticline in southwestern Montana). The amplitudes of the folds at the basement cover contact, restored for dip separation on the fault or fault zone, vary from about 0.1 km (north Twin Mountain, Colorado) to about 3 km (Elk Mountain, south-central Wyoming, and Brooks Creek anticline). Our aim is to describe the different styles of basement behavior and to make a preliminary attempt to evaluate the factors that control basement behavior.

In order to avoid any disagreement about what constitutes basement, we employ the usage of Brown (1988), who included in basement all of the rocks of the Archean and Proterozoic igneous and metamorphic complex in the Rocky Mountain foreland. Any Middle or Late Proterozoic mafic dikes are likewise considered to be part of the basement.

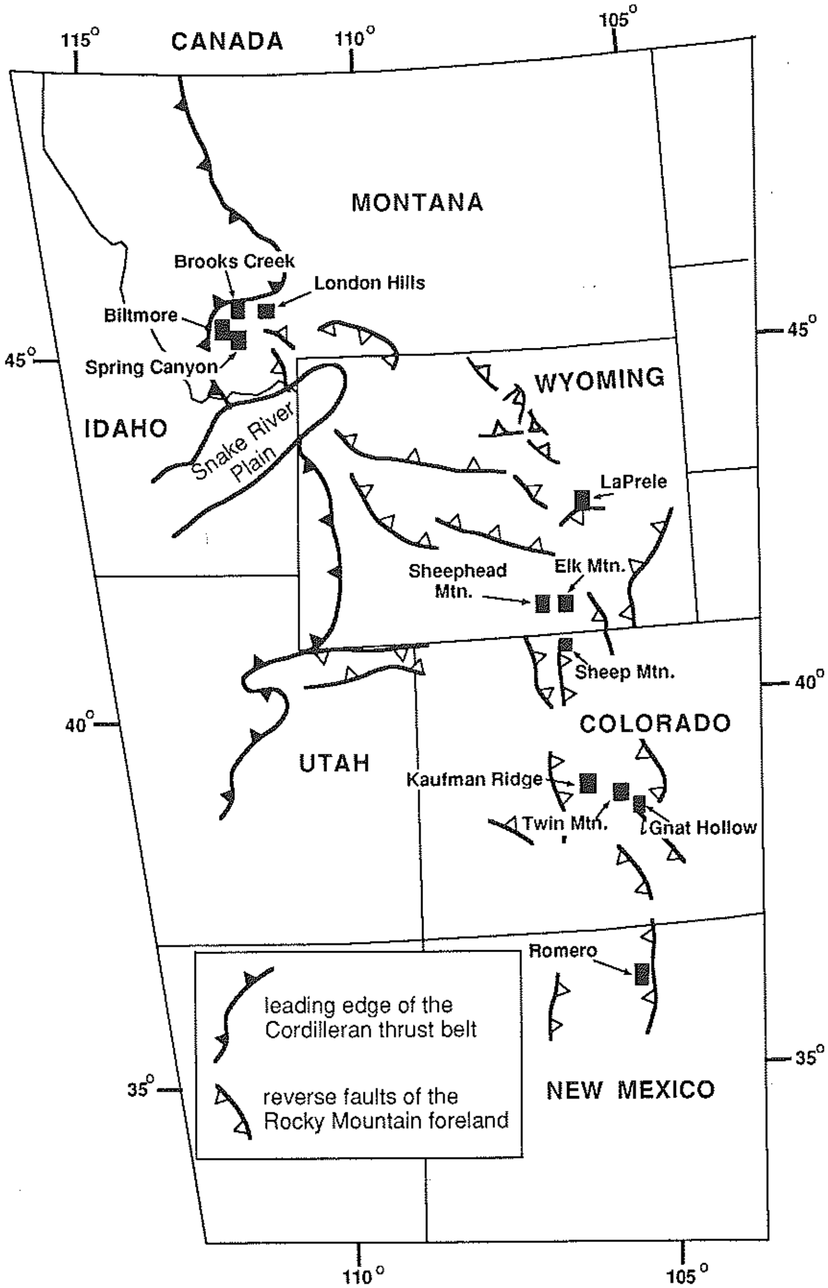

Figure 1. Regional tectonic map showing the locations of the 12 folds discussed in this chapter.

FOLD AND FAULT GEOMETRY

Descriptive geometry

Here we provide a brief description of each structure before attempting to group the folds and evaluate possible controls on deformational style. More detailed descriptions and maps of four of the structures (London Hills, Sheephead Mountain, Gnat Hollow, and Romero) are included in Chase and others (this volume).

In order to focus on the deformation of basement in these folds we define three regions or domains of basement below the sedimentary cover (Fig. 2). The footwall basement domain is the region on the footwall of the principal reverse fault, usually below a gently-dipping panel of cover rocks on the synclinal limb. The backlimb basement domain is the region below the backlimb of

TABLE 1. SUMMARY OF PRINCIPAL GEOMETRICAL AND MECHANICAL CHARACTEDRISTICS OF THE TWELVE BASEMENT CORED ANTICLINES DESCRIBED IN THIS STUDY

Anticline and Location	Fold Geometry, Sized, Attitude of Axis, Interlimb Angle, Wedge Taper*	Cover Rock Types, Estimated Thickness, Percent Carbonate in First 350 m†	Basement Rocks and Anisotropy	Mechanical Behavior of Basement	Width and Development of Forelimb Basement Domain§	Structural Mode**	Role of Faulting, Estimated Dip, Displacement	References Role of Faulting Continued
London Hills Northeast Tobacco Root Mountains in southwest Montana	S.W. verging anticline with forelimb locally vertical. ½ λ = 2.4 km A = 1 km B = 19°N44°W IA = 92° Θ = 45°	Basal sandstone overlain by thick, alternating shale and limestone units. T = 3.9 km C = 45%	Well-foliated gneiss and amphibolite with foliation nearly parallel to cover rocks. Diabase dikes in hinge surface orientation.	Rotation of layering and slip on foliation beneath forelimb accompanied by shearing parallel to dike along hinge surface. Backlimb deformed only by faulting and block rotation.	350 m, bounded above by fault along diabase dike. Bounded below by bedding on forelimb.	Mixed mode. Wide basement forelimb domain as in Mode 2 structures. Thinned, steeply dipping forelimb as in Mode 1 structures.	Synclinal hinge surface cut by a reverse fault. Anticlinal hinge surface cut by shear zones along diabase dikes. Steep limb cut by major reverse fault. Steep limb fault dips 60° to 70° NE, 2 km left separation, ≈1 km right	Wagner (1966), Schmidt and Garihan (1983), Chase and others (this volume). reverse slip. Synclinal hinge fault ≈ 3 km left separation.
Brooks Creek West Tobacco Root Mountains in southwest Montana	S.W. verging anticline with forelimb locally near vertical. ½ λ = 4.5 km A = 2 km B = 39°N21°W IA = 85° θ = 45°	Basal sandstone overlain by thick alternating shale and limestone units. T = 3.9 km C = 45%	Well-foliated gneiss and amphibolite nearly parallel to cover rocks. Diabase dikes with various orientations.	Rotation of layering between faults in backlimb. Local slip on foliation in fault zone. Pervasive cataclasis in fault zone and extensive hydrothermal alteration associated with syntectonic intrusion of nearby batholith.	About 200 m. Footwall not exposed well enough to be certain.	Mixed mode like London Hills anticline.	Anticlinal hinge controlled by reverse fault with small displacement. Diabase dikes are locally a factor. Extensive backlimb faulting. Principal fault zone strain softened by hydro-thermal alteration. Principal fault (Bismark fault) dips 75°NE,	Reid (1957), Hanley (1975), Schmidt and Garihan (1983). transects synclinal hinge and has 2 to 4 km left-reverse slip. Thrust faults of thrust belt impinge on the structure.
Spring Canyon North Ruby Range southwest. Montana	West-verging anticline-syncline with forelimb overturned. ½ λ = 1.7 km A = 1 km B = 32°N8°W IA = 98° Θ = 70°	Basal sandstone overlain by thick, alternating shale and limestone units. T = 3.2 km C = 80%	Well-foliated gneiss and amphibolite. Thin marble layer below cover. Thick marble at a deeper level. Adjacent syncline contains no marble. Foliation is nearly parallel to cover rocks.	Flexural slip of thin marble only in hinge and forelimb region. Closely-spaced faulting and rotation of gneiss and thick marble beneath forelimb.	270 m, bounded above by less deformed and unrotated basement foliations. Bounded below by bedding on forelimb and major fault.	Mixed mode like London Hills Anticline. Wide forelimb domain in basement but some thinning of cover on forelimb.	Synclinal hinge transected by reverse faults with 6.5 km left separation. Splay of main fault transects steep forelimb. Dip changes from 45°–65°NE to 75°–90°W. Minor fault transects anticline hinge surface.	Tysdal (1976, 1981), Karasevich (1981), Schmidt and Garihan (1983). Backthrusts present. Main fault is reactivated.

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Anticline and Location	Fold Geometry, Sized, Attitude of Axis, Interlimb Angle, Wedge Taper*	Cover Rock Types, Estimated Thickness, Percent Carbonate in First 350 m†	Basement Rocks and Aisotropy	Mechanical Behavior of Basement	Width and Development of Forelimb Basement Domain§	Structural Mode**	Role of Faulting, Estimated Dip, Displacement	References Role of Faulting Continued
Biltmore Northeast McCartney Mountains, southwest Montana	West-verging anticline with forelimb overturned. Backlimb is not preserved. ½ λ = 1 to 3 km A = 1 km B = NNW (plunge unknown) IA = 75° Θ = 45°(?)	Basal sandstone overlain by thick, alternating shale and limestone units. T = 4.2 km C = 42%	Mostly muscovite and biotite schist with subordinate lenses of amphibolite. One or more diabase dikes parallel well-developed foliation. Foliation probably parallel to hinge surface.	Foliation-parallel shear on widely spaced (25 to 100 m) faults. Local flexural slip on foliation in small drag folds adjacent to faults. Zone is cataclasis beneath cover on forelimb.	Uncertain. Hinge surface cannot be precisely located. However, entire outcrop belt is pervasively deformed by probable slip on faults parallel to foliation. Outcrop belt is 2 km wide.	Probably mixed, but tendency to mode 2 because of overall weakness of basement and wide deformed zone.	Anticlinal hinge not detectable in basement and not exposed in cover. Faults present in backlimb as much as 1.5 km east of forelimb. No discrete "hinge controlling" fault. Minor faults cut forelimb.	Brandon (1984), Schmidt and others (1988), Lopez and Schmidt (1985). Late Cenozoic (McCartney fault) occupies probable position of anticline hinge surface.
LaPrele North Laramie Range, east-central Wyoming	West-verging anticline with steep to locally overturned forelimb which has been refolded. ½ λ = 0.8 km A = 0.6 km B = 30°N7°E IA = 70° Θ = 35°	Basal sandstone overlain by thick, alternating shale sandstone and limestone units. T = 4.8 km C = 43%	Granite augen gneiss with parallel amphibolite layers. Foliation parallels fold hinge surface. Non-foliated gabbro stock in core of fold.	Pervasive cataclasis in forelimb along preexisting foliation surfaces in augen gneiss. Forelimb basement is a cataclastic wedge. Rigid rotation of backlimb.	170 m, bounded above by undeformed foliation parallel to hinge surface and amphibolite dike. Bounded below by bedding on forelimb and a minor fault.	Mostly mode 2 with possibly some elements of mode 1. Forelimb is locally overturned but not appreciably thinned.	Anticlinal hinge surface is a shear zone controlled by basement foliation and an amphibolite layer. One very minor synclinal thrust on north half of structure.	Barlow (1953, Swenson (1980). Principal fault cuts synclinal hinge surface, dips N and has 250 m dip separation. Minor thrust cuts forelimb and dips 50°N.
Sheephead Mountain North Medicine Bow Mountains, southeast Wyoming	East-verging anticline with locally overturned forelimb. ½ λ = 1.0 km A = 0.6 km B = 50°N22°W IA = 55° Θ = 30°	Massive limestone above basement with alternating shale and sandstone higher in the section. T = 5 km C = 20%	Well-foliated quartzofedspathic gneiss with high angular discordance to layering in cover rocks.	Extensive fracturing and integrated slip in a broad "shear zone" beneath forelimb. Much jointing in backlimb. Foliation attitude not affected by folding and faulting.	100 m, bounded above by less-deformed rock. Bounded below by bedding on forelimb and probably a fault.	Mixed mode. Thinning and overturning of cover. Relatively wide forelimb basement domain when compared to size of entire structure.	Principal thrust is inferred to cut hinge surface of syncline. It dips 40°W, 1.5 km dip separation. Minor splay present at basement cover contact on forelimb. Anticlinal hinge surface	Beckwith (1941), Houston and others (1968), Banks (1970), Blackstone (1983). defined by the decrease in fracture spacing of fault-parallel fracture.

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Elk Mountain North Midicine Bow Mountains, southeast Wyoming	Northeast-verging with steep, overturned forelimb. $\frac{1}{2}\lambda = 4$ km A = 1 km B = 16°N30°W IA = 51° $\Theta = 45°$	Massive limestone above basement with alternating shale and sandstone higher in the section. T = 5 km C = 20%	Moderately well foliated quartzofeldspathic gneiss, coarse-grained granite, quartz monzonite, mafic dikes.	Extensive fracturing and movement along and across foliation planes in forelimb. Hinge surface defined by increase in fracture intensity (decreased spacing).	500 m, bounded above by less-fractured rocks. Bounded below by bedding on forelimb and probably a fault.	Mixed mode. Relatively wide basement forelimb domain, but fault at basement-cover contact along with thinning of bedding and overturning on forelimb.	Anticlinal hinge surface controlled by a Laramide basement shear zone. Major displacement on a subsurface fault that is inferred to break through synclinal hinge surface. Dip is 40° to 50°W. Dip separation 1.6 to 3 km.	Beckwith (1941), Houston and others (1968), McClurg and Matthews (1978), Blackstone (1980, 1983). Fault of smaller displacement between basement and cover on forelimb.
Sheep Mountain Never Summer Range, north-central Colorado	West-verging doubly-plunging with overturned forelimb. $\frac{1}{2}\lambda = 2.4$ km A = 1.2 km B (north) = 36°N-17°W B (south) = 57°S-42°E IA = 55° $\Theta = 35°$	Basal mudstone overlain by thin-bedded, alternating sandstone, shale, and limestone. T = 24 km C = 0%	Gneiss and amphibolite in north plunging section, massive granite in south plunging section. Foliations are at a high angle to cover rocks.	In the major fault zone there is integrated movement along fault-parallel fractures. Elsewhere there is extensive fracturing and minor backlimb rotation.	No noticable forelimb basement domain except for a few meters above main fault.	Mode 1. Basement-cover contact clearly a fault. Forelimb highly thinned.	Single fault divides narrow anticlinal hinge from overturned forelimb. Dip 55°NW; stratigraphic separation 2 km. Fault is probably an anticlinal hinge surface break-through. At least	Hail (1965), McConnell (1989). two other faults cut forelimb.
Kaufman Ridge Mosquito Range, central Colorado	West-verging with steep, upright forelimb. $\frac{1}{2}\lambda = 2.8$ km A = 1.5 km B = 25°N3°E IA = 105° $\Theta = 45°$	Basal dolostone overlain by sandstone and thick limestone. T = 4.5 km C = 78%	Granitic augen gneiss and massive granite with a few schistose zones. Gneissosity is at high angle to cover rocks.	Pervasive cataclasis in forelimb between anticlinal and synclinal hinge surfaces.	650 to 750 m, bounded above by less-deformed rocks. Bounded below by bedding on forelimb and a fault.	Mode 2. Wide basement forelimb domain, no thinning of cover, upright forelimb.	Two faults exposed, interpreted as forelimb splays, dipping 60° to 75°E, total dip separation less than 0.5 km.	DeVoto (1971), McConnell (1989).

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Twin Mountain South Front Range, south-central Colorado	Southwest-verging with steep, upright to overturned forelimb. $\frac{1}{2}\lambda = 1.5$ km A = 0.3 km B = 20°S55°E IA = 60° $\Theta = 60°$	Basal dolostone overlain by sandstone and thick limestone. T = 2.7 km C = 15%	Weakly foliated granodiorite with pegmatitic pods and mafic dikes.	Intensely sheared margin of diabase dike in hinge surface position. Fracturing parallel to hinge surface away from shear zone.	100 to 200 m, bounded above by sheared diabase dike bounded below by bedding on forelimb and synclinal hinge fault.	Mixed mode, narrow forelimb basement domain. Thinned and overturned forelimb suggests closer to mode 1.	Synclinal hinge fault with minor displacement (30 m), dips 75°NE. Anticlinal hinge shear zone along mafic dike, does not break into cover.	Webster (1959).
Gnat Hollow South Front Range, south-central Colorado	Northwest-verging with overturned forelimb. $\frac{1}{2}\lambda = 1.2$ km A = 0.9 km B = 8°N54°E IA = 50° $\Theta = 25°$	Basal dolostone overlain by sandstone and conglomerate. T = 2.5 km C = 15%	Well-foliated interlayered gneiss, schist, and amphibolite with granitic sills, small stocks, and pegmatitic lenses.	Cataclasis and slip on foliation near faults that are essentially parallel to foliation. Much layer-parallel slip in schist and in gneiss.	60 to 80 m, bounded above by less deformed basement, bounded below by fault against cover rocks.	Mixed mode but mostly mode 1. Very narrow forelimb basement domain. Single fault uplift with steeply upturned footwall beds and little flexure on hanging wall.	Single synclinal hinge-surface fault, dips 44°SW; 600 m dip separation. Minor bedding plane thrust in footwall.	Gerhard (1961), Wobus and others (1985), Chase (1985), Chase and others (this volume).
Romero Hills Sangre de Cristo Mountains, north-central New Mexico	East-verging with steep forelimb, locally overturned. $\frac{1}{2}\lambda = 2.5$ km A = 1.2 km B = 5°S22°W IA = 65° $\Theta = 45°$	Basal limestone overlain by thick sandstone, limestone, and conglomerate. T = 4.1 km C = 10%	Gneiss, schist, amphibolite, gabbro, quartzite, and pegmatite. Precambrian age structure is a large isoclinal fold that is roughly concordant to cover folds.	Extensive shearing along and across foliation planes on flanks of the Precambrian isoclinal fold. Numerous thrust surfaces and imbricate stacks can be mapped.	500 to 600 m, bounded above and below by faults that follow foliation.	Mixed Mode but somewhat more characteristic of Mode 2 with wide forelimb basement domain and generally weak basement rocks	Numerous thrust faults in an imbricate pattern in both basement and cover rocks. Precambrian lithologies and structural patterns clearly control fault geometry. Synclinal hinge surface fault dips 50°NW and has 600 m dip separation.	Baltz and O'Neill (1984), O'Neill (1990), Chase and others (this volume). Total dip separation about 2 km on all faults.

*λ = wavelength; A = amplitude; B = fold axis; IA = interlimb angle; Θ = wedge taper.
†T = Estimated thickness above basement at onset of folding; C = Amount of carbonate (percent) in first 330 m (1000 ft) of section.
§Forelimb domain is described in text and illustrated schematically in Figure 2.
**Structural modes (illustrated in Fig. 23) are described in text.

the anticline on the hanging wall of the principal fault. It is separated from the forelimb domain by the anticlinal hinge surface in the cover rocks projected downward into the basement rocks. The forelimb basement domain is the region between the anticlinal hinge surface and either the steep forelimb, the principal fault, or both (Fig. 2). Although these domains are defined here to aid description of the folds, in a later section we show that, for most of the folds, the only significant deformation in basement related to the folding of the cover occurs in the forelimb domain.

London Hills anticline. The London Hills anticline in the northern Tobacco Root Mountains (Fig. 3) was described and analyzed by Schmidt and Garihan (1983), Brown (1983), and Chase and others (this volume). It is an asymmetrical, southwest-verging anticline that plunges 18°–24° northwest. The forelimb at the basement cover contact is nearly vertical locally and averages about 66°. The backlimb dips about 31° and the interlimb angle is 92° (Fig. 4). Only the anticline is well exposed. The principal fault (London Hills fault) is not well exposed, but is inferred to transect the synclinal hinge surface (Fig. 3) (Schmidt and Garihan, 1983). The splay of the London Hills fault that cuts the steep foreland dips 60°–70° northeast, and although it has about 2 km of left separation at the basement-cover contact, the net slip (left-reverse) is probably about 1 km (Schmidt and Garihan, 1983; Chase and others, this volume). The lower part of the stratigraphic section (Cambrian sandstone, shale, and limestone) is thinned by 30%–50% on the steep limb, but there is no direct evidence that the basement-cover contact is a fault at this position.

The London Hills anticline has two angular hinges at the basement-cover contact (Fig. 4). Cover rocks (Flathead Sandstone) at these hinges are highly fractured but not offset. Below each of these hinges there are faults and/or shear zones in the basement rocks. Although the basement rocks are highly deformed along these zones, with cataclasis and slickensides in hinge-parallel positions (Chase and others, this volume), no significant offset of basement rock units has occurred. The basement rocks are well-foliated gneisses cut by diabase dikes that parallel the London Hills fault and the anticlinal hinge surfaces. The largest diabase dike (10 m wide) occupies the hinge surface position between the backlimb and more gently dipping part of the forelimb (Fig. 4). The dike is cataclastically deformed and hydrothermally altered. The entire region of the forelimb domain is 350 m wide and contains small hinge-parallel faults. Foliation in the gneisses changes its orientation in this domain and generally remains closely parallel to the cover rocks (Fig. 4). Slip surfaces (slickensides and polished surfaces) on foliation are ubiquitous in this domain, as is hydrothermal alteration of biotite to chlorite. Slip surfaces and hydrothermal alteration are absent in the backlimb domain. The footwall domain is not well exposed, but appears to be relatively undeformed.

Brooks Creek anticline. The Brooks Creek Anticline in the northern Tobacco Root Mountains (Fig. 3) is similar to the London Hills anticline. It is a southwest-verging anticline that plunges 39° northwest at the basement-cover contact (Fig. 5). It has forelimb and backlimb dips nearly identical to those in the London Hills anticline. Unfortunately, only the backlimb and the major fault zone are well exposed, because the forelimb has been largely cut off by thrusts on the leading edge of the Cordilleran thrust belt that impinges on the anticline (Schmidt and others, 1988; Figs. 3 and 5). We estimate the interlimb angle to be 75°–100°.

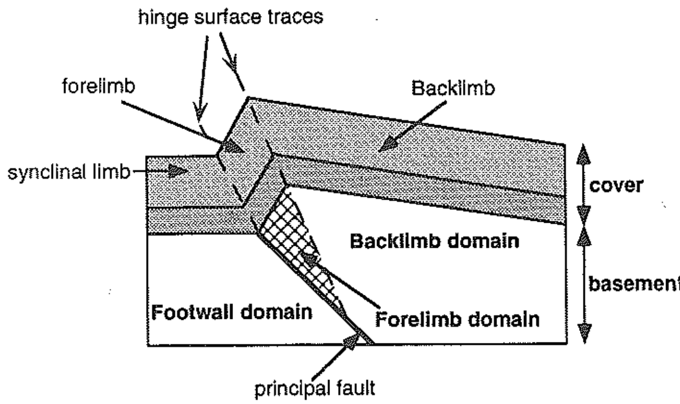

Figure 2. Idealized sketch cross section of a basement-cored fold showing dip domains in the cover corresponding to different domains of basement deformation below.

The Bismark fault is inferred to cut the synclinal hinge of the structure. The fault dips about 75° NE. It is a left-reverse, oblique-slip fault with a net slip of 2 to 4 km (Schmidt and Garihan, 1983). Because restoration of slip does not restore Archean marker lithologies across the fault, it is clearly a reactivated Proterozoic fault (Schmidt and Garihan, 1986). The fault transects the Late Cretaceous Tobacco Root batholith (Fig. 3) and has been shown to have been active during the emplacement of that pluton (Schmidt and others, 1990, 1991). The fault zone along the main anticlinal hinge trends north and is the principal splay of the Bismark fault. This fault zone along the fold hinge is 10 to 30 m wide and contains highly altered gneiss and amphibolite that is intensely sheared (Fig. 6A). Where the quartzofeldspathic gneiss is involved in the fault zone, thin sections (Fig. 6B) show it to be altered completely to sericite, chlorite, and quartz. Although several of the other structures we observed (e.g., London Hills anticline and Gnat Hollow fold-fault structure) have some hydrothermal alteration along fault zones, nowhere is it as extensive as in the Brooks Creek structure.

Because the cover rocks in the forelimb area below the main fault are poorly exposed, it is difficult to tell whether the basement-cover contact on the forelimb is a fault or a stratigraphic contact. However, because the basement-cover contact appears to be cut by the main fault zone, we suggest that it is mainly a displaced stratigraphic contact. The fault zone passes through the hinge in the cover rocks, and although the hinge is very sharp, the cover rocks are only separated a few tens of meters.

