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Geologic Map and Structural Analysis of the Twin Rocks 7.5 Minute Quadrangle, Wayne County, Utah

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GEOLOGIC MAP AND STRUCTURAL ANALYSIS OF THE TWIN ROCKS QUADRANGLE, WAYNE COUNTY, UTAH

by

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ABSTRACT

GEOLOGIC MAP OF THE TWIN ROCKS QUADRANGLE, WAYNE COUNTY, UTAH

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A new geologic map of the Twin Rocks 7.5 minute quadrangle primarily located within Capitol Reef National Park, south-central Utah, provides stratigraphic and structural detail not previously available. This map has also been instrumental in understanding the evolution and development of fluvial terraces associated with Sulfur Creek and the structural geology of the backlimb of the Miners Mountain uplift.

Nine bedrock stratigraphic formations and eight types of Quaternary deposits were mapped throughout the quadrangle. Bedrock stratigraphy ranges in age from Permian to Jurassic. New details absent on previous geologic maps include members of the Chinle and Moenkopi Formations and the Jurassic Page Sandstone, a stratigraphic unit herein separated from the Navajo Sandstone.

Terraces associated with Sulfur Creek record the central pathway of ancient streams rather than the lateral extent of the floodplain. Volcanic boulder-rich terrace deposits were likely created as stream channels were clogged with volcanic boulders and subsequently abandoned. The boulder-fill effectively armored the underlying softer bedrock. As the stream moved away from the abandoned, boulder-filled channel, it eroded and downcut into the adjacent softer mudstone bedrock, rather than eroding through the more resistant boulder alluvium. Thus, the abandoned boulder-filled channel becomes elevated relative to the stream. This inverted topography is preserved as elevated fluvial terrace deposits. This style of preservation of linear terraces developed over a broad area is in contrast to nearby terraces along the Fremont River which are preserved as "steps" cut into the resistant sandstones of the Glen Canyon Group along the Waterpocket Fold. These terraces have been used to identify changes in the location of Sulfur Creek through time.

Kinematic analysis of structures in the backlimb of the uplift show a principle compressive stress orientation nearly perpendicular to the uplift axis and rotated 30° counter clockwise from the stress indicated by deformation bands measured in the forelimb. These data suggest that stress transmitted through the basement is partitioned and rotated in the backlimb, likely due to decoupling and differential slip in strata with low shear strength. Such decoupling would allow the stress to be rotated perpendicular to the resisting fold axis, rather than parallel to the far-field stress transmitted through the basement. Sandbox models produced in this study display boundary perpendicular structures similar to those measured in the backlimb of the Miners Mountain uplift.

PREFACE

This thesis is divided into two chapters; each with their own figures, references, and appendices. The appendix, (i.e. the geologic map and legend), is currently in press to be published by the Utah Geological Survey along with geologic maps of the Fruita and Golden Throne quadrangles.

Chapter 1 contains an overview of the geologic map of the Twin Rocks quadrangle, including a summary of previous geological research in the area, a description of methods, and lists of bedrock and surficial deposits mapped in the quadrangle. It also contains a discussion of the patterns and processes involved in the recent landscape evolution of the quadrangle.

Chapter 2 contains a detailed structural and kinematic analysis of the backlimb of the Miners Mountain uplift, part of which is located within the Twin Rocks quadrangle.

ACKNOWLEDGMENTS

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Special thanks to Dan Martin and James Eddleman for letting me tag along and for teaching me how to do field work. Their humor and contagious love of Capitol Reef geology has remained an inspiration throughout my graduate work. Thanks to Jeremy Gillespie and Anne Dangerfield for their dedicated help and valuable insights, and to Tom Clark and the staff at Capitol Reef National Park for their logistical support.

On a more personal note, I would like to express my gratitude to Dr. Thomas Morris for his help, mentoring guidance, and friendship throughout my time at BYU. Thanks to my loving wife Rachel and daughter Natalie for all of their support as well as field assistance, and to my parents for always believing in me and pushing me to be the best I can be.

