Pennsylvania sinistral faults along the southwest boundary of the Uncompahgre uplift, Ancestral Rocky Mountains, Colorado

William A. Thomas*
Department of Geological Sciences, University of Kentucky, Lexington, Kentucky 40506-0053, USA

ABSTRACT

Resolution of the large-scale kinematics of the Pennsylvania-Permian Ancestral Rocky Mountains requires definition of sense of slip and time of movement on specific faults within the system of fault-bounded basins and uplifts (e.g., Paradox basin, Uncompahgre uplift). Along an east-west-striking segment of the boundary between the Paradox basin and Uncompahgre uplift, a system of steep faults defines a horst and graben system, which includes the Grenadier fault block. Positive flower structures (anticlines) along both the bounding (Coal Bank Pass and Molas Creek faults) and internal (Snowdon fault) faults of the Grenadier fault block indicate strike-slip displacement, and oblique subsidiary folds show sinistral slip. On both sides of the Snowdon fault, stratigraphic thinning of parts of the Pennsylvania Hermosa Group toward the fault documents synsedimentary growth of the positive flower structure, suggesting Pennsylvania sinistral slip along this part of the Ancestral Rocky Mountains. Sinistral strike-slip along one east-west-striking segment of the fault system between the Paradox basin and Uncompahgre uplift is compatible with reverse slip on northwest-striking segments, demonstrating that a regional assembly of data to define sense of slip and time of movement on specific faults will better constrain regional-scale models for kinematics and mechanics of Ancestral Rocky Mountains deformation.

Keywords: Ancestral Rocky Mountains, sinistral fault, synsedimentary fault, Pennsylvania, Uncompahgre uplift.

INTRODUCTION

The large-scale tectonic setting and driving mechanisms of the basement faults of the Pennsylvania-Permian Ancestral Rocky Mountains have attracted a wide range of interpretations, each of which ultimately depends on the time and sense of slip on each of the specific faults within a large array of generally high-relief basement fault blocks (Fig. 1) (e.g., Baars, 1966; Kluth and Coney, 1981; Baars and Stevenson, 1982, 1984; Kluth, 1986, 1998; Stevenson and Baars, 1986; Thomas and Baars, 1995; Ye et al., 1996; Marshall et al., 2000; Dickinson and Lawton, 2003). Thick accumulations of locally derived, coarse clastic sediment of Pennsylvania-Permian age provide the primary evidence for the large-scale structure of the Ancestral Rocky Mountains. Fault boundaries between large-scale basement uplifts (e.g., Uncompahgre and Front Range) and basins (e.g., Paradox and Central Colorado) are mapped from scattered exposures of faults, sedimentary thickness and facies distribution, and subsurface data (e.g., summaries in Baars, 1966; Mallory, 1972; Rascoe and Baars, 1972; Weimer, 1980; Baars et al., 1988). For many of the faults, the dip is not well constrained, and a clear definition of slip sense is rare.

Resolution of the various large-scale tectonic models for the Ancestral Rocky Mountains has been hampered by lack of data for the time and sense of slip on specific faults from which interpretations of an integrated regional stress field can be derived. This article reports on faults along the Grenadier fault block, which is within a system of faults at the boundary between the southwestern side of the Uncompahgre uplift and the Paradox basin in southwestern Colorado, where the time and sense of slip can be interpreted. The objective is similar to that of a study of faults along the boundary between the northeastern side of the Uncompahgre uplift and the Central Colorado trough in southern Colorado, where sedimentary facies and folded angular unconformities document Pennsylvania-Permian synsedimentary northeast-directed thrusting (Hoy and Ridgway, 2002). While these examples alone will not resolve the regional-scale mechanics, they illustrate the kinds of data that are necessary for resolution of the alternative interpretations, and the conclusions provide testable implications for integration of regional kinematics.

The Pennsylvania-Permian Ancestral Rocky Mountains structures reflect protracted tectonic inheritance from Precambrian basement faults, as well as a history of episodic reactivation of Precambrian and Paleozoic faults (e.g., Baars and See, 1968). In turn, the Ancestral Rocky Mountains structures have been variously overprinted by Cretaceous-Eocene Laramide basement-rooted structures, and the relative magnitudes of Ancestral Rockies and Laramide components of deformation remain in question along many structures. This article begins with a summary of pre-Pennsylvaniaan fault movements and concludes with an evaluation of Pennsylvania-age fault movements in the regional context of the Ancestral Rocky Mountains and possible Laramide overprints.

Parts of the boundary-fault system between the Uncompahgre uplift and the Paradox basin on the southwest are exposed in the Laramide- age San Juan dome in southwestern Colorado (Fig. 1). In that area, a system of faults defines horst and graben blocks (the Grenadier and Sneffels fault blocks, Fig. 1) within the northeastern part of the Paradox basin (Baars, 1966; Baars and See, 1968; Weimer, 1980). A Pennsylvania-Permian (Hermosa Group and Cutler Group) succession fills the Paradox basin, overlaps the Grenadier and Sneffels fault blocks, and pinches out against the Ridgway fault at the southwest boundary of the Uncompahgre uplift. The Ridgway fault strikes east-west for some distance, constituting a “kink” in the generally northwest-striking boundary between the Uncompahgre uplift and Paradox basin (Fig. 1) (Stevenson and Baars, 1986), and the boundaries of both the Sneffels and Grenadier fault blocks strike approximately east-west, parallel with the Ridgway fault. West of the kink, the boundary between the Uncompahgre uplift and Paradox basin curves to northwest strike. East of the kink, the Sneffels and Grenadier fault blocks along with the uplift boundary bend abruptly to...
the southeast and south (Fig. 1). These structures are now exposed in Precambrian to Pennsylvanian rocks in the structurally highest part of the Laramide San Juan dome. The Laramide structure is framed by relatively low-angle dips in Permian and younger rocks around the west and south sides of the dome; however, Tertiary rocks of the San Juan volcanic field overlap Precambrian rocks on the north and east sides of the core of the dome.