The region to the northeast of the main hinge and fault zone

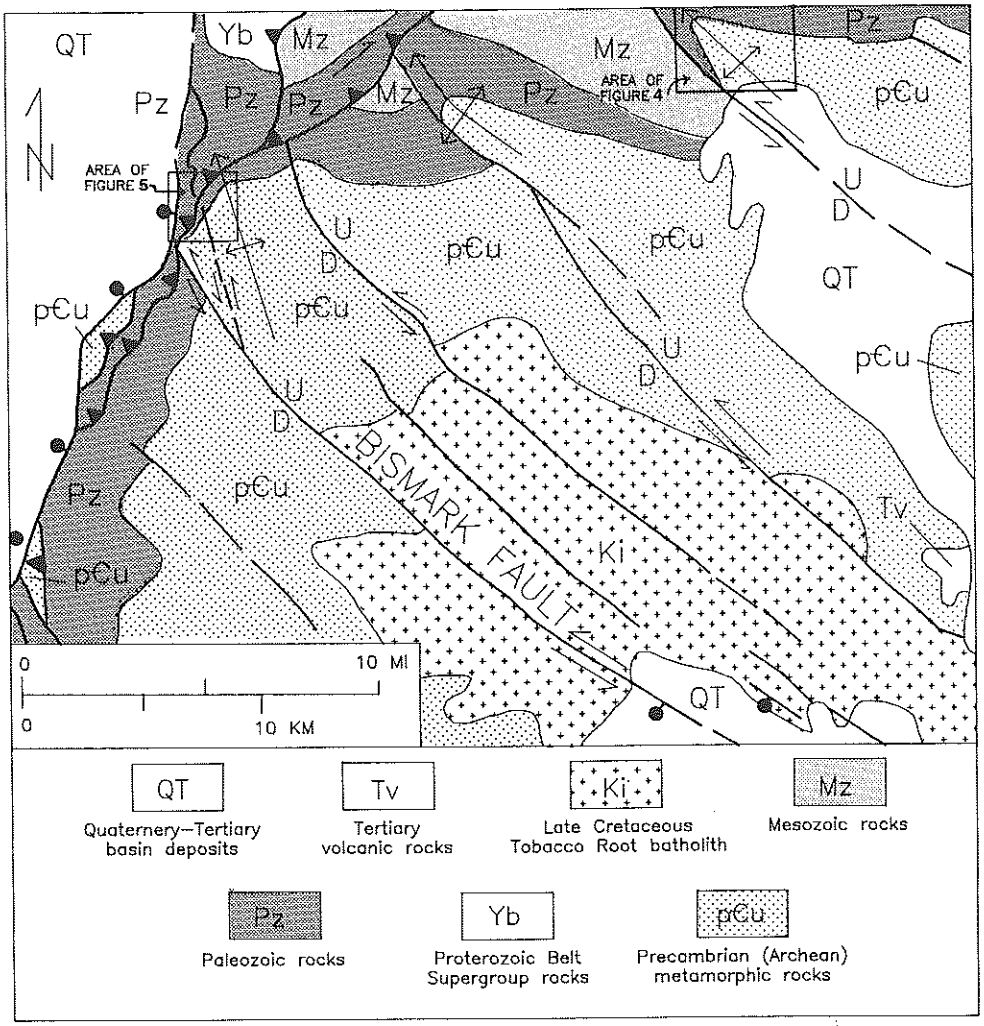

Figure 3. Geologic sketch map of the northern Tobacco Root Mountains showing the locations of the London Hills and Brooks Creek anticlines (Figs. 4 and 5).

contains at least four other hinges with abrupt, though small, changes in attitude of the cover rocks. A fault in the basement is located below each hinge. Two of these faults are parallel to the fault below the main anticlinal hinge. The easternmost faults strike northeasterly (Fig. 5) and appear to be backthrusts.

Like the basement rocks in the London Hills anticline, the gneisses and amphibolites of the Brooks Creek anticline are well foliated, and foliation is at a low angle to bedding. Foliation attitude changes slightly between each fault-bounded block of the backlimb domain and abruptly across the main fault below the principal hinge, so that it maintains a constant angular discordance to the cover (15°–20°).

Spring Canyon anticline. The cover rocks of the Spring Canyon anticline in the northern Ruby Range, Montana, were first mapped in detail by Tysdal (1976). The fold verges west and is locally overturned in the Cambrian through Mississippian section (Fig. 7). It plunges 32° NNW and is transected by a splay of the Hinch Creek fault on its steeply dipping forelimb. Our interpretation of the fault-fold geometry of the cover rocks and basement-cover contact follows closely that of Tysdal (1976), except that we do not interpret the basement-cover contact here as a fault. Rather, it appears that the contact, although steeply dipping (75°–80°) and almost parallel to the fault, is actually cut by the fault. The basement-cover contact has a geometry very similar to the London Hills anticline, with one main angular hinge separating the backlimb from the forelimb and a smaller (less abrupt) hinge within the forelimb, separating moderately dipping bedding (<45°) from more steeply dipping bedding (>45°). The interlimb angle is 98°, nearly the same as that in the London Hills anticline. Like both the London Hills and Brooks Creek anticlines, east-verging backthrusts with small displacement cut the backlimb (Fig. 7). Tysdal (1976) indicated the presence of a fault in the basement below the main hinge in the cover. Although it is difficult to determine if a fault exists here

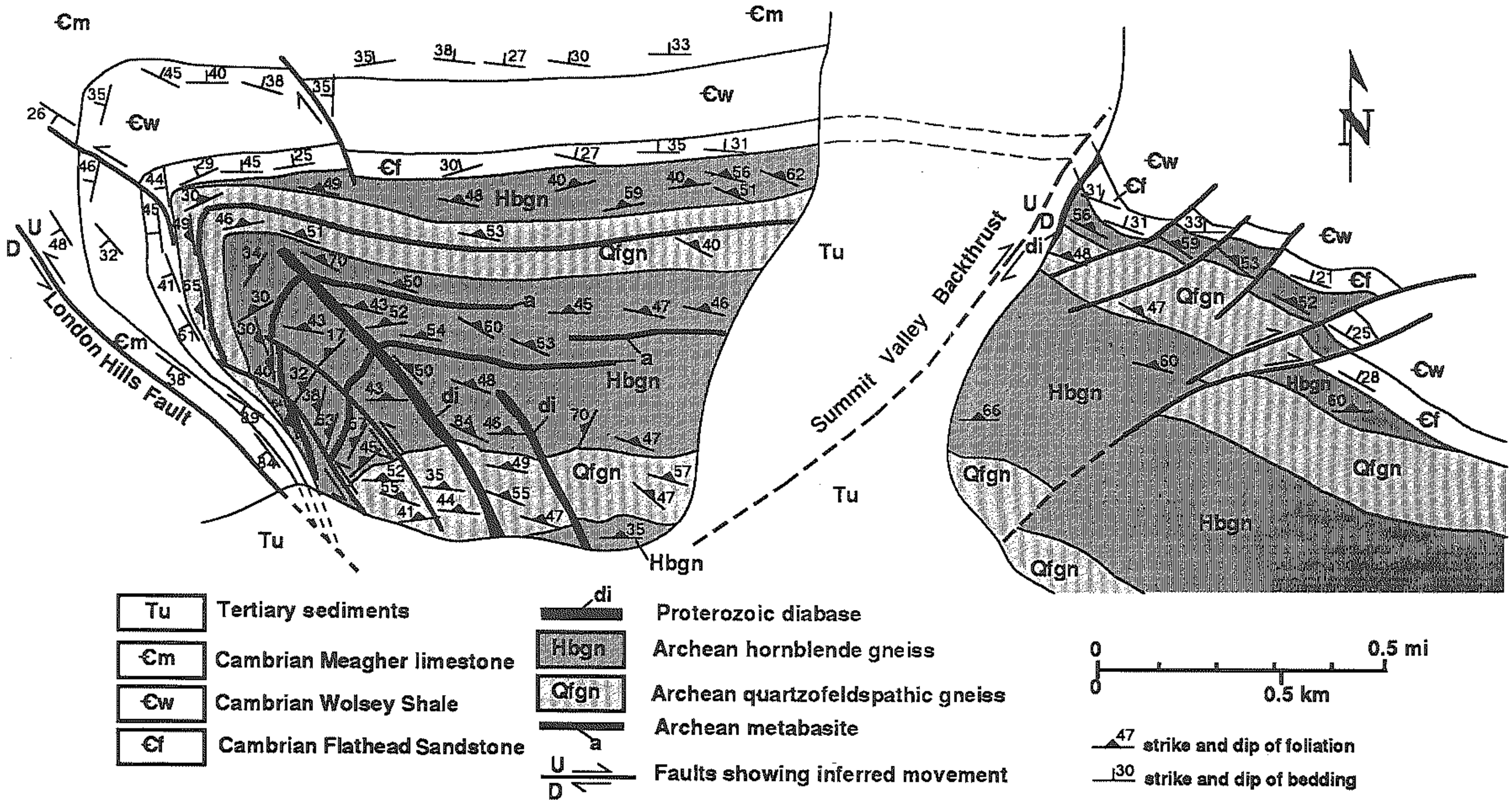

Figure 4. Geologic map of the London Hills anticline. The deformed basement forelimb domain exists between the cover rocks on the forelimb and the largest diabase dike (in hinge-surface position). The foliation and lithologic contacts are rotated in this domain by the same amount as the cover rocks (see Chase and others, this volume). See Figure 3 for map location.

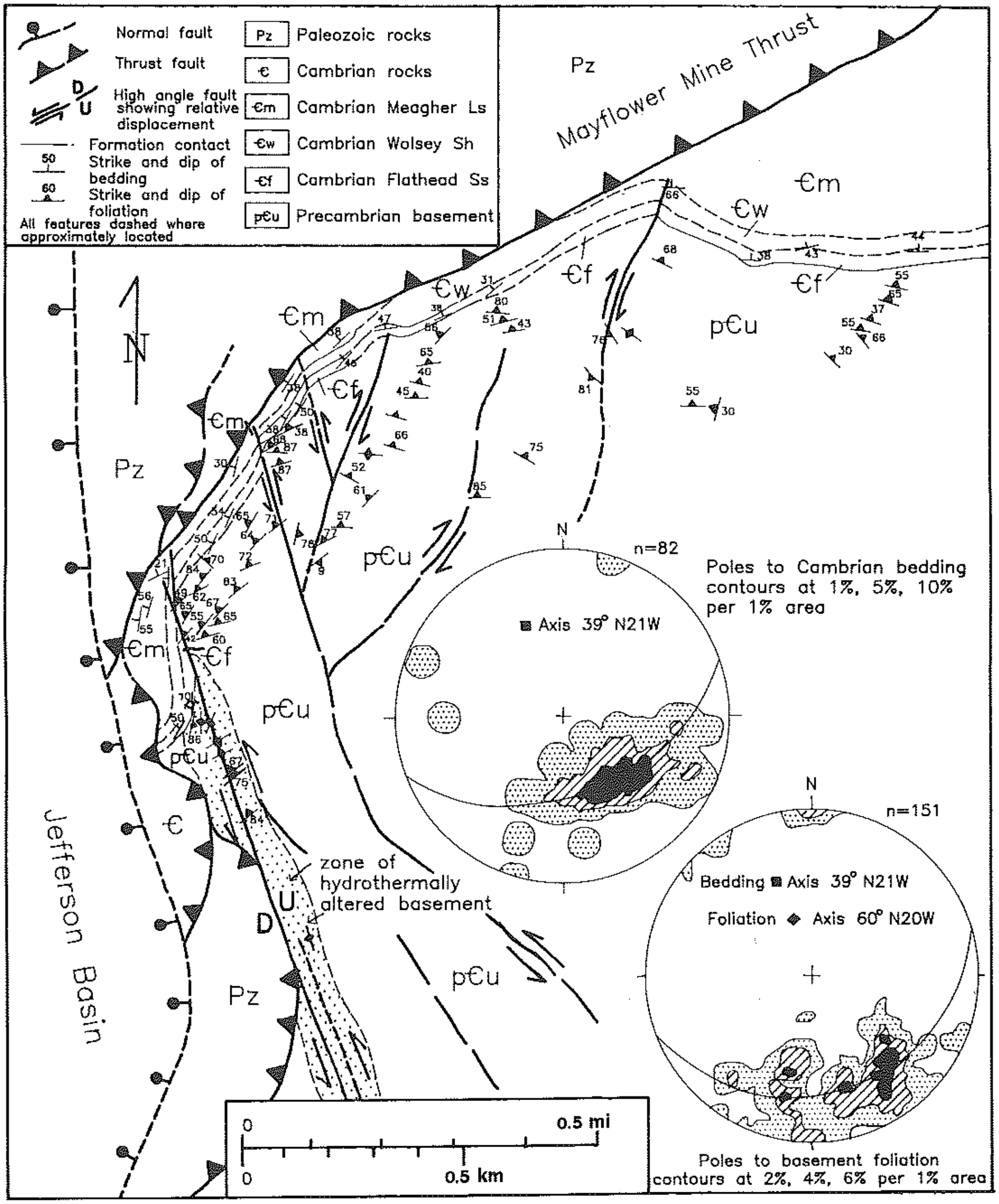

Figure 5. Geologic map of the Brooks Creek anticline with inset stereoplots of poles to bedding in the cover and poles to foliation in the gneiss. Thrust faults are elements of the Cordilleran thrust belt that impinged on the foreland structure in Late Cretaceous time (Schmidt and others, 1988).

because the cover rocks are not offset, there is a very abrupt transition between cataclastically deformed basement in the forelimb domain, with closely spaced, hinge parallel fractures (3–4 cm), to basement that is simply jointed (0.5–5.1 m) in the backlimb domain.

Karasevich (1981) mapped the Archean rocks in the anticline, showing the presence of a thin (10–20 m thick) folded marble unit a few tens of meters below the Cambrian Flathead Sandstone. He also showed a thick marble unit (425–550 m thick) about 400 m below the contact. Examination of the thin marble unit indicates that it is folded about an axis oriented 43°, N10°E, and that this axis is the same as that for folded foliation in the amphibolite layer below the marble. This axis is similar to that for the folded cover rocks (32°, N8°W) (Fig. 7). The marble unit is folded slightly more tightly than the Flathead Sandstone above it, with an interlimb angle of 87°. In addition, the

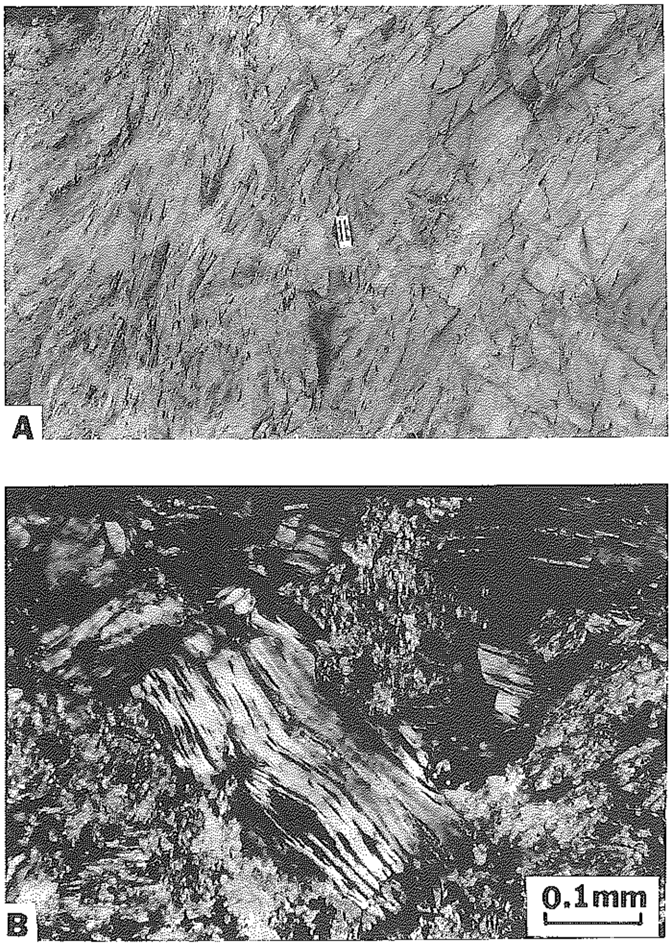

Figure 6. A: Outcrop photo of the hinge-surface fault zone of the Brooks Creek anticline showing highly altered foliated feldspathic gneiss. B: Photomicrograph from the Brooks Creek fault zone showing chlorite with open cleavage planes containing fine-grained sericite. Chlorite and sericite are typical of the alteration products in the fault zone.

basement-cover unconformity cuts progressively lower in the Archean section around the fold, and on the backlimb, about 1.4 km east of the hinge, the thin marble unit is absent below the unconformity (Fig. 7).

The Hinch Creek fault has a strike separation of 6.5 km at the basement-cover contact (Tysdal, 1976; Schmidt and Garihan, 1983). Restoration of this separation does not provide a match of the thick marble bed on the hanging wall to comparable rocks on the footwall. In fact, there are no thick marble beds underneath the cover on the footwall of this fault. This suggests that it is a reactivated fault in which the hanging-wall Archean rocks were originally downthrown, allowing the thick marble unit to be eroded off the uplifted footwall (Schmidt and Garihan, 1986) (Fig. 8, A and B). The Hinch Creek fault also appears to be a concave-upward fault. This interpretation is suggested by the fact that it changes attitude from north-south, 75°–90°W, where it cuts the steep anticlinal forelimb, to N65°W, 45°–65° NE, where it cuts the basement-cover contact along the hinge surface of the footwall syncline. All of these data and interpretation of data suggest that there may have been early (Proterozoic) folding associated with listric normal faulting on the Hinch Creek fault. When this fault was reactivated with a reversal of throw, the thin Archean marble unit was folded coaxially with the overlying cover, but it assumed a tighter interlimb angle because it had already been broadly folded (rollover-style) during normal faulting (Fig. 8, B and C).

Biltmore anticline. The Biltmore anticline and associated Biltmore fault are located on the easternmost edge of a small eastward-convex thrust salient (McCartney Mountain salient) in southwestern Montana. The regional geology and relations of thrust-belt structures to the anticline were described by Brandon (1984) and Schmidt and others (1988). Only the forelimb of the structure is exposed (Fig. 9), because the northeastern part of the structure that contains the backlimb has been downfaulted along a normal fault (Fig. 9). The presence of the Paleozoic section on the downfaulted backlimb has been detected in a seismic profile that extends east-west across the structure about 5 km south of the outcrops of the forelimb (Lopez and Schmidt, 1985). Restoration of the downfaulted backlimb (Schmidt and others, 1988, Fig. 23) indicates that it probably dips about 15° to the northeast. The Cambrian rocks in contact with the basement rocks on the forelimb are generally near vertical, but are locally overturned and dip as low as 54° NE, making the interpreted interlimb angle as small as 39°. The mean interlimb angle is probably closer to 75°.

Basement rocks below the forelimb are well exposed. They are very well foliated muscovite and biotite schists with subordinate lenses of amphibolite and a foliation-parallel diabase dike. In the northern two-thirds of the basement exposures (on the northwest side of the Big Hole River) (Fig. 9) foliation strikes consistently N60°W and dips steeply northeast (Fig. 9). It strikes about 15°–20° more westerly than bedding on the forelimb and has about a 15°–20° dip discordance relative to bedding. Although the backlimb of the fold cannot be reconstructed with certainty, it is likely that foliation here is nearly parallel with the hinge surface. Foliation is also folded in a series of northwest-trending (Precambrian) isoclinal folds with a wavelength of 50–100 m. Shear parallel to foliation has occurred on widely spaced (25–100 m) faults. These faults cut across the fold hinges of the Precambrian isoclinal folds. Locally distributed shear on northeast-dipping foliation is indicated by slickensides on foliation surfaces. Slickenlines plunge to the southeast and indicate approximately equal components of strike slip and dip slip on foliation. However, sense of movement cannot be determined unambiguously. Small, brittle kink folds in foliation are relatively common but do not have a consistent orientation. Most of these indicate a component of left slip.

In summary, the Biltmore anticline appears to be similar to the other basement-cored folds in this region with a low angular discordance between cover-rock bedding and foliation and evidence that shear along foliation has been important only on the steeply-dipping to overturned forelimb of the fold. However,

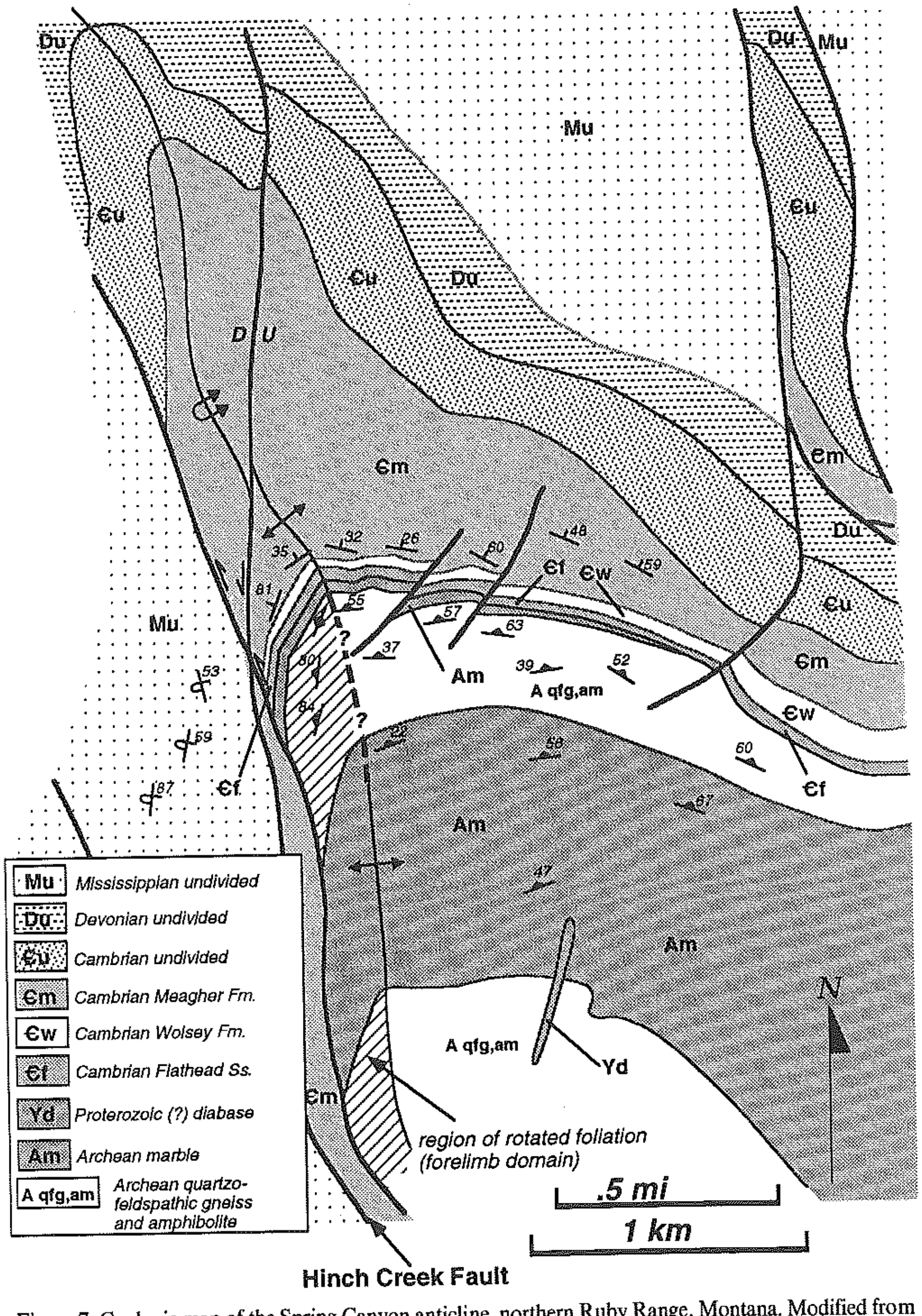

Figure 7. Geologic map of the Spring Canyon anticline, northern Ruby Range, Montana. Modified from Tysdal (1976) and Karasevich (1981).

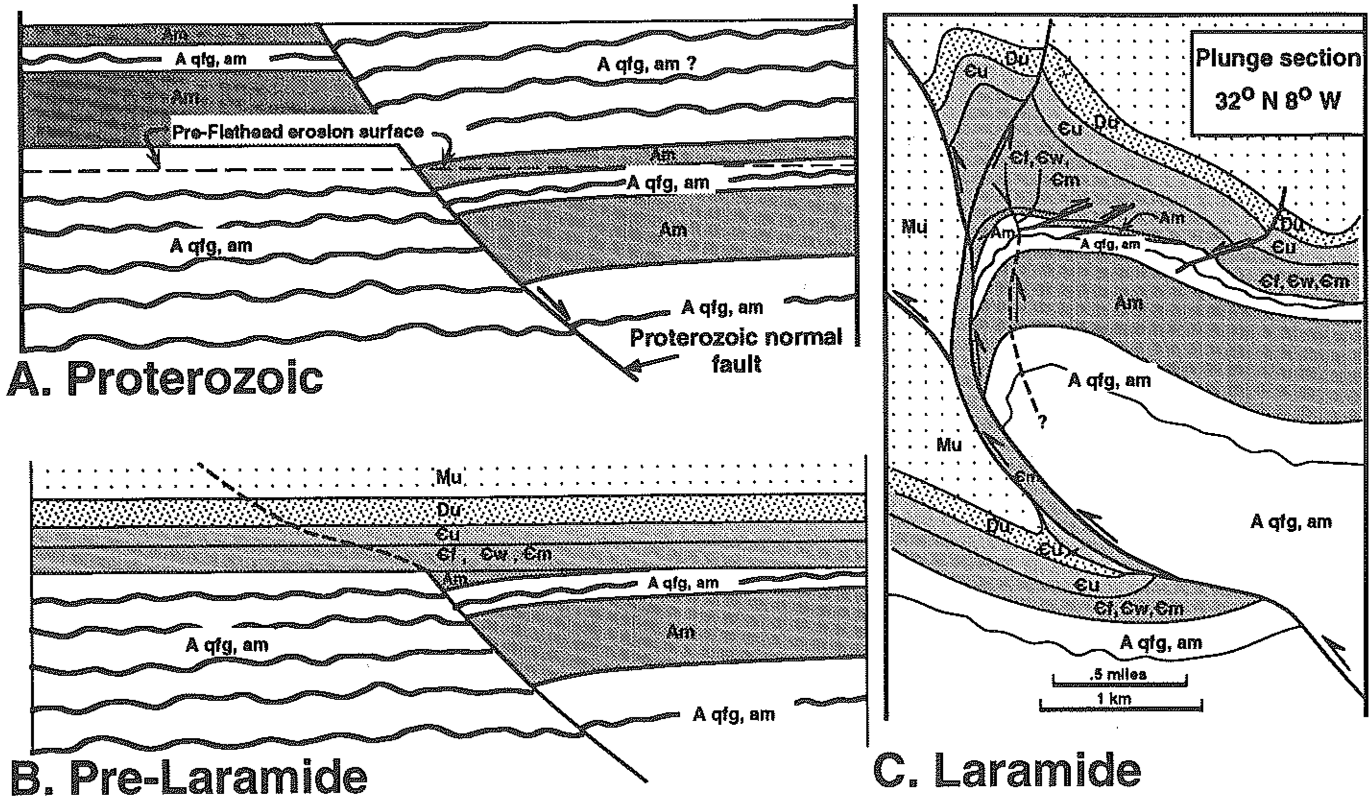

Figure 8. A: Interpreted pre-Proterozoic normal-fault geometry of the Spring Canyon area in the northern Ruby Range. B: Interpreted pre-Laramide geometry of the Spring Canyon area. C: Present (post-Laramide) structure of the Hinch Creek fault–Spring Canyon anticline. Structure is shown in plunge section. (All symbols are the same as in Fig. 7.)

without more data on slip sense and data from the backlimb it is not possible to say whether the foliation was rotated on the steep limb along with the cover rocks, as interpreted for the other folds in this region, or whether it was oriented northwesterly prior to folding and underwent shear without rotation. Foliation in the southernmost outcrops trends more easterly or northeasterly (Fig. 9), defining a broad north-trending fold in foliation that is consistent with the pattern of foliations in the southern Highland Mountains 10 km to the north (O'Neill and Schmidt, 1989). Because of this consistency with foliation patterns directly north, where no Late Cretaceous folding is evident, we think that it is likely that shear occurred on foliation surfaces that were already oriented northwesterly.

