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The Cockscomb Segment of the East Kaibab Monocline: Taking the Structural Plunge

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ABSTRACT

The East Kaibab monocline in northern Arizona and southern Utah is a north- to northeast-trending fold in Paleozoic and Mesozoic sedimentary rocks on the eastern margin of the Kaibab uplift. The east-dipping monoclinal fold developed above a west-dipping fault in underlying Precambrian basement rocks between 80-50 million years ago (Ma). Erosion has since carved the monocline into a narrow series of ridges and valleys of colorful, candy-striped layers of rock, the most spectacular of which lie in Grand Staircase-Escalante National Monument.

A sequence of processes including folding, fault growth, uplift, and erosion formed the breathtaking and variable landscapes visible along this 'Cockscomb,' and left clues helpful to unraveling the three dimensional geometry and growth history of the monocline. The fold plunges gently to the north, exposing different stratigraphic levels, fault patterns, degrees of folding, and topographic and structural relief along its surface trace. Some of the changes in surface geology indicate variations in fault and fold geometry at depth, but some simply reflect the effects of erosion and exposure level. Analysis of these characteristics based on map relationships and field observations leads to the conclusion that the East Kaibab monocline formed by gradual upward propagation of a basement-rooted oblique-reverse fault, and its associated 'fault tip fracture zone,' within the core of the growing fold. This paper describes visualization techniques, conceptual models, and geological arguments that support an oblique-reverse fault-propagation-fold interpretation of the Cockscomb segment of the East Kaibab monocline.

INTRODUCTION

The Cockscomb in Grand Staircase-Escalante National Monument is one of the most spectacular geologic features of the Colorado Plateau, and the elegant details of its structural growth through time are exposed in outcrops stretching from the Grand Canyon in northern Arizona to Table Cliff Plateau in Utah. The steeply inclined, candy-striped layers of rock along the Cockscomb are part of an abrupt fold, the East Kaibab monocline, that interrupts the otherwise flat-lying sedimentary rock sequence (figure 1). Changes in the form of the fold and the surface fault pattern along its 60 km trace in southern Utah are evidence of the changing character of the underlying fault and fault-fold relationships. Subtle differences in the stratigraphy and structural geology exposed at the surface are clues to the complicated interactions among folding, faulting, uplift, and erosion that created this stunning geologic feature.

Early explorers in the Grand Canyon area described the region's monoclines and speculated that they formed by simple bending of sedimentary strata over differentially uplifted basement blocks (Dutton, 1882; Powell, 1873) (figure 2). This kinematically simple explanation is sufficient to describe the form of the Cockscomb at any one location, but differences in the surface expression of the monocline along its northeast-southwest trend are the result of more complicated processes. Tindall and Davis (1999) presented quantitative data and analyses to demonstrate that the Utah segment of the fold formed by oblique motion (a combination of strike-slip and reverse-slip offset) on the underlying basement fault, and propagation of oblique faulting into high structural and stratigraphic levels of the fold during its growth. In fact, the map pattern of the Cockscomb itself exposes equally compelling evidence for this interpretation when certain concepts of structural geology and geologic map interpretation are applied.

Because development of the Cockscomb involved interaction of many processes, understanding the structure's complexity requires incorporation of a number of tech-

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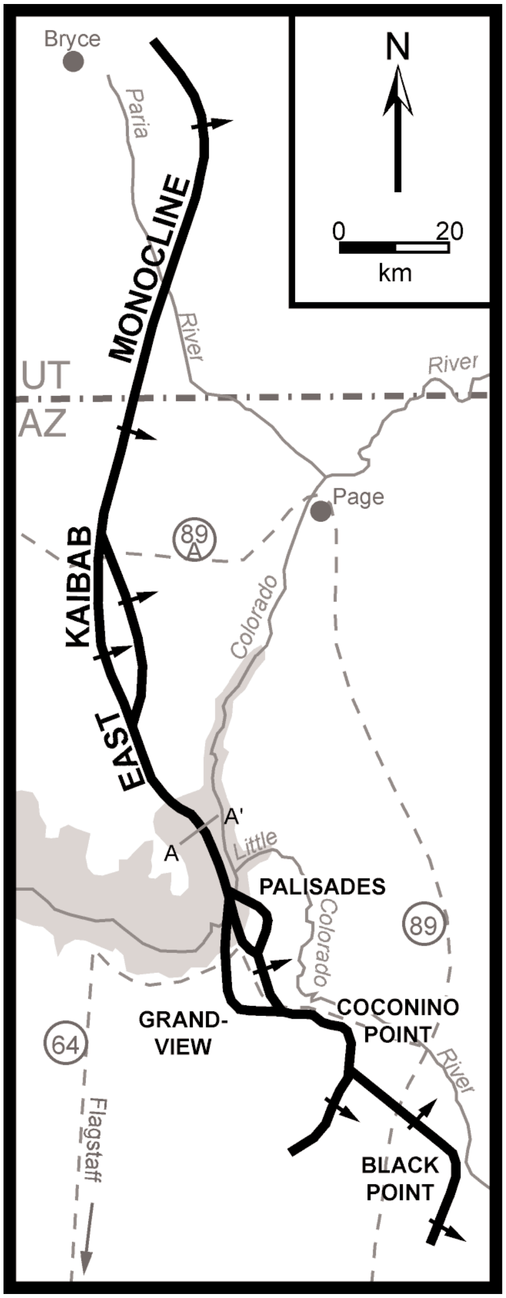


Figure 1. Location of the East Kaibab monocline and its branching segments (Palisades, Grandview, Coconino, Black Point) in northern Arizona and southern Utah. Shaded area is the Grand Canyon. Line A-A' shows the location of the cross section in figure 5.

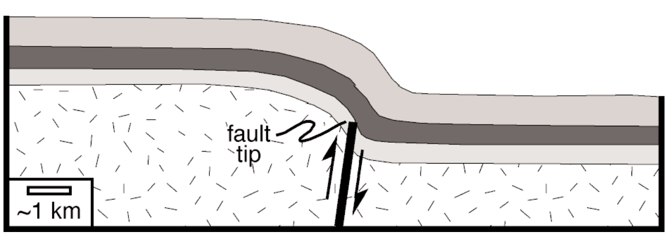


Figure 2. Simple cross section sketch of a Colorado Plateau monocline. Basement faulting at depth has caused folding of overlying sedimentary strata.

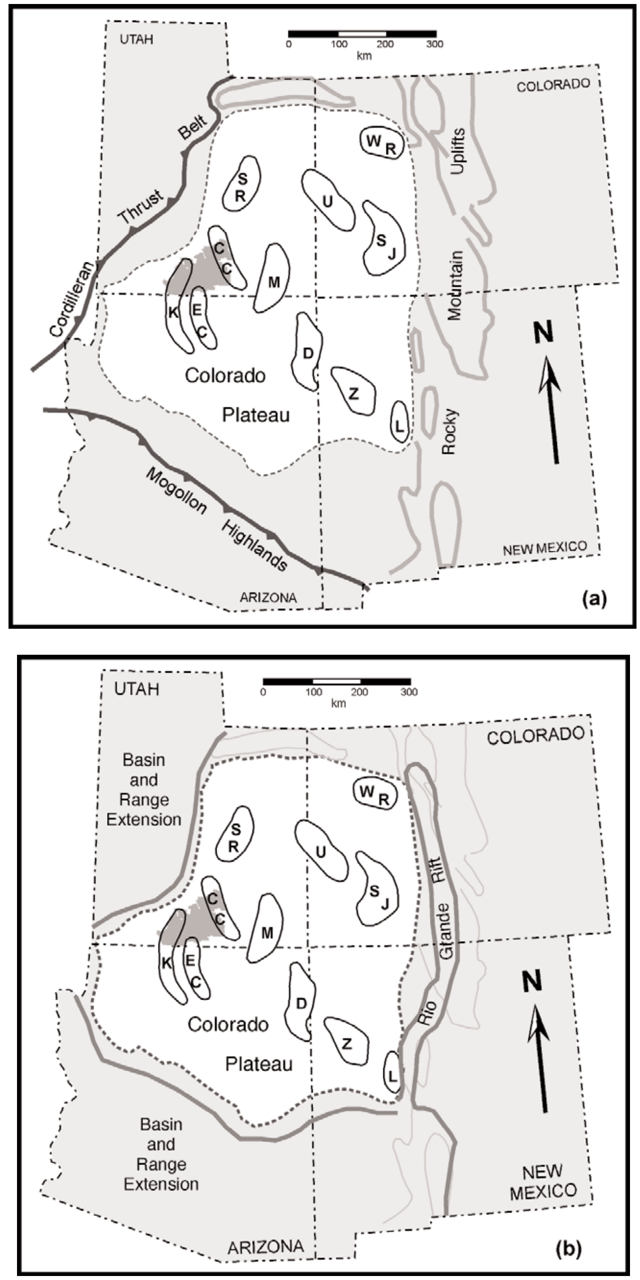


Figure 3. Regional maps of Mesozoic and Cenozoic structures of the Colorado Plateau and surrounding geographic provinces. Shaded area on the Colorado Plateau is Grand Staircase-Escalante National Monument. Deformation of the Plateau region has been minimal compared to that in surrounding areas throughout Phanerozoic time, for reasons that are still poorly understood. 3(a). Mesozoic and early Tertiary compressional tectonic events caused uplift of the Cordilleran thrust belt and Mogollon highlands on the west and southwest edges of the Colorado Plateau, and formation of enormous Rocky Mountain uplifts to the north and east. Deformation affected the Colorado Plateau region only mildly, resulting in broad, low uplifts bounded by monoclinal folds. Colorado Plateau uplifts include the Circle Cliffs (CC), Defiance (D), Echo Cliffs (EC), Kaibab (K), Lucero (L), Monument (M), San Juan (SJ), San Rafael (SR), Uncompahgre (U), White River (WR), and Zuni (Z). 3(b). More recently, Tertiary and Quaternary extension of the western United States has dissected the Cordilleran thrust belt, Mogollon highlands, and Rocky Mountain uplifts to form the modern Basin and Range and Rio Grande Rift. The Colorado Plateau remains largely unaffected by recent extensional tectonics.