PRE-PENNYSylvanian TECTONIC HISTORY OF THE GRENA DiER FAULT BLOCK

The Grenadier fault block consists of Precambrian quartzite and phyllite (Uncompahgre Group) with a Paleozoic sedimentary cover. The bounding faults of the Grenadier fault block, the Coal Bank Pass and Molas Creek faults on the south and north, respectively, juxtapose the Uncompahgre Group and cover against older Precambrian gneiss and granite, indicating a nonconformable sedimentary cover over crystalline basement rocks (Barker, 1969; Gibson, 1990); alternatively, a zone of sheared, foliated rocks along the contact suggests a thrust boundary (Tewksbury, 1985). Cuspat e in folding of the cover strata into the basement provides a mechanism for thrusting along the contact between the parautochthonous Uncompahgre Group and the basement rocks (Harris et al., 1987, Fig. 3 therein). A convex-upward geometry of the limbs of cuspat e folds is expressed in upwardly and outwardly decreasing dips, and the limbs are broken by strike-slip shear zones. Although a cuspat e-infold geometry adequately explains the east-striking elongate outcrop area of the Uncompahgre Group between contacts with the older Precambrian gneiss and granite, the contact subsequently was displaced by steep faults with substantial vertical separation, defining a structurally low block (Grenadier graben) between the Coal Bank Pass and Molas Creek faults (Baars and See, 1968).
Figure 2 (see footnote 1). Geologic map of the Grenadier fault block between the Coal Bank Pass and Molas Creek faults (base map from Engineer Mountain and Snowdon Peak 7.5-min quadrangles; topographic contour values in feet; topographic contour interval 40 ft = 12.2 m). The map is compiled in four layers, which may be viewed in any combination. Layer 1—Geologic map. Layer 2—Structure contour map of base of Pennsylvanian strata (base of Molas Formation) (structure contour values in meters; structure contour interval 100 m). Elevations of outcrops of base of Molas Formation provide elevation control for structure contour lines. Spacing and orientation of structure contour lines are projected from measured bedding attitudes throughout the map area. Layer 3—Lines of cross sections in Figures 3 and 5. Lines of cross sections in Figure 3 (X–X', Y–Y') extend along the outcrop trace of Cambrian-Mississippian rocks; end points of the cross sections at X' and Y are shown, but end points X and Y' are outside the area of the map. Map shows locations of lines of cross sections in Figure 5 (A–A' to J–J'). Layer 4—Locations of Figures 4, 6, 7, 9, and 10. Locations of map in Figure 4 and aerial photograph in Figure 6 are shown by outlines. Locations of photographs in Figures 7A, 7B, 9A, 9B, 10A, and 10B are shown by orientation of views.
Cambrian

The Upper Cambrian Ignacio Formation is characterized by quartzite sandstone and locally includes quartzite-boulder (50+ cm) conglomerate in irregular elongate areas along the Coal Bank Pass, Snowdon, and Molas Creek faults (Baars and See, 1968; Block, 1986). The rounded quartzite boulders are lithologically identical to quartzite in the Uncompahgre Group, indicating local sources from Uncompahgre quartzite.

The Ignacio quartzite-clast conglomerate and sandstone south of the Coal Bank Pass fault rest nonconformably on the older Precambrian Twilight Gneiss, and the entire Ignacio Formation pinches out northward a few meters south of the fault (sections 5–7, X–X′ in Fig. 3). The boulder-conglomerate beds pinch out southward away from the Coal Bank Pass fault into a southward thickening sandstone succession (from section 7 to section 3, X–X′ in Fig. 3). Distribution of the quartzite boulders indicates supply from Uncompahgre Group quartzite in the Grenadier fault block north of the Coal Bank Pass fault and proximal transport southward onto paleotopographically lower Twilight Gneiss south of the fault (Baars and See, 1968; Block, 1986). The large size and local distribution of the quartzite boulders indicate a steep scarp between the eroded surface on the Uncompahgre Group north of the Coal Bank Pass fault and that on the Twilight Gneiss south of the fault.

Quartzite-boulder conglomerate is scattered along the south side of the Snowdon fault, where the conglomerate rests on quartzite and phyllite within the Uncompahgre Group (Fig. 2, section 15, X–X′ in Fig. 3). On the fault block (southern part of Grenadier fault block) between the Snowdon and Coal Bank Pass faults, the Ignacio boulder conglomerate thins abruptly southward away from the Snowdon fault, and the formation either pinches out or is represented only by a pavement conglomerate (a single bed with thickness equal to the diameter of single clasts) over the southern part of the block (sections 8–14 in contrast to 15, X–X′ in Fig. 3). North of the Snowdon fault, on the fault block (northern part of Grenadier fault block) between the Snowdon and Molas Creek faults, the Ignacio Formation is unconformably absent, and Devonian strata overlie the Uncompahgre Group quartzite (section 16, Y–Y′ in Fig. 3). The restriction of the Ignacio quartzite-boulder conglomerate to the south side of the Snowdon fault indicates a south-facing paleotopographic scarp, along the base of which boulders were concentrated on the Uncompahgre bedrock.

