Oblique Laramide Convergence in the Northeastern Front Range: Regional Implications from the Analysis of Minor Faults

Eric A. Erslev and Joe D. Gregson
Department of Earth Resources
Colorado State University
Fort Collins, CO 80523
(970) 491-6375
erslev@cnr.colostate.edu
Joe_Gregson@nps.gov

TOC

TRIP OVERVIEW

Faulting in the northeastern Front Range provides both an excellent test of Laramide tectonic models as well as surface analogs of fractured petroleum reservoirs. The field trip will examine the large-scale back-thrusting on the northeastern margin of the Front Range arch and the associated fractured strata. Several different methods of fracture analysis, ranging from simple conjugate geometry methods to complex stress tensor inversion calculations, will be compared on the outcrop. Examples of structures produced from regional and localized stress fields will be shown.

INTRODUCTION

The excellent, accessible exposures of the plunging structures in the northeastern Front Range of Colorado have made the area a classic locality in the Rocky Mountain foreland (Fig. 1). The southeastern plunge of the structures allows the observation of different structural levels within single structures. Well-preserved slickensided fractures are common in the quartz arenites of the Ingleside, Lyons, and Dakota sandstones. These fractures can be used to test kinematic and tectonic models for the Laramide foreland and provide surface analogs for sub-surface faulting in fractured hydrocarbon reservoirs.

This field trip will examine the structural geometry and fracture patterns in the zone of backthrusting on the northeastern flank of the Front

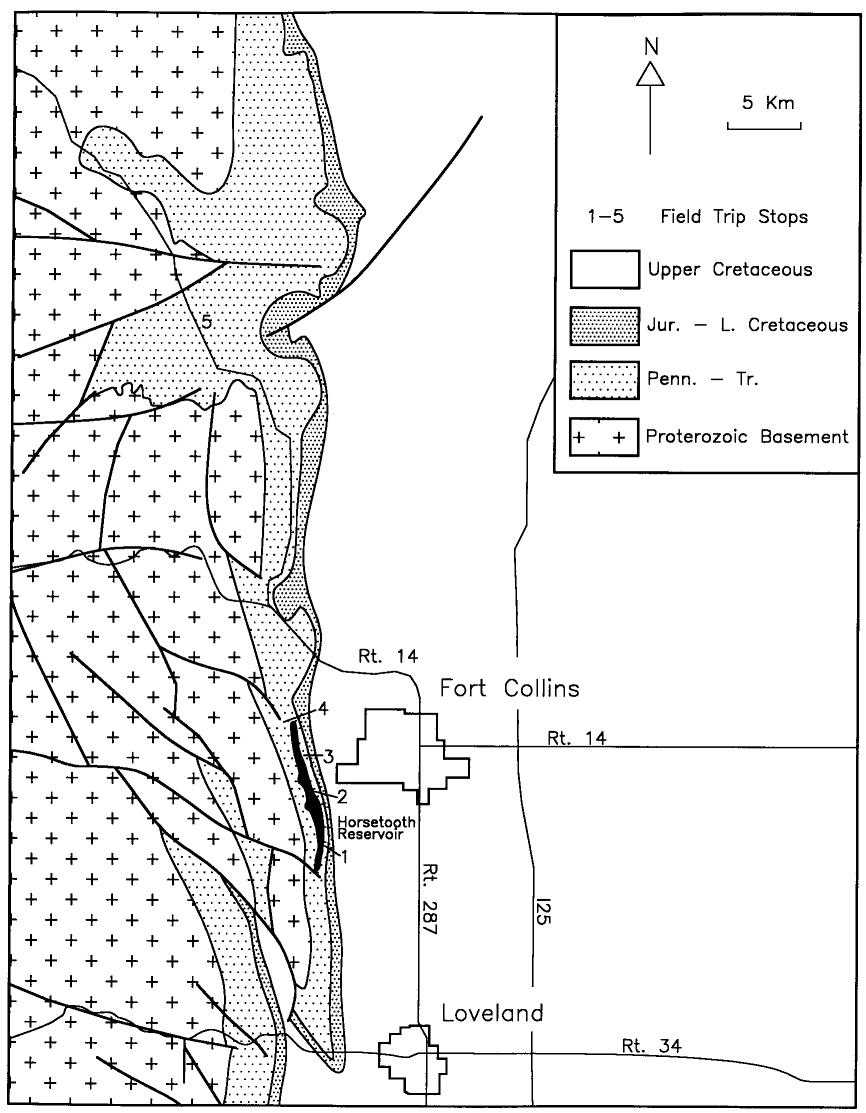

Figure 1. Simplified geologic map of the northern Front Range area showing field trip stops (1-5).

Range arch. The implications of the fracture patterns to the structural geology, tectonics, and petroleum potential of Laramide basement-cored structures will be discussed. Different methods of fracture analysis will be compared on the outcrop, illustrating the strengths and weaknesses of several techniques. Major differences in faulting between compression-perpendicular and compression-oblique structures will be used to illustrate the importance of structural trends to faulting within folds. Effects of regional vs. local stress fields on strain patterns will also be discussed.

LARAMIDE STRUCTURAL AND TECTONIC MODELS

The multiplicity of Laramide structural geometries in the Rocky Mountains has resulted in a mirroring multitude of kinematic hypotheses. In the 1970s and 1980s, hypotheses were strongly polarized into the antagonistic horizontal compression and vertical tectonics schools. The vertical tectonics school was dominant in the 1970s, represented by upthrust models (Prucha et al., 1965) and block uplift models (Stearns, 1971; 1978; Matthews and Work, 1978). In the 1980s, incontrovertible well and seismic evidence for thrusting of Precambrian basement over Phanerozoic sediments (e.g., Smithson et al., 1979; Gries, 1983; Lowell, 1983; Stone, 1985) swung opinion back towards models invoking horizontal shortening and compression.

The last decade has seen a broad agreement that horizontal compression is responsible for the Laramide orogeny. Seismic profiles (Smithson, 1979, Gries and Dyer, 1985), subthrust petroleum drilling at Laramide basin margins (Gries, 1983a), and balancing arguments (Stone, 1984; Erslev, 1986; Brown, 1988; Spang and Evans, 1988) have demonstrated that the Laramide was dominated by shortening due to horizontal compression, coincident in time with the thin-skinned Sevier thrust belt to the west (Schmidt and Perry, 1988). Still, it is important to note that high-angle dip-slip faults do occur in numerous locations in the Laramide foreland and may be of major importance in the basins, indicating distinct differences in the state of stress within thick- and thin-skinned foreland orogens.