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CHAPTER 1

GEOLOGIC MAP OF THE TWIN ROCKS QUADRANGLE, WAYNE COUNTY, UTAH

INTRODUCTION

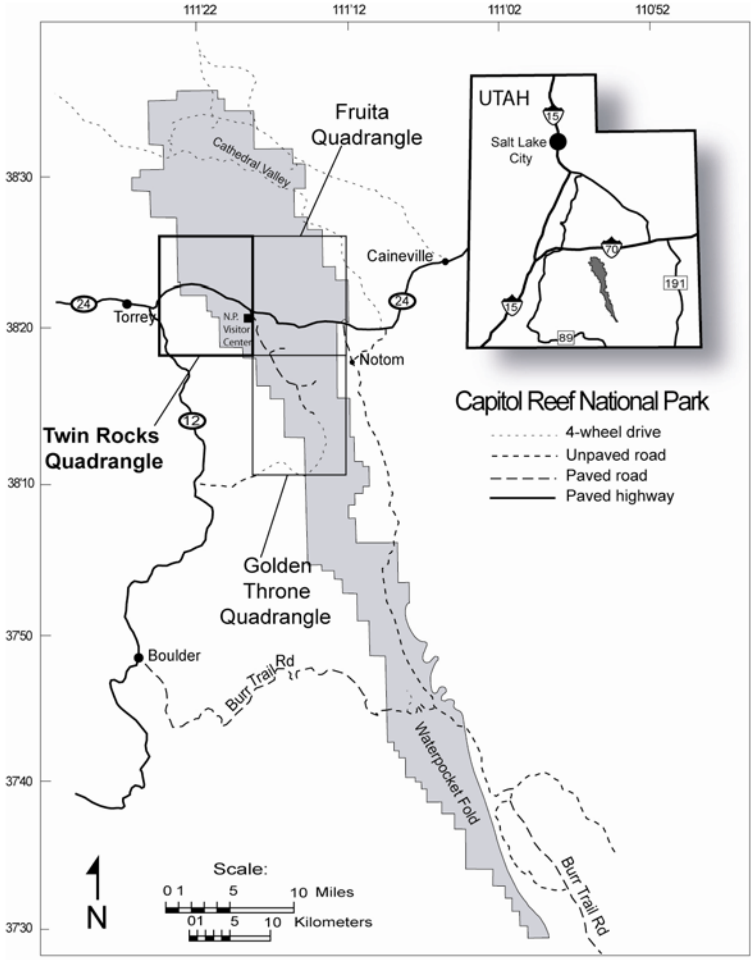

Figure 1. Reference map showing the locations of the Twin Rocks, Fruita and Golden Throne quadrangles relative to Capitol Reef National Park, Utah (modified from Morris, et al., 2000).

Capitol Reef National Park, located in south-central Utah (Figure 1), was created by act of Congress in 1971 in order to protect the natural beauty and promote study of the Waterpocket Fold region. The Twin Rocks quadrangle is located in the northwestern part of Capitol Reef National Park, Utah, and includes Chimney Rock, the Mummy Cliffs, Spring Canyon, portions of the Fremont River Gorge, and the park Visitor Center. These sights constitute some of the most visited areas in the park.

High resolution geologic mapping of the Twin Rocks quadrangle is of interest to the National Park Service for public education purposes, biological studies, and for use in identifying geologic hazards.

BACKGROUND AND PREVIOUS WORK

The geology of Capitol Reef National Park has been a topic of study since it was first explored in the late 1800's. Early structural and geomorphic work in the area was pioneered by Howell (1875), Gilbert (1877), and Dutton (1880). Gregory and Anderson (1939) provided the first detailed descriptions, measurements and analysis of stratigraphic units in the area. In the 1950's, the U.S. Atomic Energy Commission funded the creation of the first geologic maps (1:24,000) of the Capitol Reef area as part of a regional uranium exploration effort (Smith et al., 1957). These maps were later used as the basis for the first regional geologic maps (1:62,500) of the Capitol Reef area that were included in a 1963 U.S. Geological Survey Professional Paper (Smith et al., 1963). Early geologic mapping of portions of the northern Capitol Reef area was done by Luedke (1953), Smith et al. (1957), and Smith et al. (1963). In 1987, Billingsley et al. published a 1:62,500 scale map of the entire national park and its vicinity. Their map included structural information as well as refined stratigraphic contacts and quaternary unit descriptions.

In 2001, the U.S. National Parks Service funded a project to create 1:24,000 scale geologic maps of the Fuita, Golden Throne, and Twin Rocks 7.5 minute quadrangles, including the most visited portions of the National Park (McLelland et al., 2002; Martin et al., 2005). The Twin Rocks quadrangle represents the third and final part of this project.

NEW DATA

This map provides the following details unavailable in older maps of the quadrangle:

- Division of the Chinle Formation into its component members: the Owl Rock Member, Petrified Forest Member, Monitor Butte Member, and the Shinarump Conglomerate Member.