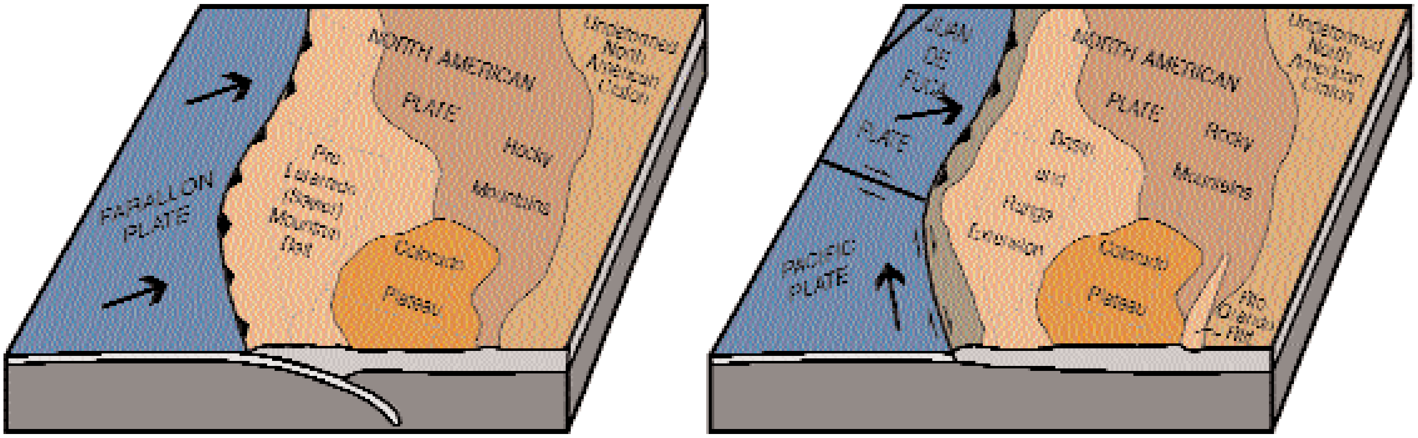


Figure 4. (a) Simple sketch of the plate tectonic setting of western North America during the Laramide orogeny (80-40 Ma). Shallow-angle subduction of the Farallon Plate beneath the North American plate transmitted horizontal compressive stress thousands of kilometers eastward into continental North America, forming the Rocky Mountain uplifts. The Colorado Plateau was only slightly affected by Laramide deformation. (b) After the end of Laramide subduction, a right-lateral transform boundary developed between the North American and Pacific plates (the San Andreas fault). Areas previously subjected to compressive stress began to collapse due to gravitational forces and crustal extension, forming the Basin and Range province and Rio Grande Rift, and dissecting the Rocky Mountain uplifts. The Colorado Plateau remains relatively unaffected by recent extensional tectonics. For the sake of simplicity, tectonic provinces far from the Colorado Plateau (for example the Cascade Mountains, Columbia Plateau, Coast Ranges) are not shown.

niques and ideas. Structural geologists use maps and measurements of folds, fractures and rock types exposed at the Earth's surface to build a thorough understanding of the three dimensional geometry of rock units both buried beneath the surface and removed by erosion from above. This task comes naturally to some geologists accustomed to filling in the missing puzzle pieces through application of concepts derived from simplified models of geologic structures. However, even under the best circumstances some important map clues are easy to overlook. This paper describes the changes in surface expression of the East Kaibab monocline north of the Grand Canyon, and presents models and diagrams of basic structural concepts as a tutorial for interpreting the three dimensional geometry of the Cockscomb in Grand Staircase-Escalante National Monument.

BACKGROUND

Regional Setting

The Colorado Plateau geographic province of the western United States occupies parts of Utah, Arizona, New Mexico, and Colorado. It is a region of relatively undeformed Phanerozoic sedimentary rocks surrounded by highly deformed rocks of adjacent tectonic provinces — the Rio Grande Rift on the east, Rocky Mountains on the east and north, and the Basin and Range province on the west and south (figure 3). The Rocky Mountains are an expression of the Laramide tectonic event that affected western North America approximately 80-40 Ma (Brown, 1988). This mountain building event was driven by east-directed subduction of the Farallon tectonic plate (ancient floor of the Pacific ocean) beneath the western margin of North America (figure 4). Interaction of the Farallon and North American plates transmitted horizontal compressive stress thousands of kilometers eastward into the North American continent (Coney, 1976). Compression caused differential uplift of crystalline basement blocks and overlying sedimentary rocks on the east and north sides of the relatively rigid Colorado Plateau, and formed a belt of folded and thrusted sedimentary rocks to the west and south of the Plateau. More recently, extensional tectonics and crustal thinning affected the regions that were previously compressed and uplifted; tensional forces dissected the Rocky Mountain uplifts and formed the distinctive Rio Grande Rift and Basin and Range extensional provinces (Windley, 1995) (figure 4). Thinning of the crust began soon after the end of Laramide subduction and is still active in the Basin and Range and Rio Grande Rift today (Wernicke, 1992). Given the intense tectonic deformation expressed in rocks of these bordering regions, it is remarkable that the sedimentary rock layers of the Colorado Plateau have remained so undeformed. Within the Colorado Plateau, the effect of Laramide deformation is expressed in the landscape by broad, low uplifts separated from vast shallow basins by erosional cliffs or low-amplitude folds in Paleozoic and Mesozoic sedimentary rocks, and evidence of recent extension is almost entirely absent.

The Cockscomb

The Kaibab uplift in northern Arizona and southern Utah and its steep eastern limb, the East Kaibab monocline, are examples of Colorado Plateau structures formed during the Laramide orogeny. The landscape expression of the northern part of the East Kaibab monocline is often called the Cockscomb because erosion of the steep, east-dipping sedimentary layers has exposed strike-parallel ridges of near-vertical red and white rock that resemble a rooster's comb. The most visually stunning parts of the Cockscomb lie in Grand Staircase-Escalante National Monument, extending from near Kodachrome Basin State Park in Utah to the Arizona-Utah border. This stretch coincides with the area of greatest structural relief (vertical separation between anticlinal hinge and synclinal trough), ranging from 1,200 m to 1,600 m in most of the Monument. The East Kaibab monocline actually continues southward into Arizona and across the Grand Canyon to near Flagstaff, bifurcating in places to form several branching segments (for example the Grandview, Palisades, Coconino, and Black Point segments) (figure 1). Structural offset decreases southward from the Monument to 800 m in the Grand Canyon, 700 m at Coconino Point, and 150 - 300 m along the Black Point segment (Babenroth and Strahler, 1945). The total trace length of the monocline is approximately 240 km, making it one of the largest of the monoclines on the Colorado Plateau (Reches, 1978).

Structural Roots

The East Kaibab is one of the best studied of the Colorado Plateau monoclines, in part for its enormous trace length and considerable vertical offset. Perhaps more importantly, the Grand Canyon offers a deep cross-sectional exposure that reveals the nature of deformation in Paleozoic and underlying Precambrian rocks. This cross-sectional exposure reveals that a steep (60°-70°) west-dipping fault zone in Precambrian basement rocks, the Butte fault, underlies the folded Paleozoic and Mesozoic rocks that

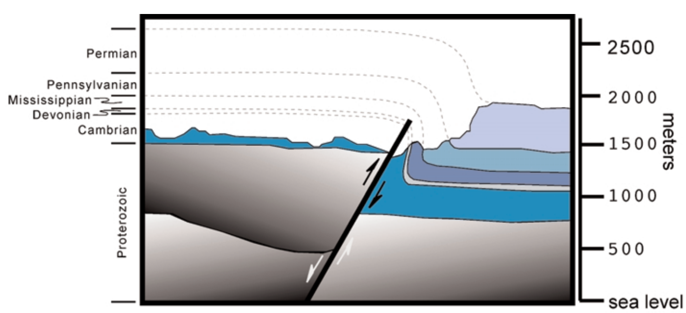


Figure 5. Cross section showing East Kaibab monocline fault-fold relationships in the Grand Canyon. A west-dipping fault in Precambrian and lower Paleozoic rocks underlies the east-dipping monoclinal fold in upper Paleozoic strata. Dashed lines represent Paleozoic rocks that have been removed by erosion. Overlying Mesozoic rocks also have been stripped away by erosion. Note that the lowest Precambrian layer shows normal (west side down) offset, indicated by white arrows. Normal faulting occurred before deposition of Paleozoic sedimentary rocks. After deposition of the Paleozoic and Mesozoic sedimentary section, reverse movement along the same fault (black arrows) formed the East Kaibab monocline. The magnitude of reverse offset must have been smaller than the magnitude of ancient normal offset, since normal separation is still preserved at the Precambrian level. Cross section location is shown on figure 1.

