Structural geologic evolution of the Colorado Plateau

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ABSTRACT

The Colorado Plateau is composed of Neoproterozoic, Paleozoic, and Mesozoic sedimentary rocks overlying mechanically heterogeneous latest Paleoproterozoic and Mesoproterozoic crystalline basement containing shear zones. The structure of the plateau is dominated by ten major basement-cored uplifts and associated monoclines, which were constructed during the Late Cretaceous through early Tertiary Laramide orogeny. Structural relief on the uplifts ranges up to 2 km. Each uplift is a highly asymmetric, doubly plunging anticline residing in the hanging wall of a (generally) blind crustal shear zone with reverse or reverse/oblique-slip displacement. The master shear zones are rooted in basement, and many, if not most, originated along reactivated, dominantly Neoproterozoic shear zones. These can be observed in several of the uplifts and within basement exposures of central Arizona that project “down-structure” northward beneath the Colorado Plateau. The basement shear zones, which were reactivated by crustal shortening, formed largely as a result of intracratonic rifting, and thus the system of Colorado Plateau uplifts is largely a product of inversion tectonics. The overall deformational style is commonly referred to as “Laramide,” and this is how we use this term here.

In order to estimate the dip of basement faults beneath uplifts, we applied trishear modeling to the Circle Cliffs uplift and the San Rafael swell. Detailed and repeated applications of trishear inverse- and forward-modeling for each of these uplifts suggest to us that the uplifts require initiation along a low-angle shear zone (between ~20° and ~40°), an initial shear-zone tip well below the basement-cover contact, a propagation (p) to slip (s) ratio that is higher for mechanically stiffer rocks and lower for mechanically softer rocks, a planar shear-zone geometry, and a trishear angle of ~100°. These are new results, and they demonstrate that the basement uplifts, arches, and monoclines have cohesive geometries that reflect fault-propagation folding in general and trishear fault-propagation in particular. Expressions of the shear zones in uppermost basement may in some cases be neoformed shear zones that broke loose as “footwall shortcuts” from the deeper reactivated zones.

Structural analysis of outcrop-scale structures permitted determination of horizontal-shortening directions in the Paleozoic and Mesozoic sedimentary cover of the uplifts. These arrange themselves into two groupings of uplifts, one that reveals NE/SW-directed shortening, and a second that reveals NW/SE shortening. Because the
strain in cover strata is localized to the upward projections of the blind shear zones, and because the measured shortening directions are uniform across a given uplift (independent of variations in the strike of the bounding monocline), it seems clear that the regional stresses ultimately responsible for deformation were transmitted through the basement at a deeper level. Thus, the stresses responsible for deformation of the cover may be interpreted as a reflection of basement strain. The basement strain (expressed as oblique shear displacements into cover driven by reactivations of dominantly Neoproterozoic normal-shear zones) was a response to regional tectonic stresses and, ultimately, plate-generated tectonic stresses.

The driving mechanism for the Sevier fold-and-thrust belt was coupled to subduction of the Farallon plate, perhaps enhanced by slab flattening and generation of higher traction along the base of the lithosphere. However, the disparate shortening directions documented here suggest that two tectonic drivers may have operated on the Colorado Plateau: (1) gravitational spreading of the topographically high Sevier thrust belt on the northwest side of the plateau adjacent to an active Charleston-Nebo salient of the Sevier thrust belt, which imparted northwest-southeast shortening; and (2) northeast-southwest shortening driven by the flat slab. The effect of the two drivers tended to “crumple” part of the region in a bidirectional vise, creating added complications to structural patterns. Testing of this idea will require, among other things, very precise age determinations of progressive deformation of the Colorado Plateau within the latest Cretaceous to early Tertiary time window, and sophisticated finite-element modeling to evaluate the nature of the deformation gradients that would be induced by the two drivers.
INTRODUCTION

Viewed in the context of the “Backbone of the Americas Conference” and the papers presented within this volume on the Cordillera (from “top” to “bottom”), the Colorado Plateau appears as a small “outcrop.” Yet, it is a phenomenal outcrop from the standpoint of scenic beauty and tectono-structural insight, and it is an informative outcrop in disclosing how distinct geologic structures and tectonic provinces reflect the interplay of mechanical stratigraphy, rheology, shear zone deformation, and tectonic loading. Even though the Colorado Plateau was affected by and responded to the major plate-generated movements and stresses, it was never overwhelmed. The fact that this region is marked by superb exposures of rocks and structures, and it resides as an island of structural coherence surrounded by a sea of strain, provides special opportunities in interpreting structure and tectonics.

Variously motivated by oil, uranium, and academic curiosity, distinguished, now classic, geologic work has been carried out on the Colorado Plateau for over a century (Powell, 1873; Gilbert, 1876; Dutton, 1882; Baker, 1935; Strahler, 1948; Eardley, 1949; Gilluly, 1952; Kelley, 1955a, 1955b; Kelley and Clinton, 1960). This work was done in a pre–plate tectonic era, and the results have had a relative lasting impact on interpretation because of the relative hiatus of investigations on the Colorado Plateau when work along or near plate margins held such attraction. The early work, among other things, elucidated the highly variable trends of Laramide folds, faults, and uplifts within the Colorado Plateau, an observation that has proven to be an enduring thorn for scientists trying to come up with a unifying tectonic model, and it is especially frustrating because the geology looks so simple. Models that form the early core of tectonic interpretations variously emphasized compressional shortening (Baker, 1935), differential vertical uplift (Stearns, 1978), compressional shortening with discrete shifts in regional stress directions (Kelley, 1955a), compressional shortening with incremental rotation of regional stress fields (Gries, 1990), progressive rotation of regional strain within a province-wide zone of distributed progressive transpression (Sales, 1968), and one self-described “outrageous” hypothesis (Wise, 1963).

P.B. King’s (1969) Tectonic Map of North America presents the Colorado Plateau in an artistic and scientifically informative way. The simplified black-and-white version here (Fig. 1) captures the lightly deformed cratonic assemblage of the Colorado Plateau, bordered by the more substantial deformation of the Wyoming Province to the north (Brown, 1988, 1993), the Rocky Mountains to the east and east-southeast (Tweto, 1979), the Rio Grande rift on the southeast, and the Sevier fold-and-thrust belt on the west. Basin and Range faulting marks adjacent tectonic provinces to the south and west of the Colorado Plateau, and examples of this faulting include the several major normal faults that define the Western High Plateaus of southwestern Utah (Fig. 1). Basin and Range faulting and volcanism in the Basin and Range tectonic province proper are superimposed on intense older tectonic products of deformation, including superposed rifting, thrusting, magmatism, core complex development, detachment faulting, and Basin and Range faulting.

The apparent cohesiveness of the Colorado Plateau derives importantly from the sharp tectonic boundaries on the west and south. On the west, the boundary is not simply one of abutting “against” the Basin and Range, but dropping off the Cordilleran hinge line from craton sediments on the east to passive-margin basin sediments on the west. To the south, there are the north-west-trending Mogollon Highlands, which are fundamentally controlled by a tectonic fabric that originated at least as far back as the Jurassic. Boundaries to the north and east are more transitional and are related to abrupt increases in structural relief of the Laramide-style basement cored uplifts (Wyoming uplifts, Rocky Mountain uplifts).

The tectonic and structural characteristics of the Colorado Plateau reflect a combination of the initial character of pre–Upper Cretaceous lithotectonic assemblages, including the Precambrian basement; the heterogeneous nature of the basement, including the presence of crustal shear zones; a distinctive combination of loading conditions; and the changed rheologic conditions brought about by plate dynamics in the late Mesozoic and early Tertiary. We review and address these characteristics in this paper, with the goal of explaining, both from structural and tectonic perspectives, the variability in orientation of the uplifts, and the shifts in vergence from some groupings of uplifts to others. These fundamental descriptive facts have posed major difficulties in achieving coherent tectonic deformation plans to explain them. There is irony in this, for this “outcrop” seems tectonically so simple! To achieve our goals, we not only review pertinent literature, but also contribute some new observations and findings that have emerged from our recent work.