The diversity of Laramide structural trends, with faults, folds, and arches trending in nearly every direction, has been attributed to multiple stages of differently oriented compression (Gries, 1983b, 1990; Chapin and Cather, 1983; Bergh and Snoke, 1992), reactivation of pre-existing weaknesses in the basement (Hansen, 1986; Stone, 1986; Blackstone, 1991; Chase et al., 1993; Huntoon, 1993), transpressive motions (Wise, 1963; Sales, 1968), indentation by the Colorado Plateau (Hamilton, 1988), and detachment of the crust (Lowell, 1983; Brown, 1988; Kulik and Schmidt, 1988; Verrall, 1989; Oldow et al., 1989; Erslev, 1993). These hypotheses may all be valid for individual areas within the foreland but their regional importance is not clear.

Throughout this debate, investigations in the northeastern Front Range have uniformly reported fault angles greater than 45^{o}, postulating a predominance of vertical motion over horizontal motion. In fact, the interpreted ratio of vertical motion over horizontal compression has increased through time (Fig. 2). Ziegler (1917; Fig. 2a) proposed motion on a planar, 50^{o}-dipping reverse fault underlying the Milner Mountain anticline. Boos and Boos (1957; Fig. 2b) also showed a planar reverse fault in an analogous section, but steepened the dip to 80^{o}. Prucha et al. (1965) introduced the concept of a concave-downward upthrust to the area, showing an increase in fault dip downward from 30^{o}-dipping thrusts in the sedimentary strata to vertical faults cutting basement. This allowed the authors to explain low-angle thrusts in the cover within a vertical tectonic framework. This upthrust geometry was adopted by Braddock et al. (1970) and Le Masurier (1970; Fig. 2c) for the Milner Mountain anticline, showing a 60^{o} dipping reverse fault at the surface that becomes vertical at depth. The most extreme interpretation of fault dips was contributed by Matthews and Sherman (1976; Fig. 2d) and Matthews and Work (1978) who suggested that a planar, 80^{o}-dipping normal fault formed the western margin of the Milner Mountain anticline.

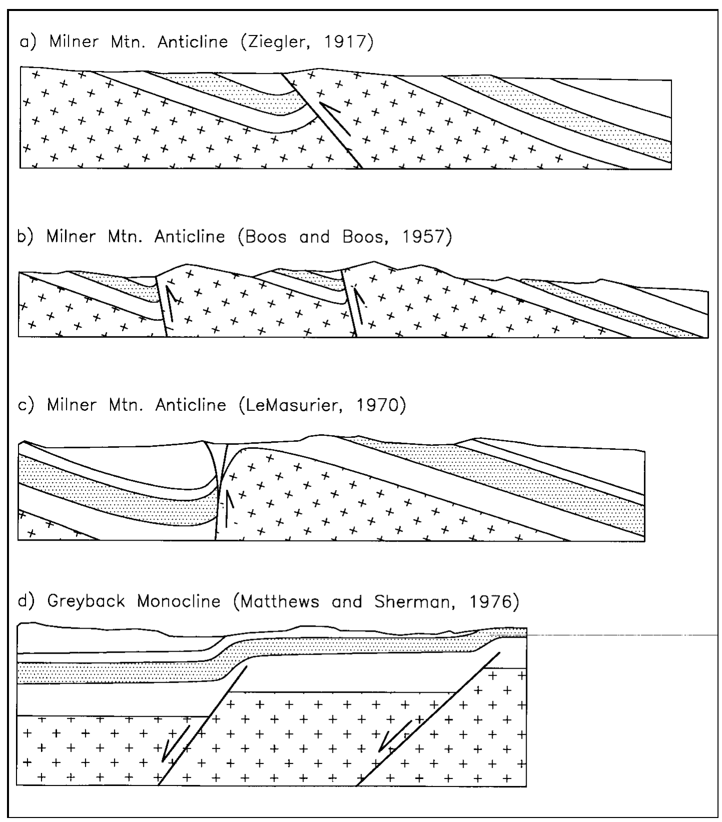

Figure 2. Evolution of structural interpretations through time as discussed in text.

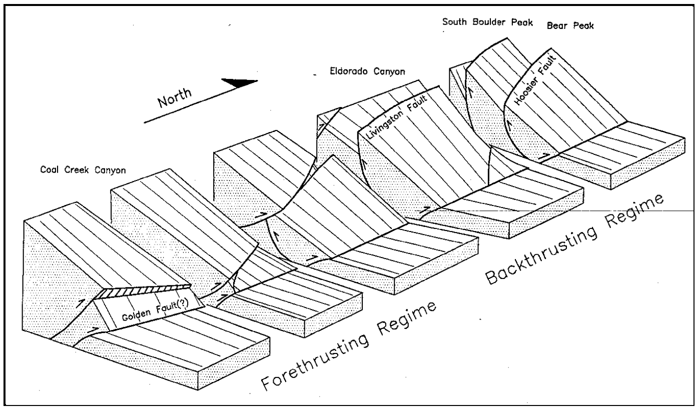

Figure 3. Block model of transitional thrust structure near Rocky Flats (from Selvig, 1994).

These interpretations of fault angle are in clear conflict with the evidence for horizontal compression in the Rocky Mountain foreland. Recent work at C.S.U. (Erslev and Rogers, 1993; Erslev, 1993; Selvig, 1994) has shown that fault dips in the Fort Collins area range from 20^{o} to 70^{o} to the northeast, consistent with the first cross sections of the area by Ziegler (1917). These angles of faulting are more compatible with the lateral compression indicated by seismic information to the north (Laramie Range) and south (Golden Fault: Jacob, 1983; Bieber, 1983; Selvig, 1994) which indicate large west-dipping thrust faults overlapping the western margin of the Denver basin. But the fault dip directions are opposite, with exposed thrust and reverse faults in the northeastern Front range near Fort Collins dipping to the northeast. These faults uplift the eastern, basinward side of the structure, in direct contrast to the overall uplift of the crystalline core of the range to the west.

Selvig (1994) addressed the origin of this along -strike variability of fault dip direction in the area of the Rocky Flats plant near Boulder, Colorado (Fig. 3). In this area, west-dipping thrusts of the Golden fault system diverge, with intervening blocks rotating toward the Denver basin by domino-style backthrusting. This zone of backthrusting widens to the north, with the hypothesized master, west-dipping Golden fault system becoming blind and never leaving the basement near Fort Collins.