LaPrele anticline. The LaPrele anticline, located in the northern Laramie Range of Wyoming, was initially mapped by Barlow (1953). It is a doubly-plunging (probably refolded) anticline with a west-verging, overturned sector plunging 21°, N7°E and an upright sector plunging 38° S21°W (Fig. 10). Our discussion focuses on the much better exposed, overturned sector. The forelimb dip varies from 78° (upright) to 74° (overturned). The backlimb dips essentially parallel to the plunge of the fold hinge, but is horizontal in profile (Fig. 11A). The minimum interlimb angle is about 70°. Exposures are excellent in cover rocks and widely scattered, but evenly distributed, in the basement. A small thrust fault cuts the forelimb and displacement amounts to only a few meters. It is interpreted to be a splay from the principal fault that strikes easterly and dips 35°–55°N (Barlow, 1953) (Figs. 10 and 11B).

The sedimentary cover consists of basal sandstone and very thick carbonates with sandstone and shale at the top of the section. The Madison Formation is exposed continuously around the entire fold. Maximum layer thinning in the forelimb is about 20%.

Basement rocks consist of granitic augen gneiss, tabular amphibolite bodies parallel to gneissic foliation, and massive gabbro. Backlimb basement shows normal metamorphic textures in gneiss and amphibolite, and no directional fabric in the gabbro. The granitic augen gneiss in the forelimb shows extensive foliation-parallel cataclasis (Fig. 12A). The transition from backlimb basement to highly sheared forelimb basement is abrupt at the axial surface of the fold (Fig. 12B). It appears as though folding of cover rocks was accomplished by forelimb rotation and stretching accommodated by distributed shear along foliation surfaces in forelimb basement rocks.

Elk Mountain anticline. The Elk Mountain anticline in

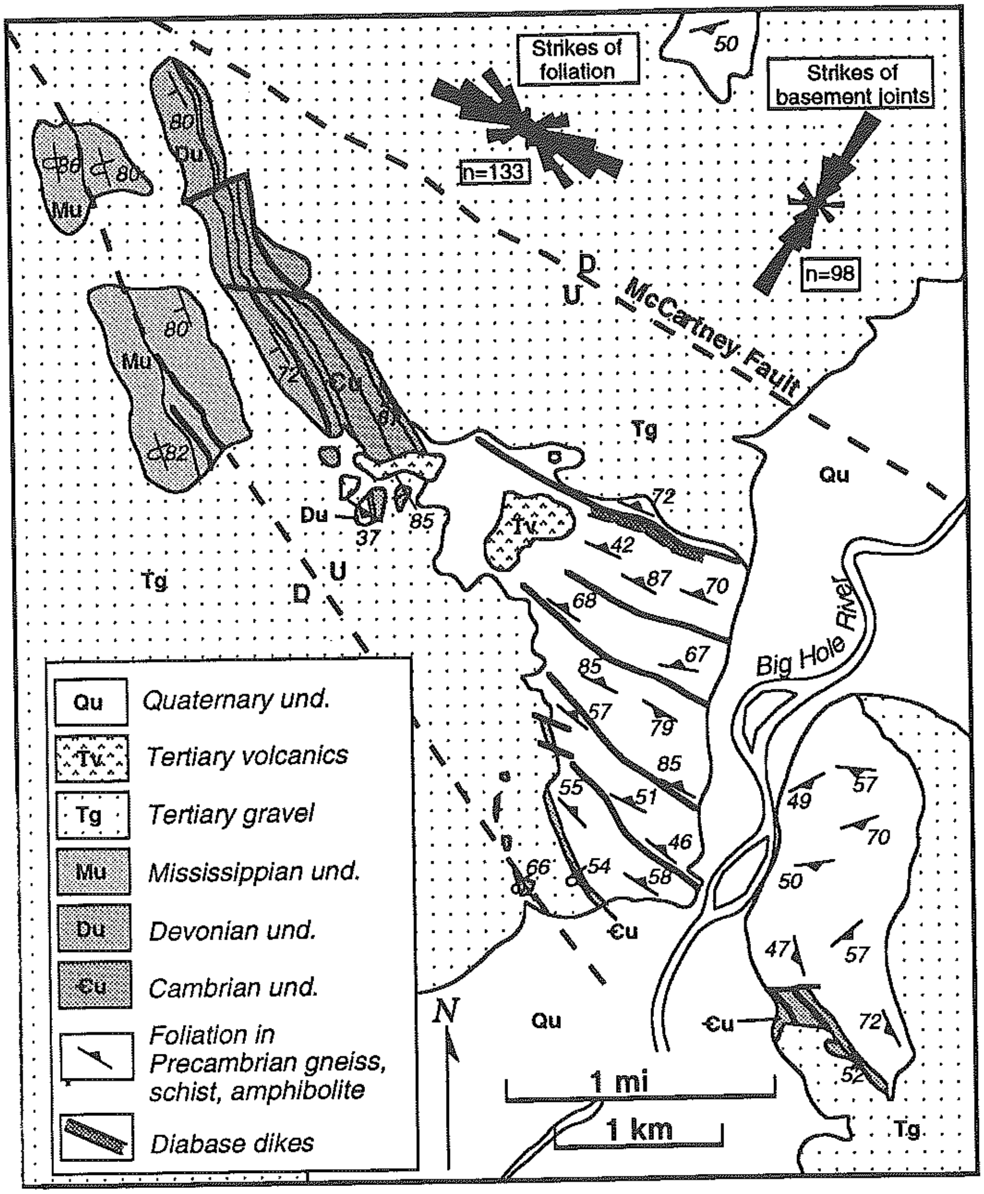

Figure 9. Geologic map of the Biltmore anticline, southwestern Montana. Modified from Brandon (1984). Northernmost fault (McCartney fault) is interpreted from seismic reflection and air-photo data and marks the inferred position of the hinge-surface trace.

the northern Medicine Bow Mountains was first mapped by Beckwith (1941). It is a historically important structure from the perspective of deformation in the Rocky Mountain foreland, because the compressional interpretation implied by Beckwith (1941) was challenged by McClurg and Matthews (1978), who offered a vertical uplift alternative. This interpretation was subsequently challenged by Blackstone (1980), who supported the horizontal compression origin of the structure. Although the observations of all of these authors were valuable in our own interpretation, none of the authors examined the basement rocks in detail.

The Elk Mountain anticline plunges gently northwest, is overturned, and verges northeast (Fig. 13). A plunge section constructed from data from the northernmost part of the structure (Fig. 13B) indicates that the cover rocks can be divided into four dip domains separated by relatively sharp, angular, fault-controlled hinges along the basement-cover contact. The back-limb region has two dip domains on either side of a hinge that we interpret to be controlled by a steep reverse fault (backthrust?) in the basement rocks. The principal anticlinal hinge is likewise interpreted to be controlled by a fault zone in the basement rocks. The steeply northeast-dipping forelimb curves abruptly into an

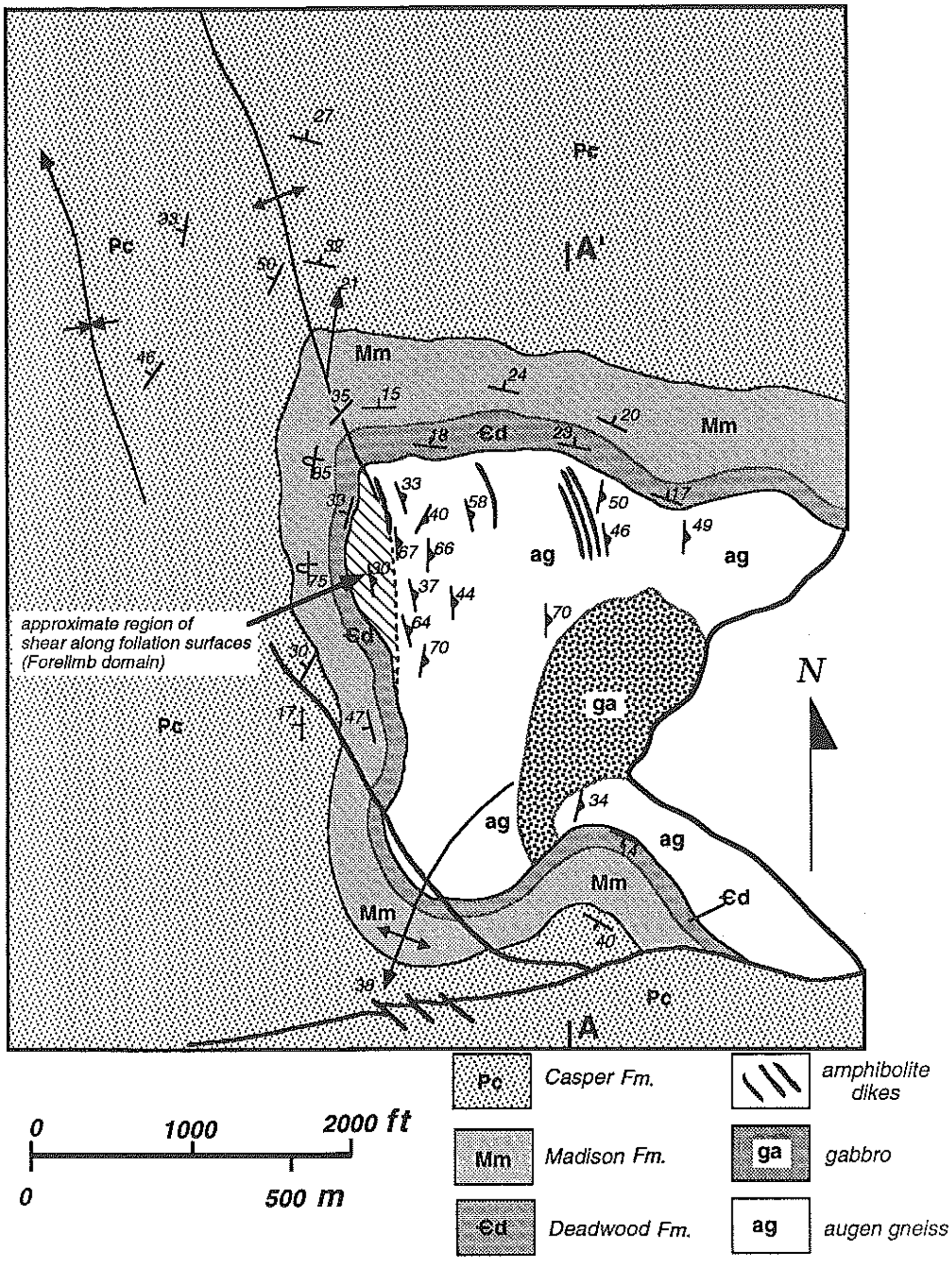

Figure 10. Geologic map of the La Prele anticline, Wyoming. Modified greatly from Barlow (1953).

overturned position. Like McClurg and Matthews (1978), we interpret the basement-cover contact along the overturned part of the forelimb as a fault. Formations (Mississippian and Pennsylvanian Amsden, Madison, and Casper) are significantly thinned on the overturned part of the forelimb. The interlimb angle between the overturned part of the forelimb and the backlimb (horizontal part of plunge section) is about 50°. The principal fault that separates the overturned forelimb from the footwall syncline is largely covered. According to Blackstone's balanced sections, based on well data from the footwall, the fault dips 40°–50° west and has a dip separation of 1.5 km (Blackstone, 1983, Fig. 8). If footwall beds at the basement-cover contact are not turned up against the fault as shown by Blackstone, dip separation increases to nearly 3 km.

The basement rock in the Elk Mountain anticline is a moderately well foliated quartzofeldspathic gneiss with areas of poorly foliated, coarse-grained granite and quartz monzonite and an occasional mafic dike. Foliation generally strikes east-

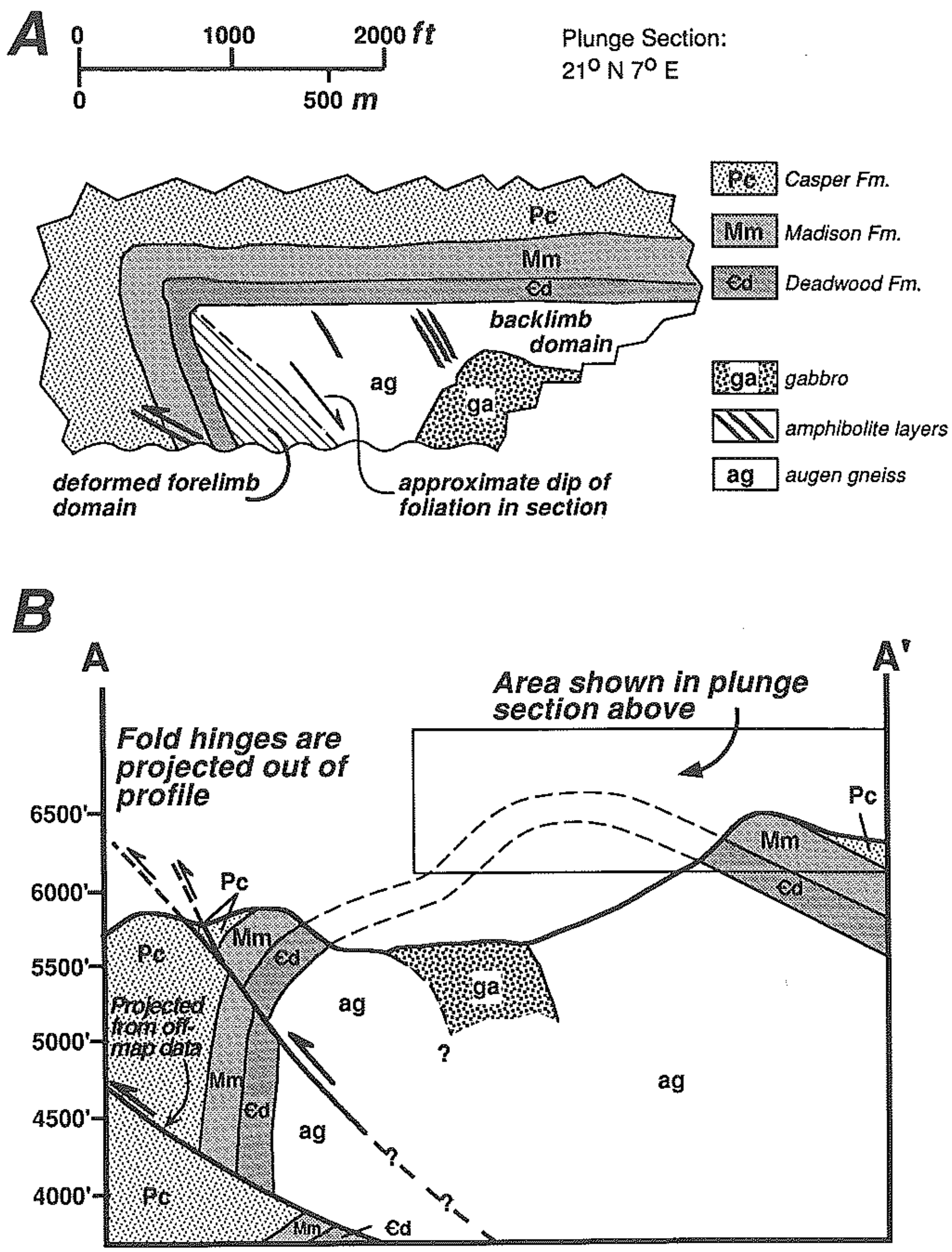

Figure 11. A: Plunge section of the northern part of the LaPrele anticline, Wyoming, showing augen gneiss deformed below the forelimb by shear parallel to the axial surface. B: Cross section through the twice-folded LaPrele anticline showing the position of the plunge section.

northeast and dips steeply south (Fig. 14, A and B). It is nearly perpendicular to the hinge surface of the folded cover. Although foliation is broadly folded (axis oriented 74° S50°E, Fig. 14B), there is no systematic relation of this broad fold to the Late Cretaceous structure and there is clearly no rotation of foliation below the steeply-dipping forelimb cover.

The basement rocks contain three prominent joint and/or fracture sets (Fig. 14C). One set, found throughout the basement exposures of northern Elk Mountain, strikes west-northwest and dips steeply southwest. West of the hinge surface (backlimb basement domain) these are joints spaced from 15 cm to more than 1 m apart. In the forelimb domain this set is more closely spaced (5–20 cm) and locally follows foliation. In addition, many of the surfaces in the forelimb domain show faint, steeply plung-

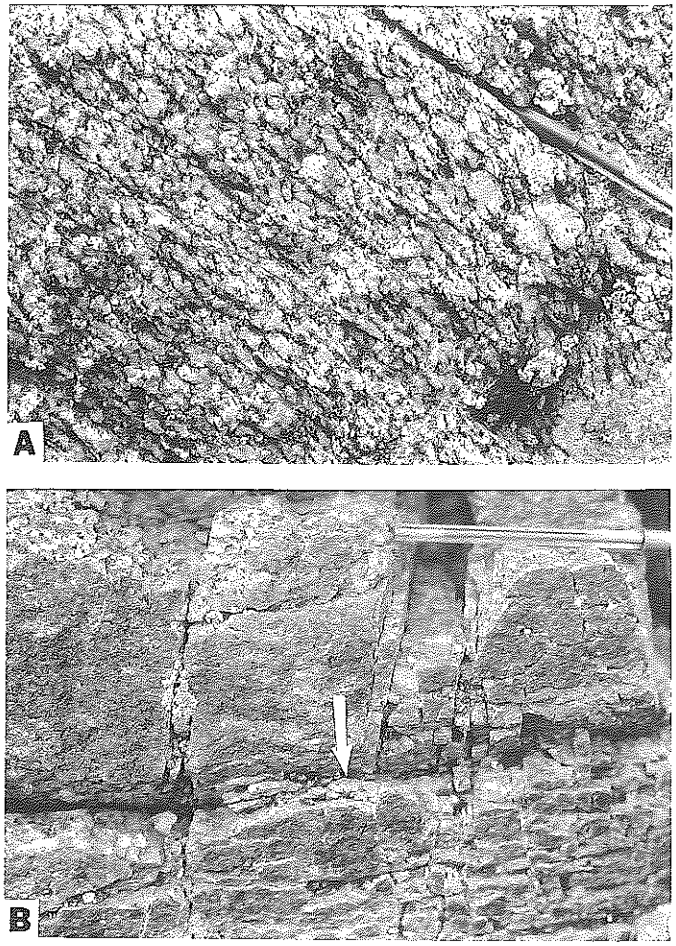

Figure 12. A: Outcrop photo of fractures that follow foliation in augen gneiss below the steep limb of the La Prele anticline. Fractures and foliation are parallel to the hinge surface in the basement rocks. B: Outcrop photo showing the abrupt change from undeformed to deformed domain along the axial surface at the La Prele anticline, Wyoming. Arrow points to the location of the hinge surface. Pen is in the undeformed (unfractured) domain. Deformed area is below hinge surface in the photo.

ing slickenlines. Another regional joint set is nearly horizontal (Fig. 14C). These are probably sheeting joints. A third set strikes nearly north-south and is vertical to steeply east dipping. This set is developed only in the forelimb domain (shaded region of Figs. 13 and 14), frequently contains steeply plunging slickenlines, is locally very closely spaced (3–10 cm), and is commonly associated with narrow (3–10 cm) zones of cataclasis. This fracture set is the most closely spaced, with qualitatively the greatest cataclasis, just below the main anticlinal hinge in the cover rocks where it follows the hinge surface in the basement rocks. We interpret this zone of fracturing as a fault in Figure 13B. Although it does not offset the cover, the cover is slightly thinned on the gently-dipping part of the forelimb. The forelimb basement domain, defined by the development of this fracture set and a closer spacing of regional joints, is about 500 m wide at the surface (Figs. 13 and 14).

Sheephead Mountain anticline. The Sheephead Mountain anticline is also located in the northern Medicine Bow Mountains 9 km west of the Elk Mountain anticline. It was first mapped by Beckwith (1941) and was described by Houston and others (1968) and Blackstone (1983). The details of the structure are also described by Chase and others (this volume). In almost every respect it is nearly identical to the nearby Elk Mountain anticline, except that it is smaller (less than one-half the amplitude and dip separation along the principal fault compared to Elk Mountain). It plunges gently northwest, is overturned, and verges northeastwardly (Fig. 15). The cover rocks have a constantly northwest dipping backlimb. The principal anticlinal hinge is sharp and angular. The forelimb has a secondary hinge where dips change abruptly from 37° NE to 75° SW (overturned). The interlimb angle, between the gently dipping backlimb and overturned part of the forelimb, is about 55°. As in the Elk Mountain anticline, we have interpreted the basement-cover contact on the overturned forelimb to be a fault that splays from the principal synclinal hinge thrust (Fig. 15).

The basement rocks of the anticline are well-foliated quartzofeldspathic gneiss and minor amphibolite (Banks, 1970). Two small north-trending diabase dikes crop out in the forelimb domain and parallel the dominant fracture set in that domain. Foliation strikes west-northwest and dips steeply southwest. It is highly discordant to cover-rock bedding (60°–90°) and does not show any noticeable change in orientation across the Late Cretaceous fold (see Chase and others, this volume, for a detailed analysis). As described by Chase and others (this volume), all of the basement rocks are highly jointed and fractured. However, the forelimb domain is more densely fractured (2–5 cm spacing locally) than elsewhere. In addition, there is a well-developed, north-striking, moderately west dipping, hinge-surface–parallel fracture set present in the forelimb domain that is not present west of the hinge surface (Chase and others, this volume, Fig. 17). Many of the fractures in this set have dip-slip slickenlines, and we concur with Banks (1970) that they may be genetically related to the thrust that cuts the steep forelimb. The highly fractured forelimb domain is about 90 m wide.

Sheep Mountain anticline. The Sheep Mountain anticline is a doubly-plunging, southwest-verging anticline located on the east flank of the Never Summer Range in north-central Colorado. It was mapped and described by Hail (1965). The northern closure plunges 36°, N17°W, and the southern closure plunges 57°, S42°E. The first 250 m of section above the basement rocks consists of Permian-Triassic shales, siltstones, and sandstones of the Chugwater Formation. The backlimb dips about 20°NE (Figs. 16 and 17). The forelimb is steeply overturned (75°NE) and is cut by at least three northeast-dipping thrusts (Sheep Mountain thrust-fault zone of Hail, 1965). The total stratigraphic displacement across the fault zone is about 2000 m (Hail, 1965). The entire section on the forelimb is thinned by more than 30%. The basement-cover contact is a fault that occupies the anticlinal

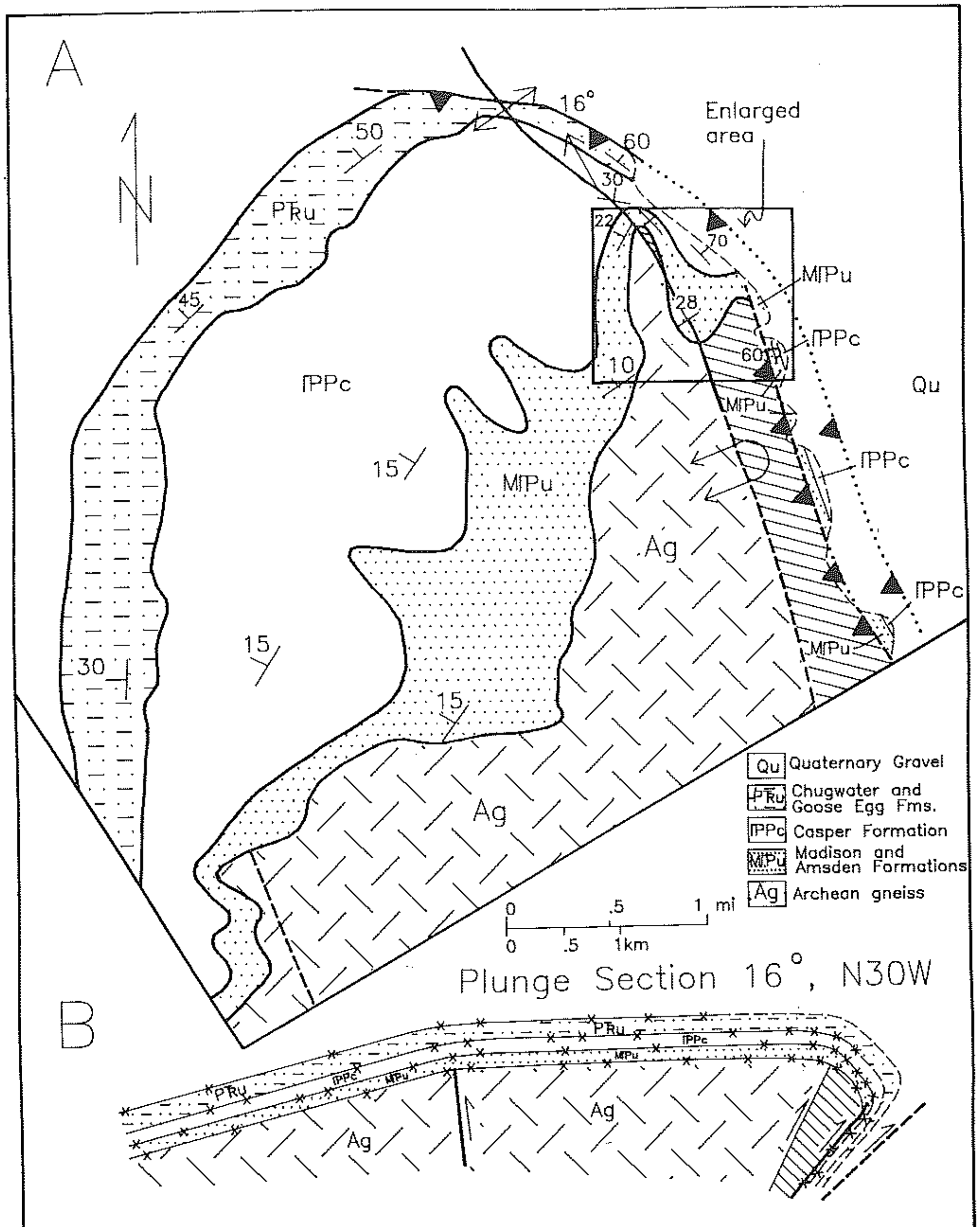

Figure 13. A: Geologic map of the northern half of the Elk Mountain anticline, Wyoming. Modified from McClurg and Matthews (1978) and Blackstone (1983). Cross-hatched area indicates highly fractured basement. B: Down-plunge section of the northern Elk Mountain anticline. Hatched area is a region of highly fractured basement. Xs mark data points.

hinge surface of the fold. The interlimb angle is about 55°.