BASEMENT-CORED UPLIFTS OF THE COLORADO PLATEAU

The uplifts and folds of the Colorado Plateau were first studied in detail by Kelley (1955a, 1955b), who carried out comprehensive analyses of structures in the Colorado Plateau in relation to minerals (notably uranium), energy, and Laramide-style tectonics. His work not only features the Colorado Plateau system of uplifts and monoclines (Fig. 2), but also folds and fracture patterns (Kelley and Clinton, 1960). Kelly’s descriptions of the uplifts were informed importantly through assembling structure-contour maps of the Colorado Plateau tectonic province (Kelley, 1955b). Mapping reveals that the Colorado Plateau, Laramide-style, basement-cored uplifts are not simply rectilinear blocks with sharp monocline margins, but they instead are more nuanced doubly-plunging asymmetric anticlinoria that typically have conspicuous monoclines along their steep flanks (e.g., see detailed descriptions by Davis, 1999) (Figs. 3 and 4). Over the entire span of the Colorado Plateau, shortening accommodated by these uplifts is less than several percent; in fact, Davis (1978) ran a rough calculation showing that shortening achieved by monoclines in the Arizona part of the Colorado Plateau is no more than
Figure 1. The Colorado Plateau tectonic province (light gray) in relation to the Wyoming province to the north, the Rocky Mountains to the east, the Rio Grande rift system to the southeast, and the front of the Sevier fold-and-thrust belt to the west. Not shown is the Basin and Range province, which borders the Colorado Plateau on the south and west. (Several Basin and Range faults that encroach upon the Colorado Plateau are shown in the lower left, where they demarcate the Western High Plateaus of Utah.) Map is from P.B. King (1969). pC—pre-Cambrian, SL—sea level.
The long back-limbs of the uplifts tend to be homoclinal or almost-undetectably curviplanar, with dips ranging from 0.5° to several degrees, whereas the short forelimbs of the uplifts tend to be curviplanar, with maximum dips as low as 10° (or less) and as high as 85° overturned. Individual uplifts tend to trend NNW, but there are N-trending and NNE-trending uplifts as well.

The Colorado Plateau uplifts are generally greater than 100 km in strike length and broader than 30 km. Structural relief associated with the uplifts is as great as 2000 m (e.g., the Circle Cliffs uplift!) (see Figs. 2 and 3). Kelley (1955a) noted that the system of Colorado Plateau uplifts can be subdivided into two systems. In the western part of the Colorado Plateau, the uplifts are asymmetric toward the east, and in the eastern part of the Colorado Plateau, the uplifts are asymmetric toward the west (see Fig. 2A). The western group consists of the San Rafael, Circle Cliffs, Kaibab, Monument, Echo Cliffs, and Defiance uplifts. The eastern group consists of the Uncompahgre, Zuni, and Nacimiento uplifts. The monoclines themselves are more variable in orientation than the uplifts (see Fig. 2B). NNW-trending monoclines are the most abundant, but some are NE- and N- to NNE-trending within the system as a whole.

Based on a variety of observations, the Colorado Plateau uplifts are interpreted as underlain by faulted basement. In the cases of the Kaibab and Uncompahgre uplifts, faulted basement is directly exposed (Lohman, 1963; Cashion, 1973; Huntoon, 1971; Huntoon and Sears, 1975; Stern, 1992; Huntoon, 1993). In the case of the San Rafael Swell, Allmendinger et al. (1987) demonstrated through the Consortium for Continental Reflection Profiling (COCORP) seismic data the presence of a basement high beneath this uplift. Furthermore, Cook et al. (1991) showed that Colorado Plateau uplifts express themselves as gravity highs, which they interpreted as expressions of uplifted basement.
Figure 3. Structure contour map of the northern Colorado Plateau showing the approximate areas of the uplifts (shaded gray) in this study and their local shortening directions (black arrows) (from Bump, 2004, Fig. 1). Contours are drawn at 200 m intervals on the base of the Cretaceous Dakota sandstone. Source for contours, modified after Baker (1935), O’Sullivan (1963), Williams (1964), Williams and Hackman (1971), Haynes et al. (1972), Cashion (1973), Hackman and Wyant (1973), and Haynes and Hackman (1978). Structural elevations are given in meters above sea level. The Colorado River and its tributaries (dark gray) are shown for reference. FTB—fold-and-thrust belt. Reprinted from Bump, A.P., 2004, Three-dimensional Laramide deformation of the Colorado Plateau: Competing stresses from the Sevier thrust belt and the flat Farallon slab: Tectonics, v. 23, doi: 10.1029/2002TC001424, with permission from the American Geophysical Union.
Finally, the Colorado Plateau uplifts are similar in style to uplifts in Wyoming and Colorado, which are known to be basement-cored. Where exposed, these basement faults are ancient features that show multiple episodes of slip, further complicating the kinematic picture (e.g., Huntoon and Sears, 1975; Stone, 1977).

The Colorado Plateau was modified by faulting related to (Miocene to present) regional extension to the west and to the east, but the uplifts shown in Kelly’s regional structure map (see Fig. 2A) for the most part escaped this superposed deformation. One exception within the Colorado Plateau proper is the Kaibab uplift, which is cut by the Paunsaugunt and Sevier faults of Basin and Range origin (Davis, 1999). One more Colorado Plateau uplift completely escaped Kelly’s detection because of the effects of post-Laramide superposed extension. This uplift, the Apache uplift (see Fig. 2A), lies in the Arizona transition zone between the Colorado Plateau and Basin and Range. Davis et al. (1981) named this uplift, basing its presence on the work of Finnell (1962), Granger and Raup (1969), Peirce et al. (1979), Peirce (1981, personal commun.), and their own structural mapping and analysis along the Salt River Canyon in central Arizona. Much of this uplift lies within the Fort Apache Indian Reservation, which is thus the context for its naming.

SHEAR ZONES IN COLORADO PLATEAU BASEMENT

It has been known for decades that many monoclines in the Grand Canyon “root” into Laramide reverse shear zones that are reactivated Upper Proterozoic normal faults, Noble (1914) recognized this in the Shinumo quadrangle, Maxson (1961) recognized this in the Bright Angel quadrangle, and Huntoon and Sears (1975) recognized it in their analysis of structures in the eastern part of the Grand Canyon. In particular, Huntoon (1974) concluded that the abrupt shifts in trend of individual monoclines in the eastern Grand Canyon are expressions of parts of the original Precambrian fault-trace geometry in the underlying basement. Huntoon (1974) emphasized that the basement faults formed originally as normal faults during the latest Mesoproterozoic and Neoproterozoic, but later, during the Laramide (late Mesozoic through early Tertiary), they were reactivated with a reverse sense of displacement to form monoclines involving Neoproterozoic, Paleozoic, and Mesozoic strata (Fig. 5). In the footwall immediately beneath the Butte fault, there is outcrop-scale evidence of shortening in the form of thrust faults and associated folding (Fig. 6).

Figure 4. North-directed photograph of the East Kaibab monocline (from Davis, 1999, Fig. 35A, p. 39). Gently dipping Navajo Sandstone (Jurassic) caps the top of the monocline, on the far left. More readily eroded Carmel Formation (Jurassic), Dakota Sandstone, and Tropic Shale (Lower Cretaceous) crop out in the foreground. Straight Cliffs Formation (Upper Cretaceous) is on the upper far right. Breadth of view is ~1 km.

Figure 5. Structure section showing the Butte fault in relation to basement and cover. During the Neoproterozoic, movement on the Butte fault created normal displacement. During the latest Cretaceous and early Tertiary, reactivation of the Butte fault produced reverse displacement, tipping out upward into monoclinal folding. The magnitude of reverse throw was less than Neoproterozoic normal throw, and thus net offset of Mesoproterozoic basement remains of normal displacement. From Tindall (2000a, Fig. A5, p. 54), used with permission of Sarah Tindall.
Indeed, the structural history of the Butte fault, which is exposed in the Grand Canyon directly below monoclinally folded Paleozoic and Mesozoic strata, permits the salient relationships between monoclines and basement faults to be understood. There are well documented west-side-down offsets along the west-dipping Butte fault in the Grand Canyon Supergroup (Walcott, 1890; Maxson, 1961; Huntoon, 1969, 1993; Huntoon and Sears, 1975; Tindall, 2000b). Reactivation of this fault, beginning presumably in the latest Cretaceous, caused west-side-up reactivation of the Butte fault during the creation of the Kaibab uplift and East Kaibab monocline (Huntoon, 1993; Huntoon and Sears, 1975). As reemphasized by Tindall (2000b, p. 632): “The magnitude of reverse offset must have been smaller than the magnitude of ancient normal offset, because normal separation is still preserved at the Precambrian level.”