FAULT ANALYSIS METHODS

Fault studies at CSU have focused on Laramide faults in strata deposited before the Laramide orogeny and after the Ancestral Rocky Mountain orogeny. Multiple fault orientations, usually at least 30 per locality, are measured and evaluated for shear sense from Riedel shear fractures using the methods of Petit (1987; Fig. 4) supplemented by direct thin section observations of representative faults. Slip directions on major Laramide faults are determined by slickenlines on parallel minor faults. Average slickenline (slip) directions are determined by eigenvector calculations. Regional stress directions are determined from strain-hardened minor faults in gently dipping Mesozoic strata several kilometers from major faults. By measuring faults from strata with variable dip directions, the effects of local stresses can be resolved.

Once the faults are divided into subsets, stress orientations can be determined using conjugate relationships, P-T dihedra (Allmendinger et al., 1989), and reduced stress tensor methods (Angelier, 1990). The possibility of multiple compression directions is evaluated by using the Compton (1966) method which calculates the ideal σ_1 orientation for each fault based on the average angle between conjugate pairs. Preliminary studies of strain-hardened faults show that this method can discriminate different compression directions when conventional conjugate, direct inversion (Angelier, 1990), and P-T dihedral methods just average the compression directions. Comparison of σ_1 directions with average slip directions allows the estimation of regional pure shear and simple shear deformation.

ROAD LOG AND FIELDTRIP STOP DESCRIPTIONS

This road log starts southeast of Fort Collins at the gravel parking lot at the northwest corner of the intersection of Interstate 25 and Harmony Road. The location of stops are shown on the geologic sketch map in Fig. 1. The first 4 stops are in the Horsetooth reservoir Quadrangle (Braddock et al., 1989), and stop 5 is in the Livermore Quadrangle (Braddock et al., 1988b).

0.0 Drive west toward the mountains on Harmony Road.

4.4 Cross College Ave. (U.S. Highway 287), the main street of Fort Collins.

6.5 Right turn and head north on Taft Hill Road.

6.9 Left turn and head west on County Road 38E.

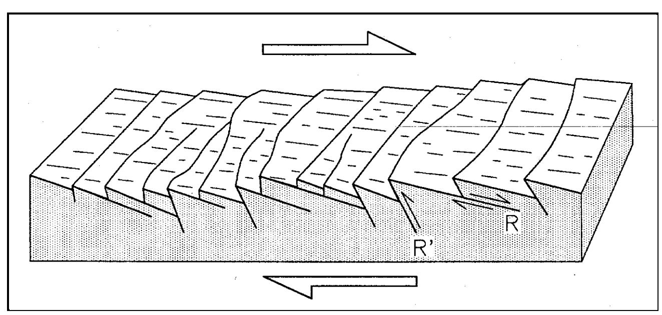

Figure 4. Diagram of a striated fault surface illustrating the stepped Riedel shear morphology (after Petit, 1987; Allmendinger et al., 1989; Gregson 1994).

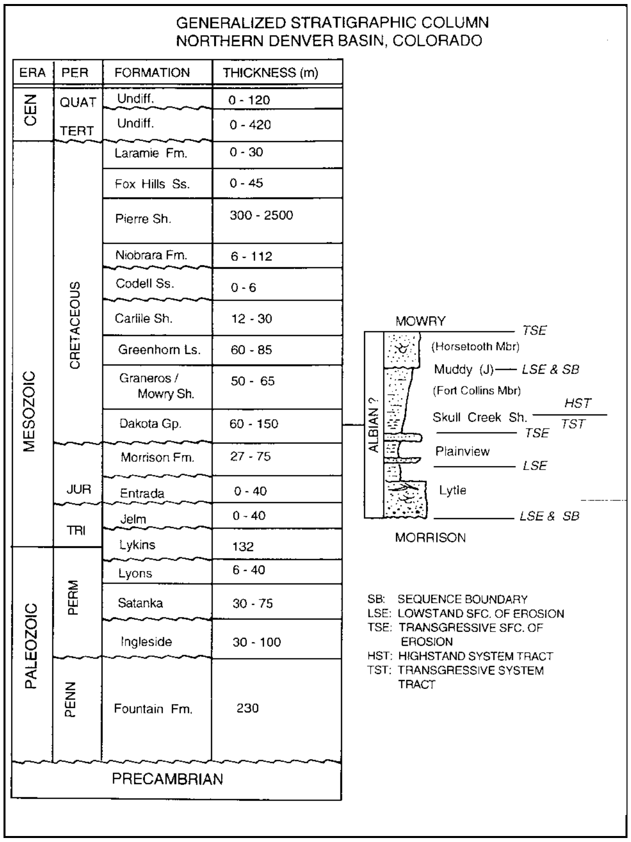

Figure 5. Stratigraphic column of the fieldtrip area. (from Graham and Ethridge, 1995).

7.8 On right, Niobrara Formation crops out between the Pierre Shale (to east) and the Benton Shale (to west).

8.4 Contact between Benton Shale (to east) and Dakota Group sandstones.

8.8 Area of road which collapsed in the Spring of 1995. Unusually wet conditions saturated the roadbed above the Skull Creek shale and accelerated slumping of the road. Repair of the roadbed included the installation of a culvert to drain the Skull Creek strike valley, replacement of the earth fill, and regrading of the slope below the road.

8.9 Turn right to head north on County Road 23.

9.1 Park on right in gravel lot at north end of Spring Dam.

Stop 1: Local Stratigraphy and Faulting

From the lip of Duncan's Ridge, a popular Fort Collins climbing cliff in the Lytle sandstone west of the parking lot, the rugged and irregular topography underlain by Proterozoic crystalline rocks lies to the west and is overlain by a late Paleozoic to Mesozoic clastic sequence (Fig. 5). This sequence contains three resistant sandstone units, the Permian Ingleside Formation, Permian Lyons Formation, and Cretaceous Dakota Group, which form well-defined hogbacks. The Dakota Group forms a sandwich of units, with the Lytle and Plainview Sandstones below the Skull Creek Shale (Fig. 6.), which is overlain by the Fort Collins and Horsetooth sandstones (also called the Muddy Sandstone). Strike -valleys are formed by the less resistent Fountain, Owl Canyon, and Triassic-Jurassic formations. Units generally dip 15^{o} to 30^{o} east toward the northern Denver basin.

Laramide basement faulting in the area caused folding of the overlying sedimentary strata. All workers in this area have proposed basement block motion, with the detailed analysis by LeMasurier (1970) and Erslev and Rogers (1993) showing only minor (20^{o}) basement rotations in the tip of the largest structure in the area, the Milner Mountain anticline. This can be seen on the excellent geologic maps of the region by Braddock et al. (1970, 1988a, 1988b, 1989) which show planar basement contacts offset by faults with minimal folding of the contact in the vicinity of the faults. These faults progressively lose displacement upward in the folded sedimentary strata, forming fault-propagation folds (Erslev, 1991; Erslev and Rogers, 1993). Of the six major faults that cut the Precambrian-Pennsylvania contact near Fort Collins, only the Milner Mountain Fault cuts the Dakota formation.

