Inversion of Proterozoic extensional faults: An explanation for the pattern of Laramide and Ancestral Rockies intracratonic deformation, United States

Stephen Marshak
Department of Geology, University of Illinois, Urbana, Illinois 61801, USA
Karl Karlstrom
Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, USA
J. Michael Timmons

ABSTRACT

The Rocky Mountains, Colorado Plateau, and Midcontinent, regions of the North American cratonic platform, display similar styles and patterns of Phanerozoic deformation. In these regions, movement on basement-penetrating faults during the late Paleozoic Ancestral Rockies event and/or during the Mesozoic-Cenozoic Laramide event generated flat-topped uplifts bordered by outward-verging, monoclinal forced folds. We suggest that these structures, divided into two sets on the basis of orientation (west to northwest and north to northeast), formed by inversion of Proterozoic extensional-fault systems. In this model, Proterozoic rifting events formed weak faults in the cratonic platform crust, and these faults were reactivated by stress transmitted during Phanerozoic compressional orogenies. If this model is correct, the pattern of Ancestral Rockies and Laramide contractional structures reflects the trends of Proterozoic extensional faults, and regional variation in forced-fold vergence reflects the control of antecedent fault dips on fault-propagation fold geometry during inversion. Late Proterozoic rifts formed throughout Rodinia, so inversion tectonics likely occurred in cratonic platforms worldwide.

Keywords: Laramide, Ancestral Rockies, inversion tectonics, Colorado Plateau, Proterozoic rifting, Rocky Mountains, intracratonic deformation, Midcontinent, fault-propagation folding.

INTRODUCTION

Ranges of the Rocky Mountains, monoclines of the Colorado Plateau, and fault-and-fold zones of the U.S. Midcontinent differ dramatically in structural relief and degree of exposure, but resemble each other in structural style and regional orientation (Marshak and Paulsen, 1996; McBride and Nelson, 1999). Here we characterize this intracratonic deformation, focusing on that of the Rocky Mountains and Colorado Plateau (Fig. 1). We argue that both Ancestral Rockies and Laramide deformation reflect inversion of extensional faults formed during the assembly and breakup of supercontinents during the Proterozoic. This paper builds on ideas presented in Marshak and Paulsen (1996), Karlstrom and Humphreys (1998), and Timmons et al. (2000).

North America’s craton, continental crust that is relatively cool and mechanically strong, consists of a shield in which Precambrian crystalline basement crops out, and a platform in which a section of Phanerozoic strata as much as 7 km thick covers the basement. The cratonic platform in the United States includes both the Midcontinent and the Rocky Mountain–Colorado Plateau province (Fig. 1A). The latter consists of the Rocky Mountains, south of the Lewis and Clark fault zone, and the Colorado Plateau tablelands.

Two Phanerozoic deformation events affected the Rocky Mountain–Colorado Plateau province. The late Paleozoic Ancestral Rockies event created basins and basement-cored uplifts both in the region occupied by the present-day Rocky Mountains, and in the Midcontinent (Fig. 2; McBride and Nelson, 1999). These basins and uplifts represent the craton’s response to stress generated by collisional orogeny along North America’s eastern and southern margins (Kluth and Coney, 1981; Ye et al., 1996). The Laramide orogeny occurred in Cretaceous–Tertiary time. This event, a response to plate convergence along the west coast, overlapped in age with the end of the Jurassic–Cretaceous Sevier orogeny. South of the Lewis and Clark fault zone in the United States, the inception of the Laramide represents a change in the locus and style of deformation, relative to the Sevier deformation belt. Specifically, Sevier deformation shortened the former passive margin of western North America to form an east-verging fold-and-thrust belt (Fig. 2A). Laramide deformation, in contrast, formed basins and basement-cored uplifts in the cratonic platform, well to the east of the fold-and-thrust belt front (Fig. 1B).