Because a fault occupies the principal hinge-surface position and cuts up into the cover rocks for several hundred meters (Fig. 17), the basement-cover geometry does not show the multiple angular hinges that are seen in many of the other folds we studied. Instead, there is an abrupt termination of the backlimb against the fault with little or no folding at the basement-cover contact. This abrupt termination is more noticeable on the north-plunging segment, where transition from backlimb to forelimb occurs within a few tens of meters of the fault. At the south-plunging end of the structure there is a more gently curved fold that begins to roll over about 75 m from the fault on the hanging-wall side. Rapid loss of fault displacement on both the north and south ends of the structure suggests that fault-fold formation may follow a

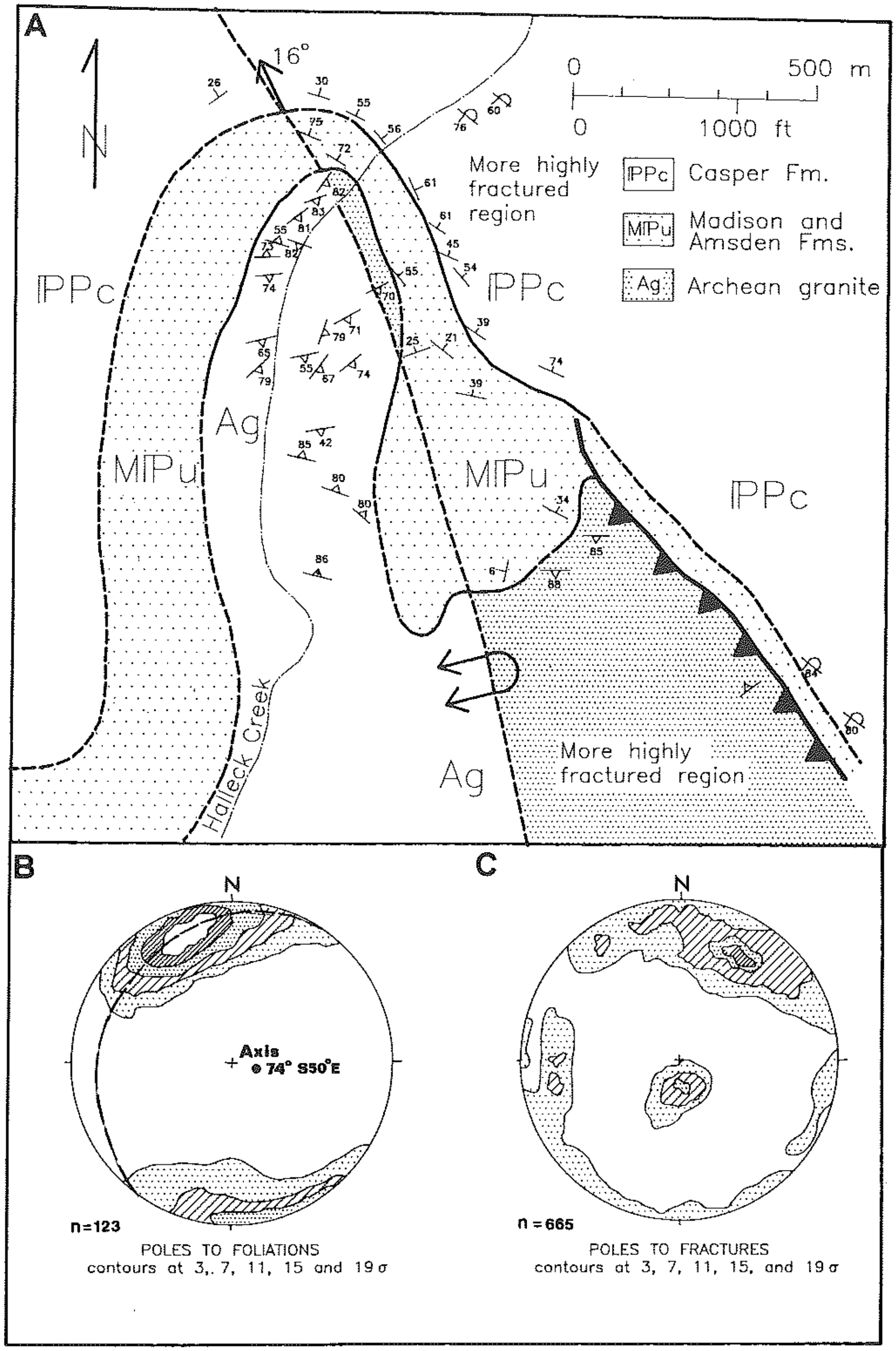

Figure 14. A: Geologic map of the northernmost part of the Elk Mountain anticline showing foliation in basement and the region of more highly fractured basement. B: Equal-area stereoplot of poles to foliations and equal-area stereoplot of poles to fractures and joints in basement rocks.

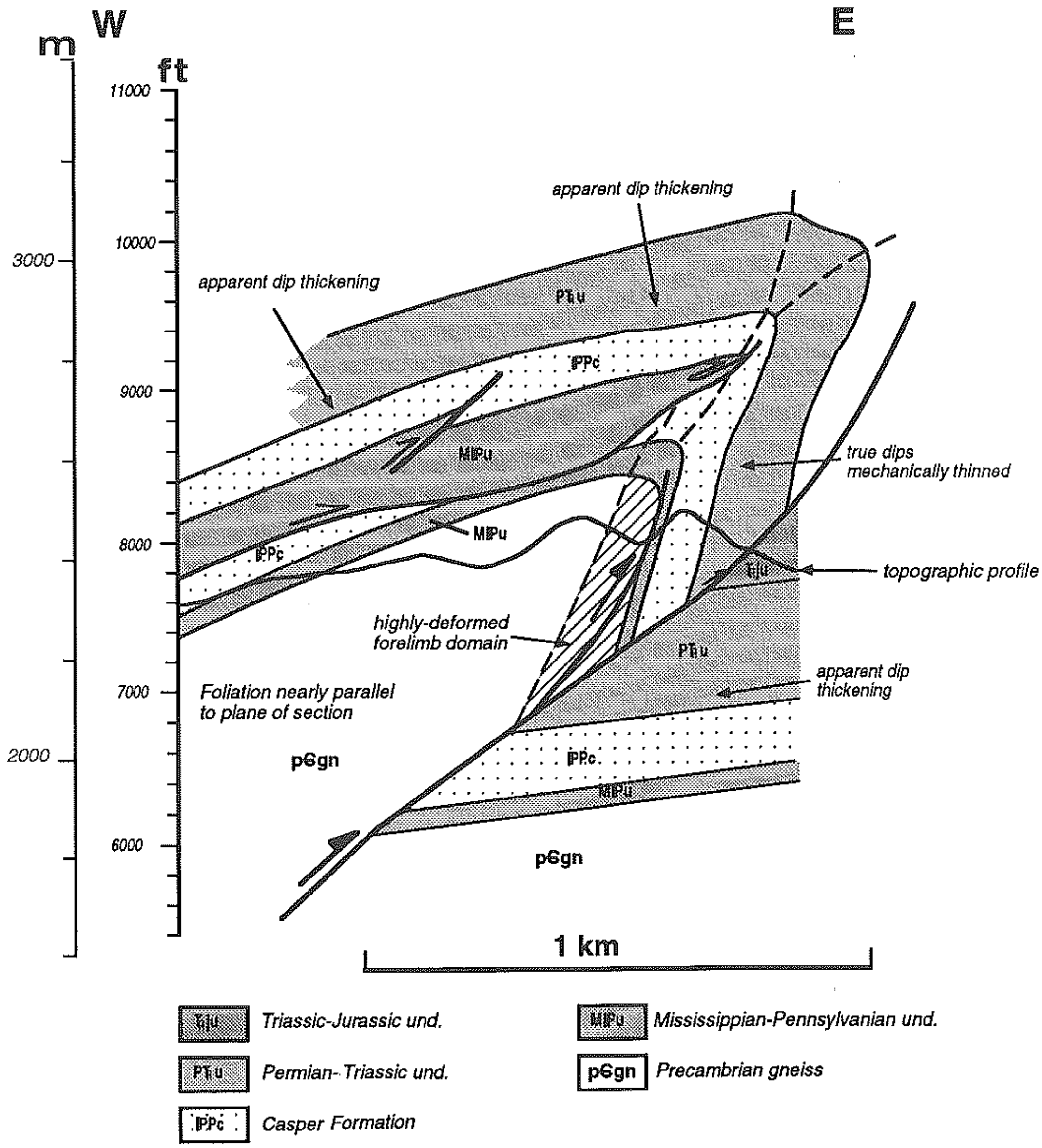

Figure 15. West-east cross section of the Sheephead Mountain anticline with cover-rock geometry projected from plunge section. See Chase and others (this volume) for section location. From Chase and others (this volume).

simple basement wedge model as described by McConnell and Wilson (this volume), with little fault propagation into the cover.

Basement rocks on the north end of the Sheep Mountain are moderately well foliated quartzofeldspathic gneisses and amphibolites with foliation at a high angle to the cover rocks (Fig. 16). Foliation shows no systematic change across the width of basement exposures. The basement rocks at south Sheep Mountain are massive granites. There is no noticeable change in style of basement deformation from the north to the south, and foliation on the north appears to have been unaffected by later deformation. The forelimb basement domain is a very narrow (10–15 m) zone of fractures (3–5 cm apart). These closely spaced fractures dip 35°–46° NW and are interpreted to parallel the hinge-surface fault. There are three sets of fractures and/or joints present in the backlimb basement domain. One set strikes parallel to the major fault and is ±10° from being vertical. Another set parallels the main fault zone and has a 0.5–3 m spacing, and a third set is perpendicular to the fold axis.

Kaufman Ridge anticline. The Kaufman Ridge anticline is a west-verging anticline in the Mosquito Range east of Buena Vista, central Colorado. It was mapped and described by DeVoto (1971). It plunges 25°, N3°E. In strong contrast to the cover

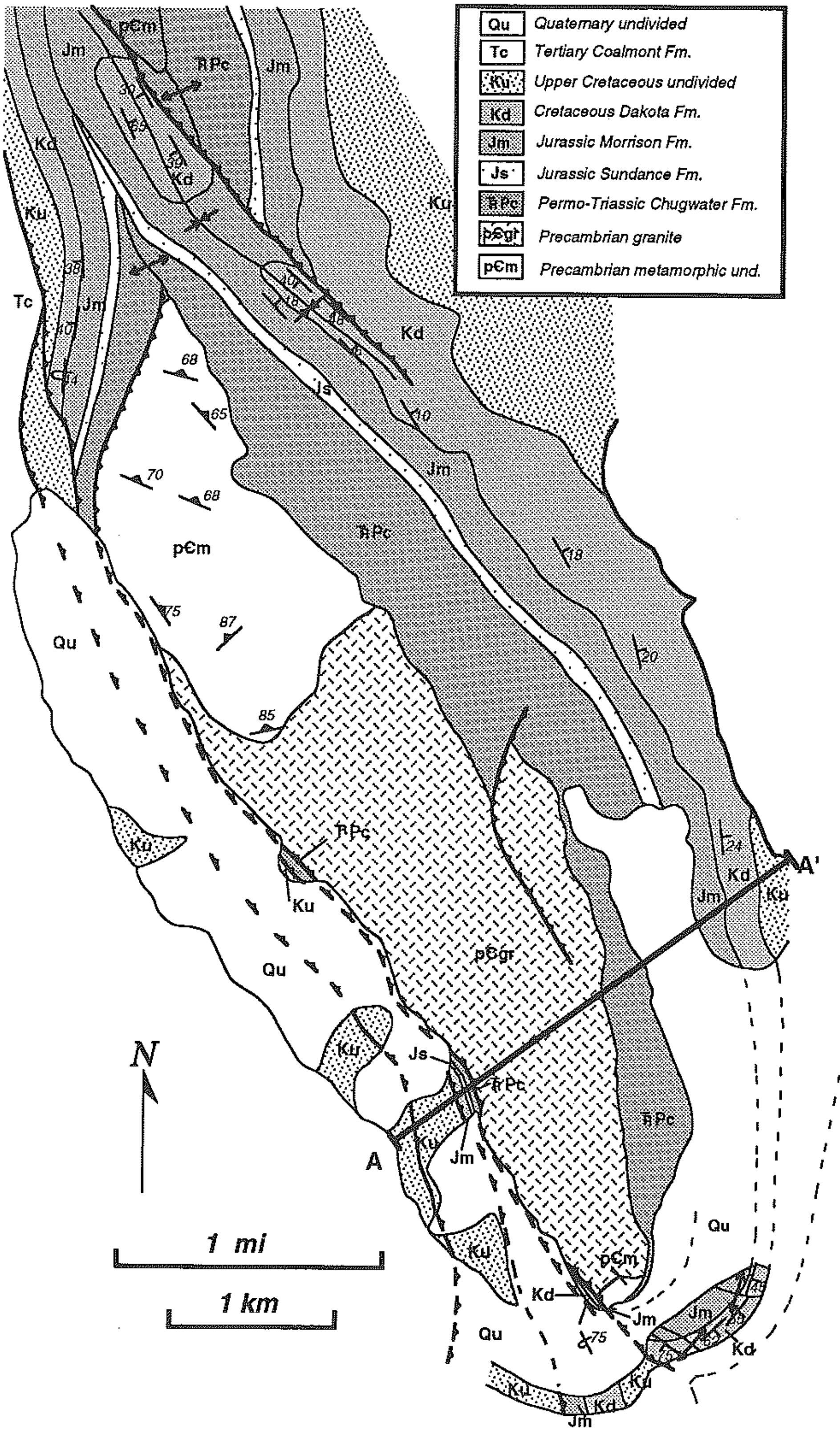

Figure 16. Geologic map of the Sheep Mountain anticline, North Park, Colorado. Modified from Hail (1965).

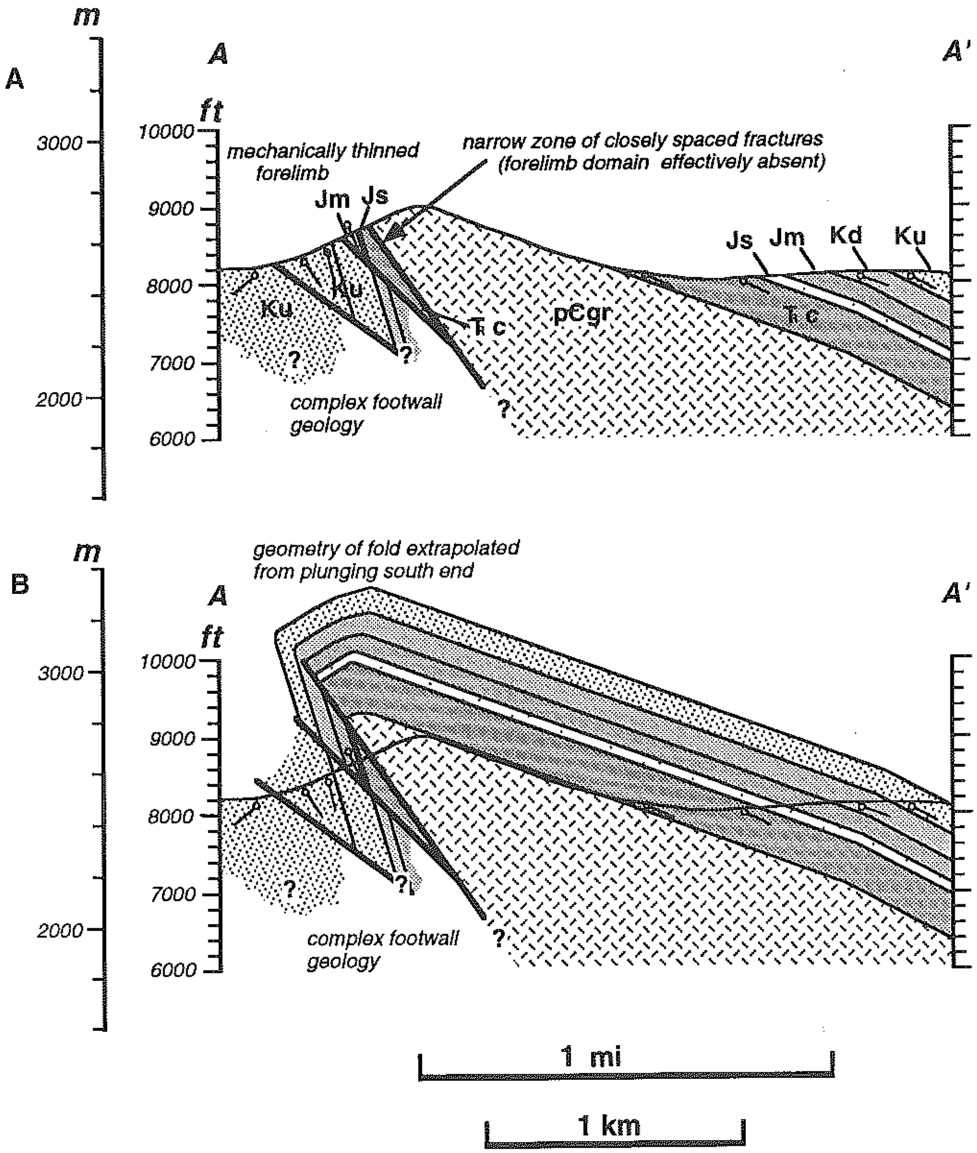

Figure 17. A: Cross section across the Sheep Mountain anticline. B: Interpretive cross section using down-plunge data.

rocks in the Sheep Mountain anticline, the first 350 m of stratigraphic section overlying the basement at Kaufman Ridge consists of massive Ordovician and Devonian dolomite, sandstone, and limestone. The backlimb and footwall syncline limb have about the same dip (15°–25° NE). The forelimb is upright and dips 55°–70° NE. It is cut by at least two steeply-dipping reverse faults (Figs. 18 and 19), but the stratigraphic section is not noticeably thinned. The basement-cover contact on the forelimb is interpreted to be largely an unconformity (Fig. 19); the forelimb-backlimb interlimb angle is 105°, the largest for all of the folds we studied. The continuity of dip in the backlimb is broken by a 0.5-km-long region of steeper dips, suggesting the presence of a local kink in the backlimb (Fig. 19). Along strike this part of the backlimb is underlain by a west-dipping zone of visually greater cataclasis.

The basement rock in the Kaufman Ridge anticline consists of granitic augen gneiss, massive coarse-grained granite and pegmatite, and some amphibolite. Foliation is at a high angle to the cover rocks. All three basement rock domains are exposed. The forelimb domain is 650–750 m wide and is a wide zone of extensive cataclasis. The cataclastic fabric appears to be related to distributed shear (spacing of 3–5 cm) parallel to the major fault and anticlinal axial surface. The contact between the forelimb basement domain and the backlimb domain is gradational. In the backlimb domain distributed shear is absent, but one of the principal joint sets is parallel to the major fault and axial surface. The

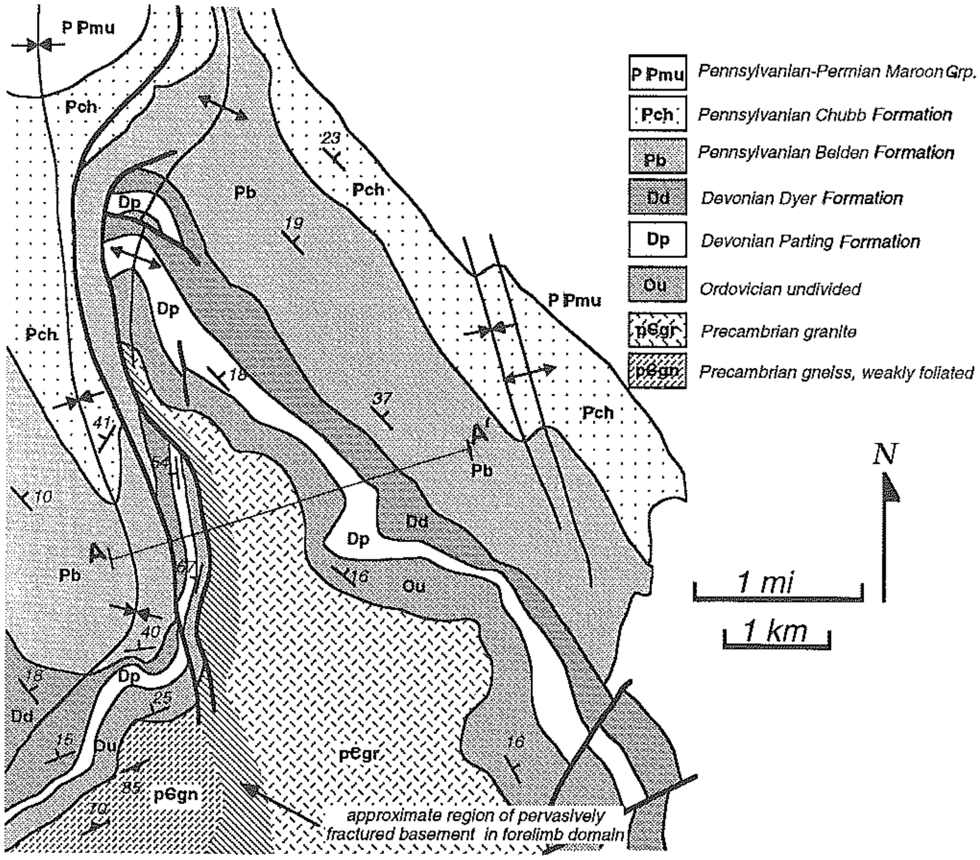

Figure 18. Geologic map of the Kaufman Ridge anticline, Colorado. Modified from DeVoto (1971).

footwall domain has several joint sets but no cataclastic fabric or closely spaced shear fractures. The boundary between the footwall domain and the forelimb domain is poorly exposed, but we have interpreted it as a fault (Fig. 19).

North Twin Mountain anticline-syncline. The North Twin Mountain structure is located on the southwestern margin of the Front Range, Colorado. It was mapped in detail by Webster (1959). The structure is one of two very well exposed, overturned anticline-syncline pairs that verge to the southwest. It plunges 20°, S55°E. The dips are 82° for the forelimb, 20° for the backlimb, and 24° for the lower synclinal limb (Fig. 20). The interlimb angles are 52° for a rather rounded anticline and 60° for a syncline with a tight, cuspate hinge zone. The fault that controls the anticlinal hinge dips about 75°NE and does not penetrate upward into cover rocks. The principal fault along the synclinal hinge surface dips at about the same angle and breaks the cover at the synclinal hinge; however, it loses displacement within a few hundred meters of the basement-cover contact (Fig. 20). Maximum dip separation on the latter fault is 30 m.

The cover rocks are basal cherty dolomite, sandstone, massive limestone and dolomite, and massive sandstone and conglomerate. Features of cover-rock deformation include oblique-slip, bedding-plane thrusts likely associated with flexural-slip folding, small-scale folds and thrusts in the hinge zones of the folds that resulted from crowding, small normal faults at the basement-cover contact in the anticline that developed by arc extension, numerous slickenside surfaces, and joints. Cover-rock layers are thinned by at least 50% in the forelimb, mainly by pervasive extensional faulting.

Basement rocks consist of weakly foliated granodiorite with large feldspar megacrysts, mafic dikes (both metamorphosed and unmetamorphosed), and irregular or tabular bodies of pegmatite. Foliation is oriented about N50°–80°W, 60°NE, and is therefore at a steep angle to the cover but nearly parallel to the hinge surface. It does not appear to have been rotated during folding. The anticlinal hinge fault follows the contact of a metamorphosed mafic dike, and the synclinal fault is in granodiorite. These faults appear in basement rocks as narrow zones of cataclasis. Brittle deformation elsewhere in basement rocks resulted in three joint sets, one of which parallels the faults and foliation.

Gnat Hollow anticline-syncline. The Gnat Hollow structure, initially mapped by Gerhard (1967) and Wobus and others (1985), is located in the south-central sector of the Front Range, Colorado. It is a very well exposed, asymmetrical anticline-

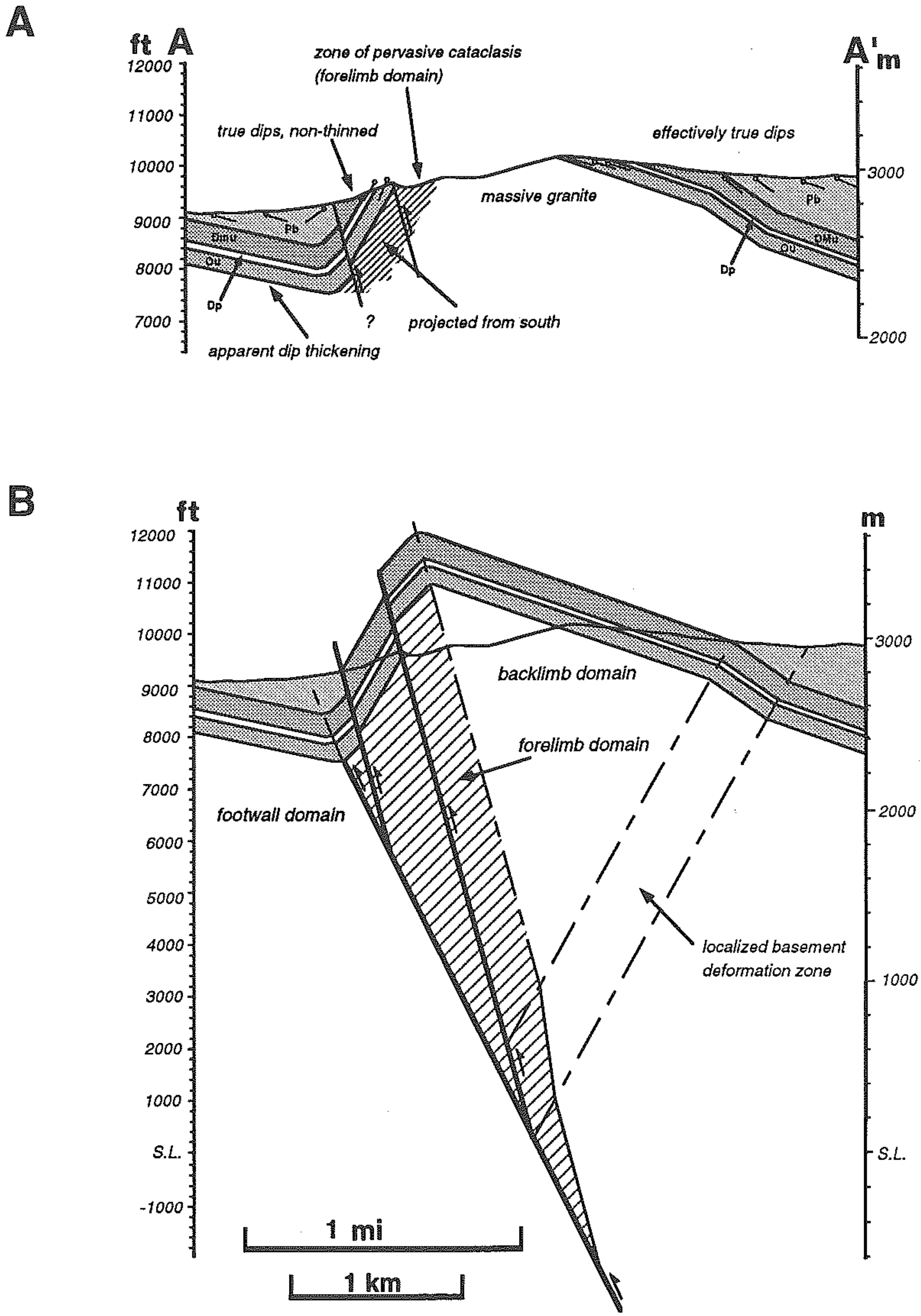

Figure 19. A: Cross section across the Kaufman Ridge anticline. B: Interpretive cross section using up- and down-plunge data.