- Division of the Moenkopi Formation into its component members: the Black Dragon Member, Sinbad Limestone Member, Torrey Member, and the Moody Canyon Member.
- Mapping the Page Sandstone as a stratigraphic unit separate from the Navajo Sandstone and Carmel Formations.
- Division of the Navajo Sandstone into basal and upper members.
- Higher detail mapping of Quaternary deposits, including division of alluvial levels (Qal1 and Qal2), and division of volcanic boulder terrace deposits based upon their height above the present stream drainage (ex. Qatv1, Qatv2, Qatv3, etc.)

MAPPING METHODOLOGY

Data collection for the map was accomplished by field mapping and study of 1:12,000 scale true-color stereo aerial photos. Field mapping was accomplished during the summers of 2003 and 2004. Field mapping methods include: sketching fault, bedrock, and Quaternary unit contacts on a 7.5 minute topographic basemap; measuring fault planes, strike and dip of bedding surfaces, fracture sets and small scale folds for kinematic and structural analysis, and outcrop study of stratigraphic units to determine lithology, unit thickness, color, grain size, erosional profile and the nature of formation contacts and unconformities. The majority of field data was collected from the southern two-thirds of the quadrangle in the Chinle and lower formations due to the inaccessibility and extremely rugged terrain in the Glen Canyon Group in the northern third of the quadrangle.

Field mapping was augmented by the study of 1:12,000 scale true-color aerial stereo photos, which allowed for detailed mapping of inaccessible areas. Faults, fracture sets, and bedrock and Quaternary unit contacts were mapped, in part, using these photos and were then field checked where possible.

Field maps and other data were subsequently digitized and compiled into a Geographic Information System (GIS) database using ArcGIS 9 and VROne software. The map legend, including unit descriptions, a stratigraphic column, correlation of units and geologic cross section were drafted using Adobe Illustrator CS. Further modifications and edits to the map were made using VROne mapping software at a workstation located at the Utah Geologic Survey (UGS) in order to prepare the map for final acceptance and publication.

BEDROCK STRATIGRAPHY

Strata of the Twin Rocks quadrangle range in age from Middle Permian to Middle Jurassic. Stratigraphic units mappable at 1:24,000 scale include (from oldest to youngest):

- Cutler Group (Lower Permian) (Pc)
- Kaibab Limestone (Lower Permian) (Pk)
- Moenkopi Formation (Lower Triassic)
  - Black Dragon Member (TRmb)
  - Sinbad Limestone Member (TRms)
  - Torrey Sandstone Member (TRmt)
  - Moody Canyon Member (TRmm)
- Chinle Formation (Upper Triassic)

    - Shinarump Conglomerate Member (TRcs)
    - Monitor Butte Member (TRcm)
    - Petrified Forest Member (TRcp)
    - Owl Rock Member (TRco)
- Wingate Sandstone (Triassic-Jurassic) (JTRw)
- Kayenta Formation (Lower Jurassic) (Jk)
- Navajo Formation (Lower Jurassic)
    - Basal Member (Jno)
    - Upper Member (Jn)
- Page Sandstone (Middle Jurassic) (Jpc)
- Carmel Formation Paria River Member (Middle Jurassic) (Jcpr)
- Intrusive mafic dikes (Neogene) (Ti)

(Mitchell, 1985; Kamola and Chan, 1988; Peterson, 1988; Hintze, 1993; Blakey et al., 1996; Jones and Blakey, 1997; and Morris et al., 2000). Detailed unit descriptions can be found in the map legend (Appendix A).

QUATERNARY GEOLOGY

Mappable Quaternary deposits in the Twin Rocks quadrangle have been divided into the following units: alluvial and floodplain deposits (Qal), older alluvial and floodplain deposits (Qal2), windblown sand deposits (Qe), mixed eolian and alluvial deposits (Qea), talus and colluvial deposits (Qmt), landslide and slump deposits (Qms), terrace deposits containing volcanic boulders found in the Fremont River drainage (Qatf2, Qatf3, Qatf4, Qatf5, and Qatfu) and other stream drainages (Qatv1, Qatv2, Qatv3, Qatv4, Qatv5, Qatvu), terrace deposits not containing volcanic boulders (Qatlo), and colluvial deposits associated with volcanic boulder terraces (Qmtv). Detailed unit descriptions can be found in the map legend.

Volcanic boulder terrace deposits have been divided according to their elevation above present stream level, using the same scale for deposits in the Fremont and other drainages after the manner of Eddleman (2005). Level 1 (Qatv1 and Qatf1) include terrace deposits 0-60 feet above present stream level, level 2: 60-120 feet, level 3: 120-180 feet, level 4: 180-240 feet, and level 5: 240-340 feet. Undifferentiated levels (Qatvu and Qatfu) represent terraces over 340 feet above present stream elevation.