constitute the East Kaibab monocline (figure 5). West-side-down stratigraphic offsets in the Precambrian sedimentary sequence of the Grand Canyon Supergroup show that the Butte fault first became active in Precambrian time, long before the deposition of Paleozoic and Mesozoic sediments that now make up the Cockscomb (Walcott, 1890; Maxson, 1961; Huntoon, 1969, 1993; Huntoon and Sears, 1975). Beginning at ~600 Ma (Bond, 1997; Timmons and others, in press) Paleozoic and Mesozoic sediments accumulated to a thickness of at least 3,500-4,000 m during a time of tectonic quiescence (Hintze, 1988). Laramide compression initiated at about 80 Ma in this region and reactivated the ancient 'basement' fault, causing the west side to move up relative to the east. Over millions of years the gradual, earthquake-by-earthquake fault movement at depth formed the broad, asymmetrical Kaibab uplift and East Kaibab monocline in the overlying Paleozoic and Mesozoic cover (Huntoon and Sears, 1975; Huntoon, 1993). Although the Grand Canyon provides the only exposure of the basement fault underlying the East Kaibab monocline, the fault (or a network of similar faults) is assumed to underlie the fold for its entire length (Davis, 1978; Stern, 1992; Rosnovsky, 1998). This exposure and other Grand Canyon exposures of fault-cored monoclines (for example the Palisades Branch, Grandview, and Hurricane) are the basis for the widely accepted assumption that similar reactivated basement faults underlie other Colorado Plateau uplifts.

A VISUAL TOUR

Both early and more recent studies of the East Kaibab monocline have focused on outcrops in and near the Grand Canyon because of their spectacular exposure of the underlying basement fault. Although the Grand Canyon outcrops have helped build a basic understanding of the deep structure associated with the Kaibab uplift, they offer only a limited view of the changes in structural character along the trend of the East Kaibab monocline. That is, the deep Grand Canyon outcrops offer only one perspective in one location along the 240-km fold. Outside the walls of the Grand Canyon the gradual changes in rock types, topography, and scenery along the Cockscomb offer additional evidence for the changing structural geometry of the fold at the surface and at depth. This evidence does not contradict basic models of monocline development, but rather adds an appreciation for the complexity of these regionally significant features.

Systematic variations in stratigraphy and structural style along the Cockscomb in northern Arizona and southern Utah provide the observations necessary for interpreting the growth history of the East Kaibab monocline. Both obvious and subtle features in the photographs of figure 6 contain clues for deciphering underlying structural relationships. Figure 6a begins the visual tour at the bottom of the Grand Canyon where the steep, west-dipping Butte fault juxtaposes Proterozoic sedimentary rocks (right side) and volcanics (left side). At this location the folded Paleo-

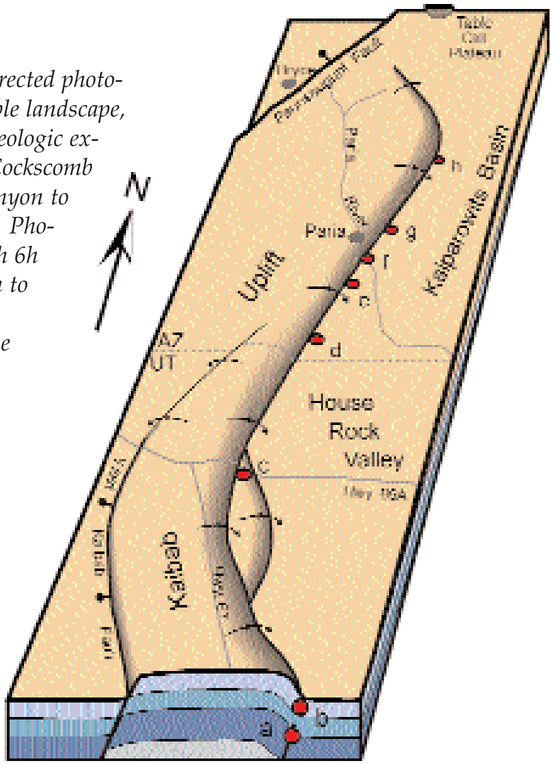
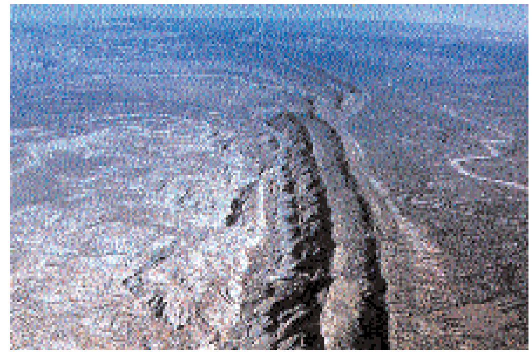


Figure 6. North-directed photographs of the variable landscape, stratigraphy, and geologic exposures along the Cockscomb from the Grand Canyon to Table Cliff Plateau. Photographs 6a through 6h progress from south to north; locations are shown on an oblique perspective map of the Kaibab uplift. Interesting features of each photograph are discussed in the text.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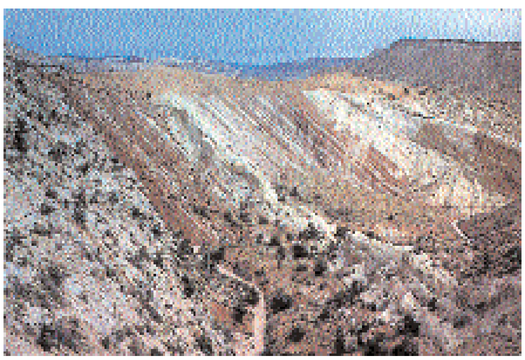
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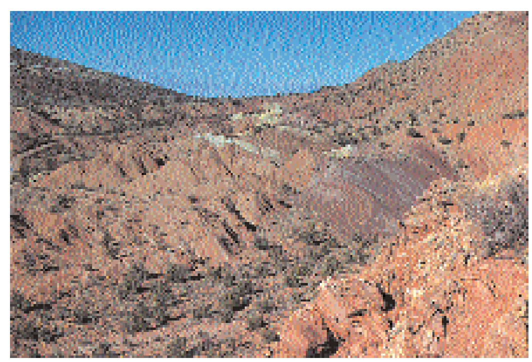
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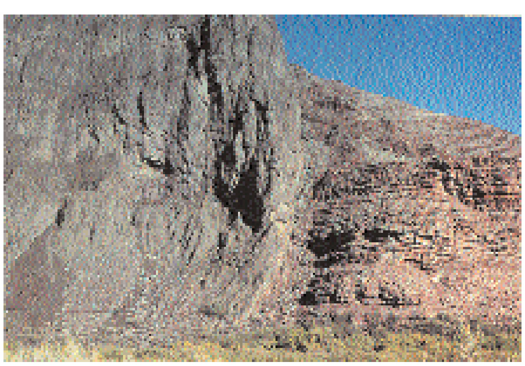
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b

zoic and Mesozoic rocks of the Cockscomb have been stripped away by erosion along the Colorado River (see figure 7 for stratigraphy). However, the overlying strata are preserved nearby in tributaries of the Grand Canyon, as shown in figure 6b. There the west-dipping fault terminates beneath the surface, but its west-side-up offset has generated an east-dipping monoclinal fold in Mississippian Redwall Limestone. Together, views 6a and 6b (figure 6) show that fault offset changes to fold-accommodated offset low in the Paleozoic stratigraphic section in the Grand Canyon. The point at which the discrete fault plane or fault zone disappears upward into folded strata is known as the fault tip (figure 2). At the location of photograph 6b, the tip of the Butte fault propagated upward through the stratigraphic section only to the level of Mississippian rocks before Laramide deformation ended.

At the stratigraphic level of upper Paleozoic rocks, House Rock Valley stretches from the north rim of the Grand Canyon northward toward the Arizona-Utah border (figure 6c). East-dipping Kaibab Limestone forms the western slope of the valley, and the flat-lying, red Moenave and Kayenta Formations compose the Vermilion Cliffs to the east. It is possible to imagine that folded, east-dipping Moenave and Kayenta Formations capped the east-dipping slope of the Kaibab uplift millions of years ago, as the Kaibab Limestone does today, but their folded and faulted layers along the crest and in the steep limb of the monocline have since been removed by erosion. The yellowish beds of Kaibab Limestone in the foreground dip gently to the east, parallel to the present edge of the Kaibab uplift in the background. Sediments on the floor of House Rock Valley obscure east-dipping Triassic strata in the synclinal hinge of the monocline.