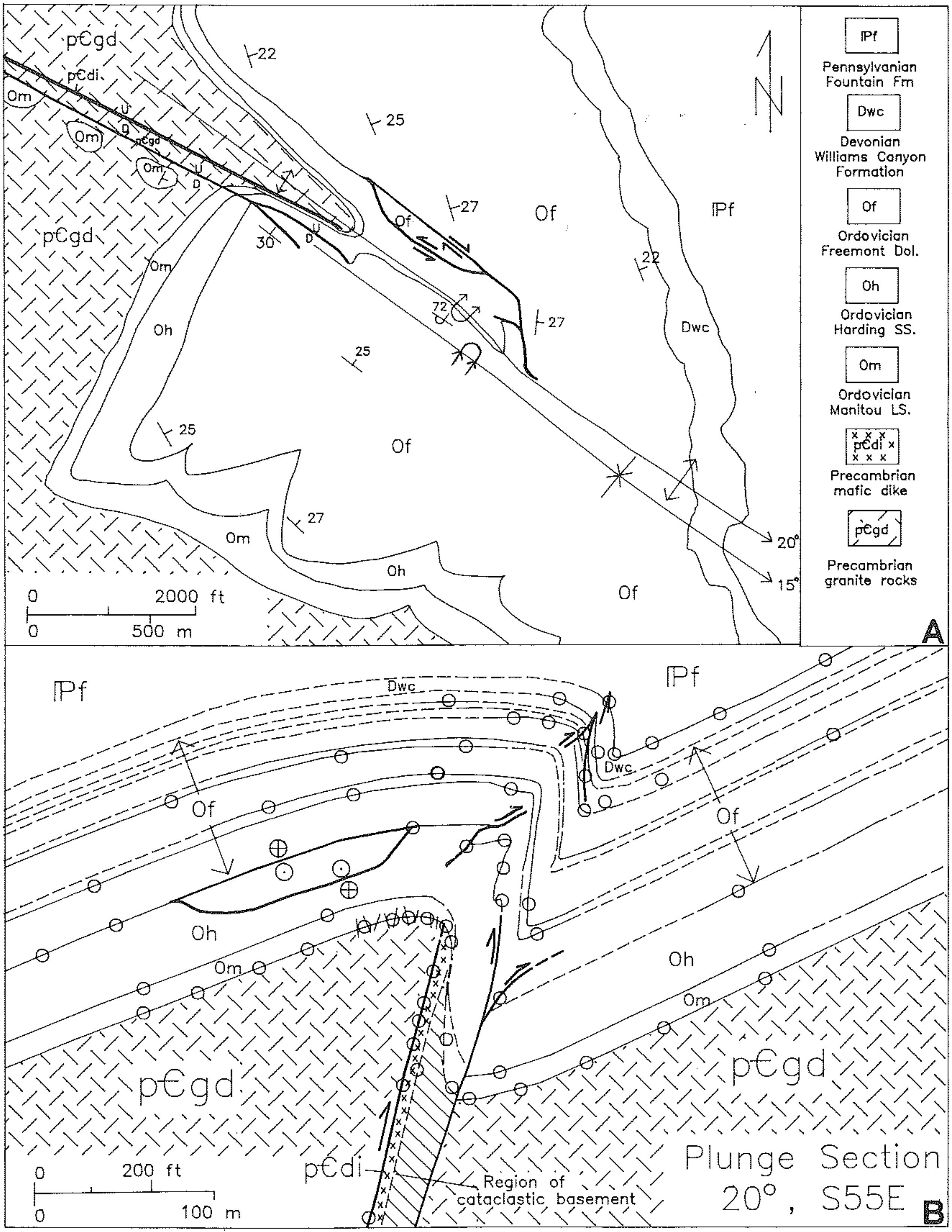

Figure 20. Geologic map (A) and down-plunge section (B) of the north Twin Mountain anticline, Colorado (geology by G. Nelson). Circles on plunge section are data points; dashed lines are interpolated or extrapolated contacts.

syncline pair that verges to the northwest and plunges 0°–10°NE (Chase and others, this volume) (Fig. 21). Where exposed, the anticline is upright with an interlimb angle of 135° between the gently-dipping backlimb and the gently dipping forelimb. The syncline has an interlimb angle of 75° and is overturned. Restored for faulting, the anticlinal interlimb angle is as low as 50°. Mean dips of the structural segments are: forelimb at 63°, backlimb of anticline at 18°, lower synclinal limb at 14°. The forelimb thrust dips 44°, has a maximum estimated dip separation of 600 m, and loses displacement upward in the cover rocks.

The Phanerozoic rocks consist of basal carbonate, sandstone, thick arkosic sandstone and conglomerate, and alternating thin layers of limestone, sandstone, and shale on top. Brittle deformation resulted in orthogonal joints and numerous faults with displacements amounting to centimeters or millimeters. Layer thinning of about 50% in the forelimb was accomplished mainly by extensional faulting. Some sectors of the thrust zone contain small horse blocks of basal cover rocks.

Basement rocks are schist, gneiss, granite, and pegmatite. Precambrian deformation produced foliation, polyphase folds, and local, high-angle faults with displacements of tens of meters (Chase, 1985). Deformation during Phanerozoic time resulted in the Gnat Hollow anticline-syncline with associated thrust-zone cataclasis and faulting, slickenside surfaces along and across foliation in some quartzofeldspathic rocks of the hanging-wall block, anastomosing shear fractures in schist of the footwall block, and joints oriented mainly parallel and perpendicular to foliation. As discussed by Chase and others (this volume), although foliation is locally sheared, on average it dips more steeply than the fault and does not appear to have played a significant role in deformation. Foliation is also locally rotated immediately adjacent to the fault in one location, but there does not appear to be any systematic rotation of foliation during folding and faulting.

Romero Hills anticline. The Romero Hills anticline (Baltz and O'Neill, 1984; O'Neill, 1990) is located in the eastern foothills of the Sangre de Cristo Mountains of northern New Mexico. It is an east-verging, overturned fold cored by a Precambrian isoclinal fold (Fig. 22). Although exposures throughout the structure are very good, the anticlinal hinge is not exposed because erosion has stripped the hinge-zone rocks down to basement level. However, analysis of small-scale folds in footwall cover rocks yields a mean hinge orientation of 5° S22°W, which is consistent with the regional trend of nearby folds and faults shown by Baltz and O'Neill (1984). The forelimb and backlimb have mean dips of 75° (overturned) and 10°, respectively. The interlimb angle cannot be measured, but extrapolation of mean limb dips yields an angle of 65°. The largest reverse fault that penetrates the structure, the Romero fault, has an exposed dip of about 50° and dip separation of 600 m as estimated from the cross section constructed by Baltz and O'Neill (1984) (see Fig. 22). Other reverse faults also contribute to the overall stratigraphic displacements in the anticline.

The cover rocks consist of thin basal carbonate overlain by a thick section of alternating sandstone, shale, and limestone. Faults

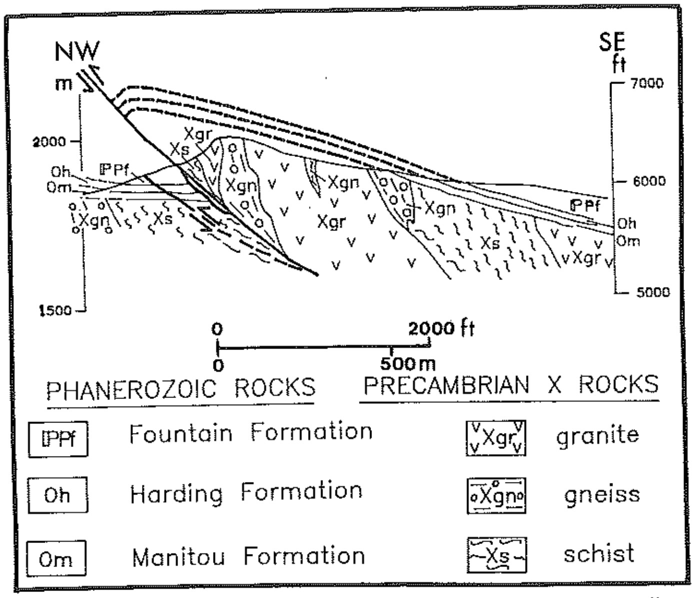

Figure 21. Geologic cross sections of the Gnat Hollow anticline-syncline, Colorado (from Chase and others, this volume) Section location is shown as B-B′ (Chase and others, this volume, Fig. 20). Fold curvature extrapolated above ground level from down-plunge data.

with displacements measured in meters, slickenside surfaces, and orthogonal joints are common in the sandstone and limestone units. The cross section constructed by Baltz and O'Neill (1984) (Fig. 22) shows local thinning and thickening of units in the forelimb that were affected by parasitic folding.

The Precambrian rocks are interlayered, well-foliated gneiss, schist, quartzite, and amphibolite. There are also local bodies of gabbro and pegmatite. Pre-Laramide structures included foliation, multiple folds (including the isoclinal eastward-verging antiform above which the cover-rock folds eventually grew), and late Precambrian faults (O'Neill, 1990). During Late Cretaceous to early Eocene deformation, foliation surfaces and preexisting faults were activated as thrust faults. Several large-scale thrusts penetrated the basement rocks and numerous foliation surfaces in schist and amphibolite became active slip planes resulting in cataclasis, slickenline development, small-scale ramping, and imbricate stacking of composition layers (Chase and others, this volume).

Summary of Observations

In this section we attempt to summarize the brief descriptions of the folds, particularly those observations related to fold shape, fault-fold relation, and basement deformational domains.

Fold shape. All of the folds we have examined are asymmetrical and related to faulting in the basement rock below the forelimbs. Of the 12 folds, 9 (all except Biltmore, Gnat Hollow, and Romero) have well-exposed basement-cover contacts on the backlimbs and reasonably well exposed hinge and forelimb con-

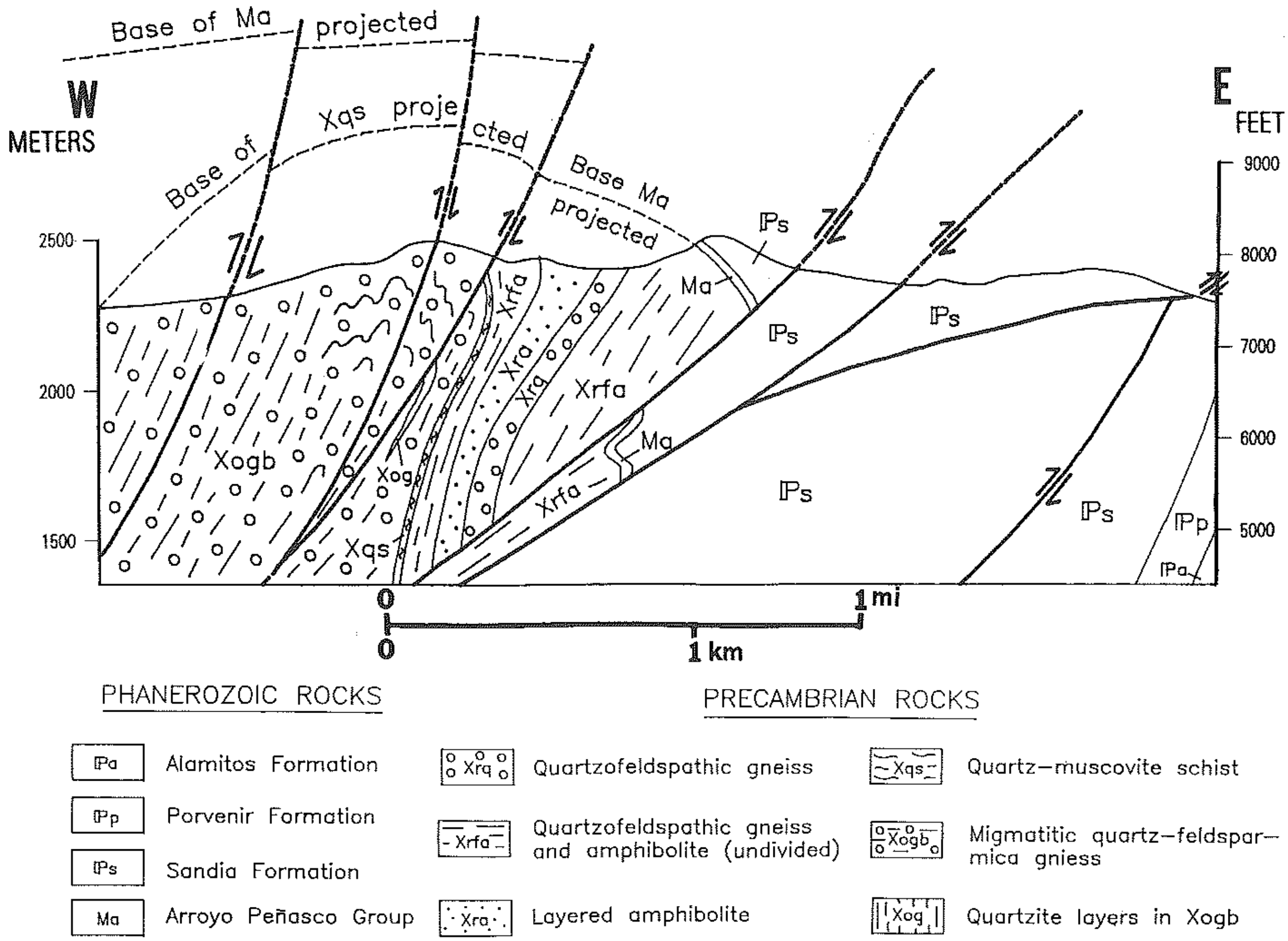

Figure 22. Geologic cross section of the Romero Hills anticline, New Mexico. Modified from Baltz and O'Neil (1984). See Chase and others (this volume, Fig. 23) for section location.

tacts. Five of the folds (London Hills, Spring Canyon, Kaufman Ridge, Twin Mountain, and Gnat Hollow) have well-exposed contacts on the footwall synclines. All of the folds, except Twin Mountain, that have good exposures of the backlimb and forelimb upper basement surface show sharp, angular hinges at that surface, giving these folds a kinklike geometry in the lower part of the stratigraphic section. The kink geometry is usually lost, or becomes less apparent, in the younger cover-rock units.

In some cases (LaPrele, Twin Mountain, Sheep Mountain, and Gnat Hollow) there appears to be only a single anticlinal hinge. Where a fault cuts through the principal hinge zone, as at Sheep Mountain, there is very little bending of the basement-cover contact into the fault, an observation made for other structures described in this volume (e.g., Owl Peak in the northern Teton Range, Wyoming–Erslev and Rogers; and the eastern Seminole Mountains Wyoming—McConnell and Wilson). Other folds, notably London Hills, Brooks Creek, Elk Mountain, Sheephead Mountain, Kaufman Ridge, and Spring Canyon, have more than one hinge at the basement-cover contact on the anticline. Typically there are two hinges: one (the principal hinge) that separates a gently-dipping backlimb dip domain from a forelimb dip domain having moderate dips in the direction of fold vergence, and another between the moderately-dipping forelimb domain and a very steep to overturned part of the forelimb. One fold (Brooks Creek—Fig. 5) has five dip domains on the backlimb side of the principal hinge. Viewed from a distance multiple hinges give the appearance of a smoothly curved surface. However, our opinion is that there are very few smoothly curved upper basement anticlinal surfaces. The north Twin Mountain fold pair appears to be an exception (Fig. 21). Although the basement-cover contact is not perfectly exposed, this contact appears to be smoothly, though tightly, curved around the anticlinal hinge.

The synclinal hinges, where exposed, are always angular, and we have seen no examples in which the basement-cover contact is smoothly curved upward below the thrust-reverse fault.

Faults and fault-controlled fold hinges. Every fold is closely associated with one or more faults at or between the anticlinal and synclinal hinges. In most of the structures the principal faults or fault zones break through into the cover rocks and separate the basement-cover contact by a large amount (see Table 1). Dip separation is 3 km or more along faults associated with the London Hills, Brooks Creek, Spring Canyon, and Elk Mountain structures. In three of the structures (Sheep Mountain, Twin Mountain, and the northern part of the LaPrele anticline) faults are present in the basement rocks, but they either do not displace the cover or they lose displacement a few tens of meters into the cover. In all of the structures the fault displacement of the upper basement surface is greater than that in any cover-rock formation.

One of the important observations about fault-related folds in basement rocks is whether the basement-cover contact on the steep forelimb of a fold is a fault contact or whether it is a rotated unconformity. Unfortunately, even in well-exposed forelimbs, observations are equivocal. In forelimbs that are not steeply dipping and cut by faults dipping in the opposite direction (e.g., Kaufman Ridge) there is no difficulty in interpretation (Fig. 19). However, where part or all of the forelimb is steeply dipping or overturned, and the cover rocks are thinned above the upper basement surface, that surface has been interpreted to be a fault (e.g., Stearns, 1978; Erslev, 1985) (Fig. 23A). The fault follows the contact and either terminates at the principal hinge or breaks through the hinge zone into the cover. An alternative is that the fault (or faults) dip less steeply than the basement-cover contact and that the contact has been rotated during faulting. Rotation of the contact is accompanied by cataclasis of the basement block below it (Fig. 23C). There are also cases where part of the forelimb is a rotated unconformity and part of it is a fault (Fig. 23B).

The identification of the contact as a fault or as a rotated unconformity appears to be important because a different type of basement behavior below the cover is implicit in each interpretation (single fault basement wedge versus wide cataclastic basement forelimb). Our current interpretation is that in all four of the anticlines in Montana and in the Kaufman Ridge, LaPrele, and Romero Hills anticlines, this surface is a rotated unconformity; in the five other structures it is a fault for part or all of its length.

In places where the hinge regions of the folds in the cover rocks are exposed at the basement-cover contact, the hinge surfaces projected into basement contain a reverse fault or fault zone or they are marked by an abrupt change from deformed basement to undeformed basement. We refer to these faults as hinge-controlling faults, because they seem to control the position of the principal fold hinges at the basement-cover contact and occupy the position of the hinge surface within the basement rocks. Kinematically, however, there is still a question about whether the faults were actually responsible for the fold hinges or whether they simply developed along an already produced axial surface within the basement rocks.

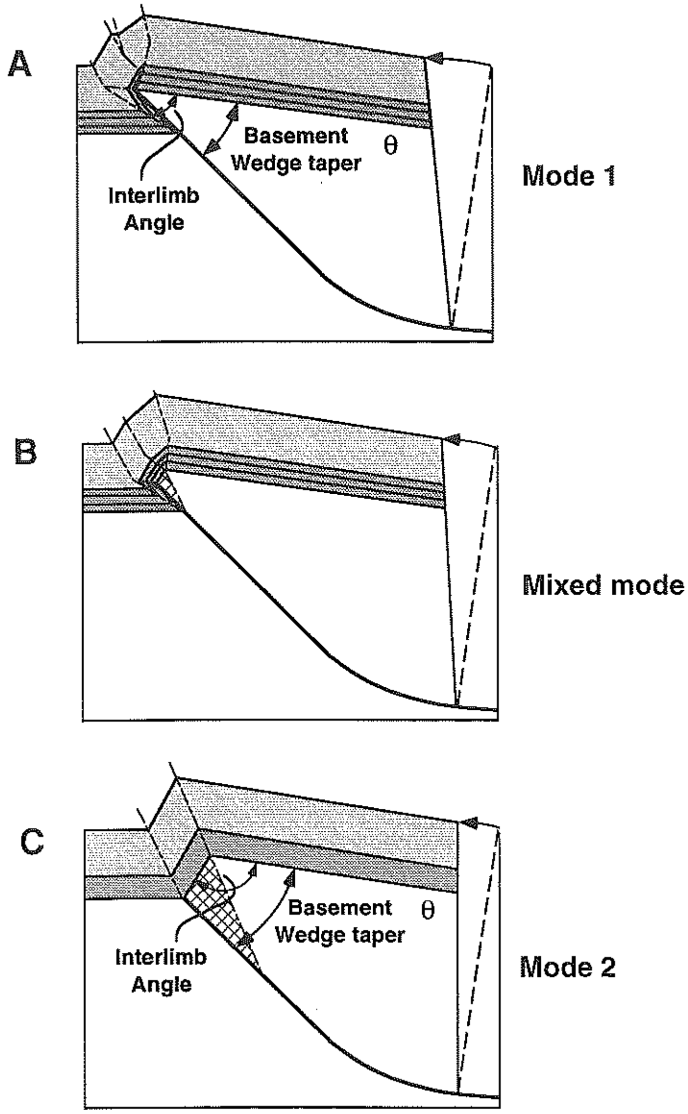

Figure 23. Structural styles in basement-cored folds. Structures may approach ideal end-member geometries (A and C) or may possess qualities of both (B). Mode 1 and mode 2 styles are described in the text. In mode 1 folds the forelimb basement-cover interface is a fault; in mode 2 folds it is a rotated unconformity. A "mixed mode" structure has a forelimb basement-cover interface that is partly a fault and partly a rotated unconformity. Cross-hatched regions are cataclastically deformed forelimb basement domains. All sketches show early stages of development of these modes. Interlimb angle and basement wedge taper angle are shown in A and C.

In at least two cases (London Hills and Twin Mountain) faults controlling the anticlinal hinges are localized along Precambrian mafic dikes that are highly sheared by the fault movement (Figs. 4 and 20). Four other folds (Brooks Creek, Spring Canyon, Biltmore, and Sheephead Mountain) have exposures of mafic dikes along the faults. In the Brooks Creek anticline the principal fold hinge and each of the four major hinges on the backlimb of the fold is controlled by a fault.

In some of the folds with well-defined hinges and axial surfaces in the cover there is not a distinct fault or fault zone in the basement. Rather, the basement below the axial surface is marked by a transition from mildly deformed and/or jointed rocks to rocks that have more closely spaced fractures and/or distributed shear. In the LaPrele anticline, for example, the axial surface in the basement is defined by the appearance of closely spaced shear fractures that follow an earlier foliation in an augen gneiss (Figs. 10, 11, and 12). In the Sheephead Mountain anticline shear fractures parallel to the axial surface are present throughout the basement rocks, but the spacing of the fractures decreases from several tens of centimeters to 2–5 cm at the axial surface (Chase and others, this volume). In the Elk Mountain anticline there is no prominent fracture set parallel to the axial surface, but the fracture intensity increases (spacing decreases) at the axial surface (from 15–100 cm to 3–10 cm) (Fig. 14).

In one case (Romero Hills anticline) the anticlinal hinge is not well defined and is interpreted to be broadly curved (Baltz and O'Neill, 1984). Here the hinge region is a wide zone of distributed shear along foliation surfaces (Chase and others, this volume).

Basement deformation domains. Regardless of the type of fault or deformation change that defines and controls the hinge surfaces of the folds, these surfaces divide the basement fold pairs into the three basement deformation domains (illustrated in Fig. 2). The forelimb domain is always the most highly deformed region of basement. Its width varies greatly among the folds. Where the basement-cover contact on the forelimb of the fold is a fault the forelimb domain is narrow to absent (Fig. 23A). In the Gnat Hollow anticline, for example, it is no wider than a few tens of meters (Fig. 21; see also Huntoon, this volume). It is only a few meters wide in the Sheep Mountain anticline. Here, however, only the hinge region is exposed in basement; forelimb basement is on the footwall of a large-displacement reverse fault and is therefore not exposed. Where the basement-cover contact is a rotated unconformity for much of the length of the forelimb (Fig. 23C), and particularly where much of the forelimb is upright and relatively long (e.g., London Hills, Kaufman Ridge, Elk Mountain, Romero Hills, and Spring Canyon anticlines), the forelimb is comparatively wide (350, 700, 500, 550, and 270 m, respectively) (Figs. 4, 18, 14, 22, and 8). For the purpose of later discussion it is convenient to define, or propose, two end-member geometric styles (mode 1 and mode 2) of basement behavior in small Rocky Mountain foreland anticlines. In mode 1 anticlines (Fig. 23A) the deformed basement forelimb domain is narrow or absent, and the basement-cover interface on the forelimb is a fault for at least part of its length. In these structures the interlimb angle is defined by the angle between the cover rocks on the backlimb and the overturned forelimb. The corner made by the fault and the backlimb basement surface has been referred to elsewhere in this volume as the hanging-wall basement wedge or tip (e.g., Erslev and Rogers, this volume). In mode 2 anticlines (Fig. 23C) the deformed forelimb domain is relatively wide and the basement-cover contact is a rotated unconformity. The interlimb angle is the angle between the backlimb and most steeply-dipping part of the forelimb. The interlimb angle in mode 1 anticlines tends to be somewhat smaller than in mode 2 anticlines, presumably because of the mechanical difficulty of rotating the basement-cover unconformity and producing an actual fold in that surface (see also Erslev and Rogers, this volume). The cover rock geometry for mode 2 structures, particularly in competent units low in the stratigraphic section, is most commonly kinklike, the number of dip domains in the cover being controlled by faults in both forelimb and backlimb domains. Some of the mode 1 structures, notably the Sheep Mountain anticline as seen in its south-plunging section, parts of the Sheephead Mountain anticline and Twin Mountain structure, also appear to have multiple dip domains. The dip domains focus downward toward the hanging-wall basement tip or the footwall basement-cover cutoff.