The strata sometimes form doubly-plunging anticlines, like Bellvue dome to the north, or more commonly, southeast-plunging anticlines cored by northwest-striking faults. Trenching of the major faults near Fort Collins show that they dip 20^{o} to 70^{o} northeast, consistent with the earliest interpretations of Ziegler (1917). Absolute slip directions, which have been interpreted as everything from strike-slip to dip-slip, are hard to determine from the major faults because their strain-softened gouge zones only preserve the last motion

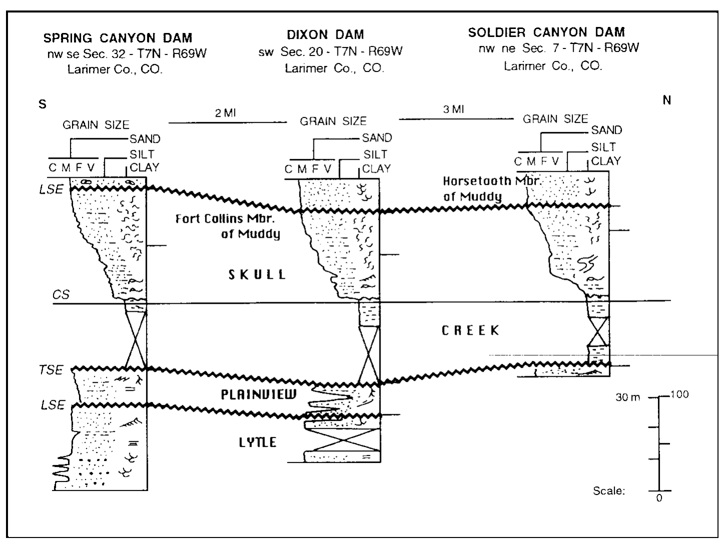

Figure 6. Stratigraphic cross section of Dakota rocks illustrating unconformities and sequence systems tracts (from Graham and Ethridge, 1995).

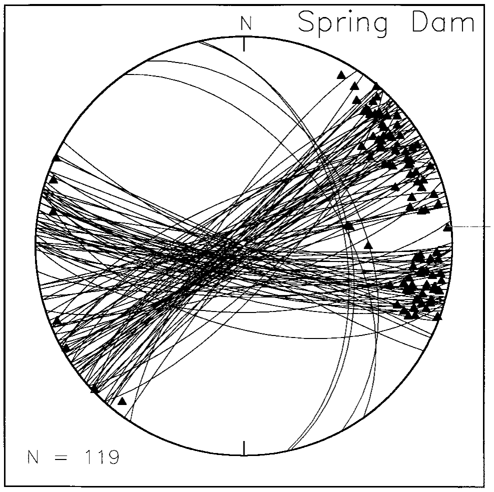

Figure 7. Slickensided fractures and lineations northeast of Spring Dam.

on the fault.

After the overview at Duncan's ridge, the trip will go east across the road to the Horsetooth sandstone which has excellent exposures of strike-slip fractures indicating near-horizontal N79E compression (Fig. 7). The silica-cemented quartz arenites of the Ingleside, Lyons, and Dakota formations preserve slickensided fractures throughout the region. Shear fractures in these units rarely follow bedding planes, suggesting that they form on ideal, "Andersonian" planes symmetric to the stress axes. Minor fault surfaces show excellent slickenlines in the fine-grained, low-porosity cataclasite which forms the surfaces. The multitude of shear fractures suggest that these planes are strain hardened, annealing after slip to be stronger than the original sandstone. This means that early phases of slip can be preserved along with later phases of slip. As a result, if multiple slip directions existed during Laramide deformation, they should be recorded by the fractures. Shear sense on the fractures is usually clearly indicated by Riedel fractures which intersect the major fault planes at an angle, giving a roughness to the plane in the direction of slip (Fig. 4).

9.1 Continue north on County Road 23 up the Skull Creek strike valley.

- At top of hill, note closed depressions often occupied by ephemeral ponds.

- Bear left at Y intersection with County Road 42C to continue northward on County Road 23.

10.6 Middle dam of Horsetooth Reservoir. Note the uniform bedding in the Dakota Group shales and sandstone.

11.2 Note tree on ridge to the right. This spot has a single fault plane with slickenside directions, indicating multi-directional, multi-stage Laramide compression. This is one of 2 localities in the region where we have found evidence of multiple stages of differently oriented compression.

11.8 Park on left in second gravel lot. Walk north to ridge crest.

Stop 2a: Regional Structural Overview

The basement-cored anticlines in the northeastern Front Range have been used to support several proposed styles of vertical uplift in the Rocky Mountain foreland. However, surveyed fault attitudes, stratal rotations, and balancing criteria document the overriding importance of horizontal compression. Northeast-dipping thrust and reverse faults cut the crystalline rocks with only localized basement folding. At higher structural levels, fault slip is transferred to folding in asymmetric fault-propagation folds.

However, none of the observations really explain the fundamental structural problem posed by the foothills of the northeastern Front Range: what is the relationship of these faults and folds to the main Front Range arch? All of these faults and folds exhibit the opposite shear sense of the regional structure. Their northeastern dip brings the basin-side up and the mountain-side down, in direct conflict with the overall uplift of the range.

Exposures of emergent, west-dipping master thrusts north and south of this area suggest blind thrusting in the northeastern Front Range. The surface faults appear to be backthrusts off of a blind master thrust that looses slip eastward to these backthrusts (Fig. 8). This hypothesis is consistent with the west-vergent asymmetries of the Wellington and Fort Collins oil fields and explains the gradual transition from range to basin in the Fort Collins-Loveland area. To the south and north, the master thrust emerges from the basement and forms the west-dipping thrusts along the Laramie Range and central and southern Front Range (Golden thrust). While this hypothesis remains somewhat speculative without direct evidence of a blind master thrust in the northeastern Front Range, no other published explanation can account for the reversals of thrust vergence in the eastern margin of the Front Range.