Davis (1978, p. 215) expanded the fault-specific conclusions reached by Noble (1914), Maxson (1961), Huntoon (1974), and Huntoon and Sears (1975) (Fig. 7) and concluded that the monocline fold pattern as a whole in the Colorado Plateau reflects the expression of many elements of a provincewide basement-fault system. Davis further suggested that the shapes of many of the Colorado Plateau uplifts are the muted expressions of underlying basement-block edges (Davis, 1978, p. 225). These conclusions were not entirely new. Case and Joesting (1972), based on analysis of gravity and magnetic gradients evident in Precambrian basement, interpreted a “fundamental” fracture pattern of Precambrian age in Precambrian basement beneath a part of the Colorado Plateau.

We suspect that those who have studied the faults into which the uplifts and monoclines root would agree that major deep-seated “faults” associated with Colorado Plateau uplifts and monoclines are “fault zones.” Strictly speaking, these “fault zones” are most accurately described as “brittle, semibrittle, or ductile shear zones,” depending upon depth-level of observation, rheology, and superposition of fabrics, reflecting histories of activation and reactivation (Davis and Reynolds, 1996). Thus, throughout the remainder of this paper, we have chosen to replace the term “fault” with “shear zone” in our descriptions and interpretations, though in referencing past work of other workers, we will continue to use the term “fault” in the same way used by them in the literature.

**NATURE OF BASEMENT SHEAR ZONES ADJACENT TO THE PLATEAU**

Given the limited exposures of Precambrian rocks and structures within the Colorado Plateau, observations regarding Precambrian shear zones in the central Arizona “transition zone” between the Colorado Plateau (to the north) and the Basin and Range (to the south) become very important. We here introduce this kind of analysis as a variation on Mackin’s (1950) “down-structure” method to examine a geologic map as if it were a cross section and, in this case, to visualize Precambrian shear zones beneath the southern edge of the Colorado Plateau. The transition zone lends itself to this evaluation because this part of Arizona was uplifted during the late Mesozoic and early Tertiary in such a way that Paleozoic and Mesozoic strata were eroded, extensively exposing the Precambrian basement (Kamilli and Richard, 1998). Furthermore, the region was tilted slightly northeastward (by ~1° to 2°). According to Peirce et al. (1979), and as summarized in Faulds (1986, p. 126–127), the tilting was accomplished in two episodes, the first between the Late Jurassic and Late Cretaceous, and the second during the latest Cretaceous and Eocene. Because of this history, a very low-plunging northward viewing of the transition zone in relation to the Colorado Plateau becomes an approximation of a structure-section.

The framework for being able to identify shear-zone boundaries within the Precambrian of southwestern North America was built by Lee Silver and his students and colleagues, based upon extensive geologic and geochronologic surveying (e.g., Cooper and Silver, 1964; Silver, 1965, 1967, 1969, 1978; Anderson et al., 1971; Anderson and Silver, 1976; Anderson and Silver, 2005). This work led to the understanding that the late Paleoproterozoic and early Mesoproterozoic of southwestern North America grew through accretionary crust-forming events, expressed importantly as NE-SW–trending provinces of cogenetic suites of volcanic and plutonic rocks (Anderson and Silver, 2005). Recognition of these distinctive provinces was based upon crystallization ages derived from developing and using the U-Pb system on zircon (e.g., Silver, 1963; Silver and Deutsch, 1961, 1963). Anderson and Silver (2005, p. 12, their Figs. 5A–5C) nicely summarized the progressive delineation of two dominant provinces in southern Arizona and southern New Mexico: the Pinal Province (to the southeast), marked by crystallization ages of ca. 1.7–1.6 Ga, and the Yavapai Province (bordering the Pinal Province on the northwest), marked by crystallization ages of ca. 1.8–1.7 Ga (Conway et al., 1987).
Karlstrom and Humphreys (1998) and Nourse et al. (2005) presented interpretations of Proterozoic crustal provinces complementary to the aforementioned Yavapai-Pinal accretion map, but they used a “Yavapai-Mazatzal” province taxonomy (Fig. 8) and split out relationships in more detail based on the work of Karlstrom and Bowring (1988), Karlstrom and Williams (1998), Wooden and DeWitt (1991), Bender et al. (1993), Karlstrom (1993), Karlstrom and Daniel (1993), Ilg et al. (1996), and Eisele and Isachsen (2001). The conclusion remains: the Paleoproterozoic of central Arizona was assembled by tectonic shortening between ca. 1.8 and ca. 1.6 Ga (Karlstrom, 1993; Conway et al., 1987; Karlstrom and Humphreys, 1998; Anderson and Silver, 2005).

The principal tectonic grain resulting from this tectonic accretion is northeast-oriented (see Fig. 8), as expressed by the trends of the provinces themselves (e.g., the Mojave province, the Mojave-Yavapai transition, the Yavapai province, the Yavapai-Mazatzal transition, and the Mazatzal province), but also by the “thrust-sense shear zones” (Karlstrom and Humphreys, 1998, p. 162) that separate each province from one another. From northwest to southeast, these late Paleoproterozoic–early Mesoproterozoic shear zones are the Gneiss Canyon shear zone, the Crystal shear zone, the Moore Gulch shear zone, and the Slate Creek shear zone (see Fig. 8). As emphasized by Karlstrom and Humphreys (1998), these shear zone boundaries influenced the distribution and character of Laramide magmatism and metallogenesis but were not reactivated in any conspicuous way during the formation of Laramide basement-cored uplifts. However, Karlstrom and Humphreys (1998) pointed out that it is possible for northeast grain to have been reactivated from place to place in the form of transfer zones or accommodation zones oriented parallel to the direction of Laramide shortening, i.e., NE/SW. We point out here that this may have occurred in fashioning the NE-trending Cow Springs monocline near Kayenta, Arizona, just southwest of the Monument uplift (see Fig. 2B) (Davis and Kiven, 1975; Davis, 1978, his Figs. 4 and 5).

It was the late Mesoproterozoic and Neoproterozoic shear zones of normal-sense shear displacement that were reactivated preferentially during the formation of the Laramide-style basement-cored uplifts (Karlstrom and Humphreys, 1998). The best examples of such normal-sense displacement shear zones are the Canyon Creek and Butte faults (Karlstrom and Humphreys, 1998) (Fig. 9). Continental-scale rifting created these faults between 1.1 Ga and 700 Ma, which coincided with syntectonic diabase intrusions and rift-basin sediment accumulations (Silver, 1960; Shride, 1967; Silver, 1978; Granger and Raup, 1969; Elston, 1979). Indeed, the Canyon Creek “fault,” as a Paleoproterozoic shear zone, controlled the emplacement and distribution of dikes and sills of Neoproterozoic diabase (Finnell, 1962; Shride, 1967; Granger and Raup, 1969), which were dated by Silver (1960, 1978) as 1.1 Ga. This overall timing of rifting makes sense in the context of plate reconstructions for the Neoproterozoic (Burke and Dewey, 1973; Stewart, 1976; Stewart and Suczek, 1977; Dickinson, 1977).
The map relationships of the Apache uplift and its bounding shear zones (Canyon Creek shear zone on the east, Cherry Creek shear zone on the west) are quite pertinent to understanding Laramide-style basement-cored uplifts (Fig. 10), and thus we will discuss them here in some detail, drawing together some dispersed literature that has tended to be “off the radar.” Finnell (1962) and Granger and Raup (1969) concluded decades ago that the Canyon Creek fault zone coincides with a major Precambrian shear zone. The presence of this shear zone was felt tectonically in Neoproterozoic time, for it exerted control on the emplacement of ca. 1.1 Ga diabase sills and dikes. Finnell (1962) recognized that the Canyon Creek fault was the site of a major east-facing monocline that deformed Neoproterozoic and Phanerozoic strata. Peirce et al. (1979), more specifically, determined that the Canyon Creek (Precambrian) fault accommodated at least two major reactivations in the Phanerozoic. During the latest Cretaceous and early Tertiary, the Canyon Creek fault experienced eastward-directed reverse displacement of at least 1.5 km (Peirce et al., 1979). Subsequently, as the result of extensional faulting in middle to late Tertiary time, this structural relief was countermanded when the Canyon Creek fault accommodated westward-directed normal displacement on the order of 1.5 km. Because the vertical component of the (older) reverse faulting exceeded the offset achieved by the superposed normal faulting, Tertiary rocks to the west of the Canyon Creek fault are structurally higher than equivalents to the east. Thus, the requisite throw related to reverse faulting must have exceeded 1.5 km of structural relief (H.W. Peirce, 1981, personal commun.).