Erslev (1991) and Erslev and Rogers (this volume) recognized two end-member behaviors (hanging-wall fixed and footwall-fixed trishear) that are much the same as modes 1 and 2 described here. If these are considered end-member styles or behaviors, it would be expected that the majority of styles or behaviors would fall between these end members and show some characteristics of both. We use the term "mixed mode" (Fig. 23B) to describe the geometric styles of these anticlines.

It seems clear from the limited number of folds we have examined, as well as others described in this volume, that from the standpoint of basement behavior on the scale that we have studied, there is no single style (e.g., rigid rotation of fault-bounded wedge, or pervasive cataclasis) of Laramide folding. It is also apparent that no single kinematic model will apply to all of the cases. However, before attempting to test existing kinematic models or to porpose new ones, we will attempt to evaluate those factors that have most likely affected the geometry of the folds and the mechanical behavior of basement within them.

FACTORS CONTROLLING BASEMENT BEHAVIOR

On the basis of the descriptions of the 12 folds presented and the compilation of data from Table 1, there are several factors that we believe may have controlled the fault and fold geometry, particularly the width of the forelimb deformation domain, and the mechanical response of the basement rocks. These are (1) the inferred temperature and confining pressure during deformation, (2) the degree of control of pre–Late Cretaceous faults on the fault and fold geometry, (3) the taper of the hanging-wall basement wedge, (4) the nature and orientation of the pre–Late Cretaceous fabric of the basement rocks, and (5) the competence of the cover rocks. All of these factors are related, either directly or indirectly, to the relative strength of the basement rocks on the hanging wall of the faults. Because the strength of the basement is an illusive quality that is impossible to measure in the field, we consider the possible effect of those factors on which the strength of basement may depend. We emphasize that this is a very preliminary attempt to identify some of the factors that control basement behavior. The purpose of this section is to test the suggestion that the factors we list have influenced fold and fault geometry and basement behavior. In order to observe the effect of each of the factors, we need to isolate a measurable quantity that represents the effect of each factor and compare that quantity with a scale-independent quantity that discriminates between styles of basement folds (i.e., between mode 1 and mode 2 styles). The width of the forelimb domain, for example, is not scale independent, but the cover-rock anticlinal interlimb angle probably is.

Confining pressure and temperature

We estimated the thickness of sedimentary cover rocks that were present during deformation (Table 1) in order to estimate the approximate pressure and temperature conditions during deformation. In most cases, because the structures are either Late Cretaceous or Paleocene in age, we simply based estimates on the measured thicknesses of the sedimentary section up to the mid-Tertiary unconformity, which is present in most of the areas. However, local problems with exact syndeformational thicknesses are present in nearly every area. For example, the Paleocene Hanna Formation in the northern Medicine Bow Mountains was syntectonically deposited during the formation of the Laramide uplifts (Houston and others, 1968). This was not included in thickness calculations. In another example, the Late Cretaceous Elkhorn Mountains Volcanics were still being erupted and deposited during the last episodes of folding in the northern Tobacco Root Mountains (Schmidt and Garihan, 1983). This formation was included in the thickness calculations.

Estimated thicknesses during the beginning of uplift range from 2.5 km in the Sheep Mountain anticline to 5 km in the Elk Mountain and Sheephead Mountain anticlines. If we assume a lithostatic pressure gradient of 27 MPa/km and a geothermal gradient of 20 °C/km (+20° for surface temperatures), lithostatic pressure varied from 68 to 135 MPa and temperature varied from 70 to 120 °C at the upper basement surface during folding. Higher temperatures and pressures at somewhat deeper levels of basement may in part be offset by lower temperatures and pressures due to erosional stripping during uplift. It has also been suggested that the geothermal gradients for the folds in southwestern Montana may have been slightly higher than those elsewhere in the Rocky Mountain foreland because of nearby syntectonic plutonic activity (Boulder and Tobacco Root batholiths; Schmidt and others, 1985, 1990). Nevertheless, we conclude that the range of temperatures and pressures during folding suggests a brittle or semibrittle mechanical behavior for the basement rocks. This conclusion is supported by observations at the thin-section scale (in this volume, see Chase and others; Evans; Evans and others; Schmidt and others).

A graph of inferred depth of burial versus the interlimb angle (Fig. 24) suggests that there is no systematic relation between the inferred depth of burial during folding and the gross mechanical behavior of the basement. If such a relation exists, it is masked by more-important factors.

Pre-Late Cretaceous faults—The reactivation problem

The question of the degree of control of old faults on the localization of younger ones is frequently asked about structures in the Rocky Mountain foreland, but is seldom answered satisfactorily. However, we can examine the evidence from each structure and establish the relative likelihood that it was reactivated. Because this is difficult to quantity, as is the effect that reactivation may have actually had on the mechanical behavior of basement in a fold, we will evaluate this factor in only a qualitative way.

The likelihood of fault reactivation in the 12 structures ranges from unequivocal to nonexistent. The northwest-trending faults in southwestern Montana provide a complete and unassailable record of reactivation of Middle Proterozoic faults (Schmidt and Garihan, 1986). These faults separate Archean marker units in different directions than they separate the Precambrian-Cambrian unconformity (Hinch Creek fault–Spring Canyon Anticline and Bismark fault–Brooks Creek anticline). Some have Middle Proterozoic (Wooden and others, 1978) diabase dikes within the fault zone itself; others have one or more fault-parallel dikes in the deformed forelimb domain. As discussed earlier, one of the faults (Hinch Creek—Fig. 8) had its hanging-wall block down during Proterozoic time. Because of its documented listric geometry and pre-Cambrian hanging-wall rollover of Archean units, we interpret this fault as having been a reactivated listric normal fault. Because of the ubiquitous presence of diabase dikes along the other northwest-trending faults and a documented listric geometry for the London Hills and Bismark faults (as well as several others not described herein; Schmidt and Garihan, 1986), we conclude that all of these faults are probably reactivated listric normal faults.

In addition to those faults and folds in southwestern Montana, five of the other folds (LaPrele, Sheephead Mountain, Twin Mountain, Ghat Hollow, and Romero Hills) have some evidence for fault reactivation. The northwest-trending forelimb fault and hinge surfaces in the La Prele anticline are parallel to amphibolite dikes that intrude the augen gneiss, parallel to its foliation. One of these dikes occupies the hinge zone of the Laramide fold near the basement-cover contact (Fig. 10).

At Sheephead Mountain two small unmetamorphosed diabase dikes that crosscut foliation are parallel to the north-trending Laramide structure. One of these dikes is within a few meters of the principal forelimb fault. The other occupies the hinge surface of the Laramide fold, but is not itself noticeably sheared.

At north Twin Mountain a narrow unmetamorphosed mafic dike is highly sheared by the principal hinge-controlling fault. The fault trends west-northwest and is therefore anomalous compared to the north-south trends of the principal Laramide structures of the region. Nearby, the northeast-trending Gnat Hollow fault parallels faults of known Precambrian ancestry (Chase, 1985).

The Laramide Romero Hills anticline is parallel to the Precambrian El Oro anticline in the Romero Hills (Baltz and O'Neill, 1984; O'Neill, 1990; Chase and others, this volume). Faults of known Precambrian age are subparallel to Laramide

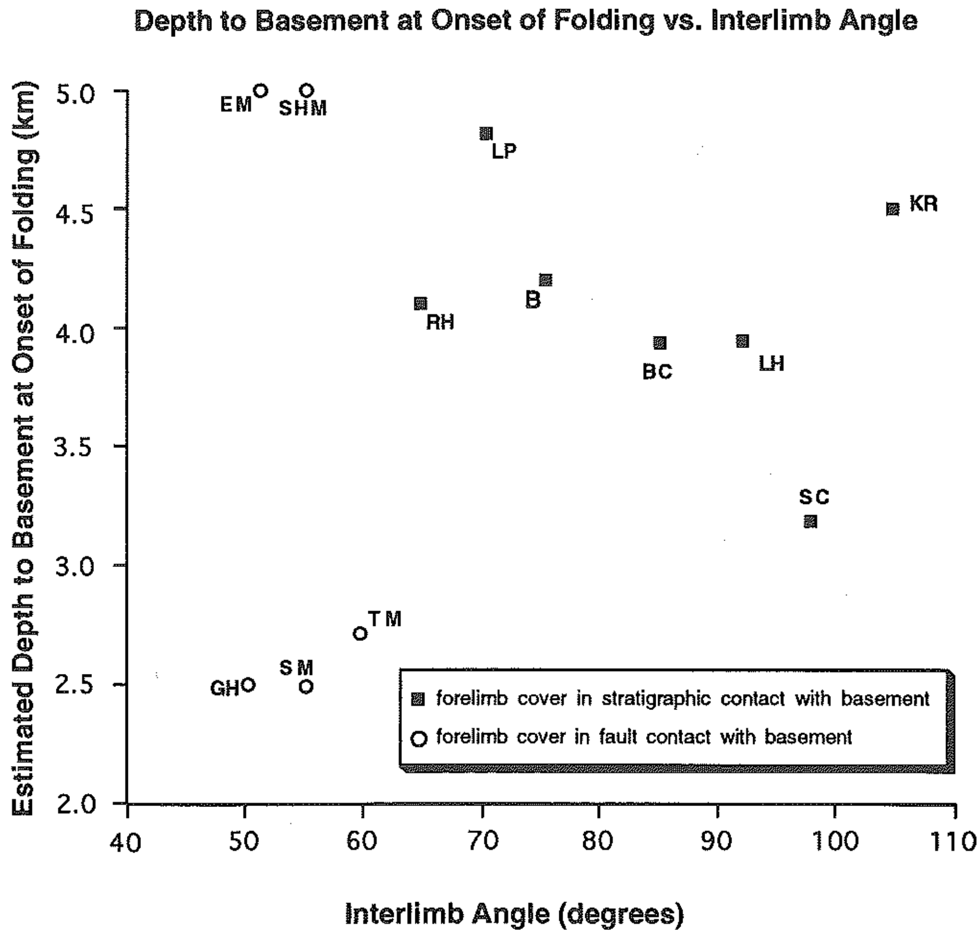

Figure 24. Graph of estimated depth of burial at the onset of Laramide folding and faulting vs. interlimb angle. See Table 1 for data and references and text for discussion. Abbreviations for folds are London Hills (LH), Brooks Creek (BC), Spring Canyon (SC), Biltmore (B), La Prele (LP), Elk Mountain (EM), Sheephead Mountain (SHM), Sheep Mountain (SM), Kaufman Ridge (KR), Twin Mountain (TM), Gnat Hollow (GH), and Romero Hills (RH).

faults (O'Neill, 1990). However, there is no direct evidence that Precambrian faults were reactivated in this structure.

In only three structures (Elk Mountain, Sheep Mountain, and Kaufman Ridge) is evidence of reactivation completely absent. All of these structures have the same northerly trends that the major regional structures have in southern Wyoming and northern Colorado.

The controlling influence of earlier structures is best analyzed for the three structures (London Hills, Brooks Creek, and Spring Canyon) that are well exposed and have unequivocal evidence of reactivation. Unfortunately, these structures also have much the same basement fabric and cover-rock section, so it is difficult to separate the effects of reactivation from the other factors that may have influenced fold geometry. There are some common features that may be controlled by the previous fault geometry. The width of the deformed forelimb domain is similar for Spring Canyon and London Hills (270 and 350 m, respectively), which may be due to the fact that both the principal forelimb fault and the hinge-controlling fault follow old fault zones in the basement, and therefore the width of the domain is determined by the spacing of the old fault zones. Backlimb geometry of the Spring Canyon, Brooks Creek, and London Hills structures is also nearly identical, i.e., a relatively long segment (flat in plunge section) containing one or more backthrusts, separated from a more steeply-dipping (fault parallel?) segment by a backthrust. This flat segment is 2 km long in the London Hills anticline (Fig. 4), 1.5 km long in the Brooks Creek anticline (Fig. 5), and 0.8 km long in the Spring Canyon anticline (Fig. 7). The geometry is nearly identical to that which was produced in experimental rock models by Chester and others (1988, Fig. 4c). In the rock models the geometry of the fold was the result of a ramp-flat fault geometry in "basement." Although the rock-model geometry is somewhat more simple than the complexly curved, and imperfectly known, fault geometry in the three Montana field examples, the striking similarity of the experimental rock models and these three field examples suggests that the fold size, shape, and the presence of backthrusts may be partly consequences of the inherited fault geometry of the associated faults.

Many of the faults we observed as well as others described in this volume and in earlier literature are high-angle faults (50° to vertical), and are therefore too steep to have formed as primary coulomb fractures in a compressive stress field. In view of the unequivocal presence of reactivated faults in the Rocky Mountain foreland, it is possible that many of these steep faults are reactivated normal faults.

Taper of hanging-wall basement wedge

Erslev and Rogers (this volume) suggested that the taper of the hanging-wall basement wedge (the angle θ between the backlimb basement surface and the principal fault; Fig. 23) may have been an important factor in determining the basement behavior in individual basement-cored folds. As they indicate, the experimental rock models for high-angle faults (Friedman and others, 1980) show a comparatively narrow zone of deformed basement compared to low-angle (45°) precut basement faults (Chester and others, 1988). The latter have a comparatively wide zone of cataclasis and replicate most of the features of mode 2 structures.

Unfortunately, it is often difficult or impossible to determine θ, especially when the dip of the principal fault is not determinable. In addition, for some structures (e.g., probably the Sheep Mountain anticline) the fault that is exposed at the surface may be a secondary splay along the anticlinal hinge surface (a hinge-controlling fault) and the principal fault may not be exposed. Nevertheless, in a plot of estimated θ against interlimb angle for the folds we studied (Fig. 25), there does not appear to be a consistent relation between the two angles. Although Erslev and Rogers may be correct to infer a general relation between wedge taper and basement behavior, the relation is not obvious in the folds we studied. Furthermore, one of the steepest-dipping faults below a basement-cored fold described by studies in this volume is the Ross Lakes shear zone in the northeastern Wind River Range (Evans and others, this volume). This shear zone, below the Jakey's Fork fold, dips 70° to 85° and makes a wedge taper of about 80° (Evans and others, this volume, Fig. 4). Nevertheless, the hanging-wall anticline has a cataclastic forelimb domain that is 300–500 m wide with an anticlinal hinge-zone fault and an interlimb angle of about 120°. Wedge taper may be important in some cases, but there are probably more important factors that control strength of basement and the style of basement-cored folds.

Basement fabric

That the nature and orientation of the pre-folding basement fabric has influenced the mechanical behavior of the basement during folding is a suggestion made by other authors in this volume (see Chase and others; Miller and Lageson; and Schmidt and others, this volume). Their conclusions support the hypothesis of Brown (1988, p. 73) "that the basement of the Wyoming foreland will behave in several different ways, depending on rock type and orientation of various anisotropic discontinuities." The purpose of this section is to further evaluate this conclusion.

Two of the folds (south Sheep Mountain and Kaufman Ridge) have basement rocks that are isotropic. The northern half of the Sheep Mountain structure contains foliated rocks and will be considered separately. In the Kaufman Ridge area there are schistose zones in the footwall-basement domain, but the critical forelimb domain and much of the backlimb domain contain only massive granite. All of the other folds have some planar anisotropy defined by a preferred orientation of phyllosilicates. The nature of the anisotropy varies considerably among the folds, making quantitative comparisons impossible. In two cases (Romero Hills and Biltmore) the basement rock consists mostly of aluminous schists with a pervasive schistosity. In all of the other cases, the foliation is accompanied by compositional layering with alternating layers of gneiss, schist, amphibolite, and (in one case) marble (Table 1).

The folds may be divided into four categories based on the role of preexisting layering and foliation (Fig. 26): (1) foliation present, but without any observed change in orientation due to folding or significant control on folding (Fig. 26A); (2) foliation rotated in the forelimb domain (Fig. 26B); (3) foliation an active slip surface parallel to the hinge surface of the fold (Fig. 26C); and (4) foliation absent (Fig. 26D).

Foliation not affected or not significantly effective (Fig. 26A). There are five folds in this category (Elk Mountain, Sheephead Mountain, north Sheep Mountain, north Twin Mountain, and Gnat Hollow). At Elk Mountain the foliation is broadly folded, but that folding (Precambrian?) appears to have no relation to the Late Cretaceous folding. The axes of folded foliation and folded cover have nearly the same trend (S50°E for foliation, N30°W for cover), but are nearly mutually perpendicular (88°) (Fig. 14B). The main concentration of poles to foliation is less than 10° from the fold-axis position of folded cover. It is also perpendicular to the axial surface and to bedding on both the backlimb and forelimb. Except for the presence of one joint set that locally follows foliation in the forelimb domain, foliation does not appear to have controlled deformation during the Late Cretaceous fold event, nor has it been affected by that event.

In the Sheephead Mountain anticline the foliation orientation with respect to bedding varies from 60° to 90° and does not show any noticeable change in orientation across the Late Cretaceous fold (Chase and others, this volume). The mean foliation orientation (N70°W, 80°SW) is 60° to the hinge surface orientation (N10°W, 62°SW). Fractures that parallel foliation do occur throughout the basement rocks in the fold and are particularly common in the forelimb domain (Chase and others, this volume, Fig. 17). Therefore, although foliation may have had a small affect on folding to the extent that it helped to control one of the fracture orientations in the forelimb domain, foliation orientation was not affected by folding of the cover.

The northern half of the doubly-plunging Sheep Mountain

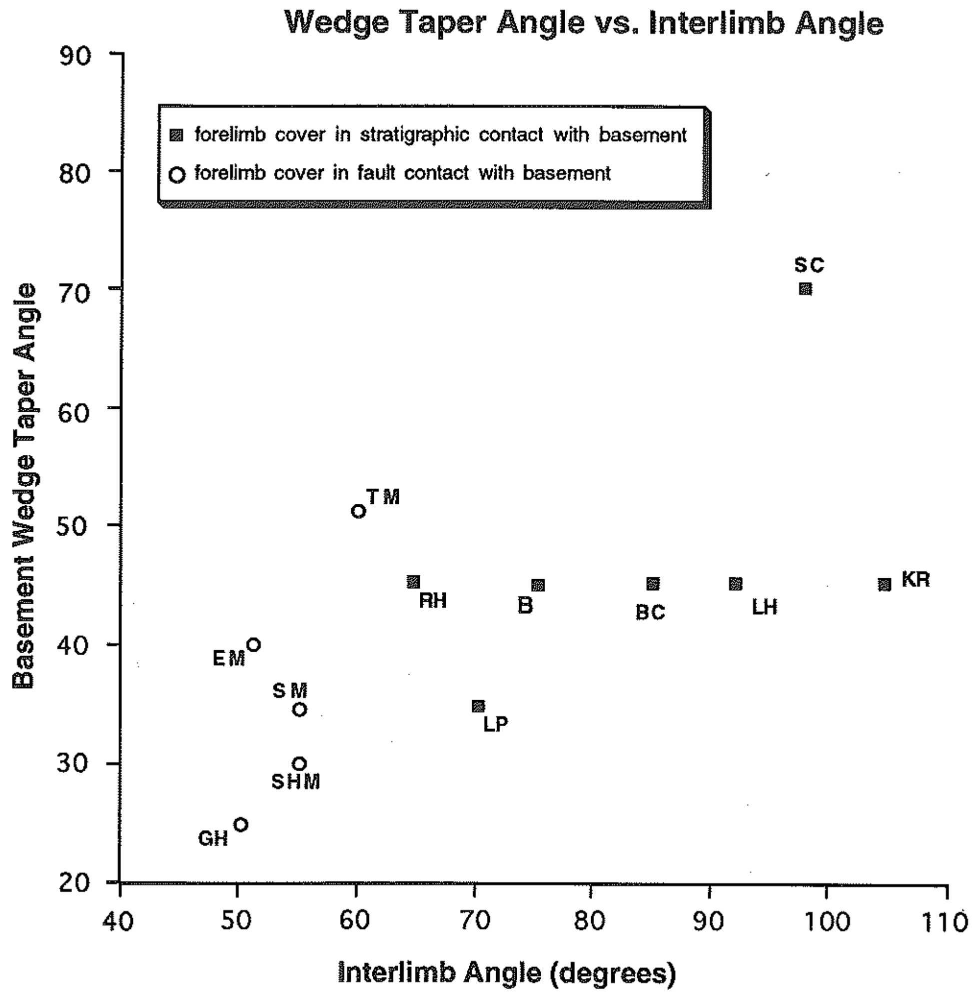

Figure 25. Graph of estimated basement wedge-taper angle vs. interlimb angle. See Figure 23 for definition of these angles. Abbreviations as in Figure 24.

anticline contains foliated gneisses and amphibolites oriented N35°–55°W with dips steeply northeast (75°–90°). Mean foliation attitude has approximately the same strike as the hinge surface (N40°–50°W) but dips 25° more steeply. Foliation also has about the same strike as bedding on the backlimb, but dips 60°–65° more steeply. Foliation attitude does not change systematically over the area, and, although basement is exposed mainly on the backlimb, there does not appear to be any change of foliation attitude related to Late Cretaceous folding. One of the three principal joint sets on north Sheep Mountain follows foliation. This set is not present on the south end of the mountain where the basement rocks are isotropic. Nevertheless, the similarity in style between north and south Sheep Mountain suggests that foliation was not an important factor controlling deformation.

Foliation in the Gnat Hollow structure appears to have the same general relation to the structural elements that it does at north Sheep Mountain. The basement rocks are well-foliated schists and gneisses that strike parallel to the main fault and hinge surface of the fold (N60°E) (Chase and others, this volume). The mean dip of foliation (70°SE) is 15°–25° steeper than the fault-axial surface of the anticline-syncline pair (45°–55°SE) and 53° steeper, with the same strike, than the cover rocks on the hanging wall of the fault. Although one joint set follows foliation and foliation is locally folded in the fault zone, there is no systematic change in foliation attitude due to Laramide folding, and foliation does not appear to have exerted a significant control on this single fault-dominated structure.

Foliation at north Twin Mountain is poorly developed. It strikes generally northwest and is steeply dipping. Although it has the same general orientation as the hinge surface and fault, close examination of the basement rocks in the core of the anticline did not reveal any obvious or systematic shearing along foliation. One thing that is present in the core of the anticline that is not present elsewhere is a weathering pattern that follows foliation and causes 6–10-cm-wide elongate slabs of granite to weather

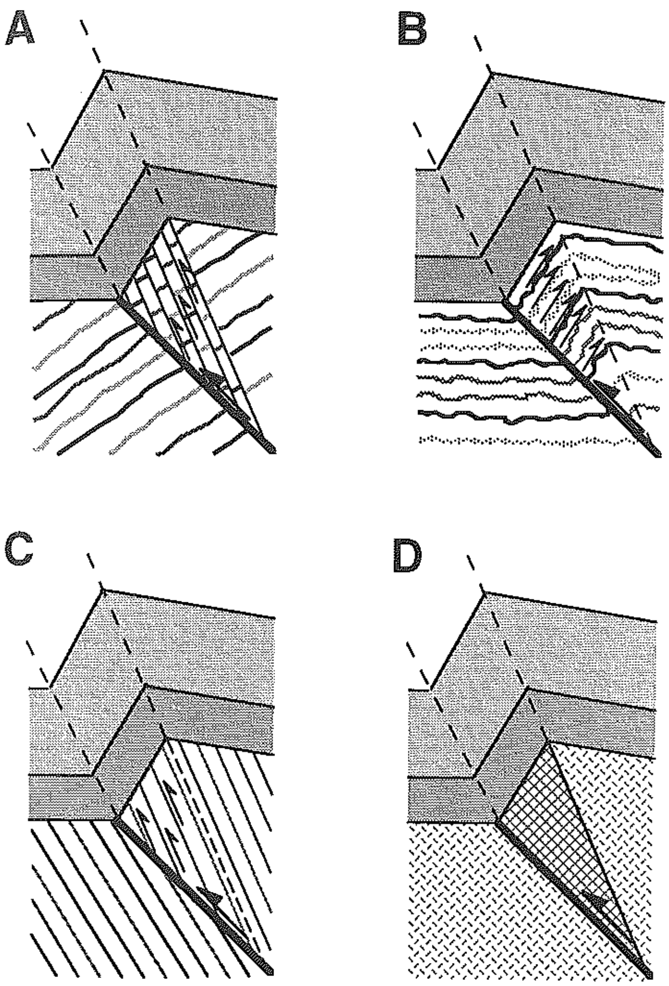

Figure 26. Role of basement fabric in the nature of basement deformation on the forelimb of basement-cored folds. A: Foliation and/or layering present but ineffective. B: Foliation and/or layering at low angle to cover and rotated in forelimb domain with flexural slip. C: Foliation and/or layering favorably oriented for slip parallel to anticlinal hinge surface. D: Foliation and/or layering absent. All of the cases illustrated are mode 2 styles at the same stage of development.

out. That this pattern only exists in the core of the anticline suggests that a narrow zone of fault-parallel shearing or jointing may exist along foliation near the fault and near the basement-cover contact. However, because such shearing is not obvious and foliation is weak, our preliminary conclusion is that foliation did not exert a significant control on deformation and was not rotated by Late Cretaceous folding and faulting.

Foliation rotated in forelimb domain (Fig. 26B). The folds in southwestern Montana have basement rocks that are very well foliated and layered. In three of these folds (London Hills, Brooks Creek, and Spring Canyon anticlines) the foliation is nearly concordant with bedding, striking less than 10° from the strike of bedding and dipping less than 20° steeper than bedding. In all three of these anticlines rotation of foliation by about the same amount as bedding can be demonstrated. Preliminary examination of these folds by Schmidt and Garihan (1983) and the observation by Wagner (1966) that foliation was folded below bedding in the London Hills anticline, led to the suggestion that folding had occurred in the basement rocks by flexural slip on foliation on both the forelimb and backlimb of the folds (Schmidt and Garihan, 1983). Closer examination of these three folds indicates that, although slip on foliation surfaces can be demonstrated in the forelimb of the London Hills anticline, it is not present on the backlimb (Chase and others, this volume).

In the London Hills anticline there is about a 10° strike and 15° dip discordance between bedding and foliation on the gentle limb of the fold, and the attitude of the axis of folded basal Cambrian bedding (19° N44°W) and that of folded foliation (34° N32°W) reflect this discordance (Chase and others, this volume). Furthermore, the spread of the poles to bedding and poles to foliation is about the same suggesting that the two were folded together (Chase and others, Fig. 9, this volume). Steeply dipping to vertical foliation planes in the forelimb domain show evidence of shear (slickenlines). No slickenlines were found along foliation in the backlimb domain, suggesting that slip along favorably oriented foliation planes took place only in the forelimb domain.