- Either walk north on ridge crest to cattle guard and then follow the road (.3 miles) or return to the cars and drive

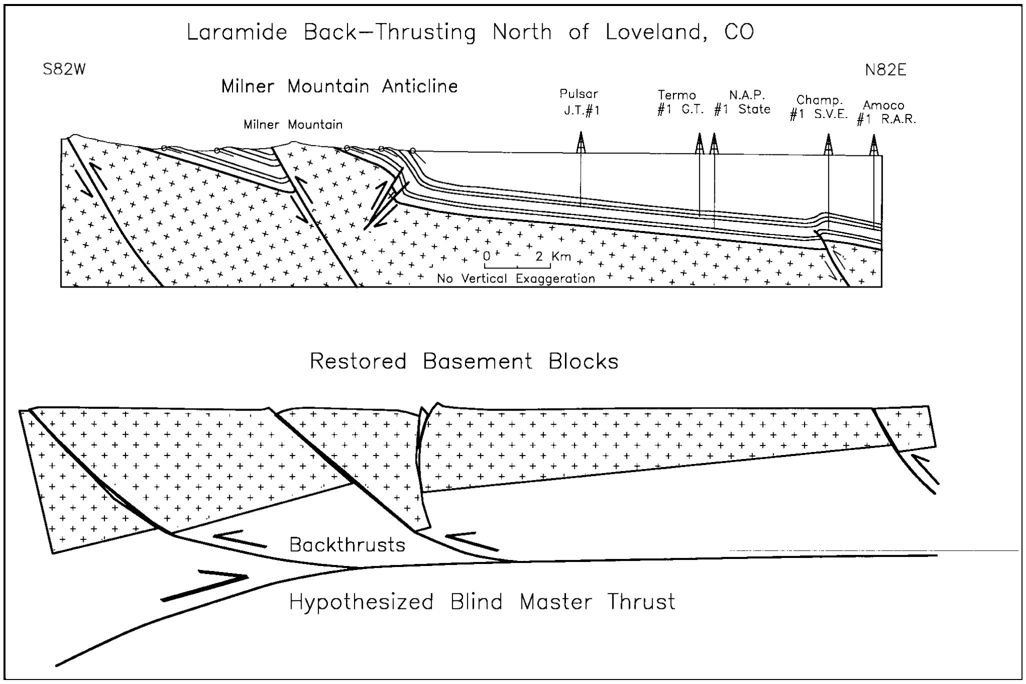

Figure 8. Blind master thrust hypothesis explains reversed thrust vergence along the eastern margin of the northern Front Range.

north, parking on the side of road (minimal space, not recommended) beyond cattle guard.

Stop 2b: Slab failure during Spring 1995

Just east of this spot, the Horsetooth and Fort Collins members of the Dakota Group are folded into a canoe-shaped syncline due to detachment on the Skull Creek Shale (Braddock and Eicher, 1962). To the north, the detachment moves to the contact between the Horsetooth and Fort Collins members, causing a buckling of the overlying Horsetooth member. The mechanism for these large scale landslides is important for the evaluation of the current stability of the hogbacks. The ponding of water in the Skull Creek Shale may have caused fluid overpressuring at the base of the hogbacks, facilitating failure.

Recent road construction exposed the well-bedded Plainview Formation at this stop last year and provided a perfect analog structure for this detachment. The daylighting of the planes combined with the unusually heavy precipitation last spring to cause the slab failure west of the road. Near the top of the ridge is a 1-meter-wide crown fracture which defines an upper boundary of the detached slab. The down-slope displacement of the slab was absorbed by buckle folding near the base of the slope.

11.8 Continue north on County Road 23.

13.7 Park at northeast corner of Soldier Canyon Dam and inspect the roadcut.

Stop 3: Syndepositional deformation of the Skull Creek Shale and oblique thrusting of the Muddy Sandstone

This locality shows a large recumbent fold in the Skull Creek Shale. Both syndepositional (Graham and Ethridge, 1995) and Laramide origins (Braddock et al., 1989) have been proposed. The fold axis is nearly perpendicular to the slickenlines, suggesting a tectonic origin, but the planar strata have nearly identical orientations on either side of the folded strata, suggesting a syndepositional slump origin.

Laramide faulting is evident in the overlying Muddy Sandstone. Initial Angelier (1990) analysis of faults from this area (Fig. 9A) indicated one stage of motion, but movement planes with 2 distinct slickenline directions suggest 2 directions of motion and stress. This is also indicated at this locality by the fact that the apparent conjugates have lineations which are not perpendicular to the intersection of the faults. Contouring Compton (1966) ideal σ_1 orientations shows 2 distinct maxima (Fig. 9B), indicating multi-directional stresses consistent with field observations. This possible dual stage deformation may be due to the termination of the Bellvue fault west of the outcrop.

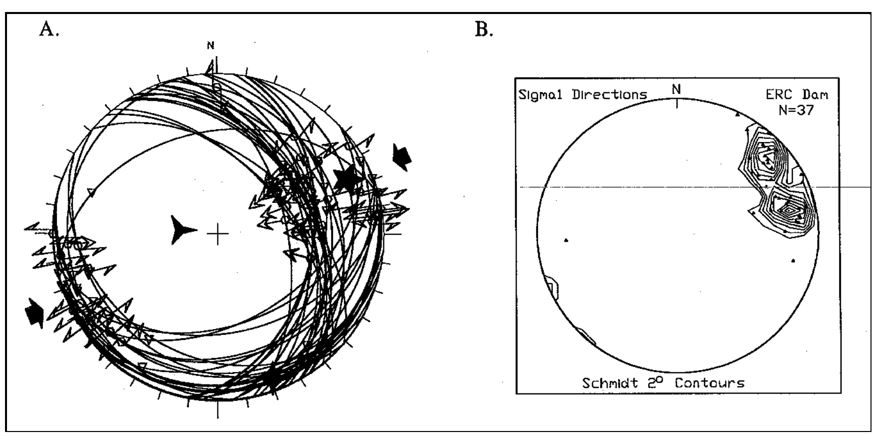

Figure 9. Paleostress analysis of slickensides seen at Stop 3 using A) the direct stress inversion method of Angelier (1990) and B) Schmidt contours of the ideal σ_1 direction method of Compton (1966).