Faulds (1986, p. 231) placed the up-on-the-west reverse throw at 1650–1750 m and calculated a down-to-the-west normal displacement of 750+ m. The Cherry Creek shear zone, which marks the western margin of the Apache uplift (see Fig. 10), also coincides with a Paleoproterozoic shear zone, a ca. 1.1 Ga reactivation history during diabase sill and dike emplacement, a shortening-induced reactivation history of down-to-the-west monocline development, an extension-induced down-to-the-west Oligocene normal faulting, and post–14 Ma normal faulting of Basin and Range tectonic origin (Faulds, 1986). Overall, as emphasized by Davis et al. (1981), the Apache uplift is less obvious because it lacks the stripped structural form so characteristic of typical Colorado Plateau uplifts. However, its breadth (~16 km), length (~100 km), and structural relief (at least ~1650 m) are quite comparable to that of other Colorado Plateau uplifts, such as the Circle Cliffs uplift (Davis et al., 1981, p. 94).

The development of the Apache basement-cored uplift was followed by extensive erosion, as revealed by the nonconformity atop the Apache uplift between late Paleoproterozoic and Mesoproterozoic basement beneath Tertiary sedimentary and volcanic strata above (see Fig. 10). Monoclines associated with the Apache uplift are shown in Figure 11. The orientations and locations of the monoclines associated with the Apache uplift are nicely compatible with the East Kaibab system of monoclines (see Fig. 11), and they convincingly match the Butte–Canyon Creek fault system (Fig. 9) as presented in Karlstrom and Humphreys (1998).

**OBLIQUE SLIP ALONG REACTIVATED BASEMENT SHEAR ZONES**

As noted earlier, reactivation of the Neoproterozoic Butte shear zone within the Grand Canyon is well documented, and it contributed importantly to the development of the East Kaibab monocline along the eastern margin of the Kaibab uplift. Prior to the work of Davis and Tindall (1996), interpretations developed for the Butte shear zone exclusively reported vertical throw component(s). It is important to recognize that some shear-zone reactivations associated with Colorado Plateau uplifts have oblique-shear expressions. A case in point is the NNE stretch...

Mesozoic strata within the East Kaibab monocline (see Fig. 4) display an elegant, penetrative system of NNE-striking and WNW-striking faults first identified by Sargent and Hansen (1982). Based upon detailed structural analysis and geologic mapping, these fault sets are recognized as right-handed and left-handed oblique slip faults, respectively (Davis and Tindall, 1996; Tindall and Davis, 1998; Davis, 1999; Tindall, 2000a, 2000b). Sarah Tindall comprehensively mapped the faulting along the full 60 km stretch of the East Kaibab shear zone within Utah (Fig. 12) (Tindall, 2000a). The faults and fault sets are synthetic and antithetic with respect to a major, overall, reverse right-handed strike-slip shearing along this N20°E-trending segment of the East Kaibab monocline (Davis, 1999; Tindall and Davis, 1999; Tindall, 2000a, 2000b). Slickenlines and grooves along the major shear zone consistently rake 30°S to 40°S, and the shear zone surfaces dip steeply (~75°) westward. As first emphasized by Davis and Tindall (1996), this oblique right-handed strike-slip shearing is the natural consequence of reactivation of a
NNE-striking basement shear zone in response to NE-SW shortening (Davis, 1999; Tindall and Davis, 1999). A N65°E-trending horizontal-shortening direction acting across a N10°E-striking, steeply W-dipping basement shear zone is ideally suited to reactivate the shear zone in right-handed strike-slip fashion (Fig. 13).

Reverse right-handed oblique slip also characterizes the NNE-trending stretch of the East Kaibab monocline north of Flagstaff, Arizona, within Wupatki National Monument (see Fig. 11). There, strata of the Permian Kaibab and Triassic Moenkopi Formation exhibit abundant low-raking slickenlines on slickenlined fault surfaces. Where individual fault zones tip out, there are relays that conform to right-handed (oblique) strike-slip shearing.

Another good example of oblique-slip shearing associated with monoclinal folding was recognized along the southwest margin of Miners Mountain in Utah. This Colorado Plateau uplift is situated just north of the Circle Cliffs uplift (see Fig. 3). A doubly plunging NW-trending Colorado Plateau uplift, Miners Mountain is bordered on the southwest by the N65°W-trending Teasdale faulted monoclone, the structural relief of which is 150 m (Smith et al., 1963; Billingsley et al., 1987; Davis, 1999). Anderson and Barnhard (1986) documented that this faulted monoclone accommodated left-handed strike-slip movement. Bump et al. (1997) later studied this relationship and determined independently that the Teasdale faulted monoclone is a reverse, left-handed transpressive structure, with perhaps 1–2 km of left-lateral offset.

COLORADO PLATEAU UPLIFTS AND INVERSION TECTONICS

The evidence is abundant to support the hypothesis that individual Neoproterozoic shear zones were reactivated as reverse faults and/or transpressive reverse/oblique-slip shear zones. These observations have led to an important province-wide perspective, namely, that Colorado Plateau uplifts are an expression of “inversion tectonics,” and in particular “intracratonic rift inversion” (Marshak et al., 2000, p. 736). Marshak et al. (2000) made a compelling argument for this, building on some of their previous work (Marshak and Paulsen, 1996; Karlstrom and Humphreys, 1998; Timmons et al., 2001). Marshak et al. (2000) inserted an important and necessary concept into the story of structural evolution of the Colorado Plateau uplifts in particular.

The mechanical basis for understanding reactivation of normal faults and shear zones as reverse/thrust faults is long established (e.g., Donath, 1961), and it is perhaps best summarized in Byerlee (1978), the contribution for which “Byerlee’s law” was coined. Byerlee’s law describes the conditions necessary to cause slip on a preexisting fault, namely, by assessing the product of the coefficient of sliding friction and normal stress acting on a given preexisting fault, and comparing that product to the sum of the shear strength and cohesive strength of the body of rock, where unfaulted. Certain products of the first faulting can reduce the coefficient of sliding friction, including breccia, gouge, and other fault-rock products; weak hydrothermally altered mineral assemblages; and finer-grained and/or highly foliated rocks (e.g., in shear zones) (Etheridge, 1986). The final necessary condition for reactivation is suitability of orientation of the preexisting fault surface (or zone) within the prevailing stress field (Donath and Cranwell, 1981; Etheridge, 1986). Etheridge (1986) emphasized that reverse (thrust) reactivation of normal faults is the most likely circumstance of reactivation, since normal fault systems and thrust systems may have very similar geometries (see, for example, Cooper and Williams, 1989; Boyer and Elliott, 1982).

Etheridge (1986) applied the conceptual framework of fault reactivation to deformation systems, using primarily examples from southeastern Australia. He emphasized that insightful models for lithospheric stretching (McKenzie, 1978; Le Pichon and Sibuet, 1981; and Dewey, 1988) provide a basis for understanding the formation of primary extensional fault systems in basement and cover, thus setting up conditions for reactivation during subsequent compressional deformation (Etheridge, 1986, p. 185).