Figure 1. A: Map of United States showing location and trend of faults and folds in cratonic platform. Rocky Mountain–Colorado Plateau province (RM-CP) is shaded. OA—Oklahoma aulacogen; LCFZ—Lewis and Clark fault zone, TWL—Texas–Walker line, MSM—Mojave–Sonora megashear, MCR—Midcontinent rift. B: Cross-sectional sketches indicating contrasts in deformatonal style among different continental provinces. C: Rose diagrams illustrating approximate dominant fault trends in (upper) Rocky Mountain–Colorado Plateau province and (lower) Midcontinent (derived from map in A). D: Map indicating faults and dikes (MDS—McKenzie dike swarm) formed between 1.3 and 1.1 Ga. E: Map indicating structures formed between 900 and 700 Ma (D and E modified from Marshak and Paulsen, 1996; Timmons et al., 2000).
CHARACTERISTICS OF INTRACRATONIC PLATFORM DEFORMATION

Erosion and post-Paleozoic deformation obscure Ancestral Rockies fault geometries, so to characterize the style of intracratonic platform deformation, we focus on Laramide examples in the United States. Laramide uplifts are basement cored (thick skinned) in that their formation results from reverse-sense to transpressional displacement on underlying basement-penetrating faults. (In this regard, Laramide faulting contrasts with that of a foreland fold-thrust belt, in which thrusts affect only sedimentary cover above a subhorizontal detachment.) In the present U.S. Rocky Mountains, displacements on Laramide faults reach 15–20 km, whereas in the Colorado Plateau, they reach 1–2 km. Cenozoic erosion exposed basement in uplifts of the Rocky Mountains, a region of 3–4 km-high mountains. In the Colorado Plateau region, uplifts are gently tilted or flat-topped tablelands; erosion breached the cover to expose underlying basement in relatively few examples. Close to the surface, faults bordering Laramide uplifts steepen and divide updip into splays that die out in a monoclinal forced fold involving cover. Laramide monoclines are fault-propagation folds, the steep limb of which faces the downdropped block (Erslev, 1991; Mitra and Mount, 1998; Allmendinger, 1999). The shape of Laramide faults at depth remains debatable. In some examples, faults dip steeply (>60°) near the surface, but the fault dip decreases at depth, whereas elsewhere, thrusts dip at about 35° to a depth of 20 km (Stone, 1993). The faults may merge with a mid-crustal detachment (Gries, 1988; Erslev, 1993).

In map view, Laramide faults and associated folds of the Rocky Mountain–Colorado Plateau province define a rhombohedral grid dominated by west to northwest and north to northeast trends (Figs. 1 and 2; e.g., Davis, 1978; Erslev and Wiechelman, 1997). Thus, in marked contrast with structures in foreland fold-and-thrust belts, intracratonic folds of the Rocky Mountain–Colorado Plateau province do not display regional parallelism. Furthermore, the folds verge in various directions (Fig. 2B); the vergence of these folds depends on the dip of the underlying fault. Specifically, folds over west-side-up faults verge east, folds over north-side-up faults verge north, and so on. It has been argued that the two trends formed during distinctly different stages of the Laramide orogeny, but a consensus is building that both sets were active coevaly, but with different local kinematics (e.g., Erslev and Wiechelman, 1997).

In addition to faults and folds, strata in the Rocky Mountain–Colorado Plateau province locally developed strain by growth of mesoscopic fault arrays (Varga, 1993; Molzer and Erslev, 1995) and by development of cataclastic deformation bands (Davis, 1999). These strata do not contain widespread tectonic cleavage, however, indicating that, in contrast to foreland fold-and-thrust belts, significant (>10%) layer-parallel shortening did not broadly develop in the province. Notably, studies of calcite twinning indicate that strata have been subjected to differential stresses of <100 MPa (van der Pluijm et al., 1997). The orientation of stress fields during deformation of the province remains controversial, due to the wide range structural trends.

ORIGIN OF ROCKY MOUNTAIN–COLORADO PLATEAU PROVINCE FAULTS: A RIFT-INVERSION MODEL

Although the geometry and kinematics of Phanerozoic faulting in the Rocky Mountain–Colorado Plateau province are well understood, the origin of the faults—when and why they were first formed by rupturing of previously intact crust—remains an enigma. Two end-member explanations have been suggested for their origin. (1) They were formed during the Ancestral Rockies and Laramide events in response to compressive stress. (2) They were formed prior to the Ancestral Rockies event and thus their movement during the Ancestral Rockies and Laramide events represents fault reactivation (e.g., Davis, 1978). Here we provide arguments that favor the second explanation, and we suggest further that weak faults of the cratonic platform in the Rocky Mountain–Colorado Plateau province, as in the Midcontinent (Marshak and Paulsen, 1996), formed by crustal rupturing during Proterozoic rifting. Thus, we propose that Phanerozoic movement on faults in the Rocky Mountain–Colorado Plateau province represents intracratonic rift inversion.