Figure 6d is a view of the Cockscomb near the Arizona-Utah border. Brick red and grey strata (left center) belong to the Triassic Moenkopi Formation, and the brighter red rocks on the right side are Triassic-Jurassic Moenave and Kayenta Formations. Erosion has not dissected the monocline as deeply here, so that folded Kayenta and Moenave are preserved in the steep limb. The purplish unit in the right center is a narrow, fault-bounded sliver of Triassic Chinle Formation (faults are not obvious in this picture). From area 6c to 6d (figure 6), two obvious changes have occurred in the landscape. First, the steep limb of the fold is exposed in higher stratigraphic units at the location of figure 6d; that is, Moenave and Kayenta Formations are involved in the monoclinal fold at 6d (figure 6), but these were flat-lying on the east side of the fold at 6c (figure 6). Secondly, the dip of strata in the east-dipping monoclinal limb is much steeper at 6d than at 6c (figure 6); this reflects the gradual increase in structural relief between the two photo locations.

In figure 6e, just southeast of Paria, steeply dipping Jurassic Carmel and Entrada Formations mark the continued up-section exposure of deformation toward the north. To the northeast, in the right-hand background of the photograph, flat-lying Cretaceous rocks (Tropic and Straight Cliffs formations) compose the high cliffs. The topographic expression of the cliffs is the result of erosion by the Paria River, which flows nearby in the synclinal trough of the East Kaibab monocline. Like the cliffs of flat-lying Moenave and Kayenta Formations in figure 6c, erosion has removed the folded and deformed portion of the Cretaceous strata from the crest of the monocline here, leaving eastward-receding cliffs of undeformed rock.

Where the Paria River crosses the steep limb of the Cockscomb, the canyon mouth exposes a west-dipping reverse fault in Navajo and Carmel Formations (figure 6f). Fault movement has placed a stratigraphically lower sandstone layer (white, left side) above stratigraphically higher Carmel Formation redbeds (right side). The fault is approximately parallel to the trend of the monocline, dips steeply west, and displays a west-side-up sense of offset, similar to but much smaller than the basement fault exposed in the Grand Canyon. Several west-dipping reverse faults are exposed along the monocline in the vicinity of figure 6f.

Still farther north, as shown by figure 6g, tan and grey stripes of Cretaceous Dakota, Tropic, and Straight Cliffs Formations are preserved in the steep fold limb. In the background, white Navajo Sandstone occupies the crest of the monocline, dipping less steeply than the Cretaceous rocks in the foreground. Finally, figure 6h is an oblique aerial photograph of the northern end of the East Kaibab monocline. Flat-lying, white Navajo Sandstone forms the crest of the monocline on the west, and flat-lying Cretaceous strata of the Kaiparowits basin make up the desolate landscape on the east. Northward along the fold, dips gradually die out until the monocline disappears near Table Cliff Plateau (barely visible in the left background).

The photographs in figure 6 offer a representative sample of the changes in scenery, stratigraphy, fold form, and fault expression visible in different areas along the Cockscomb. These changes present clues about the geometry of the Cockscomb at depth, and how this geometry changes both vertically (with depth) and horizontally (along the monocline). Surface evidence can be integrated through the use of geologic maps, visualization techniques, and conceptual models in order to decipher the three dimensional geometry and growth stages of the Cockscomb.

STRUCTURAL OBSERVATIONS

The northward changes in landscape along the Cockscomb in southern Utah correspond to structural patterns and stratigraphic clues in the geologic map (figure 7). Understanding the structural implications of the map-view expression of the Cockscomb requires several conceptual tools. These include geometry of plunging folds, down-plunge viewing, Riedel fracture development, fault-slip gradient, and fault-propagation folding. The following sections contain a general description of each concept, and application of the concepts to interpreting patterns of faulting and folding exposed along the Cockscomb.

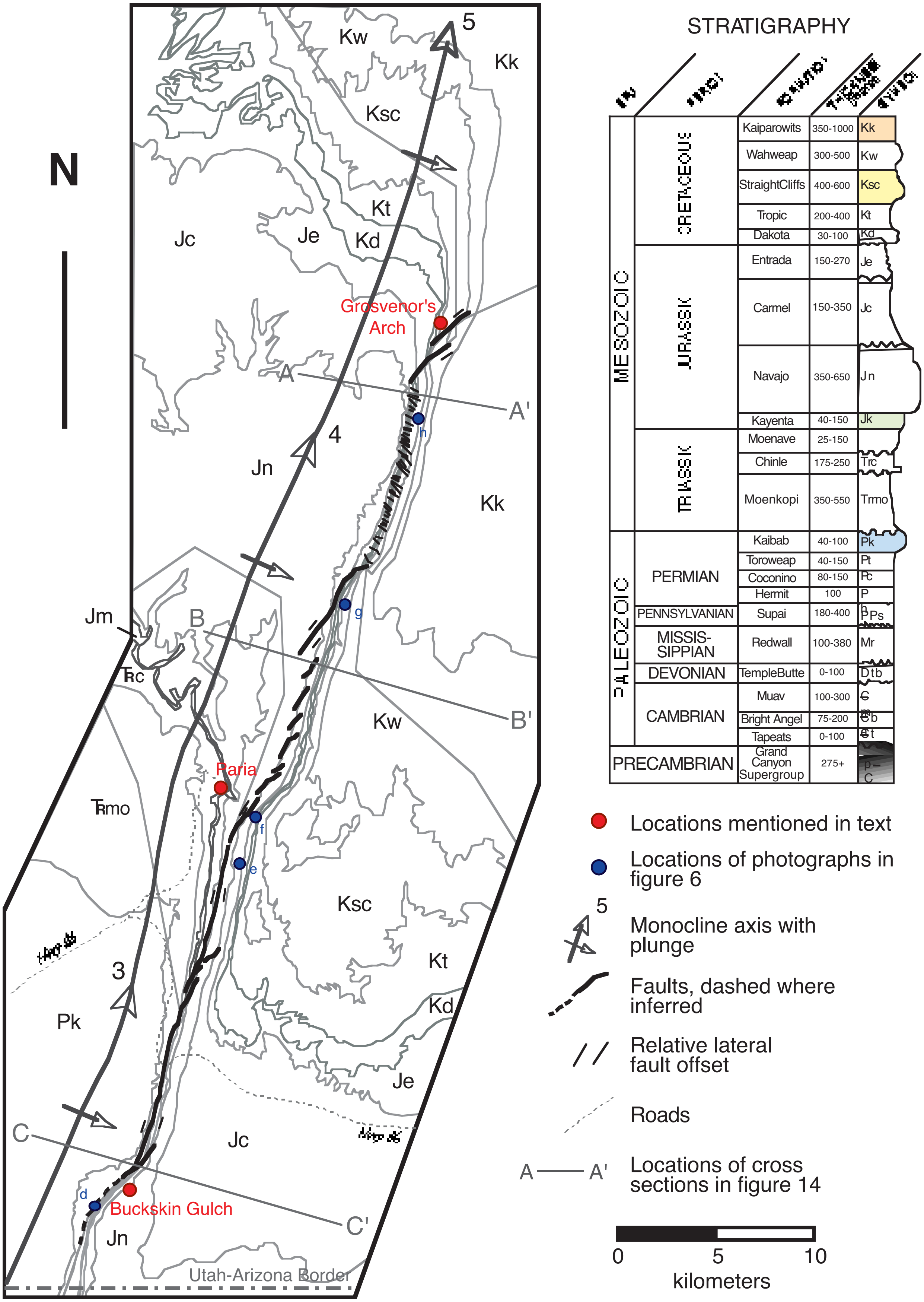

Figure 7. Geologic map of the East Kaibab monocline in Grand Staircase-Escalante National Monument. Stratigraphic column (right) includes Precambrian and Paleozoic rocks that are not exposed in the monument but are visible in the Grand Canyon. Cross sections A-A', B-B', and C-C' refer to figure 14.

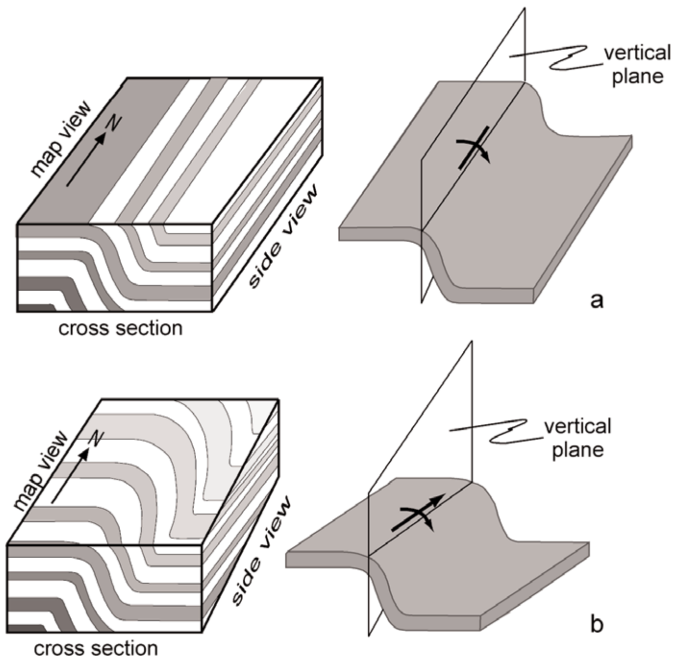

Figure 8. Diagrams of monoclinal folds with horizontal (a) and plunging (b) fold axes. Note that a monocline with a horizontal fold axis would expose the same stratigraphic units along its trend in a horizontal map view. In this non-plunging fold, a single bed intersects a hypothetical vertical plane along a horizontal line - - a horizontal fold axis. On the other hand, the plunging fold exposes progressively younger stratigraphic layers at the surface in the down-plunge direction. The stratigraphic sequence of layers can be seen in the front and side views of the block diagram. In this case, a single bed intersects an imaginary vertical plane along a line that plunges away from the viewer — a plunging fold axis.