Marshak et al. (2000) emphasized that intracratonic rift inversion is expressed in uplift structures in the Rocky Mountains, Colorado Plateau, and Midcontinent regions of North America.
Figure 12. Northern part of East Kaibab monocline. (A) Structural contour map. Structure contours (ft) are drawn on the base of the Cretaceous Dakota Sandstone. From Tindall and Davis (1999, Fig. 2, p. 1305). (B) Simplified geologic map. Faulting and folding in the steep limb move from older stratigraphic units in the south into higher stratigraphic units northward. NE-striking faults are right lateral; NW-striking faults are left lateral. From Tindall and Davis (1999, Fig. 3, p. 1306). (C) Structural details. Short, NW-striking, NE-dipping faults are left lateral. Near Grosvenor’s Arch and Pump Canyon Spring, NE-striking faults dip NW and accommodate reverse right-handed offset. Jurassic stratigraphy from oldest to youngest: Navajo Sandstone (Jn), Page Sandstone Member (Jcp), Carmel Formation (Jc), and Entrada Formation (Je). Cretaceous stratigraphy from oldest to youngest: Dakota Formation (Kd), Straight Cliffs Formation (Ksc), Wahweap Formation (Kw), Kaiparowits Formation (Kk), and Qal—Quaternary alluvium. Figures 12A, 12B, and 12C reprinted from Tindall, S., and Davis, G.H., 1999, Monocline development by oblique-slip fault-propagation folding: The East Kaibab monocline, Colorado Plateau, Utah: Journal of Structural Geology, v. 21, no. 10, Figure 6, p. 1308, with permission from Elsevier.
America, and differences between uplifts across these provinces
are only a matter of scale (Fig. 14). They reiterated that the
Proterozoic normal faults and shear zones, some of which later
became reactivated to form the Ancestral Rockies and Laramide-
style basement-cored uplifts, were created during rifting of con-
tinental crust (Fig. 15). The cratonwide Proterozoic fault orienta-
tions, according to the analysis by Marshak et al. (2000), were
marked by two dominant sets: N to NE, and W to NW. Marshak
et al. (2000) suggested that these rifting-related faults and shear
zones evolved during the Mesoproterozoic and Neoproterozoic,
specifically in the interval 1.5 to 0.7 Ga (Marshak and Paulsen,
1996; Timmons et al., 2000). Of course, different kinematics
could develop on different faults at the same time, depending on
the orientation of the faults (Marshak et al., 2003).

Reactivation of Proterozoic normal faults and shear zones
into reverse-slip and reverse/oblique-slip structures created
monocline fold vergence reflecting “antecedent fault dips” of the
basement structures (Marshak et al., 2000, p. 735). Absence of
Proterozoic rift strata in the hanging walls of many of the uplift-
bounding shear zones was not viewed as a problem by Marshak
et al. (2000, p. 738)—they pointed out that regional erosion, now
expressed in the Great Unconformity, removed at least 10 km of
crust from mid-Proterozoic basement.

Davis et al. (1981, p. 94–95) subscribed to the conclusions
reached by Silver (1978) as to why the Neoproterozoic shear
zones were prone to reactivation. Silver (1978) argued that intru-
sion of the 1.41 Ga, regionally extensive, Mesoproterozoic gra-
nitic suite was a “cratonization process” that imparted a greater
rigidity to the basement. Thus, when basement was subjected
to horizontal compressive shortening, neither the relatively
incompressible granitic batholiths could shorten, nor could the
mechanically softer pendants of metamorphic rocks insulated by
the granite. As a result, crustal shortening was accommodated
selectively on major, wide-spaced shear-zone discontinuities.

SUBSTANTIALLY DIFFERING VIEWS OF ORIGIN OF THE FOLDS

The structural geologic literature underscores how diffi-
cult it has been, over the decades, to work out the deformation
mechanism(s) responsible for the formation of the monoclines
and the regional anticlines (the uplifts!) with which they are
associated. For the longest time, there was no agreement that
the fundamental origin was due to crustal shortening, although
this conclusion had been reached early and very compellingly
by workers such as Baker (1935). End-member compressional
deformation mechanisms for folding of regional tectonic signifi-
cance are “free folding” and “forced folding.” Products of free
folding have geometric profiles with characteristics that reflect
the physical and mechanical properties of the rock layers them-
selves, especially thickness, stiffness, ductility contrast between
layers, and cohesion along layer boundaries (Biot, 1957, 1959;
Ramberg, 1959, 1962; Biot et al., 1961; Currie et al., 1962; John-

Figure 13. (A) Cross-sectional diagram showing Laramide horizontal compressive stress resolved on a steeply dipping basement fault. \( \sigma_s \) is shear component; \( \sigma_N \) is normal component. (B) Map-view diagram showing resolved shear stress on a steeply dipping basement fault, given N65°E-trending horizontal compressive stress. This configuration favors right-handed transpressive strike slip. Figure is from Davis (1999, Fig. 39, p. 42).

Figure 14. Cross-sectional sketches that emphasize the similarity of style of basement uplifts in the Rocky Mountain region, the Colorado Plateau, and the Midcontinent. Differences are fundamentally a matter of scale. Figure is from Marshak et al. (2000, Fig. 1B, p. 735). Used with permission of the Geological Society of America.
Reches and Johnson (1978) emphasized, for example, that buckling or (large-scale) kink folding are both “viable options” for the formation of monoclines on the Colorado Plateau. Based upon both mechanical and experimental modeling, they concluded that the asymmetry—so pronounced in the case of monoclines!—can be produced by layer-parallel shortening and layer-parallel shearing, with or without differential movement along high-angle faults.

Yin (1994) emphasized free folding as well, modeling the upper crust of the entire Colorado Plateau as an elastic thin plate (10 km thick) and having it become deflected into a broad NNW-trending antiform by the combination of horizontal compression and vertical edge loading. The structural relief of the antiform was modeled as 1.5 km, which corresponds to limb-dip inclinations of ~1° or less. The bending of the crust was, according to Yin (1994), accompanied by layer-parallel shear on the antiform’s broad, regional, western and eastern limbs, each of which would have been ~500 km wide. Yin proposed that the layer-parallel shear caused the monoclines to form as giant asymmetrical drag folds.

We doubt that sufficient layer-parallel shear could have been generated to achieve the final condition. Ramsay (1967, p. 392–393) has demonstrated that the actual amount of (flexural) slippage along the top of any layer within a flexurally folded sequence can be determined by multiplying the thickness of the folded layer and the dip of the layer in radians (where 1° = 0.175 radian). In Yin’s model, the folded basement layer within the “thin elastic plate” is ~7 km thick, and it resides beneath a 3-km-thick cover of Paleozoic, Mesozoic, and Cenozoic strata. If, for Yin’s model, all of the slip concentrated itself at the basement-cover interface, only 122 m of slip could be generated along the basement-cover interface during bending and formation of the antiform. If, more realistically, this flexural slip were distributed throughout the cover at the boundaries of major, thick, stiff formations, the impact would be negligible. In fact, field observations show that away from the monoclines proper, there is no physical evidence for flexural slip along bedding planes.

Tikoff and Maxson (2001) elevated the scale of application of free folding even higher and proposed that the initiation of the arches and uplifts in the Colorado Plateau, Rocky Mountains, and Wyoming Province reflected buckling at a lithospheric scale. In particular, they envisioned that the Cordilleran foreland was laterally stressed in such a way that the entire lithosphere experienced a buckling instability, and that the “stiff layer,” which controlled the dominant wavelength (~190 km), was the lithospheric mantle. The wavelength data reported by Tikoff and Maxson (2001) are marked by a very high standard deviation, perhaps unacceptably high in relation to the conclusions reached. They reported distances between arches (measured along east-west transects) as 140 km, 140 km, 80 km, 60 km, 300 km, and 230 km.

In contrast to free folding, products of forced folding have geometric profiles with characteristics that reflect the form of the faults, and the amount of displacement along the faults with which the folding is associated. Stearns (1971, 1978) was a strong proponent of forced folding in interpreting deformation associated with basement-cored uplifts in the central Rocky Mountains, emphasizing the expression “drape folding” in describing this deformation mechanism. Strata were “draped” over the edges of basement blocks, which had differentially vertically
moved with respect to one another by faulting. Descriptions of the structural geometries and rock properties by Stearns and his students and colleagues, through both field and laboratory work, are abundantly detailed (e.g., Jamison, 1979; Jamison and Stearns, 1982; Couples et al., 1994). Stearns (1978) emphasized that the specific fold geometries reflected such factors as ductility contrast between basement and cover work, absolute rheologies, and presence or absence of detachment between basement and cover. Stearns’ work sparked great debate, not so much in relation to the fold geometries and rock properties, but in relation to his emphasis that the fault movements associated with basement uplifts were not generated by layer-parallel compression and shortening, but by “vertical tectonics.” His emphasis on vertical tectonics was importantly derived from his view that the master faults steepen at depth.

Forced folding geometries and mechanisms have now been examined in excruciating detail, following the delineation of the two dominant classes of forced folding: fault-bend folding (Boyer and Elliott, 1982; Suppe, 1983; Mitra, 1990), and fault-propagation folding (Suppe, 1983, 1985; Mitra and Mount, 1998; Mosar and Suppe, 1992; Poblet and McClay, 1996). “Fault-bend folding” is germane to understanding the Sevier fold-and-thrust belt west of the Colorado Plateau, where, for example, DeCelles and Coogan (2006) reported 220 km of total shortening based on their studies in central Utah. As is evident in the classical literature on structure-tectonics of the Canadian Rockies, the Appalachian Mountains, and the Sevier fold-and-thrust belt (including the Wyoming-Idaho thrust belt), thick miogeoclinal sequences lend themselves to deformation by fault-bend folding. As emphasized in the following section, fault-propagation folding is the mechanism directly applicable to understanding the uplifts of the Colorado Plateau.