North of the Molas Creek fault, Ignacio quartzite-boulder conglomerate rests on older Precambrian granite, and the formation thickens and grades abruptly to sandstone northward away from the fault (sections 17–21, Y–Y′ in Fig. 3) (Baars and See, 1968). The Molas Creek fault is a zone that includes two distinct faults. The southern branch of the Molas Creek fault zone is an east-striking fault that defines the northern boundary of the Grenadier fault block and separates the Uncompahgre quartzite on the south from Precambrian granite on the north. Devonian-Mississippian strata overlie the southern branch of the Molas Creek fault zone, indicating no post-Devonian fault movement (Y–Y′ in Fig. 3). The northern branch of the Molas Creek fault zone diverges to the east-northeast with Precambrian granite on both sides, but the fault displaces beds as young as Pennsylvanian, distinguishing the post-Devonian northern branch from the pre-Devonian southern branch (Fig. 2). Ignacio quartzite-boulder conglomerate overlies the Precambrian granite along the north side of the southern branch and extends northward across the northern branch of the Molas Creek fault zone. Devonian strata unconformably overlie Uncompahgre quartzite south of the southern branch of the Molas Creek fault zone on the Grenadier fault block. Distribution of the Ignacio

Figure 3. Stratigraphic cross sections showing thickness and facies distributions of Cambrian through Mississippian formations with respect to locations of faults and Precambrian rock types. Datum is base of Pennsylvanian Molas Formation. The lines of cross section extend along the outcrop trace of Cambrian-Mississippian rocks, partly within the area of Figure 2, which shows the locations of end points of the cross sections. The line of cross section X–X′ is offset at the Coal Bank Pass fault, and the line of cross section Y–Y′ is offset at the northern branch of the Molas Creek fault zone. Sources of measured stratigraphic sections: 1, 5, 13, 16, 18, and 21 from Baars and See (1968); 1–7 and 18–20 from Block (1986); 6–15, 17, and 18 from field measurements by author.
boulder conglomerate shows that boulders from paleotopographically high Uncompahgre quartzite were transported onto paleotopographically lower Precambrian granite and were concentrated along a north-facing scarp at the southern branch of the Molas Creek fault zone.

Distribution of Ignacio quartzite-boulder conglomerate along the faults indicates synsedimentary south-facing scarps along the Coal Bank Pass and Snowdon faults and a north-facing scarp along the southern branch of the Molas Creek fault zone. The juxtaposition of the Uncompahgre Group against older Precambrian igneous and metamorphic rocks on the north and south indicates a structurally low Grenadier fault block in Precambrian time. Paleotopographic scarps, facing away from the Grenadier fault block during deposition of the Ignacio quartzite-boulder conglomerate, may have been a result of differential erosion of the structurally higher fault blocks on both north and south (Baars and See, 1968) and/or of a component of fault inversion after pre-Ignacio erosional planation. In contrast, both sides of the Snowdon fault are in the Uncompahgre Group. A south-facing paleotopographic scarp followed the trace of the Snowdon fault rather than Uncompahgre stratigraphic units, indicating that the scarp reflects fault movement, either pre- or synsedimentary with respect to the Ignacio boulder conglomerate.

**Devonian-Mississippian**

The McCracken Sandstone Member of the Upper Devonian Elbert Formation unconformably overlies the Ignacio Formation, thins northward toward the Coal Bank Pass fault, and pinches out northward approximately at the fault (section 7, X–X′ in Fig. 3) (Baars and See, 1968). Between the Coal Bank Pass and Molas Creek faults, the McCracken Sandstone Member is generally absent (Fig. 3) but may be represented by sporadically distributed sandstone along the south side of the Snowdon fault (Fig. 2). In an approximate mirror image of the block south of the Coal Bank Pass fault, the McCracken Sandstone Member thins southward toward the Molas Creek fault (sections 17–21, Y–Y′ in Fig. 3) and is absent directly south of the southern branch of the fault zone (section 16, Y–Y′ in Fig. 3). The distribution of the McCracken Sandstone Member duplicates that of the Ignacio Formation, indicating that the Late Cambrian paleotopography was replicated in the Late Devonian, either by differential erosion or by minor fault reactivation.

The Elbert Formation of shale and thin-beded carbonate rocks above the McCracken Sandstone Member varies little across the area (Baars and See, 1968). The succession is uniform in lithology and nearly uniform in thickness across both the Coal Bank Pass and Molas Creek faults; however, it thins locally over small fault blocks north of the Coal Bank Pass fault (sections 8–9, X–X′ in Fig. 3) and is very thin or absent locally along the south side of the Snowden fault (Fig. 2). The distribution of the upper part of the Elbert Formation indicates subdued paleotopography across both boundaries of the Grenadier fault block and possibly minor fault movement within the block.

The regionally extensive Devonian Ouray Limestone and Mississippian Leadville Limestone both are represented in a generally dolomitized and relatively massive carbonate unit on and adjacent to the Grenadier fault block (Baars and See, 1968). A karst surface on the carbonate unit is overlain unconformably by red beds of the Pennsylvanian Molas Formation. The thickness of preserved carbonate beneath the unconformity varies across and adjacent to the Coal Bank Pass, Snowdon, and Molas Creek faults (Fig. 3), suggesting fault reactivation along the Grenadier fault block. Locally, nndonolitized limestone in the uppermost preserved beds contains Devonian fossils, indicating local tilting and erosional truncation of the Mississippian Leadville part of the carbonate succession prior to deposition of the Molas Formation (sections 13–14, X–X′ in Fig. 3) (Baars and See, 1968). Locally along the south side of the Snowden fault, the Devonian-Mississippian units are thin to absent (Spoelhof, 1976).

**Pennsylvanian-Permian Stratigraphy**

The red beds (dominantly mudstone and siltstone) of the Pennsylvanian Molas Formation are highly variable in thickness on a local scale, reflecting paleotopographic relief on the karst surface on the Ouray-Leadville carbonate rocks (Baars and See, 1968; Spoelhof, 1976). The fine-grained red beds of the Molas Formation grade up into a succession of gray shale, sandstone, and limestone of the Pennsylvanian Hermosa Group.