Eddleman (2005) showed a correlation between the amount of weathering of volcanic boulder terrace deposits in the Fremont and Pleasant Creek drainages and their height above present stream elevation. His work implies that the amount of weathering, and therefore the time since deposition, was consistent between deposits of the same height above modern stream elevation along the long profile of the stream. This suggests that terraces with a similar height above present stream level were deposited at approximately the same time, along the same longitudinal profile (Merritts et al., 1994; Eddleman, 2005). Variation in the elevation and lateral location of these deposits, therefore record temporal changes in the location of the stream and floodplain. Eddleman (2005) suggests approximate ages for terrace levels in these drainages based on correlation with cosmogenic ages from Repka et al. (1997), as follows: Qatfu-150 Ka (± 20 Ka), Qatf5-102 (±15 Ka), Qatf3-60 Ka (±10 Ka). While these ages are approximate at best, they do help give an idea of the time scale associated with the observed fluctuations.

Terrace development

Fluvial terrace deposits within the Sulfur Creek drainage in the Twin Rocks quadrangle (Figure 2) represent alluvial material deposited directly on an active river floor that has subsequently been stranded. Terrace deposits are therefore useful in understanding spatial and temporal changes in river histories (Pazzaglia et al., 1998; Eddleman, 2005). Pazzaglia (1998) suggests that fluvial terraces develop during stable, graded stream conditions as the floodplain widens and erodes the terrace surface upon which alluvium is deposited. When hydrologic conditions change, incision increases, stranding terraces above the present stream level and preserving a portion of the paleovalley floor (Figure 3a).