TRISHEAR DEVELOPMENT OF COLORADO PLATEAU MONOCLINES

As is apparent, divergent views on the origin of the monoclines and anticlines have commonly been inseparable from diverging views of the orientations of the faults with which these folds are associated. Advances in structural geology in the past two decades have made it crystal clear that, almost always, the form of a major fold reflects the form of the major fault with which it is associated (often “blind” and at depth), and that folds of the type we are addressing are the products of incremental progressive development over the course of thousands of earthquake cycles. This recognition, not understood at the time when the “classical” Colorado Plateau studies were being carried out, creates leverage in determining the orientations and shapes of faults at depth, even in the absence of subsurface data.

It is fault-propagation folding that best applies to formation of Laramide-style uplifts and associated monoclines within the Colorado Plateau. Such folding takes place above the tip of the blind shear zone as it propagates upward and laterally through basement and into cover. Erslev (1991) took issue with the practice of modeling fault-propagation folding as if the fault-propagation fold was a migrating kink band (Suppe and Medwedeff, 1990), establishing its shape early (as a function of fault-ramp angle) and then simply growing in size as displacement along the master fault progressively increased. Instead Erslev (1991, p. 617) emphasized that broad zones of folding in cover tighten and constrict downward toward narrow shear zones in basement, and that the fold geometry throughout affected cover tends to be triangular in cross section.

Erslev (1991) went on to provide the “trishear” kinematic model for fault-propagation folding, and this has proven to be a powerful contribution. “Trishear” (Erslev, 1991, p. 617–618) was coined for the triangular geometry of the zone of deformation within which strain-compatible shear is distributed (see, for example, Fig. 7). Allmendinger (1998) took the precepts of trishear deformation, and the mathematical analysis of “trishear” developed by Hardy and Ford (1997), and created software for both inverse and forward numerical modeling of trishear fault-propagation folding (see also Cristallini and Allmendinger, 2001). The profile geometries that emerge from forward modeling bear a very close relationship to the profiles of Colorado Plateau monoclines. One feature in particular stands out to us, both in the models and in field observations, namely, Erslev’s (1991, p. 617) emphasis that the synclinal hinges of monoclines are especially angular. In our experience, the synclinal hinges are seldom well exposed in the Colorado Plateau monoclines, but where we have seen them (e.g., the Rock Canyon monocline on the eastern margin of the Apache uplift, and the Nutria monocline along the Zuni uplift), the synclinal hinges are strikingly angular.

We take the opportunity in this paper to insert our own modeling of Colorado Plateau folding using the trishear programs of Allmendinger (1998), using very carefully rendered field profiles of bedding dip and contact locations across uplifts for control (Cardozo, 2005). The trishear modeling itself tracks five variables: initial x and y locations of the fault tip, fault dip (ramp angle), total fault slip, trishear angle, and propagation-to-slip (p/s) ratio (Allmendinger, 1998). A common homogeneous trishear movement plan (a potential sixth variable) was assumed throughout (Erslev, 1991).

An example of our findings is revealed in the results of forward modeling of the Waterpocket monocline, which is the eastern margin of the Circle Cliffs uplift (Fig. 16). Bedding dip data were collected by University of Arizona students Darren Green and Hillary Brown, who mapped a transect across the fold, measured dips using a meter-long digital level (leveling with respect to expansive normal-profile dip exposures), and compiled well logs made available by the Utah Geological Survey. Local stratigraphic thickness data were compiled from well logs as well as from the measured sections of Smith et al. (1963), Billingsley et al. (1987), and Hintze (1988).

We ran nearly 200 forward models of the Waterpocket monocline, experimenting with different trishear angles, ramp angles, and p/s ratios. The best fit for the Waterpocket fold is one
with a fault ramp angle of 30°, a trishear angle of 100°, and an initial fault tip 2.3 km below the basement-cover contact. In our best solutions, we used a $p/s$ ratio of 6.0 within basement, reducing it to 2.1 in cover for the remainder of the total 3.5 km of fault displacement (Fig. 16).

Where basement is found to be folded, the fault tip of the shear zone to be reactivated must have started out below the basement-cover contact (Fig. 17), perhaps originating as a footwall shortcut on an inverted listric shear zone. Insight into the folding of granite, through trishear fault-propagation folding, was presented by García and Davis (2004, p. 1274), based on their analysis of the Sierra de Huallín basement-cored uplift in the Sierras Pampeanas:

> The very propagation of the tip of an advancing basement fault creates, beyond the tip, a physical ground preparation that not only may more readily accommodate further tip advance, but may also accommodate folding of the material, even granite, through which the tip may advance. Thus, in the trishear example, the trishear angle, combined with slip magnitude, influences the amplitude dimensions of the eventual basement-cover folded interface. The damage in the trishear zone, in combination with predeformation anisotropy, renders even granite a macroductility. In short, before imagining folds as fault-propagation folds, it was impossible to imagine a set of mechanisms that would incrementally, first, damage the rock appropriately, and second, impart systematic movements of all constituent parts to create a folded form, even in granite.

**REGIONAL STRESS AND STRAIN DIRECTIONS**

With few exceptions, the observations and interpretations reported up to this point in this paper have skirted the challenge of inferring shortening directions, and then perhaps stress orientations, on the basis of the structures themselves. It is one thing to call attention to the geometry and deformation plan of the Colorado Plateau basement-cored uplifts, but quite another to invert products of the strain history in order to evaluate shortening directions and causal stresses. Methods have been available to invert fault-slip data to regional stress (Angelier, 1979, 1990, 1994; Suppe, 1985). There are limitations in applying these approaches to the Colorado Plateau uplifts. Although fracturing, largely jointing, is penetrative and pervasive within and across all of the uplifts, mesoscale faulting is essentially absent, except in the deformed zones in close proximity to the monoclines. There are a number of exceptions, e.g., the Chimney Rock area of the San Rafael Swell (Krantz, 1986, 1988), the steep limbs of the Miner’s Mountain and Circle Cliffs uplifts, and the West Kaibab fault zone on the margin of the Kaibab uplift (Strahler, 1948), but the mesofaulting record far afield from the deformed zones is too spotty for comprehensive analysis.

Nevertheless, Anderson and Barnhard (1986) applied Angelier’s (1979) fault-inversion technique to mesofaults in the sedimentary cover of the Waterpocket and Teasdale monoclines. Although these are not the major uplift-bounding basement
faults, they gave a maximum compressive stress direction of N65°E/S65°W.

Kelley and Clinton (1960) studied the regional joint patterns within the entire Colorado Plateau and yet were not able to extract from those data substantive conclusions about the Laramide stress field. Zion (1966) described joints in the southeastern part of the Monument uplift, near the Four Corners region. Based on the orientations of regional sets of shear joints, he interpreted a Laramide minimum compressive stress direction of ~N20°E/S20°W, approximately parallel to the strike of the Comb Ridge monocline, which bounds the Monument uplift.

Bergerat et al. (1992) reported a detailed study of joints in selected areas of the Colorado Plateau. They identified both shear and tensile joints, from which they interpreted a progressive rotation of maximum compressive stress from 65° to 115°. They cautioned, however, that although jointing could be a useful indicator of tectonic stress directions, it was difficult to use alone.

Swanberg (1999) analyzed joints in the Wingate Sandstone across well-exposed cliff outcrops of the doubly plunging Circle Cliffs uplift. Her work also suggested that it may be productive to invert joint system data to interpret regional compressive stress (Swanberg and Davis, 1999). The joints appear to “emerge” from strain energy stored from the time of folding, for there is a tight relationship between the geometry of the Circle Cliffs anticline and the geometry of the jointing. To date, there have been no such systematic analyses across all of the many uplifts of the Colorado Plateau.