Northward Plunge

When leveled off by erosion, the geometry of a plunging fold creates interesting geometric forms in horizontal map-view exposures. Figure 8 presents two schematic block diagrams of north-trending, east-vergent monoclinal flexures. The similarity in fold form is obvious in the cross-section view of each diagram. Note that in the side view of the block in figure 8a the sedimentary layers are flat-lying where not involved in the steep limb of the monoclinal flexure. This pattern is typical of folds that have horizontal fold axes. In figure 8b the side view shows that sedimentary layers dip toward the north, reflecting the fact that the fold axis plunges north. This northward plunge produces a very different pattern in horizontal map view (representing the eroded ground surface) compared with the pattern created by erosion of a non-plunging fold. In the map view of the plunging structure (figure 8b) older stratigraphic layers (lower in the vertical cross section) are exposed up-plunge, toward the south; in the non-plunging example (figure 8a) the same stratigraphic units are exposed along the entire length of the structure. As a result, the map view of a plunging fold (like figure 8b) resembles a distorted version of the cross section, and therefore contains information about structural geometry at depth.

In southern Utah the East Kaibab monocline plunges gently (3°-5°) northward, exposing structural relationships in map view that relate to fold and fault geometry below the surface. The horizontal map view displays progressively lower stratigraphic and structural levels toward the south: Cretaceous rocks are folded in the steep limb near Grosvenor's Arch, giving way southward to Jurassic and Triassic rocks at Paria, and eventually Permian rocks near Buckskin Gulch (figure 7). This map pattern is a natural consequence of the northward plunge, and is ideal for down-plunge viewing.

Down-Plunge Viewing

Geologists use the down-plunge view technique to synthesize complicated map relationships into meaningful cross sections (Mackin, 1959). As described in the previous section, the map view of a plunging fold exposes an elongated but distorted view of fold geometry. Down-plunge viewing creates 'foreshortening' of the plunging map view, thus removing distortions imposed by the elongated horizontal perspective. The end product can be a properly scaled and accurate structural cross section based on map relationships rather than on speculation.

Figure 9 depicts application of the down-plunge viewing strategy to the map of the East Kaibab monocline. Map data from figure 7 indicate that the fold axis plunges about 5° to the north. Placing the map flat on a table and looking at it from 5° above the horizon creates a profile view of the structure (a cross section perpendicular to the fold axis). This perspective visually foreshortens the map view to create an apparent cross section of structural relationships at the level of strata shown on the map.

An accurate profile view of the Cockscomb results from applying the down-plunge viewing technique to the full map in figure 7. (Small irregularities of the lithologic contacts in the map view are caused by topography, and should be smoothed when visualizing the down-plunge cross section.) The down-plunge view reveals an abrupt monoclinal fold separating otherwise flat-lying strata, and a narrow zone of faults within the steep limb. However, an accurate cross section does not always provide the most informative view of a structure. Because the Kaibab uplift plunges at such a low angle, down-plunge viewing turns the 9-inch-long structural map into a cross section less than one inch high. The down-plunge view effectively blurs and obscures structural relationships that are only visible in the elongated and distorted map view. For example, the individual small fractures along the steep limb of the monocline visible in the plunging map view of figure 7 would not be evident in an actual vertical exposure like the Grand Canyon, or in a map view that exposed only a single structural level. With careful measurement and observation, and an understanding of shear fracture geometry, these details reveal more about lateral structural changes along the Cockscomb than does the down-plunge view.

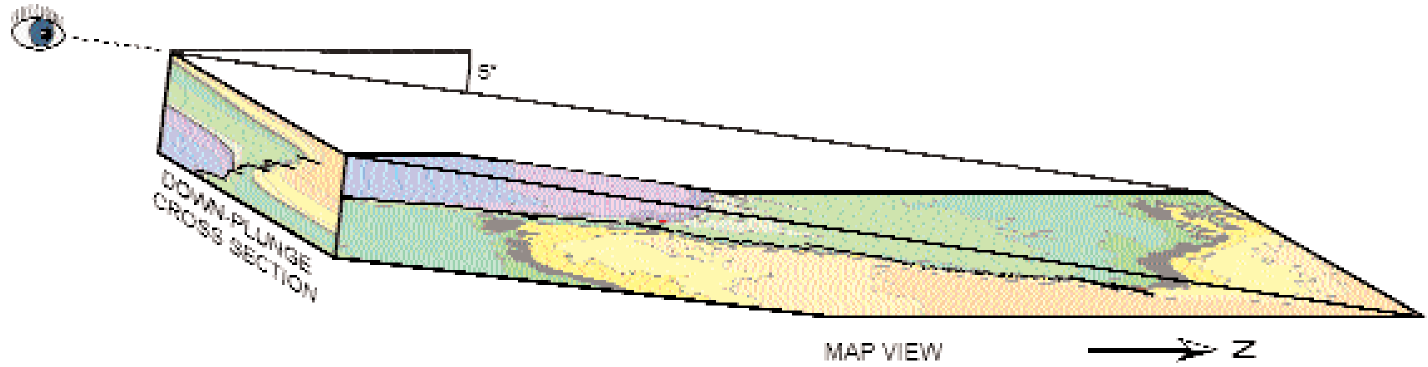

Figure 9. Down-plunge viewing involves looking at a geologic map of a plunging structure parallel to the plunge axis in order to see an accurate cross section view of structural relationships.

Fault-Tip Zone

Erosion of the Kaibab uplift to the level of the Mesozoic rocks in Grand Staircase-Escalante National Monument has exposed a monocline-parallel pattern of dense fracturing at the surface. Because the monocline plunges north the fault pattern, like the pattern of sedimentary rock layers, presents progressively deeper structural levels toward the south. Examination of the changes in fault orientations from south to north reveals a spatial and temporal sequence of fault development from deeper to shallower levels in the core of the monocline.

As shown in figure 7, faults south of Paria have long, continuous traces parallel to the surface trend of the fold. These faults accommodate apparent right lateral offset, shown by truncation and displacement of Chinle, Moenave, and Kayenta Formations. Between Paria and Pump Canyon Spring the continuous, monocline-parallel fault trace gives way to a disjointed series of faults that show right-lateral separation of Navajo and Carmel Formations. These are 'synthetic' faults because their apparent sense of offset is the same as that on the long, continuous faults farther south. The left-stepping, en-echelon synthetic faults strike about 20° clockwise from the trend of the monocline, but define a monocline-parallel zone of deformation. Between Pump Canyon Spring and Grosvenor's Arch the fault pattern consists of short, northwest-striking faults with apparent left-lateral offsets in Entrada, Dakota, and Tropic Formations. The left-lateral offset on these faults is antithetic to the sense of offset on the continuous fault surfaces south of Paria. North of Grosvenor's Arch the monocline-parallel fault zone disappears, indicating that deformation north of that location was accommodated entirely by folding rather than by a combination of folding and faulting.

The changing fault pattern along the East Kaibab monocline may represent the sequence of secondary fault development in a narrow zone of intense deformation directly ahead of the upward-propagating basement-rooted fault tip. A similar sequence of secondary fault growth has been observed in physical analog models of strike-slip (lateral offset) deformation. Models of strike-slip faulting typically develop a pattern of synthetic and/or antithetic faults on the upper surface preceding the appearance of long, continuous, shear zone-parallel faults (Tchalenko, 1970; Naylor and others, 1986; Sylvester, 1988; McKinnon and de la Barra, 1998). In such models the synthetic and antithetic faults, although discontinuous on the surface, link with the basement fault at depth. In effect, they accommodate strains that are slightly too great to be taken up by folding, but with continued deformation a discrete, shear zone-parallel fault is required to accommodate larger strains.