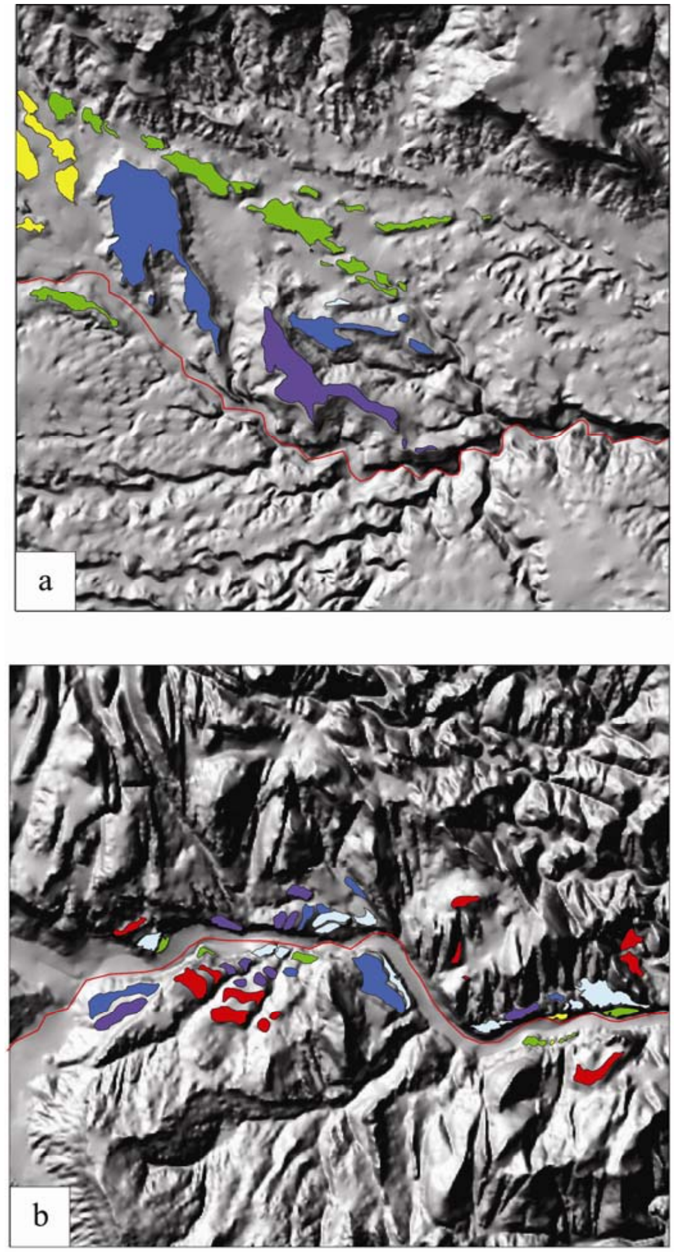

Figure 2. Comparison of terrace deposits containing volcanic boulders associated with a) Sulfur Creek and b) the Fremont River through the Waterpocket Fold. a) Sulfur Creek terraces are not confined to the walls of a well-defined canyon, but form a pattern of linear mesas, recording changes in stream location over a broad area. These terraces are found primarily within the soft, mudstone-rich Moody Canyon Member of the Moenkopi Formation. b) Fremont River terraces are cut into resistant canyon walls composed of Glen Canyon Group sandstones. Note that terraces in the Fremont River are much more confined than those associated with Sulfur Creek. Terraces are color coded according to age as follows: red - Qatvu (oldest), purple - Qatv5, blue - Qatv4, light blue - Qatv3, greed - Qatv2, and yellow - Qatv1 (youngest).

According to this model, incision rates are ubiquitous in the valley floor, eroding equally through bedrock and alluvial deposits. This kind of terrace development (shown in Figure 3a) produces paired terraces on either side of a central canyon. Where preserved, these terrace deposits record the lateral extent of the floodplain at a given time, and not the central path of the stream. While this model appears valid for terraces cut into the resistant Glen Canyon Group where the Fremont River flows through the Waterpocket Fold in the western adjacent Fruita quadrangle (Eddleman 2005; McLelland et al., 2006), an alternative model is needed to explain terrace development in the nearby Sulfur Creek area.

"Clog and abandon" terrace development

Sulfur Creek is a perennial tributary to the Fremont River that flows from east to west across the Twin Rocks quadrangle and is associated with a number of volcanic boulder terraces in the western part of the quadrangle. Several important differences distinguish terraces preserved in Sulfur Creek from those found along the Fremont River (Figure 3). In map-view, terraces along Sulfur Creek are generally linear, occur over a broad area with no central canyon, and form flat-topped topographically inverted "mesas." These terraces are cut into easily eroded mudstone bedrock of the Moenkopi Formation, where terrace deposits containing volcanic boulders form resistive caps on mesas protecting the much softer underlying mudstones from erosion. In contrast, the nearby Fremont River is marked by stepped, paired terraces, notched into resistant sandstone cliffs on either side of a central canyon.

If the volcanic terrace deposits in this area were deposited rapidly as debris flows and other major flood events rather than bedload alluvium (Waitt, 2000, Pazzaglia et al., 1998), these deposits clogged and backfilled the channel, damming the flow of the stream. Rather than downcutting through the resistant boulder deposit, the flow of the stream is diverted, forming a new channel in the adjacent softer bedrock. Volcanic alluvium in the channel is stranded and forms a resistive cap as the softer surrounding bedrock is preferentially eroded. Figure 4 shows an example of the early stages of this type of terrace development within the Sulfur Creek drainage.

While climatic factors doubtless play an important role in the evolution of the fluvial systems in this region, the difference in style of terrace development between terraces cut into the Glen Canyon Group sandstones and the Moenkopi Formation is controlled by the relative difference in susceptibility to erosion between the volcanic boulder alluvial deposit and the surrounding bedrock. Where the Fremont River cuts through resistant sandstones, the canyon is deeply entrenched and the boulder deposits have approximately the same level of resistance to erosion as do the surrounding bedrock. In Sulfur Creek, the boulder deposit is much more resistant to erosion than the soft Moenkopi Formation mudstones. This causes the stream to abandon the clogged channel and flow elsewhere. The channel-clogging deposit then acts as a resistant cap while subsequent differential erosion produces the topographically inverted features near Sulfur Creek. Thus, preserved terraces represent the central pathway of the stream, rather than the lateral extent of the floodplain, and record changes in stream location through time.