The Pennsylvanian Hermosa Group is a thick (~870 m), cyclic succession of shallow-marine limestone, mudstone, and deltaic sandstone units (e.g., Baars, 1966; Spoelhof, 1976; Evans, 2002). The limestone units are typically shallowing-upward successions no more than 12 m thick (Spoelhof, 1976). Cyclic clastic successions of mudstones, containing marine fossils; sandstones, containing fragmented plant fossils; and coarser grained, cross-stratified sandstones with scoured bases are interpreted to be prodelta, distal-bar to delta-front, distributary-channel, and delta-plain deposits (e.g., Spoelhof, 1976; Evans, 2002). The coarsening-upward clastic successions are generally no more than 20 m thick, suggesting the maximum paleobathymetry of the delta front. The coarse clastic sediments indicate proximity to a sediment source in the general area of the Uncompahgre uplift. Extensive shallow-marine limestone units interbedded with the deltaic successions are consistent with cyclic eustatic changes in sea level, which are well documented by evaporite cycles in the more distal, central part of the Paradox basin (e.g., Peterson, 1966; Hite and Cate, 1972). The shallow-marine to deltaic facies are sensitive indicators of minor differences in paleotopographic/paleobathymetric relief and, thus, are useful in recognition of synsedimentary structural relief. Facies variations in the lower part of the Hermosa Group are interpreted to indicate paleobathymetric relief at the boundaries of the Grenadier fault block (Spoelhof, 1976). Local truncation of Paleozoic units beneath the basal Hermosa beds on the south side of the Snowden fault, as well as quartzite boulders (from the Uncompahgre Group) in the lowermost Hermosa Group just north of the fault, indicates relative uplift of the south side of the Snowden fault (Spoelhof, 1976).

The Hermosa Group is overlain by the coarser red-bed succession of the Permian Cutler Group (e.g., Baars, 1966; Baars et al., 1988), which reflects an increase in clastic sediment supply from the Uncompahgre uplift. Truncation of folded Cutler Group beds at an angular unconformity beneath Triassic strata documents Permian deformation along the Sneffels fault block (Weimer, 1980).

**Structural Geology**

Fault Block between the Snowdon and Coal Bank Pass Faults

The fault block between the Snowdon and Coal Bank Pass faults consists of nearly vertical units of quartzite and phyllite in the Uncompahgre Group folded by a vertically plunging, north-facing, map-scale syncline (Figs. 2 and 4) (Harris et al., 1987). On the northwest-striking western limb, the vertical quartzite-phyllite succession is unconformably overlain by an Elbert-Ouray-Leadville succession with an average angular discordance of ~90° (X–X′ in Fig. 3). The Elbert-Ouray-Leadville succession is folded into flat-bottomed synclines and northwest-verging asymmetric anticlines broken by some steep faults (Fig. 4). Exemplifying the geometry of the folds, the Ouray-Leadville carbonate can be traced along both limbs and around the plunging nose of the most southerly anticline (Fig. 4). The angle of dip on the
Pennsylvanian Hermosa Group
Pennsylvanian Molas Formation
Mississippian Leadville Limestone and Devonian Ouray Limestone undivided
Devonian Elbert Formation and Cambrian Ignacio Formation undivided
Precambrian Uncompahgre Group
quartzite
phyllite
Precambrian Twilight Gneiss

Thomas

Snowdon fault
Coal Bank Pass fault

A
B
C
A'
B'
C'

10,000
9500
10,000
9500
10,000
9500

Pennsylvanian Hermosa Group
Pennsylvanian Molas Formation
Mississippian Leadville Limestone and Devonian Ouray Limestone undivided
Devonian Elbert Formation and Cambrian Ignacio Formation undivided
Precambrian Uncompahgre Group
quartzite
phyllite
Precambrian Twilight Gneiss

Downloaded from https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/3/3/119/865160/i1553-040X-3-3-119.pdf by guest
steep northeast limb increases southeastward along strike and up plunge, commensurate with increase in amplitude of the conical fold. A steep fault breaks the up-plunge part of the steep limb. The steep limb and the fault in the cover strata are aligned above the contact between the underlying vertical phyllite and quartzite, and the fault displaces the phyllite upward into the core of the anticline in the cover strata with respect to the quartzite beneath the adjacent syncline in the cover strata. Farther north, bedding attitudes and outcrop patterns indicate the limbs of two other, more deeply eroded anticlines. Some steep faults with small displacement appear to be nonsystematically distributed (Fig. 4).

The folds and fold hinges in the Paleozoic strata are systematically distributed with respect to phyllite and quartzite units in the unconformably underlying Uncompahgre Group. Anticlines in the cover strata are positioned over vertical phyllite units, and flat-bottomed synclines in the cover strata are positioned over vertical quartzite units. Fold hinges in the Elbert-Ouray-Leadville succession are positioned above and are parallel with the strike of the lithologic contacts in the underlying, vertical succession of quartzite and phyllite units (Fig. 4). Wavelengths of the folds in the Paleozoic strata correspond to the stratigraphic thickness of the phyllite and quartzite units, averaging ~200 m. An average enveloping surface defined on the unconformably truncated quartzite units is relatively planar, but the phyllite extends above the average truncated quartzite surface into the cores of the anticlines in the cover strata (Fig. 4). The structural relief of the folded unconformity corresponds to that of the overlying Paleozoic strata, even though bedding in the underlying metasedimentary rocks is approximately perpendicular to the palinspastic (prefolding) configuration of the unconformity. Each of three anticlines plunges and flattens northeastward along strike of the underlying quartzite-phyllite, and the plunging noses of the anticlines define a sinistral, en echelon arrangement, which trends northward between the Coal Bank Pass and Snowdon faults (Fig. 4).