The same sequence of deformation took place along the developing East Kaibab monocline as Paleozoic and Mesozoic cover rocks folded and faulted in response to movement on the reactivated basement fault. The process of folding, development of discontinuous fractures, and eventual growth of a through-going fault began at depth near the basement-cover interface, and continued upward through the core of the East Kaibab monocline as the structure grew. The cross sections in figure 10 are exaggerated

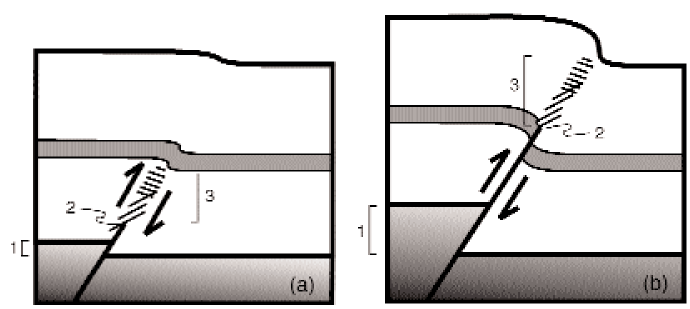

Figure 10. (a) Up-section migration of the basement-rooted fault and its fault tip deformation zone began near the basement-cover interface during initial increments of basement fault offset and overlying fold growth. (b) With continued deformation, the fault tip and associated fracture zone propagated upward through the core of the East Kaibab monocline as the fold grew. From diagram (a) to diagram (b); basement fault offset (1) increases, and the basement-rooted fault tip (2) and its fault tip deformation zone (3) migrate upward. The fracture pattern exposed along the north-plunging East Kaibab monocline in southern Utah preserves the final increment of this fault propagation and fault tip fracture formation in horizontal map view (figure 7).

sketches of fold development and simultaneous up-section migration of the fault tip deformation zone. The same structural relationships are visible in map view along the East Kaibab monocline because of the northward plunge of the fold axis. The small, discontinuous faults seen along the East Kaibab monocline represent synthetic and antithetic fractures that formed in higher structural and stratigraphic levels ahead of the upward-propagating tip of the basement fault.

Oblique Deformation

The orientations of fractures in the fault tip zone also contain clues about the vertical and lateral movements involved in growth of the East Kaibab monocline. It is simplest to imagine that movement on the basement fault was pure reverse-slip, with the west side moving up relative to the east. In fact, most early studies of Colorado Plateau monoclines assumed that the structures formed by this dip-slip reverse fault motion (Powell, 1873; Walcott, 1890; Stearns, 1971; Reches, 1978). However, the angular relationships between the monocline and the synthetic and antithetic faults in southern Utah suggest that right-lateral slip occurred in addition to reverse slip, causing the west side of the monocline and fault to move northward relative to the east side.

The angular relationships between synthetic and antithetic faults described in the previous section resemble a characteristic surface fault pattern recognized in physical modeling experiments and field studies of strike-slip fault systems (for example Riedel, 1929; Tchalenko, 1970; An and Sammis, 1996; Reading, 1980; Sylvester, 1988). This characteristic 'Riedel shear' pattern is easiest to describe using an example. Figure 11a shows the typical Riedel pattern that forms as a result of right-handed strike-slip offset. The shear fracture array that develops at the surface consists of Riedel or R-shears at an angle of 15° to the basement shear direction, Riedel-prime or R' shears at about 75° to the basement zone, and faults that are parallel to the shear zone (Y-shears). In a right-lateral shear zone the R and Y shears accommodate right-lateral offset, synthetic to the shear direction; R' fractures are antithetic to the shear zone, accommodating small left-lateral offsets. In physical models and in natural fault systems, synthetic and/or antithetic fractures can develop independently or together, producing map patterns similar to figure 11b, 11c, or 11d.

Note that in figure 7 the fault orientations in the fault-tip deformation zone strongly resemble Riedel fracture geometry. North of Paria, faulting in the steep limb takes the form of northeast-striking, left-stepping, en-echelon faults, and northwest-striking, right-stepping, en-echelon faults. These faults accommodate reverse-right-lateral and reverse-left-lateral offset, respectively. The fault pattern indicates that the steep limb of the East Kaibab acted as a shear zone during deformation, with small synthetic and antithetic faults accommodating reverse-right-lateral shear in the steep fold limb ahead of the advancing basement-rooted fault tip. The right-handed component of offset within the shear zone in southern Utah is demonstrated by the orientations of striations on fault surfaces and by small right-handed offsets of stratigraphic layers. The reverse, west-side-up component of movement is expressed by the 1,600 m, west-side-up structural relief of the Kaibab uplift as a whole. The Mesozoic-level shear zone and its underlying cause, the reactivated basement fault, therefore resulted from reverse-right-lateral, oblique deformation.

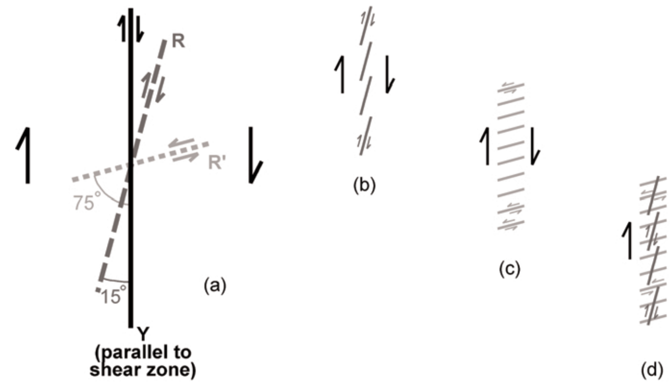

Figure 11. Riedel shear geometry. (a) In a right-handed system, synthetic faults at 15° to the shear zone accommodate right-lateral offset, and antithetic faults at 75° to the zone accommodate left-lateral offset. Synthetic and antithetic fractures can form independently or together, creating fault patterns that resemble (b), (c), or (d).

The Riedel-type fault tip fracture pattern therefore provides two key pieces of information: it leads to recognition of the presence of an upward-propagating fault tip deformation zone, and permits interpretation of the oblique motions involved in fault and fold development. In this context, the disappearance of the shear zone north of Grosvenor's Arch represents the expected up-section transition from faulting to folding; that is, the dying out of the basement-rooted fault tip and associated Riedel fractures. However, the absence of the fault pattern south of the Arizona-Utah border raises other questions (see figures 6b, 6c, and 6d). Erosion has exposed the same rocks along the monocline in northern Arizona as in southern Utah, but evidence for basement-rooted faulting at the surface disappears to the south. In fact, in the Grand Canyon basement-rooted faulting has propagated only as high as the Mississippian Redwall Limestone (figure 5). If the Riedel type fracture pattern in southern Utah represents growth of basement-rooted faulting toward the surface, why is it not visible to the south, at lower structural and stratigraphic levels? Knowledge of the three dimensional nature of fault surfaces and fault offset can explain the discrepancy.

Fault Slip Gradient

Fault surfaces are often roughly elliptical, with offset decreasing from the center of the fault plane toward the lateral terminations of the elliptical fracture (Barnett and others, 1987). The block diagram in figure 12a contains a

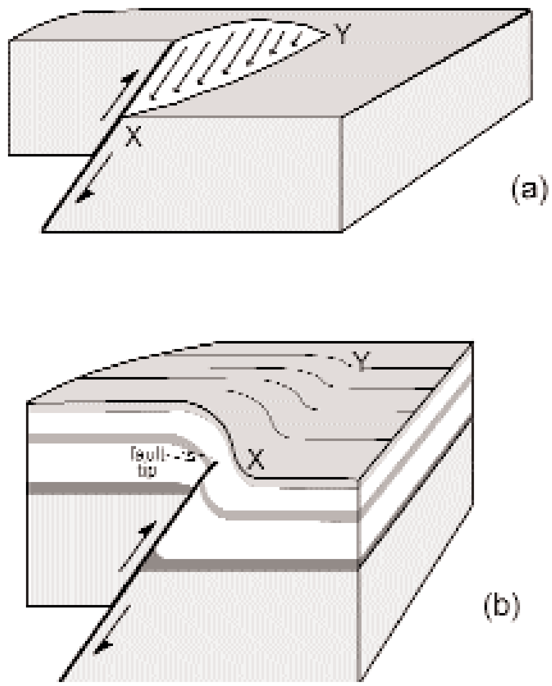

Figure 12. Faults and folds can accommodate different amounts of offset at different locations. (a) Offset on a reverse fault diminishes from point X to point Y. (b) The fault dies out beneath the ground surface. Above the fault tip, fold offset diminishes from point X to point Y.

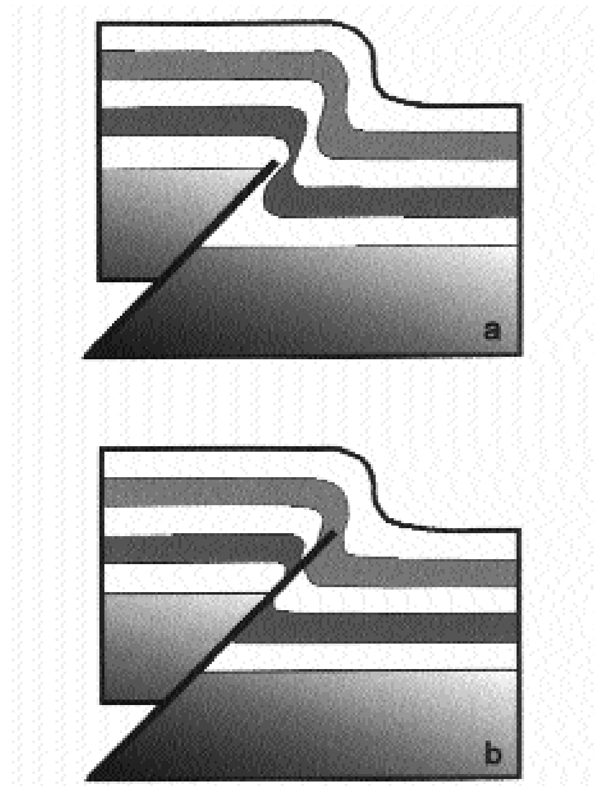

Figure 13. Schematic diagrams of drape folding (a) and fault-propagation folding (b). The drape fold model suggests that most deformation in the above-basement rocks is accommodated by stratigraphic thinning; faulting does not play a major role in above-basement deformation. In the fault-propagation fold model, increased fault offset in basement translates to increased fault development in sedimentary cover. Stratigraphic thinning may still take place during fold development, but the propagating fault accommodates increasing displacement in the sedimentary cover as the fault and fold grow.

segment of a reverse fault on which displacement gradually decreases. On the surface of the diagram, fault displacement is greatest at point X and decreases northward to zero at point Y. Gentle folding of the rock mass in the vicinity of the fault accommodates the change in fault slip along strike.