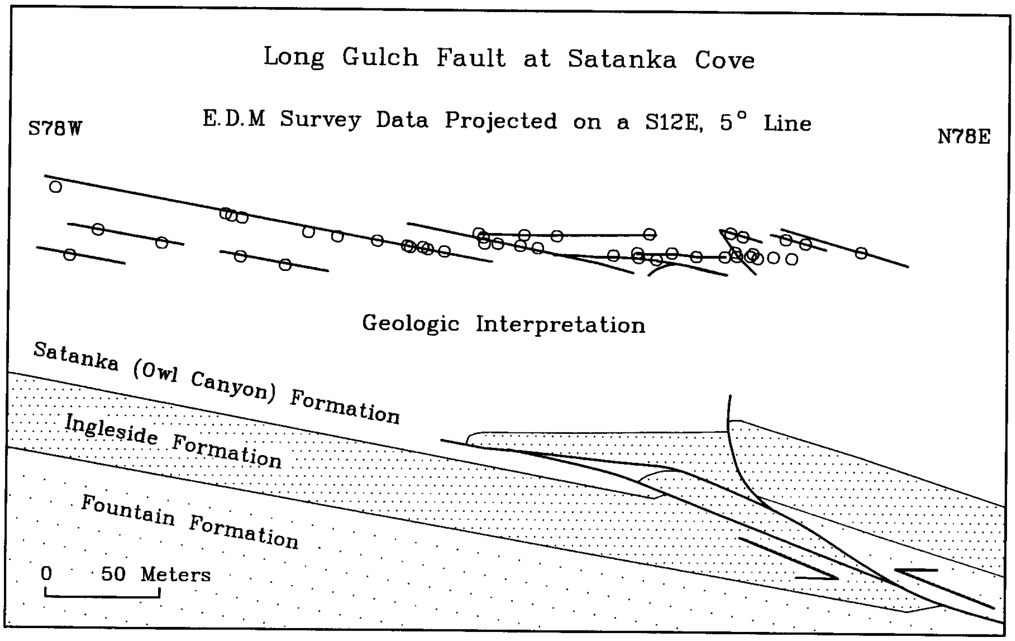

Figure 10. Down-plunge projection of Long Gulch fault at Satanka Cove.

- Continue north on County Road 23.

14.4 Turn left (west) on County Road 48C at North Dam.

14.7 Park near Satanka Cove self-service sign. Follow the northern shoreline west into Satanka cove.

Stop 4: Thrust duplication at Satanka Cove

This locality exposes the Long Gulch fault, which was described by Prucha et al. (1965) as a classic upthrust. Thrust faulting is clearly indicated by the repetition of the Ingleside Formation and the associated minor faults. But bed rotations are more consistent with listric thrusting on a concave upward fault–not a concave downward upthrust. To further document the geometry, the structure was surveyed with a laser E.D.M. unit, and the x,y,z coordinates of bedding and fault surfaces were down-plunge projected along the structural axis. The resulting down plunge projection (Fig.10) suggests a classic 'snake head' or ramp anticline caused by fault-bend folding. Since the footwall beds dip 20°, this dip is also the minimum dip of the fault.

Slickenside orientations in the hanging wall anticline were measured to evaluate the possibility of strike slip motion. Nearly all slickensides were down-dip on low-angle thrust planes, suggesting no appreciable strike-slip motion (Fig. 11). Prucha et al. (1965) did a similar analysis and concluded that horizontal compression consistent with thrusting was indicated by the low plunge of the acute bisector. This structure is roughly perpendicular to the estimated regional N70E σ_1 orientation, and the slip and stress directions do not seem to deviate as the main fault is approached.

- Return to the vehicles and go east on County Road 48C.

15.1 Turn left and head north on County Road 23C.

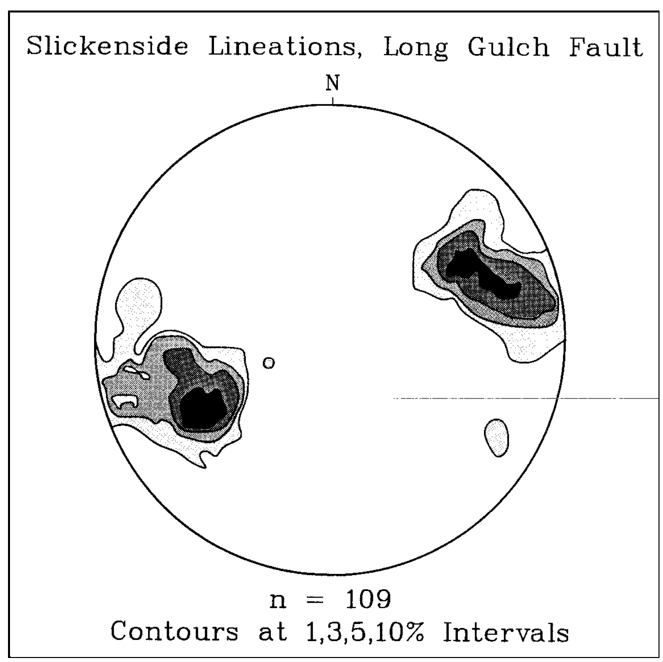

Figure 11. Lower hemisphere projection of slickenside lineations adjacent to the Long Gulch fault exposed in Satanka Cove.

16.7 Note the doubly-plunging Bellevue Dome straight ahead.

17.2 Turn right and go east on County Road 52E.

17.4 Poudre River crossing.

18.2 Turn left and head northwest on County Road 54G.

18.5 On east side of Bellevue Dome in the Owl Canyon Formation.

- Note large syncline defined by the Dakota Group directly up the road.

19.7 Turn left on U.S. Highway 287.

21.1 Turn off for Route 14 and the Poudre Canyon. Stay on U.S. Highway 287.

22.0 Optional Stop:

Note large deflection in the basement exposures caused by a major northwest striking fault. The overlying fault-propagation fold is highly conical, dying out to the southeast. The Ingleside Formation adjacent to the fault in the hanging wall anticline shows considerable bleaching, suggesting hydrocarbon migration through these rocks.

23.4 Continue north in the strike valley between the Dakota and Lyons sandstones.

23.9 Haystack Rock. Local legend has it that sharp ranchers sold the U.S. Army a haystack draped around this rock. A good deal by the pound...

28.7 Cutting through the Ingleside Formation at Owl Canyon.

30.8 Colorado Lien Limestone quarry. Limestone layers in the Ingleside Formation have been mined here for the sugar beet industry.

31.3 Entering the Livermore embayment, a structurally low area defined by northeast-striking faults.

34.5 Park on east side of road at first exposures of the Greyback monocline.

Stop 5: Greyback Monocline

The Greyback monocline exposes the Ingleside Sandstone on the northwestern side of the Livermore embayment where the unit includes limestone layers not present at Stop 4. Matthews and Sherman (1976) interpreted this structure as a drape fold over a normal fault (Fig. 2d). The obliquity of this N40E-trending structure to the regional stress direction and the existence of near vertical faults with parallel strikes to the north suggest a large component of strike-slip faulting. Minor faulting in the structure is characterized by strike-slip and extensional fracturing, with the antithetic conjugate particularly well represented. These near vertical fractures could provide vertical fluid conduits, which could have important consequences to fractured petroleum reservoirs.