The alignment of hinges in the folded Elbert-Ouray-Leadville succession with contacts between the vertically dipping quartzite and phyllite units (Fig. 4) indicates a genetic association of differential upward displacement of the phyllite with the anticlinal folding of the cover succession. The systematic asymmetry of the anticlines is consistent with compressional, top-to-northeast displacement of the phyllite with respect to the quartzite. The geometry of the folds documents northeast-southwest shortening parallel with bedding in the Elbert-Ouray-Leadville succession and perpendicular to foliation in the phyllite. The folds in the cover succession may have been a passive response to deformation of the phyllite; however, bedding-parallel shortening of the cover succession is consistent with compression perpendicular to foliation in the phyllite. No data are available to discriminate between distributed slip on phyllite foliation or brittle faulting; however, the thickness of the phyllite units must have been reduced commensurate with the shortening in the cover succession across each anticline. Asymmetry of the folds is consistent with northeast-southwest compression, and the en echelon arrangement of the fold noses indicates sinistral transpression between the Snowdon and Coal Bank Pass faults.

The time of folding in the block between the Snowdon and Coal Bank Pass faults is not constrained by available data. The Elbert-Ouray-Leadville succession thickens gradually northward across the fault block but shows no systematic relationship to the distribution of quartzite and phyllite in the substrate (Fig. 3). The folds are clearly expressed in the Ouray-Leadville massive carbonate, however, the present outcrop trace of the base of the unconformably overlying Molas Formation is northeast of the northwest ends of the plunging folds (Fig. 4), precluding determination of whether the folds are younger or older than Molas deposition.

Snowdon Fault

The Snowdon fault is within the Grenadier fault block of the Precambrian Uncompahgre Group and Paleozoic cover strata (Fig. 2). Locally, where the Uncompahgre Group on the south is juxtaposed against the upper part of the Pennsylvanian Hermosa Group on the north, the maximum vertical separation on the Snowdon fault is ~900 m (Fig. 2; E′–E′ in Fig. 5). The down-to-north vertical separation indicates inversion of the sense of separation indicated by the distribution of the Cambrian Ignacio quartzite-boulder conglomerate along the Snowdon fault. A straight map trace across the canyon of Lime Creek shows that the fault is nearly vertical (Fig. 2). Along the Snowdon fault, a narrow array of anastomosing faults bounds lozenge-shaped horses of various Pennsylvanian and older stratigraphic units, and other faults splay at small angles from the primary fault (Fig. 2). Westward along strike within ~3.5 km from the point of maximum separation, the vertical separation decreases to zero; and a distinct fault trace ends westward in the core of a steep, symmetric, upright anticline in the Hermosa Group (Fig. 2; B–B′ in Fig. 5). Small faults splay into the steep limbs of the anticline.

In the fault block north of the Snowdon fault, the Hermosa beds are folded in a distinct anticline-syncline pair (Figs. 2 and 6; D–D′ in Fig. 5). The fold axes trend approximately N70W and intersect the generally west-striking Snowdon fault at angles of 20° to 30° (Fig. 2). The folds plunge away from the fault, and amplitude decreases away from the fault along the plunge of the folds.

Determining the sense of slip on the Snowdon fault is critical to regional interpretation of kinematics of the Ancestral Rocky Mountain structures. The steep dip and down-to-north vertical separation are compatible with dip-slip displacement. In excellent exposures along Lime Creek canyon (readily viewed from an overlook on U.S. Highway 550, Fig. 7), north-dipping Hermosa beds on the north side of the Snowdon fault have the appearance of a drag fold, juxtaposed against upthrown Uncompahgre metasedimentary rocks, indicating down-to-north dip slip. The north-dipping beds, however, are the south limb of the syncline that diverges obliquely from the Snowdon fault, and that fold limb continues westward as the north limb of the symmetric anticline into which the Snowdon fault ends westward along strike. Furthermore,
Figure 5. Structural profiles of base of Pennsylvanian rocks (base of Molas Formation) showing along-strike variations in vertical separation along the Coal Bank Pass, Snowdon, and Molas Creek faults. Lines of cross section are shown in Figure 2. The scale of the vertical axes shows elevation. Short, straight lines with numbers show apparent dips in plane of cross section computed and projected from bedding-attitude measurements. Southward thinning of part of the Hermosa Group north of the Snowdon fault (Fig. 8) is in cross section F–F'; angular unconformity within the Hermosa Group south of the Snowdon fault (Fig. 9) is in cross section B–B'.

1. Molas Creek fault
2. Little Molas Lake fault
3. Snowdon fault
4. Andrews Lake fault
5. Coal Bank Pass fault
6. Snowdon fault
7. Andrews Lake fault
8. Little Molas Lake fault
9. Molas Creek fault
10. Andrews Lake fault
11. Little Molas Lake fault

1000 m scale
Figure 6. Aerial photograph of topographic flatirons on folded limestone and sandstone beds of Hermosa Group north of the Snowdon fault, showing trends of fold axes and locations of traverses of measured sections (in Fig. 8). Location of the aerial photograph is shown by outline in Figure 2.