In the Brooks Creek anticline (Figs. 5 and 6) the strike of foliation is within 5° of the strike of bedding and dips 15–20° more steeply. Although only a small part of the forelimb is exposed, the backlimb has several subdomains bounded by small-displacement faults. Each fault-bounded block has rotated slightly in the direction of fold vergence. This has produced an open fold in bedding and foliation on the backlimb in which the axis to folded foliation has the same trend as the axis to folded bedding, but has a 20° steeper plunge (Fig. 5). Although shearing on foliation is present in the forelimb domain in the vicinity of the major fault, it is not present in the backlimb domain. We conclude that both bedding and foliation were passively rotated about the same axis by rigid rotational adjustment of the faults that bound the subdomains.

The rotation of foliation and layering in the Spring Canyon anticline is nearly identical to that in the London Hills anticline. The thin Archean marble bed below the Cambrian Flathead Sandstone (as measured on the backlimb of the fold) has a 23° angular discordance to the Flathead. The marble strikes 9° more easterly and dips 23° more steeply. The fold axis for bedding in the marble and foliation in the amphibolite below it is about 10° steeper and trends 18° more easterly than the fold axis in the Flathead, with discordance of 18° between the axes. As indicated in an earlier discussion, the marble bed is folded slightly more tightly than the cover, suggesting an earlier (Proteorozic) fold event. Neither the marble nor the amphibolite below it have good evidence of shear parallel to bedding on either the forelimb or the backlimb.

In all three of the above examples, where foliation and layering in the basement are at a low angle of discordance to the cover, the foliation and/or layering in the basement has been rotated along with the cover in the forelimb of the fold. In at least one case (London Hills), slip has occurred along foliation planes to accommodate rotation. None of these folds, however, has evidence of slip on the foliation in the backlimb, although slip on backlimb foliation has been noted in basement-cored folds in the nearby Bridger Range (see Miller and Lageson, this volume). Rotation of foliation is not the only mechanism of deformation in the forelimbs of the London Hills, Brooks Creek, and Spring Canyon anticlines. As described earlier, all of these folds, especially London Hills, have shear fractures in the forelimb domain parallel to the principal fault, the hinge surface, or both.

Hinge surface-parallel slip on foliation (Fig. 26C). In the Romero Hills and LaPrele anticlines, and probably in the Biltmore anticline, foliation occupies the hinge surface position and slip on foliation has occurred during folding. In the Romero Hills anticline the overturned eastern limb and the upright western limb contain numerous foliation-parallel slip surfaces with slickensides. As described by Chase and others (this volume), slip on foliation appears to be pervasive across the structure and does not seem to be confined exclusively to the forelimb domain. Because much of the cover has been eroded, it is not possible to determine exactly how foliation-parallel slip in the basement has affected displacement of the cover.

In the LaPrele anticline only the forelimb domain shows evidence of layer-parallel slip on the earlier foliation in the granitic augen gneiss. As described earlier, the hinge surface of the fold is defined by the transition from foliation-parallel cataclasis to distributed shear (spacing of 1–2 cm) on the preexisting foliation surfaces (Fig. 12). Cover rocks on the forelimb appear to have been rotated and stretched to accommodate simple hinge-surface–parallel simple shear in basement along the previous fabric, but none of these shear surfaces breaks through the cover rocks. The minor forelimb thrust that is present is not perfectly parallel to foliation (Fig. 11).

Foliation-parallel shear is also present in the schistose basement rocks of the Biltmore anticline. However, because the backlimb cover rocks are not exposed, we cannot be certain that the foliation and shearing are parallel to the hinge surface. However, on the basis of the slightly more westerly strike and 15°–20° dip discordance with the cover on the forelimb, and the presence of the backlimb rocks with gentle easterly dips shown in a seismic profile (Lopez and Schmidt, 1985), it appears likely that the foliation is in the hinge-surface position for this fold. As we have argued earlier, this seems to be a more plausible explanation than shear on foliation due to rotation of that fabric in the forelimb domain during folding.

Summary. Of 11 of the folds examined in this study that contain visibly foliated basement rocks. three have foliation that was rotated in the forelimb domain during folding; in at least one of these the foliation was an active slip surface in the forelimb in a flexural-flip sense. No evidence of backlimb flexural slip was observed. These are special cases in which the foliation and compositional layering in the basement are well developed and have nearly the same attitude as the bedding in the overlying cover, and in each case additional deformation in the forelimb was accomplished on shear fractures parallel to the hinge surface or the major fault.

In three of the folds, folding is interpreted to have been accomplished by slip on foliation such that the hinge surface of the anticlines developed in an orientation parallel to foliation. The pre–Late Cretaceous foliation directions in each of the structures (Biltmore, Fig. 9; LaPrele, Fig. 10, and Romero, Fig. 22) is within 45° of the inferred regional horizontal-shortening direction (see Schmidt and others, 1988; Brown, 1988; and Chase and others, this volume, for estimated regional shortening in each area).

In five of the anticlines foliation has served to localize joint surfaces, but it does not appear to have been an important slip surface in producing the fold nor has it been rotated by folding. In two of these cases the strike of foliation is parallel to the strike of the hinge surface but dips more steeply and was apparently too steeply inclined to have been active during horizontal shortening (e.g., Chase and others, this volume). In the one case where foliation appears to be parallel to the hinge surface but was probably not an active slip surface, the pre-folding fabric is poorly developed.

Cover rock competence

The influence that cover-rock competence has had on the general form and kinematics of basement-cored folds was discussed in some detail by Stearns (1978), who recognized that the cover geometry is influenced by the degree to which the folded strata were "welded" to the basement rock blocks and by the presence or absence of a stratigraphic package that is competent ("relatively rigid"; Stearns, 1978, p. 22). The experimental rock-model studies of Chester and others (1988) showed that, in experimental models, the strength and ductility of layers above a strong isotropic "basement" with a precut ramp greatly influences the hanging-wall geometry and the deformational features in the hanging-wall anticline. Spang and Evans (1988) reviewed the status of experimental and theoretical studies on the role of the cover rocks in basement-cored folds and concluded that competent carbonate units are probably strong during the early stages of basement-cored folding when they are loaded parallel to bedding and during the later stages fo folding when loading is at a high angle to the forelimb.

In the field we can only assess cover-rock competence in a general way. We qualitatively described in a previous section what types of rocks are present in each fold and to what extent they are deformed (i.e., thinned or not thinned) in the forelimb. As Stearns (1978) suggested, cover-rock competence is predominantly a function of lithology. If so, measuring the relative proportions of cover-rock types in each fold permits some test of the notion that cover-rock composition is related to fold style. Because nearly all of the folds occur in areas where the Mesozoic section consists of sandstones and shales and composes 50%–80% of the section, we decided to examine the effect on fold geometry of the first 330 m (1000 ft) of stratigraphic section. The most notable compositional affect is the percentage of limestone and dolostone. When plotted against the fold interlimb angle (Fig. 27), there appears to be a roughly linear relation between percentage of carbonate and interlimb angle. Those folds that have a small interlimb angle, and have forelimb cover mainly in fault contact with basement (tending toward mode 1 style), have less than 20% carbonate in the first 330 m of section. Those folds that have larger interlimb angles (tending toward mode 2 style) have varying amounts of carbonate but generally 40% or greater.

The carbonate units that compose a large percentage of the lower cover-rock units in the folds tend to be massively bedded (e.g., Cambrian Meagher and Pilgrim limestones, which actually have a significant amount of dolostone in them, and the Ordovician Bighorn, Manitou, and Freemont dolomites, and Mississippian Madison Limestone). As analyzed in detail by Stearns (1978), these units tend to be nonthinning "struts" from the standpoint of folding behavior. Instead of thinning in the steep forelimbs of the folds, these carbonates tend to break up into massive horse blocks resembling large boudins (Stearns, 1978; Schmidt and Garihan, 1983; Hennings and Spang, 1987; McConnell and Wilson, this volume).

The implications of Figure 27 are perhaps surprising in light of the commonly-held assumption that it is the strength of the basement rocks and fault dip that control the form of the antlcines in the overlying cover. Perhaps the strength of basement is overrated. This suggestion is supported by the fact that most of the faults we examined have some evidence of control by a previous basement flaw and that, in most of the folds resulting from movement on those faults, a basement fabric has controlled the position of a shear fracture or joint surface. A well-foliated basement rock broken by a fault dipping less than 60° might have considerably more difficulty breaking through a cover section of massive carbonates than a section composed dominantly of shale. In any case, the data suggest that a strong cover-rock section may produce a wide zone of deformation in the forelimb domain of basement-cored anticlines. One caveat in the interpretation of the data is that we only have 12 data points. In addition, of the five points that plot on the high end of interlimb angle and percent carbonate, four are from southwestern Montana, where the basement rocks are well foliated and have a low angle of discordance to the cover. Furthermore, Erslev (1991, personal commun.) has noted that at Rattlesnake Mountain and along the Forellen fault in the Teton Range, significant changes in interlimb angle occur along strike in the same structure. This suggests that cover-rock lithology was probably not a primary influence on the geometry of these structures. We merely imply that our own preliminary observations indicate that cover rock may be impor-

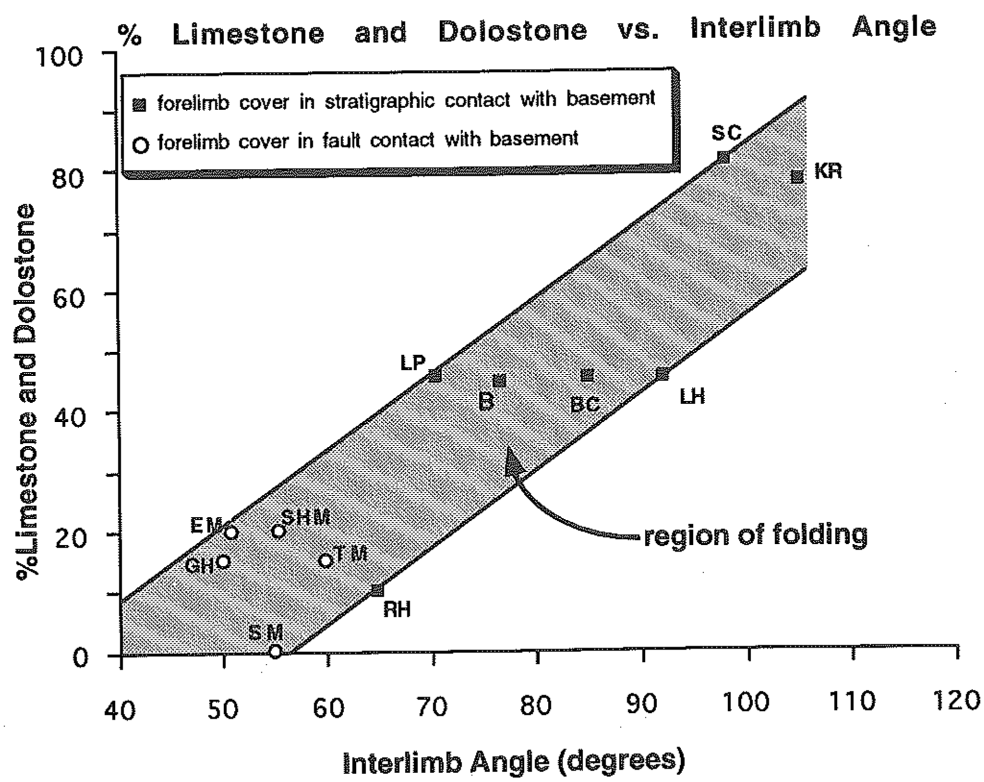

Figure 27. Graph of fold interlimb angle vs. percent carbonate rock in the first 330 m of stratigraphic section. See text for discussion. Abbreviations as in Figure 24.

tant in controlling the nature of basement behavior and the style of basement-cored folds.

KINEMATIC DEVELOPMENT

As suggested in the previous sections, we see two end-member styles of basement behavior (mode 1 and mode 2) among the 12 basement-cored folds we studied. The principal difference between these two styles of behavior is the amount and/or width of cataclastically deformed basement below the cover rocks. We suggested several possible factors that may cause a narrow zone of cataclasis (mode 1) as opposed to a wider zone of cataclasis (mode 2). The purpose of this section is to develop conceptual (as opposed to analytical) kinematic models for each of these two modes. By picking several of the factors that appear to control behavior in basement, we attempt to describe how each of these two fold styles develops.

More than half of the folds we have studied have backlimbs that dip more steeply than the adjacent synclinal limb (footwall domain). Therefore, the general model we have chosen is similar to that of Brown (1984) and Erslev (1986), in which fault slip occurs by rotation of the hanging wall along a curved fault segment combined with translation along a planar fault segment. Some of the field evidence, particularly that from the folds in Montana, is suggestive of reactivation of existing listric normal faults. Other structures that have reverse and/or thrust movement localized by mafic dikes may also have a geometry that is listric. A paradox of the most recently described seismic data over structures of the size we analyzed is that, wherever thrusts can be imaged in basement, they are planar (Stone, this volume), even when the divergence of dip in backlimbs from that of the regional dip suggests rotation on a listric fault. The geometry we have chosen as a starting fault configuration is therefore not without some supporting field and seismic evidence.

Kinematics of mode 1 structures

Mode 1 structures are distinguished by the absence of significant cataclastic basement in the forelimb domain and the presence of a discreet fault or narrow fault zone (as opposed to a wide fault zone). Other characteristics are (1) an overturned and greatly thinned basal cover-rock sequence, (2) hinge surfaces in the cover rocks that focus downward and terminate at the hanging-wall and footwall cutoffs with (in two cases) two anticlinal axial surfaces converging to the tip of the block, (3) relatively small interlimb angles (<60°) between backlimb and forelimb domains, and (4) cover rocks on the forelimb that are in fault contact with basement. One of the things we observed about these structures is that they have less than 20% carbonate in the cover rocks of the first 330 m of section, suggesting a relatively incompetent cover. Other factors contributing to mode 1 behavior may be a relatively wide basement-wedge taper, and lack of significant foliation or "zones of weakness" in the basement.

In the model presented here (Fig. 28), the preservation of

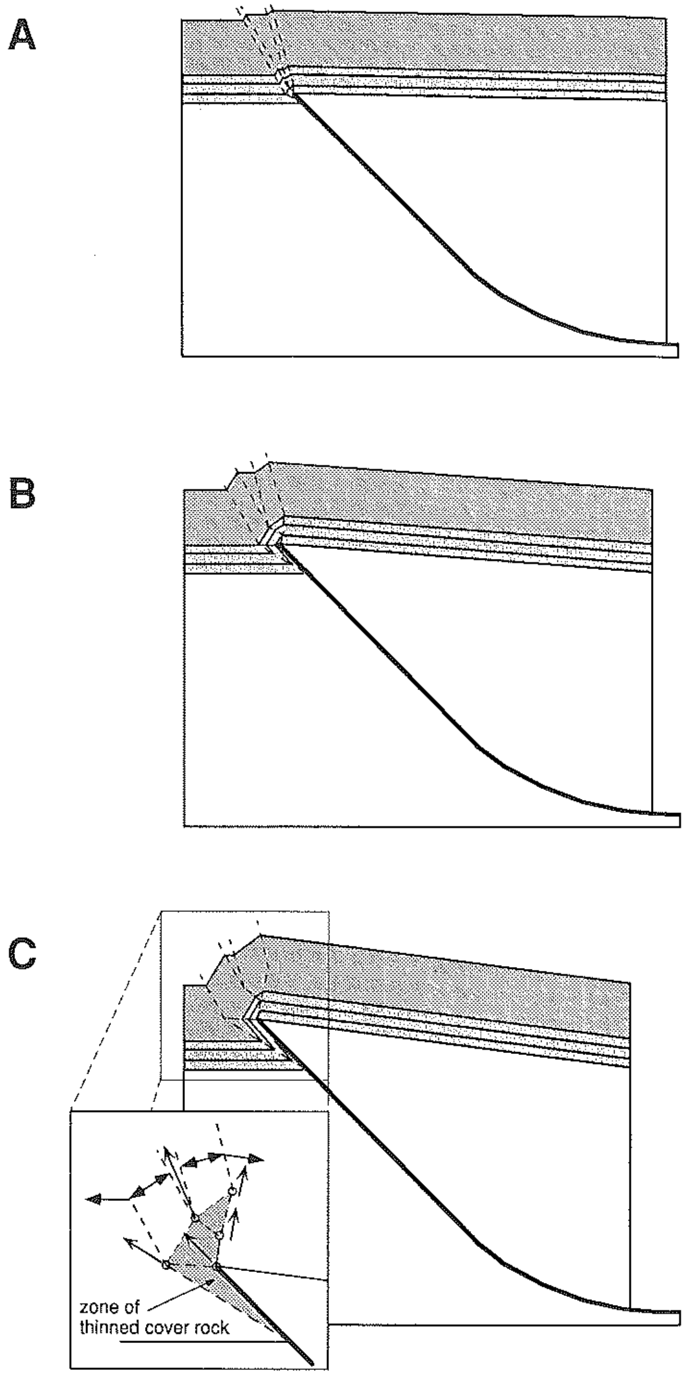

Figure 28. Evolution of mode 1 structures. As the tip of the basement block penetrates the cover, axial surfaces form at the tip of the hanging-wall basement block and footwall cutoff of the basement-cover contact during initial displacement, producing multiple dip domains in the cover (A) that do not penetrate the basement. Migration of the axial surfaces with progressive displacement of the hanging wall produces the geometries shown in B and C. The inset in C shows the instantaneous migration directions of the axial surfaces (thick arrows). Migration of non-layer-bisecting axial surfaces produces a zone of thinned cover rocks. Note that the cover on the forelimb is in fault contact with the basement and that there is no zone of localized basement deformation adjacent to the fault.

the tip of the hanging-wall wedge requires that the hanging-wall basement block is strong relative to the cover and that, along with the backlimb cover rocks, it moves along a fault (commonly preexisting) into a comparatively weak cover-rock section. As the tip of the basement block penetrates the cover, axial surfaces form at that tip and at the footwall cutoff of the basement-cover contact, producing several dip domains in the cover (Fig. 28A). Migration of the axial surfaces with continued displacement of the hanging wall produces a continually attenuated cover-rock section after initial thickening (McConnell and Wilson, this volume) (Fig. 28, B and C). The result is a fault contact between basement and cover, an overturned forelimb in the lower cover rocks, and no zone of localized basement deformation in the forelimb domain. The geometry (Fig. 28C) is not significantly different from that shown by the hanging-wall–fixed trishear model of Erslev and Rogers (this volume, Fig. 21), the basement-wedge model of McConnell and Wilson (this volume, Fig. 17), and the early-stage thrust-fold model of Stone (this volume, Fig. 6). It differs somewhat from these interpretations in showing multiple axial surfaces that give the model a kinklike geometry. We do not suggest that all lithologic units in mode 1 structures contain such domains or that all mode 1 folds can easily be divided into these domains. We suggest only that they do exist in some structures in competent lithologic units, such as the Cretaceous Dakota Sandstone in the Sheep Mountain anticline (Fig. 17) and the Ordovician Freemont Dolomite in the North Twin Mountain anticline (Fig. 20).

Kinematics of mode 2 structures

In contrast to mode 1 structures, mode 2 structures have a wide deformed basement forelimb domain with a variety of deformational features. These include fault-parallel shear on foliation or flexural slip on foliation where previous fabric is favorably oriented, fault-parallel shear with the production to new shear surfaces, and overall increase in fracture density and cataclasis when compared to the backlimb and footwall domains. Other characteristics are (1) depositional, as opposed to fault, contact between the basement and cover on the forelimb; (2) comparatively little thinning of cover rocks on the forelimb; (3) axial surfaces in the cover rocks that bisect interlimb angles so that thickness changes in the cover rocks are small through the hinges of the folds; (4) axial surfaces in the cover rocks that are coincident with the boundaries of basement domains or subdomains; (5) relatively large interlimb angles between backlimb and forelimb (65°–110°); (6) faults that commonly separate domains (e.g., between deformed forelimb and undeformed backlimb or between forelimb and footwall domain); and (7) frequently one or more backthrusts or abrupt dip changes on the backlimb.

One of the things we noted about mode 2 structures is that they generally have a relatively high (>40%) proportion of carbonate in the cover rocks in the first 330 m of section, suggesting a relatively competent cover. Other facts contributing to this style of basement-cored fold may be a relatively narrow hanging-wall basement-wedge taper and/or the presence of significant foliation that serves to localize shear fractures.

Kinematic models that show the development of structures with geometries resembling mode 2 are described by Erslev and Rogers (this volume) as footwall-fixed trishear and by Stone (this volume) as the mature stage of thrust-fold development. Spang and others (1985) and McConnell and Wilson (this volume) describe the kinematics of one type of mode 2 behavior—the multiple fault–shear-zone model.

Rock-model experiments have also provided geometries that have characteristics of mode 2 folds. The final geometry of the rock-model experiments of Chester and others (1988), in which isotropic basement is moved from a flat up a precut 20° ramp, looks similar to folds we described that contain a deformed forelimb basement and backthrusts. In these rock models the deformed forelimb domain results from the progressive deformation of the narrowly tapered basement tip as it is pushed into the cover. The main anticlinal axial surface migrates through the basement, progressively enlarging the deformed forelimb domain until the anticline locks with an interlimb angle of about 90°. In the rock-model experiments of Friedman and others (1976), movement on a steeper (60°), constant-dip, precut fault in basement also results in a downward-tapering cataclastic wedge of basement bounded by splays from the main fault. In both rock models the uppermost fault splay in basement defines the anticlinal hinge surface, and both models had some fault detachment of the baement-cover contact on the footwall. In the development of each model fold, the hanging-wall basement edge or tip was driven into the layered rock above. The resistance of the model layers above to either buckling or propagation of a fault through them caused the uplifted basement to become progressively fractured and "collapse" above the fault and below the cover. These rock models support the notion, verified in a general way by our own observations, that cover-rock competence is important in the mode of basement-cored folding.

Development of the forelimb domain. In the progressive development of the forelimb domain illustrated here (Fig. 29), we hold the synclinal hinge surface fixed in position and orientation, although we recognize that other models that allow both the synclinal and anticlinal hinge surface to migrate might be equally possible. With the synclinal position fixed, no material passes through it during progressive deformation. The implications of the model assumptions are: (1) the forelimb dip must remain constant after initial buckling if bed thickness is to be maintained on the forelimb; (2) an active anticlinal hinge surface must be generated that migrates away from the synclinal surface to produce the forelimb (Fig. 29A); (3) the anticlinal hinge surface must penetrate the basement because the basement-cover interface is a depositional contact; (4) the anticlinal axial surface must rotate progressively away from the forelimb and toward the backlimb so that it bisects the rotating backlimb to preserve layer thickness in the cover; and (5) the anticlinal hinge surface must penetrate progressively deeper into the basement as it moves away from its original position and further into the hanging wall (Fig. 29B).

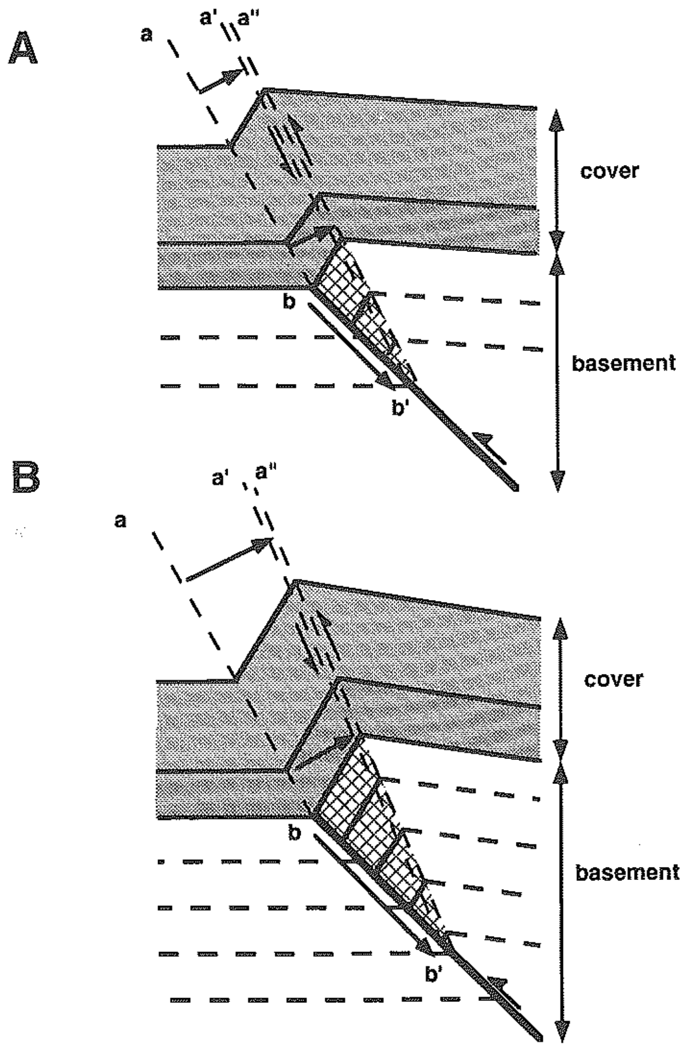

Figure 29. Kinematic development of a simple mode 2 fold. With progressive displacement the anticlinal axial surface is active and migrates through the hanging-wall block (such as a′ to a″) away from inactive axial surface (a), which is fixed to the fault tip of the basement-cover contact. Because the backlimb is dipping, axial surfaces a and a″ cannot be parallel if constant thickness of the cover is maintained; but for an infinitesimal amount of slip on the fault, material is sheared between parallel axial surfaces (a′ and a″) separated by a corresponding width. Slip on the basement fault is constant below b′ and decreases to zero from b′ to b.

The deformed forelimb domain in this model is a triangular zone of deformed basement bounded by the principal basement fault, the anticlinal hinge surface in the basement, and by the forelimb basement-cover contact. Deformation in the basement is produced as the anticlinal hinge surface migrates away from the synclinal hinge surface, enlarging the area of the deformed basement wedge. As slip on the basement fault incrases, fault slip is transferred progressively to folding in the basement. Slip on the fault decreases upward and, in the model illustrated, it is zero at the basement-cover contact and constant below the point where the upper domain boundary meets the fault.

It is not necessary for the fault tip to stick at the basement-cover contact. It is possible, even likely, that the outer arc of the synclinal hinge would fracture during folding as might be expected in the thick, brittle units. The fault might then cut into the cover along the synclinal hinge surface after or during deformation of the basement forelimb domain (Fig. 30, A and B). Fault dip would be increased as the fault propagated into the cover along the hinge surface, as commonly seen in seismic sections (Stone, this volume). Good structures that tend toward mode 2 style that have, or are interpreted to have, a fault that displaces the cover along the synclinal hinge surface are London Hills, Spring Canyon, Sheephead Mountain, and probably LaPrele, Elk Mountain, and Romero Hills.