In addition, the stress directions are anomalous and rotate within the monocline. Away from the fault, σ_1 orientations are oriented east-west, oblique to the general N70E trend of σ_1 orientations elsewhere in the area. As you approach the more steeply dipping forelimb of the monocline, the σ_1 orientations become more southeasterly. Two possible hypotheses present themselves: 1) stress directions were refracted due to the presence of an underlying weakness and/or 2) early formed faults were rotated by right-lateral strike-slip motion. What do you think?

34.5 Return to the vehicles and carefully do a U-turn and return south on U.S. Highway 287. There are several options for your return.

- Option 1: Fast but not as scenic. Return to Fort Collins on U.S. Highway 287, following Route 14 to I-25 (turn left off of Highway 287 at mile 57.6) or continuing to Harmony Road (mile 62.4).

- Option 2: Circuitous but scenic. Turn left off of Highway 287 at mile 35.9 and follow County Road 80 to Buckeye. Turn right and go south 5 miles to County Road 70. Turn left and go east to I-25.

- Option 3: Intermediate scenery and distance. Turn left off of Highway 287 at mile 40.4 on County Road 72 and go east. Jog 1 mile to the south on County Road 17 or 15 and follow County Road 70 east to I-25.

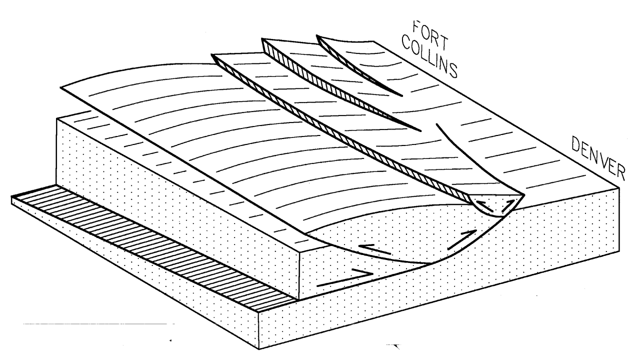

Figure 12. Block diagram of the transitional thrust structure along the Denver basin margin with the northeastern Front Range.

REFERENCES

Allmendinger, R.W., Aydin, A., Engelder, T., and Pollard, D.D., 1989, Quantitative interpretation of joints and faults: G.S.A. Short Course.

Angelier, J., 1990, Inversion of field data in fault tectonics to obtain the regional stress - III. A new rapid direct inversion method by analytical means: Geophysical Journal International, v. 103, p. 363-379.

Bergh, S., and Snoke, A., 1992, Polyphase Laramide deformation in the Shirley Mountains, south central Wyoming foreland: Mountain Geologist, v. 29, p. 85-100.

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

Blackstone, D.L., 1986a, Comments regarding Piney Creek thrust fault, Sheridan County, Wyoming: Contr. Geol., Univ. Wyoming, v. 24, p. 103.

Boos, C.M., and Boos, M.F., 1957, Tectonics of eastern flank and foothills of Front Range: A.A.P.G. Bull., v. 41, p. 2603-2676.

Braddock, W.A., and Eicher, D.L., 1962, Block-glide landslides in the Dakota Group of the Front Range Foothills, Colorado: Geological Society of America Bulletin, v. 73, p. 317-324.

Braddock, W.A., Connor, J.J., Swann, G.A., and Wolhford, D.D., 1988a, Geologic map of the Laporte quadrangle, Larimer County, Colorado: U.S. Geological Map GQ-1621.

Braddock, W.A., Calvert, R.H., Gawarecki, S.J., and Nutalaya, P., 1970. Geologic map of the Masonville quadrangle: U.S. Geol. Survey Geol. Quad. Map GQ -832.

Braddock, W.A., Calvert, R.H., O'Connor, J.T., and Swann, G.T., 1989, Geologic map of the Livermore quadrangle, Larimer County, Colorado: U.S. Geological Survey Map GQ-1618.

Braddock, W.A., Wohlford, D.D., and O'Connor, J.T., 1988b, Geologic map of the Horsetooth reservoir quadrangle, Larimer County, Colorado: U.S. Geological Survey Map GQ-1625.

Brown, W.G., 1984, A reverse fault interpretation of Rattlesnake Mountain anticline, Big Horn basin, Wyoming: Mountain Geologist, v. 21, p. 31 -35.

Brown, W.G., 1988, Deformation 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. 1-26.

Chapin, C.E., 1983, An overview of Laramide wrench faulting in the southern Rocky Mountains with emphasis on petroleum exploration, in Lowell, J.D., ed., Rocky Mountain foreland basins and uplifts: Rocky Mountain Association of Geologists, p. 169-179.

Chapin, C.E., and Cather, S.M., 1983, Eocene tectonics and sedimentation in the Colorado Plateau; Rocky Mountain area, in Lowell, J.D., ed., Rocky Mountain foreland basins and uplifts: Rocky Mountain Association of Geologists, p. 33-56.

Chase, R.B., Schmidt, C.J., and Genovese, R.B., 1993, Influence of Precambrian rock compositions and fabrics on the development of Rocky Mountain foreland folds, in Schmidt, C.J., Chase, R., and Erslev, E.A., eds., Laramide basement deformation in the Rocky Mountain foreland of the western United States: Geological Society of America Special Paper 280, p. 45-72.

Dahlstrom, C.D.A., 1969, Balanced cross sections: Canadian Jour. Earth Sci., v. 6, p. 743-757.

Elliott, D., 1983, The construction of balanced cross sections: Journal of Structural Geology, v. 5, p. 101.

Erslev, E.A., 1986, Basement balancing of Rocky Mountain foreland uplifts: Geology, v. 14, p. 259 -262.

Erslev, E.A., 1991, Trishear fault-propagation faulting: Geology, v. 19, p. 617-620.

Erslev, E.A., 1993, Thrusts, backthrusts and detachment of Laramide foreland arches, in Schmidt, C.J., Chase, R., and Erslev, E.A., eds., Laramide basement deformation in the Rocky Mountain foreland of the western United States: Geological Society of America Special Paper 280, p. 125-146.

Erslev, E.A., and Rogers, J.L., 1993, Basement-cover kinematics of Laramide fault-propagation folds: in Schmidt, C.J., Chase, R., and Erslev, E.A., eds., Laramide basement deformation in the Rocky Mountain foreland of the western United States: Geological Society of America Special Paper 280, p. 339-358.

Flores, R.M., Roberts, S.B., and Perry, W.J., 1995, Paleocene paleogeography of the Wind River, Bighorn, and Powder River Basins, Wyoming, Wyoming Geological Association Guidebook.

Graham, J., and Ethridge, F.G., 1995, Sequence stratigraphic implications of gutter casts in the Skull Creek Shale, lower Cretaceous, northern Colorado: Mountain Geologist, v. 32, p. 81-94.