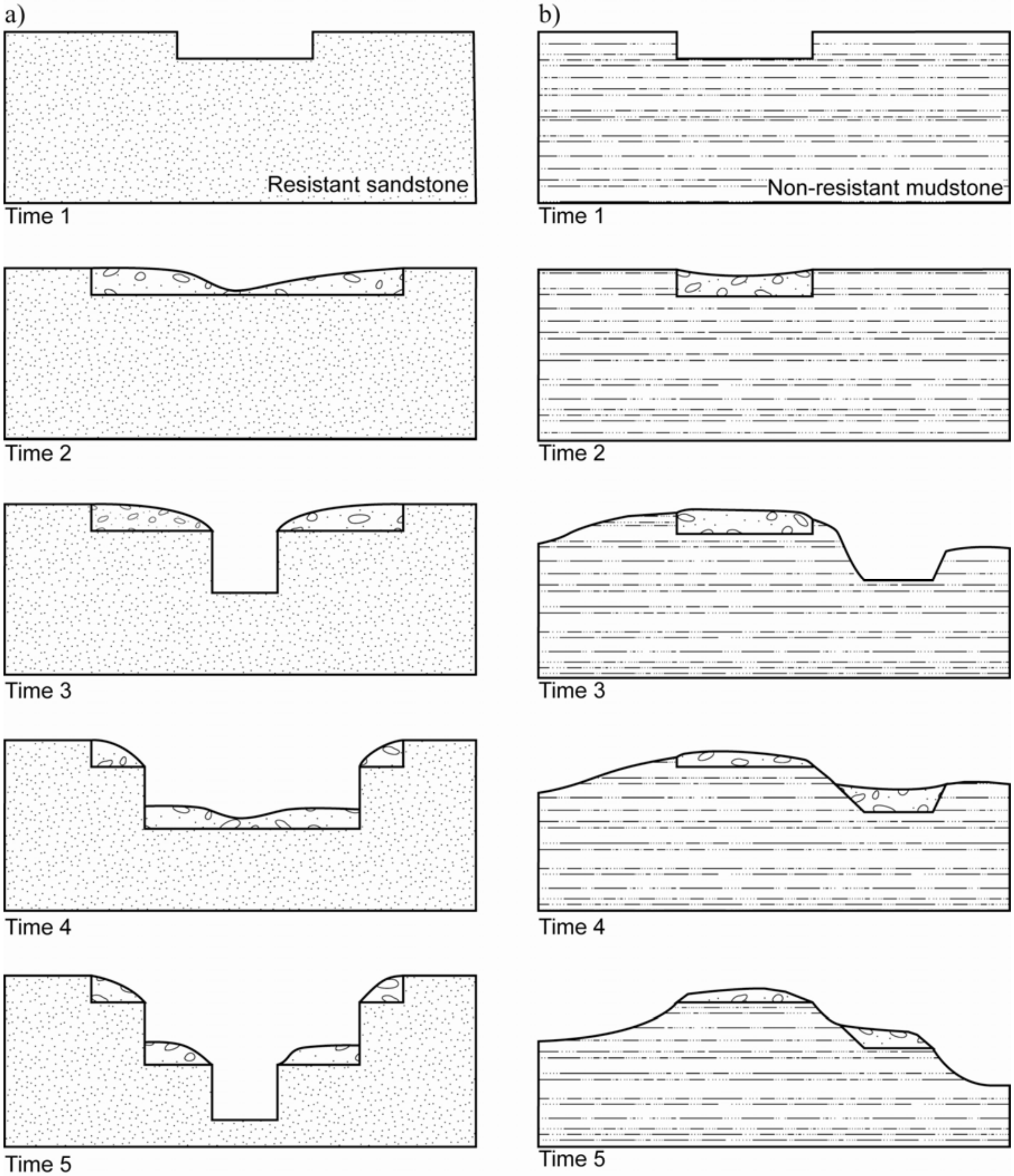

Figure 3. a) Conceptual model for the development of fluvial terrace deposits in a confined channel with resistant bedrock. This model is used to explain terrace development where the Fremont River cuts through the Glen Canyon Group in the Waterpocket Fold. According to Pazzaglia et al., (1998) incision rates increase during changing hydrologic conditions, and channels widen during stable, graded stream conditions. b) "Clog and abandon" development of fluvial terrace deposits in easily eroded mudstone bedrock of the Moenkopi Formation in the Sulfur Creek area. Clogging of channels by alluvium containing large volcanic boulders causes the stream to abandon its present course and create a new channel in the soft mudstone bedrock. The boulder-filled channels armour the less resistant mudstone bedrock, creating inverted topography.