In reality not all faults propagate to the surface of the Earth. Often fault offset at depth gives way to fold-related offset toward the surface. Figure 12b presents the same geometric relationship shown in figure 12a, with fault displacement dying out from point X to point Y. However, cover strata in figure 12b are folded in response to the fault offset. Figure 12b clearly shows that fold displacement at the surface, like fault displacement, decreases from X to Y. In complex natural structures like the East Kaibab monocline, fold profiles can vary considerably along a structural trend, indicating changes in fault offset at depth.

The East Kaibab monocline obtains its maximum structural relief of 1,600 m in southern Utah (Gregory and Moore, 1931). This structural relief decreases gradually south of the Utah-Arizona border toward the Grand Canyon where offset is only 800 m, likely reflecting variations in fault offset at depth.

The magnitude of fault slip not only affects the fold form and degree of structural relief in overlying strata, but also determines the prevalence of faulting within the fold. Greater fault slip at depth results in more extensive faulting in the overlying rocks. The fault-propagation fold model describes the elegant interplay of faulting and folding.

Fault-Propagation Folding

Formation of monoclines traditionally has been explained by drape folding. In this conceptual model, fault displacement at depth gives way abruptly to fold-accommodated displacement in the sedimentary cover. The transition is accomplished by thinning and stretching of the lowest sedimentary rock layers over the displaced fault blocks, and as a result faulting does not play a major role in above-basement deformation (Stearns, 1971; Reches and Johnson, 1978) (figure 13a).

The drape fold model was applied to Colorado Plateau monoclines for good reasons. Firstly, the surface form of monoclines tends to support a drape fold origin. The monoclines are broad folds in above-basement sedimentary cover, and show little evidence for basement-rooted fault offset at the surface (as opposed to Rocky Mountain foreland uplifts, where faulting is of major importance; for example Schmidt and Perry, 1988; Schmidt

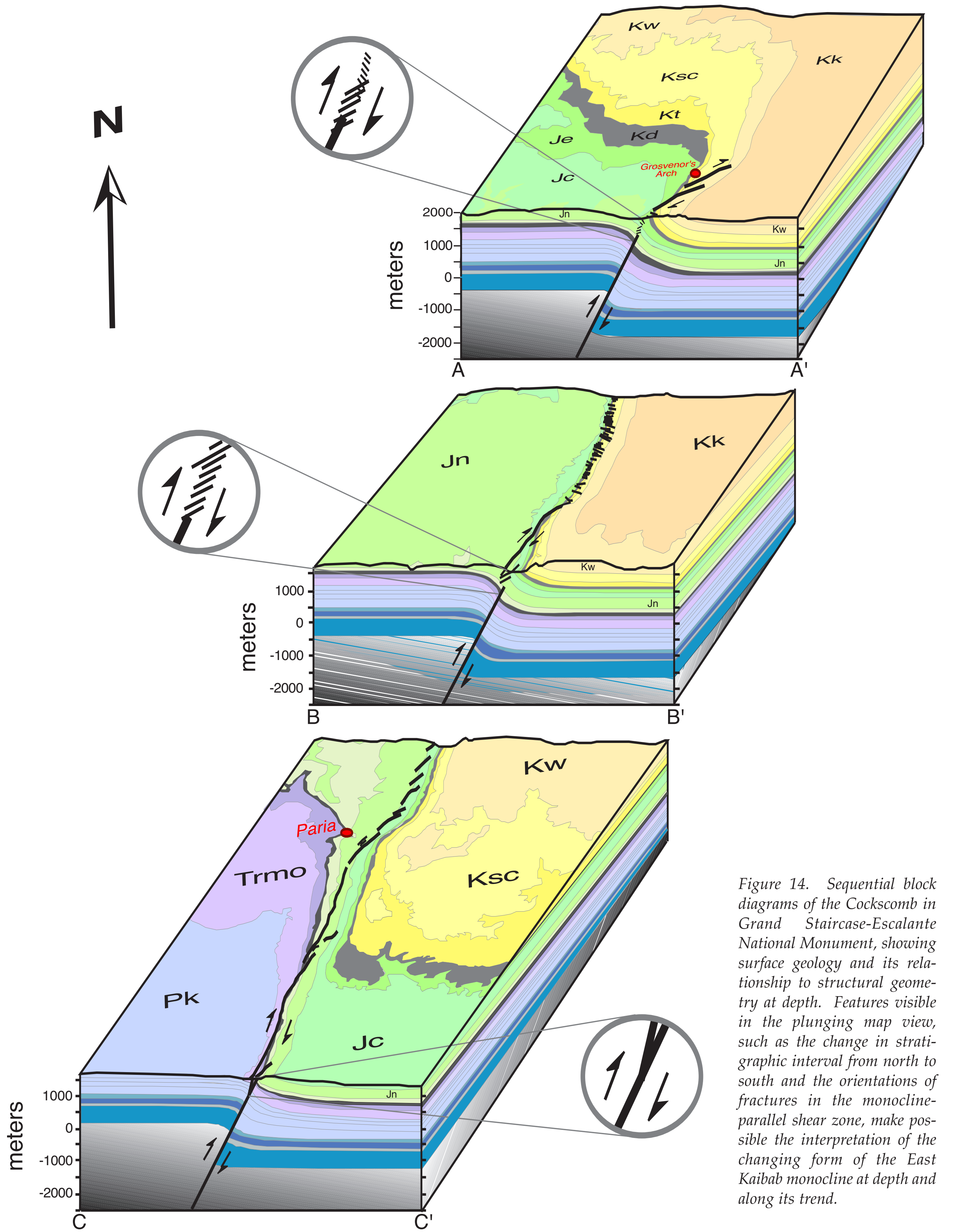

Figure 14. Sequential block diagrams of the Cockscomb in Grand Staircase-Escalante National Monument, showing surface geology and its relationship to structural geometry at depth. Features visible in the plunging map view, such as the change in stratigraphic interval from north to south and the orientations of fractures in the monocline-parallel shear zone, make possible the interpretation of the changing form of the East Kaibab monocline at depth and along its trend.

and others, 1993). Secondly, deep Grand Canyon exposures of monoclines show that fault offset changes to fold offset at very low levels in the post-Proterozoic sedimentary section (figures 2 and 5). Where the Grand Canyon incises the East Kaibab monocline the transition from fault to fold is accomplished by obvious thinning in the lower Paleozoic rocks, allowing higher stratigraphic units to fold without obvious faulting. Although fault-accommodated offset gives way to fold-accommodated offset very low in the above-basement section in the Grand Canyon, basement-rooted faulting is apparent at much higher structural and stratigraphic levels of the fold in southern Utah. The drape fold model fails to account for the prevalence of basement-rooted faulting along the East Kaibab monocline in Grand Staircase-Escalante National Monument.

The fault-propagation fold model proposes that a fault at depth progressively overtakes and displaces its overlying fold. Geologists have applied the term 'fault-propagation fold' to various structural settings because it describes succinctly the intimate relationship between faulting and fold growth. Despite some resulting confusion about the term's meaning (for example Mitra and Mount, 1999; Stone, 1999), one consistent feature of the model is that a fault tip at depth propagates upward, progressively offsetting higher levels in the overlying fold as displacement increases (Suppe, 1985; Davis and Reynolds, 1996) (figure 13b). The model implies that a fault with greater offset at depth will have propagated to higher levels in the overlying folded strata.

In the case of the East Kaibab monocline, the observation that faulting gives way to folding at a low stratigraphic level in the Grand Canyon simply reflects the relatively small amount of offset on the basement fault at that location. That is, if the East Kaibab monocline is a fault-propagation fold, greater vertical fault slip in the Grand Canyon would have resulted in propagation of faulting higher into the overlying strata. The Riedel shear pattern exposed in southern Utah represents initiation of basement-rooted faulting in the Mesozoic rocks in an area with twice as much structural relief as is present in the Grand Canyon (1,600 m versus 800 m). In a sense, the Cockscomb reached a more 'mature' stage of development in southern Utah than in the Grand Canyon.