Gregson, J.D., 1994, North-northwest shortening across Laramide structures in the southeastern Uinta Mountains, Colorado and Utah: M.S. thesis, Colorado State University, 147 p.

Gries, R.R., 1983, Oil and gas prospecting beneath Precambrian of foreland thrust plates in the Rocky Mountains: American Association of Petroleum Geologists Bulletin, v. 67, p. 1 -28.

Gries, R.R., 1983b, North-south compression of Rocky Mountain foreland structures, in Lowell, J.D., ed., Rocky Mountain foreland basins and uplifts: Rocky Mountain Association of Geologists, p. 9-32.

Gries, R.R., 1990, Rocky Mountain foreland structures: Changes in compression directions through time, in Letouzey, J., ed., Petroleum and tectonics in mobile belts: Paris, Editions Technip, p. 129-148.

Gries, R., and Dyer, R.C., 1985, Seismic exploration of the Rocky Mountain region: Denver, Colorado, Rocky Mountain Association of Geologists and Denver Geophysical Society, p. 1139-1142.

Hamilton, W.B., 1988, Laramide crustal shortening, 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. 27-40.

Hansen, W.R., 1986, History of faulting in the eastern Uinta Mountains, Colorado and Wyoming, in Stone, D.S., ed., New interpretations of northwest Colorado Geology: Rocky Mountain Association of Geologists, p. 19-36.

Huntoon, P., 1993, The influence of the inherited Precambrian basement on the localization and form of Laramide monoclines in the Grand Canyon of Arizona, in Schmidt, C.J., Chase, R., and Erslev, E.A., eds., Laramide basement deformation in the Rocky Mountain foreland of the western United States: Geological Society of America Special Paper 280, p. 243-256.

Kanter, L.R., Russ, D., and Dohmen, T.E., 1981, Laramide crustal shortening in the northern Wyoming Province: Contr. to Geol., Univ. Wyoming. v. 19, p.

Karlstrom, K.E., and Daniel, C.G., 1993, Restoration of Laramide right-lateral strike slip in northern New Mexico by using Proterozoic piercing points: Tectonic implications from the Proterozoic to the Cenozoic: Geology, v. 21, 135-142.

Kulik, D.M., and Schmidt, C.J., 1988, Regions of overlap and styles of interaction of Cordilleran thrust belt and Rocky Mountain 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. 75-98.

LeMasurier, W.E., 1970, Structural study of a Laramide fold involving shallow seated basement rock, Front Range Colorado: Geological Society of America Bulletin, v. 81, p. 435-450.

Lowell, J.D., 1983, Foreland deformation, in Lowell, J.D., ed., Rocky Mountain foreland basins and uplifts: Rocky Mountain Association of Geologists, Denver, Colorado, 392 p.

Matthews, V., III, ed., 1978, Laramide folding associated with basement block faulting: Geological Society of America Memoir 151.

Matthews, V., III, and Sherman, G.D., Origin of monoclinal folding near Livermore, Colorado: Mountain Geologist, v. 13, p. 61-66.

Matthews, V., III, and Work, D.F., 1978, Laramide folding associated with basement block faulting along the northeastern flank of the Front Range, Colorado, in Matthews, V., III (ed.), Laramide folding associated with basement block faulting: Geological Society of America Memoir 151, p. 101-124.

Molzer, P.C., and Erslev, E.A., 1995, Oblique convergence on during northeast-southwest Laramide compression along the east-west Owl Creek and Casper Mountain arches, central Wyoming: American Association of Geologists Bulletin, v. 79, p. 1377-1394.

Morley, C.K., 1986, A classification of thrust fronts: American Association of Petroleum Geologists Bulletin, v. 70, p. 12-25.

O'Connor, J.T., and Swann, G.A., 1963, Influence of Precambrian structural trends in Laramide deformation west of Fort Collins, Colorado: Rocky Mountain Association of Geologists, 14th Annual Field Conference Guidebook, p. 179-183.

Oldow, J.S., Bally, A.W., Ave Lallemant, H.G., and Leeman, W.P., 1989, Phanerozoic evolution of the North American Cordillera: United States and Canada, in Bally, A.W., and Palmer, A. R., eds., The geology of North America, an overview: Boulder Colorado, The Geological Society of America, The geology of north America, v. 1A, p. 139-232.

Perry, W.J., Jr., Nicols, D.J., Dyman, T.S., and Haley, C.J., 1992, Sequential Laramide deformation of the Rocky Mountain foreland of southwest Montana, Wyoming and north-central Colorado: U.S. Geological Survey Bulletin 2012, p. c1-c14.

Petit, J.P., 1987, Criteria for the sense of movement on fault surfaces in brittle rocks: Journal of Structural Geology, v. 9, p. 597-608.

Prucha, J.J., Graham, J.A., and Nickelson, R.P., 1965, Basement-controlled deformation in Wyoming Province of Rocky Mountain foreland: American Association of Petroleum Geologist Bulletin, v. 49, p. 966-992.

Schmidt, C.J., and Perry, W.J., Jr., 1988, Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, 582 p.

Selvig, B.W., 1994, Kinematics and structural models of faulting adjacent to the Rocky Flats Plant, central Colorado: M.S. thesis, Colorado State University, 133 p.

Smithson, S. B., 1979, Structure of the Laramide Wind river uplift, Wyoming, from COCORP deep reflection data and from gravity data: Journal of Geophysical Research, v. 84, p. 5955-5972.

Spang, J.H., Evans, J.P., and Berg, R.R., 1985, Balanced cross sections of small fold-thrust structures: Mountain Geologist, v. 22, p. 37-46.

Stearns, D.W., 1971, Mechanisms of drape folding in the Wyoming province: Wyoming Geological Association, 23rd Annual Field Conference, Wyoming Tectonics Symposium, Guidebook, p. 82-106.

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.

Suppe, J., 1983, Geometry and kinematics of fault-bend folding: American Journal of Science, v. 283, p. 684-721.

Varga, R.J., 1993, Rocky Mountain foreland uplifts: Products of a rotating stress field or strain partitioning?: Geology, v. 21, p. 1115-1118.

Warner, L.A., 1956, Tectonics of the Colorado Front Range: American Association of Petroleum Geologists, Rocky Mountain Section Geological Record, p. 129-144.

Woodward, N.B., Boyer, S.E., and Suppe, J., 1985, An outline of balanced cross sections: Uni. of Tennessee Dept. of Geological Sciences Studies in Geology, # 11.

Ziegler, V., 1917, Foothills structure in northern Colorado: Journal of Geology, v. 25, p. 715-740.

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