Figure 7. Photographs of north-dipping Hermosa beds north of the Snowdon fault. Orientations of views are shown in Figure 2. (A) Distant view of folded Hermosa beds north (left in view) of the Snowdon fault; the Hermosa beds are juxtaposed against Uncompahgre Group quartzite and phyllite along the Snowdon fault (view to east). Within the Hermosa beds, a syncline-anticline pair diverges from the Snowdon fault and plunges northwestward (toward the lower left corner of the photograph). The Snowdon fault extends obliquely across the view from just south (right in view) of the highway in the lower right corner of the photograph, and passes between Snowdon Peak (on the horizon) and the folded Hermosa beds. (B) Closer view of synclinally folded Hermosa beds north (left in view) of the Snowdon fault, which is out of view off the right side of the photograph (view to east). The north-dipping Hermosa beds have the appearance of a drag fold on a down-to-north normal fault; however, the north-dipping beds are the common limb of a syncline that diverges westward from the Snowdon fault and the anticline into which the Snowdon fault ends westward (Fig. 2). In the anticline west of this view, Hermosa beds south of the Snowdon fault dip southward away from the fault (view in Fig. 9A), showing similar dips in both directions away from the fault.
west of Lime Creek canyon, Hermosa beds in the symmetric anticline dip both north and south away from the Snowdon fault, indicating that these dipping beds are not dip-slip drag folds. Alternatively, the abrupt along-strike decrease in separation, the along-strike termination of the fault in an upright anticline, the small lozenge-shaped horses, and the geometry of the fault splays, along with the steep dip of the primary fault, conform to the characteristics of a strike-slip fault (e.g., Wilcox et al., 1973; Sylvester, 1988). Termination of the fault along strike into the symmetric anticline and the small splay faults characterize a positive flower structure (Harding, 1985). Subhorizontal slickenlines observed locally along the fault support an interpretation of strike-slip movement. The divergence of the northwesterly plunging fold axes from the west-striking Snowdon fault indicates sinistral strike-slip displacement.

Stratigraphic relationships can be used to constrain the time of the fault movement. On the northern fault block, the Hermosa stratigraphy is excellently exposed in large flatirons (Fig. 6), enabling measurement of several stratigraphic sections and precise correlation by outcrop tracing between them. Five stratigraphic sections of the middle part of the Hermosa Group were measured, using conventional field techniques, at sites spread along an alignment away from the Snowdon fault (Figs. 6 and 8). The sections include multiple, well-exposed units of limestone and sandstone, as well as intervening shale units that are poorly exposed. In addition, correlations were extended to a previously published measured section (Spoelhof, 1976) farther from the Snowdon fault (Figs. 6 and 8). The measured sections farthest north of the Snowdon fault document a relatively uniform thickness of the stratigraphic succession, including specific sandstone and limestone units (sections H-4 to H-6, Fig. 8). In contrast, the measured sections closer to the fault show progressive thinning toward the fault of the cumulative succession and of specific units within it (sections H-4 to H-1, Fig. 8). Gradual thinning is evident within 400 m of the fault, and thinning is most pronounced within 200 m of the fault (Fig. 8). Synsedimentary dip angles may be calculated from the thickness gradients. A calculation of incremental synsedimentary dips, within stratigraphic intervals ~70 m thick, shows dips as steep as 18° northward within 200 m of the fault. The cumulative dip angles in the lower part of a thicker stratigraphic interval are steeper (Fig. 8), indicating progressive rotation of the beds upward toward the fault. Synsedimentary dip angles decrease northward away from the fault. Lack of complete exposure precludes a definitive determination of whether the thinning is a result of angular unconformities or of progressive thinning of successive units; however, stratigraphic thinning toward the Snowdon fault is clearly documented (Fig. 8). Thinning toward the fault indicates a synsedimentary growing uplift with northward dip away from the north side of the Snowdon fault during Hermosa deposition.

On much of the structurally higher block south of the Snowdon fault, the Hermosa Group has been eroded, and Hermosa beds are preserved only to the west down plunge, including in the anticline near the western end of the fault (Fig. 2). A high cut along U.S. Highway 550 exposes the steep south limb of the symmetric positive flower structure (anticline) and an abrupt hinge to more gentle dips (Figs. 2 and 9A; B–B′ in Fig. 5). Within the gently dipping Hermosa beds south of the hinge, an angular unconformity between a sandstone unit and underlying beds of shale and sandstone has an angular discordance of ~4° and truncates >8 m of beds (Fig. 9). The beds below the angular unconformity dip southward, the same direction as the south limb

---

**Figure 8. Stratigraphic cross section of beds in Hermosa Group north of the Snowdon fault.** Locations of traverses of measured sections are shown in Figure 6. Because of outcrop orientations, the traverses of the measured sections are oblique to the trace of the Snowdon fault. The plane of this cross section is perpendicular to the Snowdon fault; the traverses of the measured sections are projected onto the plane of the cross section to show thickness variations with respect to distance from the fault. Cross section with 3x vertical exaggeration illustrates correlations between measured sections, and cross section with no vertical exaggeration shows true angular relationships. Section H-6 is from Spoelhof (1976).
of the anticline. The exposure of the angular unconformity extends southward from 200 m to 400 m away from the Snowdon fault. The angular unconformity exposed in the highway cut and a similar unconformity stratigraphically higher in the Hermosa Group on the same fold limb have been interpreted to indicate synsedimentary movement on the Snowdon fault and associated folds (Baars, 1966; Baars and See, 1968; Spoelhof, 1976). Alternatively, the angular discordances have been interpreted, in the context of deltaic depositional environments of the Hermosa Group, to be a result of downlap of delta-front foresets and truncation beneath reworked delta-platform deposits (Evans, 2002). The positions of these unique structures adjacent to the trace of the Snowdon fault and the associated anticline, as well as the consistency of dip directions of the truncated beds and of the anticline limb, suggest a genetic relationship to synsedimentary faulting and folding. Synsedimentary slump faults displace beds within the steep limb of the anticline (Spoelhof, 1976; Evans, 2002).

The southward dip of beds beneath the angular unconformity south of the Snowdon fault is similar in style and magnitude to the dip calculated from northward thickening in the succession north of the fault. The opposite directions of synsedimentary dip indicate an upright anticline with a crest along the Snowdon fault. The Hermosa synsedimentary anticline is identical in location and geometry, but not in amplitude, to the present structure of the Snowdon fault and positive flower structure (anticline). The incremental dip angles indicated by stratigraphic thinning toward the Snowdon fault within the Hermosa Group are less than the present structural dips on both limbs of the positive flower structure (anticline) associated with the Snowdon fault (Fig. 5), and the beds that show thinning toward the fault were subsequently folded. The structural similarities suggest a progression from a low-amplitude synsedimentary anticline into the present positive flower structure along the Snowdon fault in a persistent kinematic system. By analogy with the coincident later structure, the synsedimentary Hermosa structure is interpreted to be a sinistral strike-slip fault and positive flower structure.