Summary

The geologic concepts of plunging structure, down-plunge viewing, Riedel shear geometry, fault-slip gradient, and fault-propagation folding combine to illuminate the processes involved in the Laramide development of the East Kaibab monocline. The gentle northward plunge of the Cockscomb in southern Utah exposes structural relationships across several stratigraphic levels. Because of the northward plunge, lateral changes in landscape and map relationships along the structure correspond to different fold and fault geometry at depth. The down-plunge viewing technique offers a quick and accurate method for visualizing cross-sectional structural relationships at the stratigraphic levels exposed on the map. Geometry of fractures exposed in the steep monoclinal limb indicates fault tip fracture propagation related to a basement-rooted oblique fault zone. The absence of the shear fracture pattern south of the Arizona-Utah border is explained by fault-propagation folding combined with a decrease in fault slip to the south.

The concepts described in the preceding sections allow interpretation of the East Kaibab monocline's oblique-slip fault-propagation fold origin and visualization of its resulting fault-fold geometry at depth. Figure 14 presents block diagrams of the Cockscomb that summarize key relationships exposed by or inferred from the relationships exposed in Grand Staircase-Escalante National Monument.

CONCLUSIONS

Interpreting the three dimensional geometry and mode of formation of the Cockscomb involves several conceptual steps. Firstly, reconnaissance of the structural changes along the East Kaibab monocline forms the basis for noticing clues to underlying structural relationships. Secondly, the special north-plunging map view provides the opportunity for down-plunge viewing of an accurate profile section. Distortions imposed by the elongated map pattern bring into view a deformation zone associated with the basement-rooted fault tip, and within this tip zone secondary fault orientations indicate oblique deformation. Changes in structural relief along the trend of the monocline indicate displacement variations along the basement fault at depth. These features together reveal the role of oblique fault-propagation folding in formation of the Cockscomb. Finally, simplified block diagrams can be constructed based on these essential techniques and concepts to summarize the three dimensional geometry created by faulting, folding, uplift and erosion.

The northward plunge of the East Kaibab monocline in Grand Staircase-Escalante National Monument provides all the necessary evidence for formulating an oblique-slip fault-propagation-fold interpretation of the Kaibab uplift (Tindall and Davis, 1999). The exposure of structural and stratigraphic relationships in the monument is unique, offering insight into the formation mechanisms of Colorado Plateau uplifts that can be found nowhere else. For this reason, the importance of oblique deformation and progressive fault-fold development in formation of this, and possibly other, Colorado Plateau uplifts merits further investigation.

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REFERENCES

An, L.J., and Sammis, C.G., 1996, Development of strike-slip faults–shear experiments in granular materials and clay using a new technique: Journal of Structural Geology, v. 18, no. 8, p. 1061-1077.

Babenroth, D.L., and Strahler, A.N., 1945, Geomorphology and structure of the East Kaibab monocline, Arizona and Utah: Geological Society of America Bulletin, v. 56, p. 107-150.

Barnett, J.A.M., Mortimer, J., Rippen, J.H., Walsh, J.J., and Watterson, J., 1987, Displacement geometry in the volume containing a single normal fault: American Association of Petroleum Geologists Bulletin, v. 71, no. 8, p. 925-937.

Bond, G.C., 1997, New constraints on Rodinia break-up ages from revised tectonic subsidence curves [abs.]: Geological Society of America Abstracts with Programs, v. 29, no. 6, p. 280.

Brown, W.G., 1988, Deformational style of Laramide uplifts in the Wyoming foreland, *in* Schmidt, C.J., and Perry, W. J. Jr., editors, Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt, Geological Society of America Memoir 171, p. 1-26.

Coney, P.J., 1976, Plate tectonics and the Laramide orogeny: New Mexico Geological Society Special Publication 6 – Tectonics and mineral resources of southwestern North America, p. 5-10.

Davis, G.H., 1978, Monocline fold pattern of the Colorado Plateau, *in* Matthews, V. III, editor, Laramide folding associated with basement block faulting in the western United States: Geological Society of America Memoir 151, p. 215-233.

Davis, G.H., and Reynolds, S.J., 1996, Structural geology of rocks and regions: New York, John Wiley & Sons Inc., 776 p.

Dutton, C.E., 1882, Tertiary history of the Grand Canyon district: U.S. Geological Survey Monograph 2, 264 p.

Gregory, H.E., and Moore, R.C., 1931, The Kaiparowits region - a geographic and geological reconnaissance of parts of Utah and Arizona: U.S. Geological Survey Professional Paper 164, 161 p.

Hintze, L.F., 1988, Geologic history of Utah: Brigham Young University Geology Studies Special Publication 7, 202 p.

Huntoon, P.W., 1969, Recurrent movements and contrary bending along the West Kaibab fault zone: Plateau, v. 42, p. 66-74.

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

Huntoon, P.W., and Sears, J.W., 1975, Bright Angel and Eminence Faults, eastern Grand Canyon, Arizona: Geological Society of America Bulletin, v. 86, no. 4, p. 465-472.

Mackin, J.H., 1959, The down-structure method of viewing geologic maps: Journal of Geology, v. 58, no. 1, p. 55-72.

Maxson, J.H., 1961, Geologic map of the Bright Angel quadrangle, Grand Canyon National Park, Arizona: Grand Canyon Natural History Association.

McKinnon, S.D., and de la Barra, I.G., 1998, Fracture initiation, growth, and effect on stress field–a numerical investigation: Journal of Structural Geology, v. 20, no. 12, p. 1673-1689.

Mitra, Shankar, and Mount, V.S., 1999, Foreland basement-involved structures–reply: American Association of Petroleum Geologists Bulletin, v. 83, no. 12, p. 2017-2023.

Naylor, M.A., Mandl, G., and Sijpesteijn, C.H.K., 1986, Fault geometries in basement-induced wrench faulting under different initial stress states: Journal of Structural Geology, v. 8, p. 737-752.

Powell, J.W., 1873, Exploration of the Colorado River of the West and its tributaries explored in 1869-1972: Washington, D.C, Smithsonian Institution, 291 p.

Reading, H.G., 1980, Characteristics and recognition of strike-slip fault systems: Special Publication of the International Association of Sedimentology, v. 4, p. 7-26.

Reches, Ze'ev, 1978, Development of monoclines: Part I, Structure of the Palisades Creek branch of the East Kaibab monocline, Grand Canyon, Arizona, *in* Matthews, V. III, editor, Laramide folding associated with basement block faulting in the western United States: Geological Society of America Memoir 151, p. 235-272.

Reches, Ze'ev, and Johnson, A.M., 1978, Development of monoclines: Part II, Theoretical analysis of monoclines, *in* Matthews, V. III, editor, Laramide folding associated with basement block faulting in the western United States: Geological Society of America Memoir 151, p. 273-311.

Riedel, W., 1929, Zur Mechanik geologischer Brucherscheinungen: Centralbl. F. Mineral. Geol. U. Pal., v. 1929 B, p. 354-368.

Rosnovsky, T.A., 1998, Variation in joint and fault patterns along the East Kaibab and Waterpocket monoclines, Colorado Plateau: Stanford University, M.S. thesis, 58 p.

Schmidt, C.J., Chase, R.B., and Erslev, E.A., editors, 1993, Laramide basement deformation in the Rocky Mountain foreland of the Western United States: Geological Society of America Special Paper 280, 365 p.

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

Stearns, D.W., 1971, Mechanisms of drape folding in the Wyoming Province, *in* Renfro, A.R., editor, Symposium on Wyoming tectonics and their economic significance: Wyoming Geological Association 23rd Field Conference Guidebook, p. 125-143.

Stern, Sharon, 1992, Geometry of basement faults underlying the northern extent of the East Kaibab monocline, Utah: Chapel Hill, University of North Carolina, M.S. thesis.

Stone, D.S., 1999, Foreland basement-involved structures-discussion: American Association of Petroleum Geologists Bulletin, v. 83, no. 12, p. 2006-2016.

Suppe, John, 1985, Principles of structural geology: Inglewood Cliffs, New Jersey, Prentice-Hall, Inc., 537 p.

Sylvester, A.G., 1988, Strike-slip faults: Geological Society of America Bulletin, v. 100, no. 11, p. 1666-1703.

Tchalenko, J.S., 1970, Similarities between shear zones of different magnitudes: Geological Society of America Bulletin, v. 81, p. 1625-1640.

Timmons, M.J., Karlstrom, K.E., Dehler, C.M., Geissman, J.W., and Heizler, M.T., in press, Proterozoic multistage (~1.1 and ~0.8 Ga) extension in the Grand Canyon Supergroup and establishment of northwest and north-south tectonic grains in the southwestern United States: Geological Society of America Bulletin.

Tindall, S.E., 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, p. 1303-1320.

Walcott, C.D., 1890, Study of line displacement in the Grand Canyon of the Colorado in northern Arizona: Geological Society of America Bulletin, v. 1, p. 49-64.

Wernicke, Brian, 1992, Cenozoic extensional tectonics of the U.S. Cordillera, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., editors, The geology of North America, the Cordilleran orogen–conterminous U.S.: Geological Society of America, v. C-2, p. 553-581.

Windley, B.F., 1995, The Evolving Continents: Chinchester, John Wiley and Sons, 526 p.