It is also likely that continued fault slip could be transferred to the upper surface of the deformed forelimb wedge. We see narrow zones of pervasive deformation along this upper surface in the London Hills, Elk Mountain, and Sheephead Mountain structures. These zones are interpreted to be hinge-controlling faults, but they do not break the cover rocks. When faults break through the cover rocks along this boundary as, for example, in the Brooks Creek anticline, the wedge-shaped zone is "left behind" in the footwall of the fault (Fig. 30C) (e.g., the Owl Peak

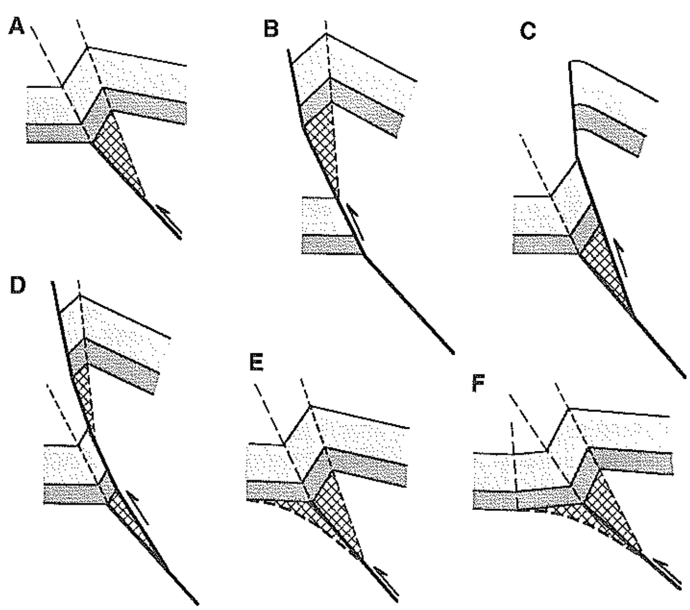

Figure 30. Modifications of simple mode 2 structures. A: Idealized mode 2 structure—early stage. B: Propagation of principal fault into cover rocks along the synclinal hinge surface. C: Propagation of a hanging-wall splay along basement anticlinal hinge surface. The deformed wedge of basement (cross hatched) is "left behind" in the footwall. D: Propagation of a hanging-wall splay across the forelimb. E and F: Development of a footwall splay and translation along the basement-cover contact on the footwall. All modifications require adjustments in basement (e.g., backthrusts).

structure section described by Erslev and Rogers, this volume). When the footwall-basement rocks are not exposed, as is frequently the case, it is difficult to distinguish the geometry shown here (Fig. 17) from a mode 1 geometry. For example, without knowing for certain that there is no deformed basement wedge on the footwall in the Sheep Mountain anticline (Fig. 17), the overall style, which we have designated as mode 1, could not be easily distinguished from mode 2.

Faults also propagate through the steep forelimb of the fold in the cover rocks, as has happened in London Hills, Spring Canyon, and Kaufman Ridge (Fig. 30D). Because the London Hills and Spring Canyon folds also have synclinal hinge-surface breakthroughs, it is apparent that some folds have fault breakthroughs in more than one location. Simple shear on pairs of forelimb splays at this stage may produce thinning in the forelimb cover rocks (Stone, this volume; McConnell and Wilson, this volume) (Fig. 31). This appears to have taken place at London Hills. Another possibility is that a footwall splay might develop from the master thrust and propagate along the basement-cover contact (Fig. 30, E and F). Although observed in rock-model experiments (e.g., Friedman and others, 1976) this phenomenon was observed in only one of the 12 folds we studied. The footwall of the Gnat Hollow fault shows minor local detachment along the basement-cover contact. Each of the modifications of the initial idealized mode 2 style (Fig. 30A) has "room" problems. One of the manifestations of these room problems is the production of backthrusts.

Development of backthrusts. Backthrusts and/or localized zones of basement deformation that produce multiple dip domains on the backlimbs are common features in mode 2 structures and were observed in five of the cases studied. As suggested by rock-model experiments (e.g., Morse, 1977; Chester and others, 1988), backthrusts can initiate at places where the fault trajectory changes from a lower to a higher dip (e.g., from flat to ramp). If the basement fault has a curved trace, it is possible that backthrusts may initiate at the point of maximum curvature where the stress concentration is highest. However, except for the Hinch Creek fault on the Spring Canyon anticline, which has a sharp change in trend (corresponding to an abrupt flattening of dip) at about 8 km from the basement-cover contact (projected depth of 2–3 km), subsurface geometries of the faults are not known with certainty. In addition, except for the backthrusts at Elk Mountain and London Hills, which are more than 3 km from the deformed forelimb domain, most of these features are relatively close to the forelimb domain, and it is unlikely that they originated very deep below the cover.

Most of the backthrust zones can be traced in the basement for a few hundred meters, and it is reasonably certain that most dip back toward the forelimb-basement domain. Most of the folds that have backthrusts also have one or more faults that break through the cover at the anticlinal hinge or along the steeply-dipping forelimb. There may be a genetic correlation between the development of backthrusts or kink domains in the backlimbs and the production of multiple forelimb faults. If the forelimb and anticlinal hinge faults can be considered to be hanging-wall splays from a master fault (Fig. 30, C and D), then the junction of the master fault and the splays are points of fault-dip change that may produce shearing strains in the hanging-wall basement block as movement is transferred from the master fault to a more steeply-dipping splay. These shearing strains may be manifested as axial surfaces producing kinked domains in the backlimb (Fig. 31, A and B) or as backthrusts (Fig. 31C) (Narr, 1990 and this volume). Some backthrusts may be reactivated normal faults antithetic to the principal normal fault. For example, the Summit Valley backthrust in the backlimb of the London Hills anticline has a diabase dike of probable Precambrian age within the fault zone (Fig. 4).

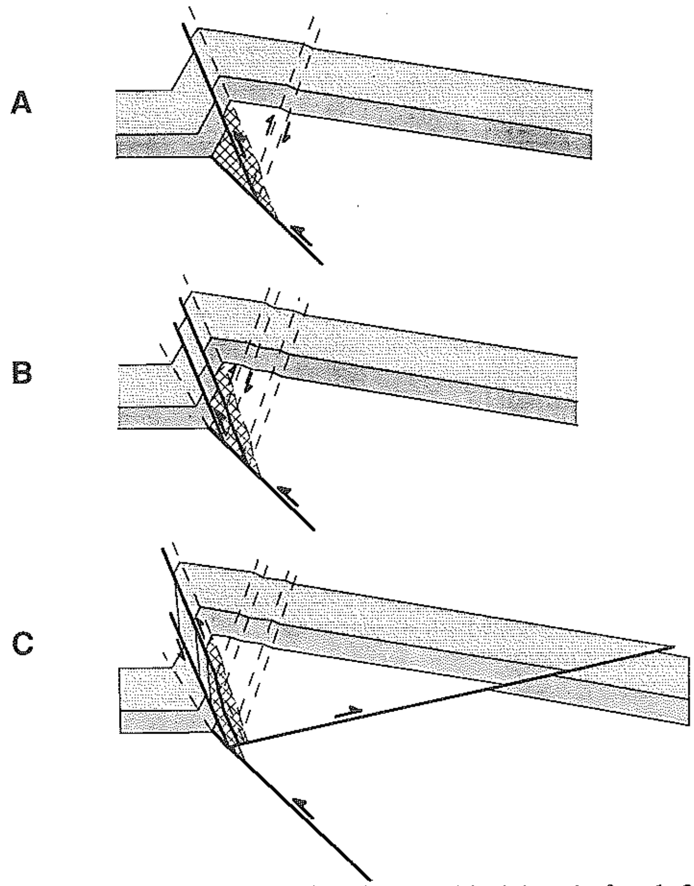

Figure 31. Modifications (forelimb thrusts and backthrusts) of mode 2 structures. One or more faults may break through the forelimb of a simple mode 2 structure producing a corresponding number of kink bands in the backlimb (A and B). In C, simple shear between two forelimb thrusts produces thinning in the forelimb cover and a backthrust accommodates the strain generated by change in dip of the propagating basement fault.

SUMMARY AND CONCLUSIONS

We recognize two styles of basement-cored folds among the 12 we studied: mode 1 and mode 2. In mode 1 folds basement deformation is confined to a very narrow zone of cataclasis adjacent to the fault. Cover rocks (1) have undergone significant thinning in the forelimb region, (2) frequently have multiple anticlinal axial surfaces emanating from the tip of the hanging-wall basement block, and (3) have a contact with the basement on the forelimb that is a fault and not a stratigraphic contact.

In mode 2 folds basement deformation occurs as a broad zone of brittle deformation between the principal fault and the anticlinal hinge surface. We call this region the deformed forelimb basement domain. In this region deformation occurs as (1) slip on sets of closely spaced fractures, (2) flexural slip on preexisting foliation or compositional layering oriented subparallel to bedding in the cover rocks, (3) slip on foliation oriented subparallel to the anticlinal axial surface in the cover rocks, (4) pervasive cataclasis, or (5) some combination of these processes. Mode 2 structures have cover rocks that (1) maintain near constant thickness through the fold, (2) are in stratigraphic contact with the basement on the forelimb, and (3) have an anticlinal axial surface that penetrates the basement.

If the styles of folds we describe really reflect end-member behaviors, there should be a spectrum of structures that shows the features of both mode 1 and mode 2 behaviors. We categorize each of the structures in this way in Table 1. To be a workable scheme any structure should be unique as to form and degree of development of the deformed basement forelimb. For example, a "mixed mode" structure (Fig. 23B) may have (1) a forelimb in which the basement-cover interface is partly a fault and partly a stratigraphic contact, (2) an anticlinal hinge surface that does not bisect the forelimb-backlimb interlimb angle so that the forelimb is slightly thinned, (3) a basement forelimb domain of moderate width, and (4) an interlimb angle with an intermediate value (60°–90°). One of the difficulties in applying the scheme to all basement cored folds is that, without good forelimb and footwall basement exposures, it would be possible to mistake a mode 2 fold with a faulted anticlinal hinge surface for a mode 1 fold that never had a deformed basement forelimb. Nevertheless, distinguishing the differences in style and basement behaviors of the folds in this way helps to focus attention on the factors that control basement behavior.

In spite of our limited data base (12 folds), it seems reasonably clear that the style of basement cored folds and fault-fold geometry depends on the nature and orientation of the prefolding basement fabric and on the competence of the cover rocks. Well-developed foliated fabrics that are either oriented subparallel to bedding or are in a "favorable" orientation for simple shear parallel to the principal fault produce mode 2 folds. Stratigraphic sections that have a lot of thick carbonates immediately above the basement rocks also tend to produce mode 2 folds.

Although it seems likely that the degree of control of earlier faults should be a factor in the style of folding and mechanical behavior of basement rocks, we have not been able to prove how it has contributed to the style of folding in general. We are certain, for example, that the faults that subtend the folds in Montana are reactivated, and, in at least one case, the position of the anticlinal fold hinge is localized along a Proterozoic dike in the basement. We are also reasonably certain that, in the Proterozoic, these faults were listric normal faults having hanging walls down. All of these structures tend toward mode 2 styles. If a single fault had the hanging wall up after once being down, we might expect a simple mode 1 style with no wide zone of basement deformation. Without knowing the details of the previous faulting (e.g., fault zone vs. single fault), it seems unlikely that we can predict the mode of basement folding based on the likelihood that the fault was reactivated.

As Erslev and Rogers (this volume) have suggested, the taper of the hanging-wall basement wedge almost certainly influences the strength of the basement and therefore controls the mode of basement behavior. Unfortunately, we will need more folds and faults with a greater variation in measurable dip to evaluate this suggestion. In addition, plotting estimated basement-wedge taper against interlimb angle may not be the best way to show the effect of wedge taper on the geometry of basement-cored folds and the mechanical behavior of basement.

Confining pressure and temperature are important factors only insofar as they determine the overall mechanical behavior (e.g., brittle vs. ductile) of the basement and the cover rocks. There does not appear to have been enough difference in these factors within the Rocky Mountain foreland to have caused noticeable differences among the structures we studied. Perhaps more noticeable comparisons could be made with basement-cored structures in other foreland regions.

There may have been other factors that have influenced the faulting and folding behavior of the basement. For example, two of the folds are within 15 km of the Late Cretaceous Tobacco Root batholith (Fig. 3). Intrusion was coeval with fault movement (Schmidt and others, 1990), and the basement rocks of both structures show significant hydrothermal alternation of biotite and feldspar. This is especially prevalent in the Brooks Creek anticline, where the principal fault cuts the batholith about 10 km along strike. The anticlinal hinge-controlling fault is a splay of this principal fault (Bismark fault), and the fault zone is a wide zone of hydrothermally-altered gneiss. If coeval with faulting, it is very possible that this hydrothermal alteration had a strain-softening affect on basement folding and faulting.

Another factor that may be important to the fold geometry and style of basement behavior is the amount of displacement or slip on the basement fault or faults. Several studies (e.g., Hull, 1988; Mitra, this volume) have shown a general increase in fault-zone width with displacement along the zone. Some structures (e.g., Rattlesnake Mountain–Erslev, 1991, personal commun.) show progressive tightening of the folded cover with increasing fault displacement. This is predicted by most fault-propagation fold models in which deformation occurs in a downward-focusing triangular shear zone (e.g., Erslev and Rogers, this volume; Stone, this volume). Among the folds we studied for which reasonable estimates of slip or dip separation could be made, we found no correlation of displacement and interlimb angle. It is likely that, as the models predict, there is an initial progressive tightening as fault slip proceeds. However, for mode 1 folds, tightening of a given cover-rock unit proceeds only up to the point where it is transected by the principal fault, and thereafter the interlimb angle does not change (Fig. 28). For mode 2 folds, the principal interlimb angle is established and locked prior to axial surface or steep limb breakthrough and remains constant thereafter during progressive slip (Figs. 29 and 30).

Existing kinematic models (e.g., Erslev, 1991; Erslev and Rogers, this volume; McConnell and Wilson, this volume) explain adequately how mode 1 structures develop. In these structures it appears that a relatively competent basement block is forced into relatively incompetent cover, and the basement does not deform much beyond the limits of the single fault zone. In mode 2 structures a relatively incompetent basement block is forced against relatively competent cover rocks. The synclinal hinge in the cover develops above the fault, and the basement corner on the hanging wall deforms by the generation of an anticlinal hinge surface that migrates away from the fault, progressively enlarging a wedge-shaped area on the hanging wall immediately below the cover. Increasingly fault slip is progressively transformed to folding of the basement. Faulting can propagate into the cover rocks along the synclinal hinge or along splays that develop within the forelimb domain or along its upper boundary (i.e., along the anticlinal hinge surface). Backthrusts, a common feature of mode 2 folds, may develop where the master fault has a sharply curved trace, but it is more likely that they propagate from the branch lines, where hanging-wall splays diverge from the main fault.

Although there are many features common to basement-cored folds in the Rocky Mountains, even when structures of the same size are compared, the variety among them is impressive. Although the faults associated with the folds described here have dips that range from 40° to vertical, other structures described in this volume (e.g., Erslev and Rogers; Evans and others; Schmidt and others) indicate that fault dips have a greater range (from vertical to horizontal). There now seems to be a consensus that these structures were a result of horizontal shortening in response to horizontal compression, and that shortening is manifested in a variety of ways, making is impossible to apply a single kinematic model or to characterize all basement deformation in a specific way. Because of the large variety among these structures and because of complexities in them that are only beginning to be studied, they will continue to provide challenging problems on every scale of observation.

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REFERENCES CITED

Baltz, E. H., and O'Neill, J. M., 1984, Geologic map and cross sections of the Mora River area, Sangre de Cristo Mountains, Mora County, New Mexico: U.S. Geological Survey Miscellaneous Investigations Map I-1456, scale 1:24,000.

Banks, C. E., 1970, Precambrian gneiss at Sheephead Mountain, Carbon County, Wyoming, and its relationship to Laramide structure [M.A. thesis]: Laramie, University of Wyoming, 39 p.

Barlow, J. D., 1953, Stratigraphy and structure of the LaPrele Reservoir region, northern Laramie Range, Wyoming [M.S. thesis]: Laramie, University of Wyoming.

Beckwith, R. H., 1941, Structure of the Elk Mountain district, Carbon County, Wyoming: Geological Society of America Bulletin, v. 52, p. 1445–1486.

Blackstone, D. L., Jr., 1940, Structure of the Pryor Mountains, Montana: Journal of Geology, v. 48, p. 590–618.

——, 1980, Foreland deformation: Compression as a cause: University of Wyoming Contributions to Geology, v. 18, p. 83–100.

——, 1983, Laramide compressional tectonics, southeastern Wyoming: University of Wyoming Contributions to Geology, v. 22, p. 1–38.

Brandon, W. C., 1984, An origin for the McCartney's Mountain salient of the southwestern Montana fold and thrust belt [M.S. thesis]: Missoula, University of Montana, 128 p.

Brown, W. G., 1983, Sequential development of the fold-thrust model of foreland deformation, *in* Lowell, J. D., ed., Rocky Mountain foreland basins and uplifts: Denver, Colorado, Rocky Mountain Association of Geologists, p. 57–64.

——, 1984, A reverse fault interpretation of Rattlesnake Mountain anticline, Wyoming: Mountain Geologist, v. 21, p. 31–35.

——, 1988, Deformational style of Laramide uplifts in the Wyoming foreland, *in* Schmidt, C. J., and Perry, W. J., Jr., eds., Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, p. 1–25.

Chase, R. B., 1985, The role of Precambrian compositions and fabrics in the development of foreland structures, southern Front Range, Colorado: Geological Society of America Abstracts with Programs, v. 17, p. 543.

Chester, J. S., Spang, J. G., and Logan, J. M., 1988, Comparison of thrust fault rock models to basement-cored folds in the Rocky Mountain foreland, *in* Schmidt, C. J., and Perry, W. J., Jr., eds., Interactions of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, p. 65–74.

Cook, D. G., 1988, Balancing basement-cored folds of the Rocky Mountain foreland, *in* Schmidt, C. J., and Perry, W. J., Jr., eds., Interactions of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, p. 53–64.

DeVoto, R. H., 1971, Geologic history of South Park and geology of the Antero Reservoir [15 minute] quadrangle, Colorado: Colorado School of Mines Quarterly, v. 66, no. 3, p. 90.

Erslev, E. A., 1985, Balanced cross-sections of small fold-thrust structures, Comment: The Mountain Geologist, v. 22, p. 91–93.

——, 1986, Basement balancing of Rocky Mountain foreland uplifts: Geology, v. 14, p. 259–262.

——, 1991, Trishear fault-propagation folding: Geology, v. 19, p. 617–620.

Friedman, M., Handin, J., Logan, J. M., Min, K. D., and Stearns, D. W., 1976, Experimental folding of rocks under confining pressure; Part III, Faulted drape folds in multilithologic layered specimens: Geological Society of America Bulletin, v. 87, p. 1049–1066.

Friedman, M., Hugman, R.H.H., and Handin, J., 1980, Experimental folding of rocks under confining pressure, Part VIII—Forced folding of unconsolidated sand and of lubricated layers of limestone and sandstone: Geological Society of America Bulletin, v. 91, p. 307–312.

Gerhard, L. C., 1961, Geology of the Phantom Canyon region, Fremont County, Colorado [M.S. thesis]: Lawrence, University of Kansas.

——, 1967, Paleozoic geologic development of Canon City embayment, Colorado: American Association of Petroleum Geologists Bulletin, v. 51, p. 2260–2280.

Hail, W. J., Jr., 1965, Geology of northwestern North Park, Colorado: U.S. Geological Survey Bulletin 1188, 133 p.

Hanley, T. B., 1975, Structure and petrology of the northwestern Tobacco Root Mountains, Madison County, Montana [Ph.D. thesis]: Bloomington, Indiana University, 289 p.

Hennings, P. H., and Spang, J. H., 1987, Sequential development of Dry Fork Ridge anticline, northeastern Bighorn Mountains, Wyoming and Montana: University of Wyoming Contributions to Geology, v. 25, p. 73–93.

Hodgson, R. A., 1965, Genetic and geometric relations between structures in basement and overlying sedimentary rocks with examples from Colorado Plateau and Wyoming: American Association of Petroleum Geologists Bulletin, v. 49, p. 935–949.

Houston, R. S., and 18 others, 1968, A regional study of rocks of Precambrian age in that part of the Medicine Bow Mountains lying in southeastern Wyoming: Wyoming Geological Survey Memoir 1, 167 p.

Hudson, F. S., 1955, Folding of unmetamorphosed strata superjacent of massive basement rocks: American Association of Petroleum Geologists Bulletin, v. 39, p. 2038–2052.

Hull, J., 1988, Thickness-displacement relationships for deformation zones: Journal of Structural Geology, v. 10, p. 431–435.

Karasevich, L. P., 1981, Geologic map of the northern Ruby Range, Madison County, Montana: Montana Bureau of Mines and Geology Geological Map 25, scale 1:24000.

Lopez, D. A., and Schmidt, C. J., 1985, Seismic profile across the leading edge of the fold and thrust belt in southwestern Montana, *in* Gries, R. R., and Dyer, R. C., eds., Seismic exploration of the Rocky Mountain region: Denver, Colorado, Rocky Mountain Association of Geologists and Denver Geophysical Society, p. 45–50.

McClurg, J. E., and Matthews, V., III, 1978, Origin of Elk Mountain anticline, Wyoming, *in* Matthews, V., III, ed., Laramide folding associated with basement block faulting in the western United States: Geological Society of America Memoir 151, p. 157–163.

McConnell, D. A., 1989, Comparison of deformation mechanisms and deformation fabrics in basement-cored folds of the Rocky Mountains: Geological Society of America Abstracts with Programs, v. 21, no. 6, p. A67.

Morse, J. D., 1977, Deformation in ramp regions of overthrust faults—Experiments with small-scale rock models: Wyoming Geological Association, 29th Annual Field Conference, Guidebook, p. 457–470.

Narr, W., 1990, Deformational behavior and kinematics of basement-involved structures and joint spacing in sedimentary rocks [Ph.D. thesis]: Princeton, New Jersey, Princeton University, 154 p.

O'Neill, J. M., 1990, Precambrian rocks of the Mora-Rociada area, southern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society Guidebook 41, p. 189–199.

O'Neill, J. M., and Schmidt, C. J., 1989, Tectonic setting and structural control of gold deposits in cratonic rocks of the Rochester and Silver Star mining districts, Highland Mountains, southwestern Montana, *in* French, D. E., and Grabb, R. F., eds., Geologic resources of Montana: 1989 Field Conference Guidebook: Montana Geological Society, p. 393–402.

Reid, R. R., 1957, Bedrock geology of the north end of the Tobacco Root Mountains, Madison County, Montana: Montana Bureau of Mines and Geology Memoir 36, 25 p.

Schmidt, C. J., and Garihan, J. M., 1983, Laramide tectonic development of the Rocky Mountain foreland of southwestern Montana, *in* Lowell, J. D., ed., Rocky Mountain foreland basins and uplifts: Denver, Colorado, Rocky Mountain Association of Geologists, p. 271–294.

——, 1986, Role of recurrent movement on northwest-trending basement faults in the tectonic evolution of southwestern Montana: International Conference on Basement Tectonics, 6th, Proceedings, p. 1–15.

Schmidt, C. J., Evans, J. P., Fletcher, R. C., and Spang, J. H., 1985, Spacing of Rocky Mountain foreland arches and Laramide magmatic activity: Geological Society of America Abstracts with Programs, v. 17, p. 710.

Schmidt, C. J., and O'Neill, J. M., and Brandon, W. C., 1988, Influence of Rocky Mountain foreland uplifts on the development of the frontal fold and thrust belt, southwestern Montana, *in* Schmidt, C. J., and Perry, W. J., Jr., eds., Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, p. 171–202.

Schmidt, C. J., Smedes, H. W., and O'Neill, J. M., 1990, Syncompressional emplacement of the Boulder and Tobacco Root batholiths (Montana-USA) by pull-apart along old fault zones: Geological Journal, v. 25, p. 305–318.

Schmidt, C. J., Evans, J. P., and Douglas, B., 1991, Pull apart origin for the Tobacco Root batholith, southwestern Montana: Geological Society of America Abstracts with Programs, v. 23, no. 4, p. 90.

Spang, J. H., and Evans, J. P., 1988, Geometrical and mechanical constraints on basement-involved thrusts in the Rocky Mountain foreland province, *in* Schmidt, C. J., and Perry, W. J., Jr., eds., Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, p. 41–51.

Spang, J. H., Evans, J. P., and Berg, R. R., 1985, Balanced cross sections of small fold-thrust structures: Mountain Geologist, v. 22, p. 41–46.

Stearns, D. W., 1978, Faulting and forced folding in the Rocky Mountain foreland, *in* Matthews, V., III, ed., Laramide folding associated with basement block faulting in the western United States: Geological Society of America Memoir 151, p. 1–37.

Stone, D. S., 1984, The Rattlesnake Mountain Wyoming debate; a review and critique of models: Mountain Geologist, v. 21, p. 37–46.

Swenson, A. L., 1980, Mechanics of Laramide deformation along the east flank of the Laramie Range, Wyoming, and Front Range, Colorado [Ph.D. thesis]: Boulder, University of Colorado, 132 p.

Tysdal, R. G., 1976, Geologic map of the northern part of the Ruby Range, Madison County, Montana: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-951, scale 1:24000.

——, 1981, Foreland deformation in the northern part of the Ruby Range of southwestern Montana, *in* Tucker, T., ed., Southwest Montana: Montana Geological Society Field Conference and Symposium Guidebook, p. 215–224.

Wagner, S. H., 1966, Effect of Laramide folding on previously folded Precambrian metamorphic rocks, Madison County, Montana [M.A. thesis]: Bloomington, Indiana University, 27 p.

Webster, G. D., 1959, Geology of the Canon City–Twin Mountain area, Fremont County, Colorado [M.S. thesis]: Lawrence, University of Kansas, 99 p.

Wobus, R. A., Chase, R. B., Scott, G. R., and Taylor, R. B., 1985, Reconnaissance geologic map of the Phantom Canyon quadrangle, Fremont County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1764, scale 1:24,000.

Wooden, J. L., Vitaliano, C. J., Koehler, S. W., and Ragland, P. C., 1978, The late Precambrian mafic dikes in the southern Tobacco Root Mountains, Montana—Geochemistry, Rb-Sr geochronology, and relationship to Belt tectonics: Canadian Journal of Earth Sciences, v. 15, p. 467–479.

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