Davis (1999) evaluated the systems of deformation band shear zones in the Colorado Plateau region of southern Utah, with an initial objective (among others) of determining if deformation band shear zones related to the Laramide-style uplifts were evident across the uplifts, and not just within the deformed zones along the boundaries of uplifts. Deformation bands and deformation band shear zones typically are distinguished by millimeter-to centimeter- to meter-scale bands or zones of cataclasis within porous sandstones (of ~20% porosity). They are shear phenomena and fault-like in their structural and kinematic significance. They “work harden” during their development and, unlike fractures and faults, do not become reactivated, thus creating a continuous record of evolving strain, which is a distinct advantage in stress-inversion studies. He found that deformation band shear zones of such origin are fundamentally restricted to the deformed zones, and although they contain an important local record of progressive structural deformation, the regional tectonic signals are much less clear.

Varga (1993) emphasized the challenge in using any mesoscale structural data within the region of Rocky Mountain foreland uplifts to interpret regional stresses within deformed zones, such as along the monoclines and faulted monoclines. He noted, on the one hand, that the regional stress signature may be masked by the local stresses inverted from the local strain conditions. On the other hand, he cautioned that if the deformed zones are weak zones, the far-field regional stresses will be rotated into principal planes parallel and perpendicular to the deformed zone(s). In both instances, local conditions rule, and regional stress signatures remain elusive.

In spite of these collective challenges, Bump (2001) and Bump and Davis (2002) analyzed, for purposes of stress inversion, mesoscale penetrative structures within and near the steep limb of the San Rafael, Miners Mountain, Monument, Uncompahgre, Circle Cliffs, and Kaibab uplifts. A goal was to resolve the challenge of whether penetrative structures observed are products of monoclinic folding and/or manifestations of regional stresses that formed the monoclines in the first place. The approach was to gather structural data at diverse locations along each deformed zone and then determine whether the preferred orientations of the small-scale structures shifted in ways that conformed to comparable shifts in the local strike of the monocline, or whether they remained fixed in preferred orientation even where the trend of the monocline itself shifted significantly.

The conventional mesostructures that proved useful were tectonic stylolites, en echelon vein arrays, deformation bands, and mesoscale slickenlined fault surfaces, including crystal-fiber lineations (Bump and Davis, 2002). We also used a relatively unconventional mesostructure, namely, Eshelby joints (Eidelman and Reches, 1992). These are millimeter- to centimeter-spaced parallel, planar fractures that occur in stiff “inclusions” (stress concentrators such as chert nodules) within soft layers (such as limestone).

For tectonic stylolites, we assumed that the orientation of maximum compressive stress (σ1) was parallel to the preferred orientation of teeth and cones. Within certain strata in the Monument uplift, the presence of conjugate semibrittle shear zones, composed of nested en echelon crystal-fiber gash veins (calcite) and en echelon tectonic stylolites (Fig. 18), revealed the direction of maximum compressive stress (i.e., perpendicular to the line of intersection of the two conjugate sets, and bisecting the acute angle between the sets). Deformation band shear zones of tectonic origin and slickenlined mesoscale faults commonly occur in conjugate sets as well, with demonstrable expression of sense-of-shear for each set, permitting the direction of maximum compressive stress to be deduced. We assumed that the strike azimuth of Eshelby joints (in the form of penetrative parallel joints in chert nodules within limestone) was the direction of maximum compressive stress.

Inferred directions of maximum compressive stress were found to be consistently oriented within each uplift, irrespective of changes in trends of monoclines associated with the uplift. The directions of maximum compressive stress were thus inferred to show the principal shortening directions (Table 1). Viewed as a system, the data reveal that there are two groupings of the Colorado Plateau uplifts, one that reveals a NE-SW principal shortening direction and a second that reveals a NW-SE principal shortening direction. The first group is composed of the Miners Mountain, Circle Cliffs, Kaibab, and Uncompahgre uplifts. The second group is composed of the San Rafael Swell and the Monument uplift. The conclusions reached regarding the N60°W/S60°E direction of maximum compressional stress (σ1) in the San Rafael Swell are in good agreement with the work...
of Davis (1999) and Christensen and Fischer (2000). The N60°-70°E/S60°-70°W maximum compressive stress (σ₁) determined for the Miners Mountain uplift is similar to observations by Anderson and Barnhard (1986). The N70°W/S70°E determination of maximum compressional stress (σ₁) for the Monument uplift is consistent with conclusions reached by Ziony (1966). The conclusions reached regarding a N50°-55°E/S50°-55°W orientation of maximum compressional stress (σ₁) for the Uncompahgre uplift are in general agreement with the work of Jamison and Stearns (1982). A N55°E/S55W interpretation of maximum compressional stress (σ₁) for the Kaibab uplift is consistent with the findings of Reches (1978), Davis (1999), and Tindall and Davis (1999), and Tindall (2000a, 2000b). Finally, the interpretation of maximum compressional stress (σ₁) of N55°-65°E/S55°-65°W for the Circle Cliffs uplift is consistent with the work of Anderson and Barnhard (1986) and Swanberg (1999).

Bump and Davis (2002) concluded that the compressive stresses identified in their study, and those inferred to have been at work during the formation of the Laramide-style uplifts, were a direct manifestation of basement strain. “[T]he direction of greatest shortening in the basement was parallel to the maximum compressive stress direction in the cover” (Bump and Davis, 2002, p. 436). Stated differently, “[T]he interpreted cover stress directions can be viewed as basement strain directions” (Bump and Davis, 2002, p. 436).

More broadly, the interpretation of ~65°-directed maximum compressive stress is consistent with the findings of many studies in Wyoming and Colorado (Erslev, 1993; Erslev and Rogers, 1993; Erslev and Wiechelman, 1997). Our interpretation—that some uplifts shortened in an ~110° direction—is not consistent with these studies. Explanations for the origins of two shortening directions for uplifts in the Colorado Plateau, and why only one of these is seen elsewhere, require examination of the timing of the uplifts and consideration of inferred tectonic conditions west of and beneath the Colorado Plateau during the Cretaceous and early Tertiary.

### TIMING OF UPLIFTS

Over the years, there have been several attempts to determine the exact timing of the uplifts in the Colorado Plateau. These have involved several approaches, from sedimentologic analysis to apatite fission-track analysis to (U-Th)/He thermochronology. The former have been most successful, but none has demonstrated any clear difference in timing among the different uplifts (Lawton, 1983, 1986; Dumitru et al., 1994; Goldstrand, 1994; Stockli et al., 2002).

Lawton (1983, 1986) examined fluvial deposits of the Upper Cretaceous Mesa Verde Group and Paleocene North Horn Formation in the Uinta Basin on the northern flank of the San Rafael Swell. Starting in the latest Campanian, he documented local thinning of stratigraphy over the northern end of the San Rafael Swell and the diversion of paleodrainages off its flank. By the Maastrichtian, sediments were also ponding against the western flank of the swell. Based on these observations, Lawton interpreted the onset of uplift in the latest Campanian. Uplift was initially rapid, waning later, and it continued until the late Paleocene.

Goldstrand (1994) examined deposits of the Upper Cretaceous Canaan Peak Formation in the Kaiparowits adjacent to the Kaibab and Circle Cliffs uplifts. Like Lawton, he documented stratal thinning onto the uplifts and diversion of the main axial drainages, starting in the latest Campanian or earliest Maastrichtian. The cessation of deformation was recorded by the presence of middle Eocene lacustrine deposits of the Claron Formation, which onlap and overtop Laramide paleotopographic highs (Goldstrand, 1994).

Dumitru et al. (1994) collected apatite-bearing samples spanning ~4 km of stratigraphy, starting with the Precambrian in the bottom of the Grand Canyon, continuing up to the Permian at the rim of the canyon, then shifting laterally to the Circle Cliffs uplift and continuing up through the Cretaceous. Fission-track analysis showed that Permian samples reached a temperature of 90–100 °C and began cooling at 74 Ma. Dumitru et al. (1994)

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<td>San Rafael</td>
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<td>Miners Mountain</td>
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<td>Kaibab</td>
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Figure 18. Photograph of semiductile conjugate shear zones composed of nested en echelon crystal-fiber gash veins (calcite) and en echelon tectonic stylolites, in the Honaker Trail Formation, Monument uplift. Note lens cap for scale. Photograph by G.H. Davis.
interpreted this as reflective of erosion triggered by the rise of the Kaibab and Circle Cliffs uplifts. Stockli et al. (2002) hoped to apply the (then) new technique of (U-Th)/He thermochronology to the problem of dating structural deformation of many of the Colorado Plateau uplifts. To that end, they collected and analyzed samples from stratigraphic profiles on the Circle Cliffs, San Rafael, Monument, and Kaibab uplifts. Unfortunately, all of the samples yielded ages from 33 to 11 Ma, consistent with uplift and denudation of the Colorado Plateau, but too young to be referencing the rise of individual Laramide uplifts (Stockli et al., 2002).