Inversion of normal faults refers to reactivation of the faults in a manner that generates reverse or oblique-slip movement. During inversion, the normal faults act as crustal weaknesses that allow slip under low differential stress when the crust undergoes later shortening (Cooper and Williams, 1989). The stress necessary to initiate sliding on preexisting faults is less than that needed to form new faults in intact rock, partly because frictional resistance is generally less than shear rupture strength under the same confining pressure (Etheridge, 1986), partly because alteration in fault zones produces weak rocks (Holdsworth et al., 1997), and partly because the presence of preexisting fractures provides a reservoir for groundwater, which may become overpressured during compression, thereby decreasing the effective normal stress holding opposing walls of the fault together (Sibson, 1993).
CASE FOR RIFT INVERSION IN THE ROCKY MOUNTAIN–COLORADO PLATEAU PROVINCE

To justify applying the rift-inversion concept to the Rocky Mountain–Colorado Plateau province, we show (1) that the province contains Proterozoic rifts, (2) that inversion has affected documented rifts, (3) that uplifts in the province parallel documented rifts, and (4) that the geometry of uplifts resembles that of inverted rifts. We also argue that the rift-inversion concept explains how significant uplifts can develop in the interior of a craton, a region that has not been subjected to large differential stress.

Existence of Rifts

Several areas in the cratonic platform preserve evidence of pre–Ancestral Rockies rifting. Specifically, the exposure of locally thick successions of rift strata (with or without volcanics) in the Grand Canyon, southern Arizona, the Uinta trough, and the Beltian embayment, along with the exposure of widespread mafic magmatism (including dike swarms), demonstrates that the craton was pervasively rifted in the Proterozoic. Marshak and Paulsen (1996) suggested that the rifts developed during three events: northeast-southwest extension at 1.5–1.3 Ga, east-west to northwest-southeast extension at 1.1 Ga (coeval with the Grenville orogeny and the opening of the Midcontinent Rift), and east-west to northwest-southeast extension at 0.7–0.6 Ga (breakaway of East Gondwana). Timmons et al. (2000) recognized two stages of rifting: northeast-southwest extension between 1.3 and 1.0 Ga, and east-west to northwest-southeast extension between 0.9 and 0.7 Ga. Regardless of the exact timing, by the end of these events, the North American craton contained two sets of basement-penetrating faults (one trending north to northeast and the other trending west to northwest; Fig. 1D and 1E) and related grabens, composing a rhomboidal network.

Geometric Similarity to Documented Examples of Rift Inversion

Several intracratonic fault-and-fold zones associated with uplifts in the Rocky Mountain–Colorado Plateau province demonstrably result from inversion of preexisting rifts. For example, reverse faulting emplaced the Precambrian rift strata of the Uinta trough over younger strata on the trough’s margins, reverse faulting occurred on the margins of the Beltian embayment in Montana (Huntoon, 1993; Schmidt, 1996), and reverse faulting occurred along fault blocks of Proterozoic strata in the Grand Canyon (Timmons et al., 2000). If all hanging-wall blocks of the Rocky Mountain–Colorado Plateau province uplifts contained rift strata, as in the examples herein, then the rift-inversion model would be self-evident. Because they do not, the ancestry of their bounding faults remains a question. We note here that fault zones of the province that do not carry Proterozoic rift strata in their hanging wall closely resemble those that do—both penetrate basement at depth and die out in a monoclinal flexure updp. This regard, the geometry of intracratonic faulting in the Rocky Mountain–Colorado Plateau province closely resembles that of documented inverted rifts elsewhere in the world (e.g., the Pampean ranges in Argentina; Schmidt, 1996) and that of inverted rifts in sandbox models (McClay, 1995).

Regional Map Pattern

To explain the presence of the two nonparallel fault sets of the Rocky Mountain–Colorado Plateau province requires that (1) faults initiated as coevally conjugate shear ruptures, (2) faults initiated at different times in response to different stress states, (3) stress fields progressively rotated during fault formation, (4) fault slip occurred on two nonparallel preexisting foliation sets, or (5) fault slip occurred on two nonparallel preexisting fault sets. Observations favor the last solution. In the Laramide structures, for example, evidence suggests that the region did not endure two mutually orthogonal compressional phases, and that slip directions on faults vary with fault orientation (slip slip occurs on some faults while strike-slip displacement occurs on others; Molzer and Erslev, 1995; Erslev and Wiechelman, 1997), as would be expected if the faults were preexisting and were reactivated during subsequent crustal shortening. Furthermore, fault-slip directions are not in the same plane, as would be expected for conjugate faults, and faults only locally parallel regional foliations (Prucha et al., 1965). However, fault sets of the Rocky Mountain–Colorado Plateau province are parallel to the two major sets of Proterozoic extensional faults and dikes of the U.S. cratonic platform (see Brown, 1988). Thus, the rift-inversion model provides an explanation for observed fault trends and slip directions.