The location of the Snowdon fault was inherited from the fault that controlled deposition of the Cambrian Ignacio boulder conglomerate. The age of the latest movements on the Snowdon fault and the associated positive flower structure are not specifically constrained; however, both structures end westward within strata of the Hermosa Group down plunge and down the dip on the west flank of the Laramide San Juan dome. The Hermosa Group dips westward beneath the Permian Cutler Group west of the western end of the Snowdon fault, and whether the fault might have projected upward into the Cutler Group cannot be determined. All of the structural relief of the Snowdon fault could be Pennsylvanian age, and no beds younger than Hermosa can be shown to be displaced by the Snowdon fault. Laramide structure as expressed in post-Pennsylvanian rocks consists of relatively gentle westward dip from the crest of the San Juan dome. Although some reactivation of the Snowdon fault could be Laramide, that cannot be confirmed because of lack of preserved post-Pennsylvanian strata over the fault.

**Coal Bank Pass Fault**

The Coal Bank Pass fault is the boundary between the Uncompahgre Group on the Grenadier fault block and the Precambrian Twilight Gneiss on the south (Fig. 2). The Coal Bank Pass fault is geometrically similar to the Snowdon fault within the Grenadier fault block, including steep dip and anastomosing splays. Maximum vertical separation of the base of the Paleozoic cover is at least 200 m, but separation decreases northward along strike (Fig. 2; A–A’ and B–B’ in Fig. 5). The Coal Bank Pass fault ends northward in the core of an upright, steep, symmetric anticline in the Hermosa Group. The fault in the Hermosa Group was inherited from the boundary fault between the Uncompahgre Group and the Twilight Gneiss. The geometry of the fault and associated anticline in Hermosa beds conforms to that of a positive flower structure along a strike-slip fault. Northwest of the end of the Coal Bank Pass fault, and northwest of the northwest-plunging anticline, the Hermosa beds dip westward beneath the Permian Cutler Group, which apparently is not deformed by the fault or the fold.

**Andrews Lake and Little Molas Lake Faults**

The Andrews Lake fault and Little Molas Lake fault are exposed entirely within the Hermosa
Lake fault (location 10B, Fig. 2), one limestone bed within a succession of sandstone and shale units is broken by sandstone dikes (Fig. 10B). Some dikes appear randomly oriented; however, most of the sandstone dikes are arrayed in distinct hexagonal patterns. The hexagonal dike sets are interconnected and aligned along a N75W trend adjacent to and parallel with the lower hinge of a low-amplitude (<1 m), local monoclone. The sandstone dikes indicate dilation of the limestone bed and injection during dewatering of the sand.

Synsedimentary dip toward the Little Molas Lake fault and dilation of brittle limestone near the fault are consistent with a negative flower structure along a transtensional segment of a strike-slip fault. The trend of the monoclone, along which the array of sandstone dikes is aligned, with respect to the Little Molas Lake fault is consistent with sinistral strike slip. In addition to the kinematic implications of the synsedimentary structures, two small extensional faults with no evident synsedimentary deformation splay southward from the Little Molas Lake fault (Fig. 2).

**Molas Creek Fault Zone**

The younger (post-Molas), northern branch of the Molas Creek fault zone obliquely intersects the older (pre-Ignacio), southern branch that formed the boundary between the Uncompahgre Group in the Grenadier fault block and the Precambrian granite on the north (Fig. 2). Anastomosing faults bound horses of Pennsylvanian and older stratigraphic units along the northern branch of the Molas Creek fault zone. Vertical separation on the post-Molas fault decreases westward along strike, and the fault ends westward in an asymmetric anticline in the lower part of the Hermosa Group (Fig. 2; J–J′ to G–G′ in Fig. 5). The termination of the Molas Creek fault in an anticline in Hermosa beds, as well as the anastomosing branches along the fault, is analogous to similar structures along both the Snowdon and Coal Bank Pass faults, suggesting that all of the faults represent a similar mechanism, which is interpreted to be dominantly strike slip.

### REGIONAL IMPLICATIONS

The time of movement on Ancestral Rocky Mountains faults, primarily the large-scale boundary faults between uplifts and basins, has been constrained generally by the age of prograding, coarse clastic facies of Pennsylvanian-Permian age (e.g., Kluth and Coney, 1981; Ye et al., 1996; Dickinson and Lawton, 2003). The minimum age of faulting is constrained in few places, and some or all of the movement...
Pennsylvania sinistral faults, Ancestral Rocky Mountains

on some faults can be inferred to be Laramide rather than Ancestral Rockies. Stratigraphic constraints presented here document Pennsylvania sinistral (Hermosa) movement on some of the faults of the Grenadier fault block, in contrast to a common inference that those faults are entirely Laramide (e.g., Evans, 2002). Because the faults of the Grenadier fault block end along strike within the Hermosa outcrops, no post-Hermosa deformation can be documented. The Grenadier fault block is exposed within the Laramide San Juan dome, which has a broadly domal geometry, in further contrast to the steep faults and associated upright folds of the Grenadier fault block. Permian structure in the Sneffels fault block (north of the Grenadier fault block) is documented by an angular unconformity beneath Triassic strata over a dome fold in the Permian Cutler Group (Weimer, 1980). Along the northeastern boundary of the Uncompahgre uplift, folded angular unconformities indicate Pennsylvania-Permian northeast-directed thrusting, and distinct Laramide structures overprint the Ancestral Rockies structures (Hoy and Ridgway, 2002). Along the east side of the Front Range uplift, Laramide deformation reactivated some structures of Ancestral Rockies vintage (Gerhard, 1967). Further work is needed to distinguish Ancestral Rockies faults from Laramide faults, which is an essential step to understanding regional kinematics of the Ancestral Rockies.