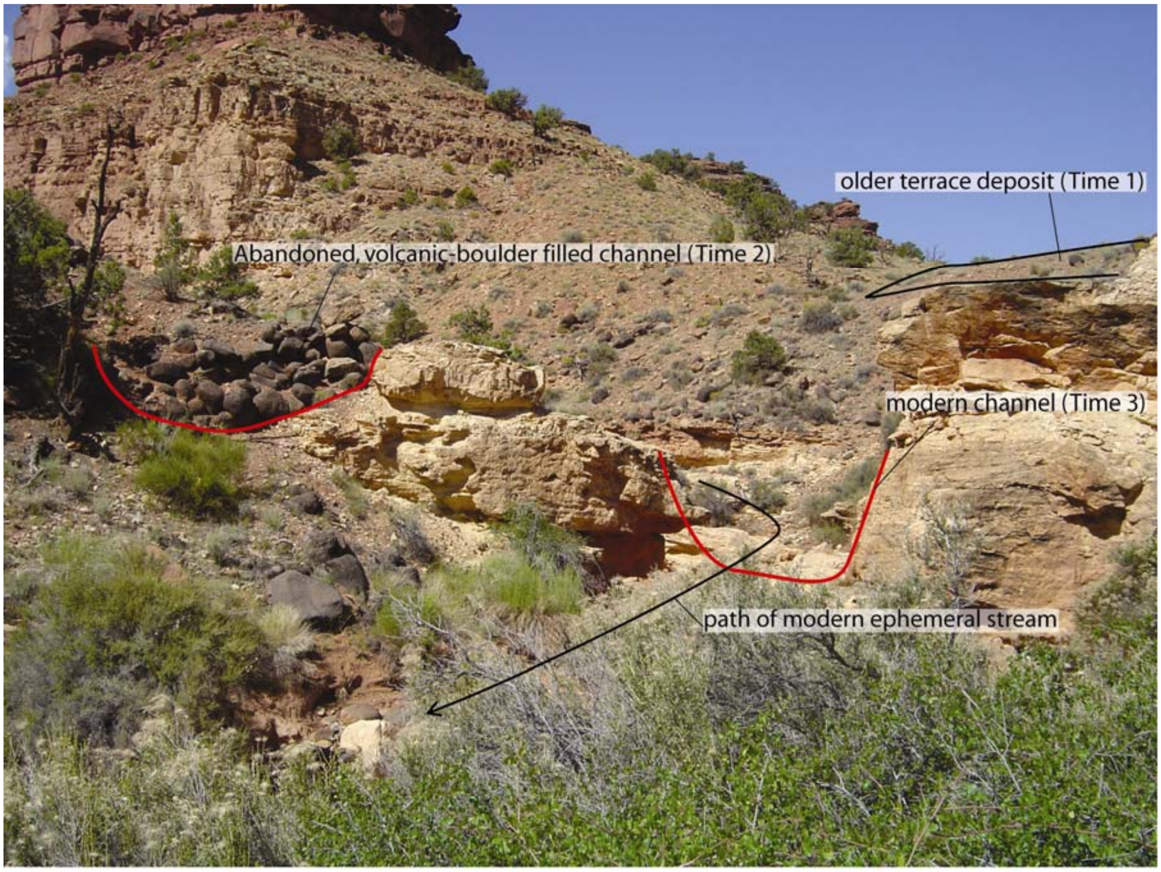

Figure 4. Small-scale, recent example of early-stage terrace development in Sulfur Creek. During a flood, the channel filled with volcanic boulders, impeding the flow of the stream. Subsequently, the stream changed course and cut a new channel through the less-resistant bedrock, rather than incising through the boulder deposit. The boulder-filled channel is approximately 15 feet above the present stream level of Sulfur Creek. Surrounding bedrock is the Moenkopi Formation.

Landscape evolution of the Sulfur Creek drainage

Map-view patterns in volcanic boulder terrace deposits within the Sulfur Creek river drainage hold keys to understanding the landscape evolution of the drainage. Division of terrace deposits by elevation above the present stream level (according to the methodology of Eddleman (2005) allows us to better understand changes in the location of the stream through time. Important to Eddleman's (2005) terrace correlation is the assumption that terraces within each grouping area at least roughly time equivalent. Using this correlation, we can view these terrace deposits as recording changes in the location of Sulfur Creek through time. Figure 5 illustrates a general northeastern migration from Qatvu (oldest, a) to Qatv2 (d), after which the stream has shifted slightly south to its current location (e).

STRUCTURE

The geologic structure of the Twin Rocks quadrangle is dominated by the backlimb of the Miners Mountain uplift. This uplift forms a broad homocline dipping between 2° and 20° to the northeast. The major exception to this pattern is a southwest verging asymmetrical anticline located in the northeast part of the quadrangle (see structural contour map and geologic cross section on map legend, Appendix A). Bounded on the southwest by a high-angle reverse to vertical fault, the structure has a northwest-southeast axial trend with a maximum structural relief of approximately 500 feet.

Four major fault systems, each with distinct character, dissect the bedrock in the map area. Lack of cross-cutting relationships precludes a clear interpretation of the relative timing of the development of the fault systems. In the southeast portion of the quadrangle, a right-lateral oblique-normal fault oriented N35°W extends over 6 km from Beas Lewis Flats into the Grover quadrangle to the south. Measured fault planes and striations indicate fault plane dip between 10° and 15° to the northeast with a rake of 68° from horizontal. Offset along this fault reaches a maximum of about 100 feet in the Fremont River Gorge.