Vergence Variations

Border faults on opposite sides of a rift commonly have opposite dip directions (even though within the rift, faults dominantly dip in the same direction), and as a consequence, fault-propagation folds formed over border faults on opposite sides of a rift have opposite vergence. Within rifts, inversion of pairs of synthetic and antithetic faults, on a local scale, form local flat-topped uplifts bordered by opposite-dipping faults. These relations have been observed in the field and have been produced with sandbox models (McClay, 1995). As noted earlier, structures of the Rocky Mountain–Colorado Plateau province include local flat-topped uplifts (e.g., the Uinta uplift) bordered by monoclinal folds, and folds on opposite sides of the uplifts have opposite vergence. It is significant that fault dips (and associated fold vergence) on opposite sides of the entire Laramide deformation belt are opposite (Fig. 3). The rift-inversion model explains this geometry.

Stress State at the Time of Faulting

The stress necessary to initiate frictional sliding on preexisting faults is less than that necessary to generate new faults in intact rock (Etheridge, 1996). Furthermore, preexisting normal faults may be particularly weak, because dilatancy during normal faulting leads to rock-water interaction that forms weak fault rocks (Holdsworth et al., 1997), and may leave residual fractured rock that can become overpressurized during inversion (Sibson, 1993). Calcite twinning studies and the lack of penetrative fabrics indicate that differential stress affecting the cover of the Rocky Mountain–Colorado Plateau province during the Phanerozoic was smaller than the differential stress affecting orogenic belts along the continental margin (van der Pluijm et al., 1997). Specifically, their measurements suggest that stress state in the craton during marginal orogenies is in the range of only 20–40 MPa, less than the experimental failure strength of rock under confined compression at shallow crustal levels (cf. Handin, 1966). The rift-inversion model explains how faulting can occur in a region where stresses may have been too low to generate new faults.

AN INTEGRATED IMAGE OF INTRAPLATFORM DEFORMATION

We argue that intracratonic faults, such as those of the Rocky Mountain–Colorado Plateau province, originated as normal faults during
Proterozoic extensional tectonics, and were reactivated as reverse or transpressional faults during the Phanerozoic. This hypothesis is compatible with the observed map pattern of faulting, with regional variations in vergence of related folds, and with fault geometry. To explain the lack of rift strata in the hanging walls of uplifts, we note that regional exhumation stripped about 10 km of crust off the surface of the province prior to the deposition of Phanerozoic cover strata (Timmons et al., 2000). The “Great Unconformity” at the base of the Paleozoic is called great for a reason—this erosion stripped away Proterozoic rift strata in all but the deepest rifts, but did not remove basement-penetrating faults. These faults remained as weaknesses in the crust, available for reactivation (Fig. 3).

In light of our proposal, we suggest the following tectonic evolution of the North American cratonic platform (the Rocky Mountain—Colorado Plateau province and the Midcontinent). After cratonicization, two or more extensional events, between 1.3 and 1.1 Ga and between 0.9 and 0.7 Ga, produced basement-penetrating faults. These faults remained as permanent weaknesses in the upper crust. Late Proterozoic exhumation stripped away the rift fill in all but the deepest rifts. Phanerozoic continental-margin orogenies inverted the weak faults, causing reverse-transpressional displacements that generated basement-cored uplifts and associated monoclines. Because not all faults were oriented appropriately to deform by dip-slip deformation, regional deformation was partitioned between reverse-, oblique-, and strike-slip movements (Varga, 1993; Karlstrom and Daniel, 1993; Tindall and Davis, 1999). Notably, west-trending faults could have served as accommodation zones bounding crustal blocks that underwent different amounts of stretching during the Proterozoic, and different amounts of shortening during the Phanerozoic.

The rift-inversion model, which may apply in cratonic platform regions worldwide, can be tested by collection of subsurface data that may document preserved normal-sense displacement and offset the rift strata in all but the deepest rifts. Further evidence could come from reexamination of slip kinematics on exposed faults and from systematic study of cooling histories across block-bounding faults in the region (Karlstrom et al., 1999).

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