Sinistral strike-slip movement along part of the southwest-boundary-fault system of the Uncompahgre uplift has important implications for kinematics of other segments of the same regional structure. The Grenadier and Sneffels faults block, and the faults associated with them, indicate the complexity of the boundary-fault system between the Uncompahgre uplift and Paradox basin. The east-west strike of the system of faults (Coal Bank Pass, Snowdon, Molas Creek, and smaller faults) along the Grenadier fault block departs from the regional more northwesterly strike of the boundary faults of the Uncompahgre uplift. The east-west–striking segment of the Grenadier fault block parallels similar east-west–striking segments of the Sneffels fault block and the Ridgeway fault, defining a distinct kink in the boundary between the Uncompahgre uplift and the Paradox basin (Fig. 1) (Stevenson and Baars, 1986). The consistent sinistral-slip sense on faults across the Grenadier fault block suggests a possibly pervasive regional system; however, the sense of slip on some faults may be a response to local stress fields within component blocks of the larger system. For example, Stevenson and Baars (1986) showed sinistral slip on the east-west–striking Ridgeway fault within a regional system of dextral slip across the Ancestral Rockies.

East of the kink, the main boundary fault (Ridgeway fault) of the Uncompahgre uplift, as well as the Sneffels and Grenadier fault blocks, bends abruptly to the southeast and south, and continues to an intersection with the north-striking Pecos-Picuris fault (Fig. 1) (Stevenson and Baars, 1986). In southern Colorado, near the intersection with the Pecos-Picuris fault, the northeastern boundary of the Uncompahgre uplift is the northeast-directed Sand Creek–Crestone thrust system (Fig. 1), which places basement rocks over Pennsylvania-Permian coarse clastic fill of the Central Colorado trough (Hoy and Ridgway, 2002). Compression along northwest-striking structures is compatible with sinistral strike slip along the east-striking kink.

Northwest from the kink, the faults curve to a northwest strike, and most of the displacement apparently is transferred to a single boundary fault at Gateway, Colorado (Fig. 1) (Stevenson and Baars, 1986). The boundary fault has been traced farther northwest into eastern Utah (Fig. 1), where seismic reflection profiles and deep wells document a northeast-dipping thrust fault at the boundary between the Uncompahgre uplift and Paradox basin (Frahme and Vaughn, 1983). A thick succession of Pennsylvania-Permian clastic sediment in the footwall beneath overthrust Precambrian crystalline rocks constrains the time of uplift. In a regional context, sinistral strike slip on the west-striking system of faults along the Grenadier fault block is consistent with top-to-southwest shortening along a northwest-striking, northeast-dipping fault to the northwest along strike of the regional system. The same regional sense of large block displacement accounts for both local expressions in the context of along-strike variations in dip and strike of the fault surface.

CONCLUSIONS

The boundary-fault system between the southwest side of the Uncompahgre uplift and the Paradox basin includes the Sneffels and Grenadier fault blocks southwest of the primary boundary fault (the Ridgeway fault); the fault systems strike east-west for some distance oblique to the regional northwesterly strike of the uplift. Following the Precambrian ancestry of the boundary faults of the Grenadier fault block, the same faults were reactivated and/or inverted episodically through the Cambrian and Devonian-Mississippian before being reactivated with more substantial vertical separation in Pennsylvania time (Baars and See, 1968). Faults associated with the Grenadier fault block have distinctive structural characteristics of sinistral strike-slip faults. Along the Snowden fault within the Grenadier fault block, vertical separation ends along strike in an upright, symmetric anticline in a pattern characteristic of a positive flower structure. Folds diverge from the fault in a pattern characteristic of sinistral strike slip. Stratigraphic thinning toward the fault and intraformational angular unconformities document growth of the positive flower structure during deposition of the Pennsylvania Hermosa Group. The timing indicates that the Snowden fault is an Ancestral Rockies structure. Other Grenadier faults have characteristics consistent with the better-documented history of the Snowden fault. The faults associated with the Grenadier fault block document sinistral strike-slip movement during Ancestral Rockies deformation, a sense of slip that is consistent with other structures regionally. Similar kinds of documentation of time and sense of slip on Ancestral Rockies faults are essential to the resolution of regional-scale kinematics and tectonics.

ACKNOWLEDGMENTS

Part of this research was supported by a grant from the National Science Foundation, including the field work of graduate research assistants, Tom Block and John Hoover. The ideas expressed here have benefited from continuing discussions and field work in the Ancestral Rockies with Don Baars; collaborations in the field with Gene Stevenson, Charles Waag, and Greg Mack; and discussions with Chuck Kluth and Eric Erslev. ArcInfo map compilation and other graphics were completed by Mike Solis and Matt Surfles. I thank Geosphere reviewers Art Goldstein, Chuck Kluth, and an anonymous reviewer.

REFERENCES CITED


Block, T.C., 1986, Tectonic controls on facies relationships and deposition of the Cambrian Ignacio and Devonian Elbert Formations, San Juan Mountains, Colorado [M.S., thesis]: Tuscaloosa, University of Alabama, 142 p.

Dickinson, W.R., and Lawton, T.F., 2003, Sequential intercontinental suturing as the ultimate control for Pennsylvanian Ancestral Rocky Mountains deformation:


Manuscript Received 7 September 2006
Revised Manuscript Received 22 December 2006
Manuscript Accepted 7 February 2007