Though the constraints on timing are poorly defined, thermochronologic and sedimentologic observations suggest that the uplifts examined all began to rise concurrently in the latest Campanian. Notably, this group includes the uplifts that developed in response to NE-SW shortening and those that developed in response to NW-SE shortening. More broadly, these results are consistent with results of similar studies in Wyoming and Colorado, namely, a rapid onset of deformation in the Campanian followed by quick eastward propagation of shortening, with little or no north-south diachronity (Bird, 1988; Dickinson et al., 1988; Roberts and Kirschbaum, 1995; Crowley et al., 2002).

**ORIGIN AND DEVELOPMENT OF THE SYSTEM OF UPLIFTS**

From the Late Cretaceous to the early Tertiary, coincident with construction of the uplifts described here, the Colorado Plateau was subjected to compressive stress from two distinctly different sources. To the west and northwest, the thin-skinned Sevier thrust belt, over the course of the preceding 80 m.y., evolved into an enormous topographic edifice (Fig. 19) (DeCelles and Coogan, 2006). Balanced cross sections (Coogan et al., 1995; DeCelles et al., 1995), pressure-time-temperature histories of midcrustal rocks now exposed in the hinterland (Hodges and Walker, 1992; Camilleri and Chamberlain, 1997; Lewis et al., 1999), flexural modeling of the foreland basin (Jordan, 1981; Currie, 1998), kinematic restorations of postorogenic extension (Coney and Harms, 1984), and paleofloral data (Chase et al., 1998) all suggest an average regional elevation of 3–4 km in western Utah. Like all thrust belts, or, for that matter, like all topographic highs, the Sevier thrust belt exerted a compressive stress operating generally perpendicular to the thrust front (Elliott, 1976; Davis et al., 1983; Molnar and Lyon-Caen, 1988; Bada et al., 2001). The Charleston-Nebo salient of the Sevier belt strikes NE-SW (see Fig. 19), and thus the local topography-derived stress was probably directed southeastward into the Colorado Plateau (Bump, 2004).

The second source of compressive stress acting on the Colorado Plateau was related to subduction of the Farallon plate, enhanced by slab flattening and attendant generation of higher traction along the base of the lithosphere. A subduction zone had sat off of the western coast of North America for much of the Phanerozoic, with the slab plunging steeply into the mantle for much or all of that time. Starting in the Late Cretaceous, however, the subducting slab shallowed, sending a pulse of magma-
by the encroaching thrust belt, and compressed NE-SW by the
shallowly subducting Farallon plate and cratonic North America.
Paleostress magnitudes are very difficult to assess, but they were
probably similar in magnitude. As Molnar and Lyon-Caen (1988)
pointed out, topographic highs are crude pressure gauges, in that
the weight of the topography must be supported by an equal lateral
force at its margins. Assuming a bulk rock density of 2550 kg/m³,
a 3–4-km-high thrust belt would exert a lateral stress of 75–100
MPa on the surrounding region (Bump, 2004). Plate-interaction
stress magnitudes are less well known, but estimates range from
tens to hundreds of MPa (Govers et al., 1992; Richardson, 1992;
Zoback and Healy, 1992; Zoback et al., 1993; Richardson and
Coblentz, 1994; Coblentz and Richardson, 1996), about the same
order of magnitude as those results for a thrust belt. Farther to
the east, the thrust-belt derived stress would have waned due to
friction on the basal detachment (be that within the crust or at the
base of the lithosphere). Stress from the flat slab, on the other
hand, would have increased to the east as the viscous coupling
acted over greater distances (Bird, 1988).

In the context of the Cordillera, the Colorado Plateau thus
sat in a unique location, subjected to unique stresses. By virtue
of the northeastward-subducting Farallon slab below and the
southeastward-propagating thrust belt to the west, the plateau
was squeezed in two directions simultaneously. Furthermore, by
virtue of its position adjacent to the thrust belt, the Colorado Pla-
treau was subjected to the greatest possible stress from the thrust
belt and a relatively low stress from the flat slab, such that the
two stresses were uniquely similar in magnitude (Bump, 2004).
Caught in this constrictional stress field, existing weaknesses in
the plateau deformed in a dominantly reverse-slip sense (Bump,
2004). NE-striking faults, such as those bounding the San Rafael
and Monument uplifts, slipped to the southeast, while NW-
striking faults, such as those bounding the Waterpocket, Miners
Mountain, and Uncompahgre uplifts, slipped to the northeast.
The Kaibab uplift, which is bounded by a north-northeast–strik-
ing fault that slipped obliquely to the northeast (Tindall and
Davis, 1999), did not slip to the southeast like those bounding
the San Rafael and Monument uplifts because it lies well to the
south of the Charleston-Nebo salient, out of the line of southeast-
directed thrust-belt stress (Bump, 2004).

CONCLUSIONS

Our present understanding of the Colorado Plateau, its
structure, and its tectonic evolution is built on the shoulders of
giants and more than 100 yr of geologic field work, analysis, and
reanalysis. Beginning with the very first explorations by Pow-
ell (Powell, 1873), Gilbert (Gilbert, 1876), and Dutton (Dutton,
1882), structural knowledge of the Colorado Plateau has pro-
gressed from basic (and elegant) description of the monoclines
and their underlying shear zones, to confusion and debate over
the tectonic significance of the range in orientations (Baker,
1935; Kelley, 1955b; Wise, 1963; Sales, 1968; Stearns, 1978;
Gries, 1990; Yin, 1994), and to yet another attempt at synthesis,
which undoubtedly will be debated and lead to other discussions
and understandings. We infer that monoclines bounding the ten
major uplifts of the Colorado Plateau are rooted downward into
ancient basement shear zones with a long history of reactivation.
These shear zones have their origins in different tectonic events
and consequently span a broad range of orientations. Like most
other workers, we have focused on reactivation of basement shear
zones that were originally created in the Proterozoic, but Marshak
et al. (2003) rightly pointed out that faults created during Ances-
tral Rocky Mountain deformation may have been reactivated as
well. The most likely areas for this are in the eastern part of the
Colorado Plateau (e.g., Paradox basin) and perhaps in the Four
Corners region (e.g., Defiance uplift). During the formation of the
Laramide-style uplifts, some shear zones were reactivated in pure
reverse slip; others were reactivated obliquely. The San Rafael
and Monument uplifts shortened toward the southeast. The Circle
Cliffs, Kaibab, and Uncompahgre uplifts shortened toward the
northeast. These two simultaneous, nearly orthogonal shortening
directions were set up by a constrictional strain field that was the
product of the northeastward-subducting flat slab and the south-
eastward-advancing Sevier thrust belt. This constrictional stress
field was unique to the Colorado Plateau. Elsewhere in the Rocky
Mountains (e.g., in Wyoming), the directions of thrust-belt propa-
gation and plate convergence were more nearly parallel.

An improved understanding of the origin of Laramide-style
basement-cored uplifts in the Colorado Plateau will simultane-
ously improve understanding of the plate-tectonic evolution of
continental interiors, including active tectonic phenomena far
removed from plate margins. In terms of testing the synthesis pre-

dented here, there is an urgent need for a nuanced, sophisticated,
very precise understanding of the timing and movement histories
of individual uplifts, and for finite-element modeling that would
elucidate likely gradients of deformation across the plateau.

It is natural to think of the Colorado Plateau region as strong,
but we believe it is more illuminating to think of its basement as
riddled with weak shear zones and tectonic displacements that
made it quite unnecessary for the shear-zone–bounded blocks
themselves, each of which occupies thousands of square kilo-
meters, to exercise layer-parallel strain. It was just a matter of
time before the Colorado Plateau thus deformed because the
“tip zone” of the Sevier fold-and-thrust belt had been marching
steadily eastward toward the Cordilleran hinge line, ultimately
advancing eastward beyond the last remaining passive-margin
basin sediments. The encounter with “new” crustal structure
capped by basement-supported craton sediments triggered a
“new” deformation mechanism, one that exploited crustal hetero-
geneties, including preexisting shear-zone weaknesses, in order
to achieve requisite shortening.

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