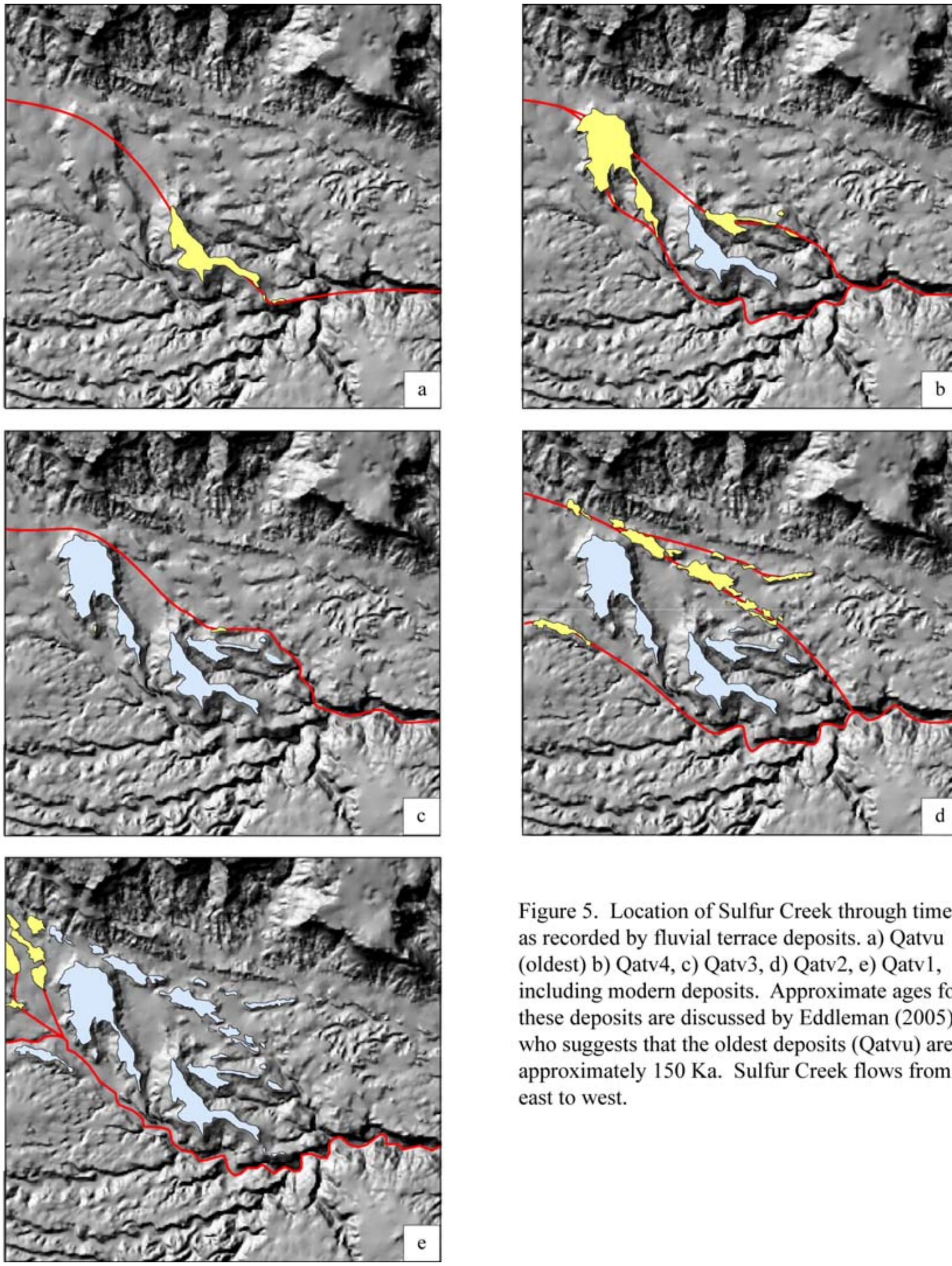

Figure 5. Location of Sulfur Creek through time as recorded by fluvial terrace deposits. a) Qatvu (oldest) b) Qatv4, c) Qatv3, d) Qatv2, e) Qatv1, including modern deposits. Approximate ages for these deposits are discussed by Eddleman (2005), who suggests that the oldest deposits (Qatvu) are approximately 150 Ka. Sulfur Creek flows from east to west.

The second fault system is located southwest of Chimney Rock, and includes a series of near-parallel vertical faults oriented N18°W. Movement along each of these faults is down to the east with no observed strike-slip motion. Along strike, these faults are relatively straight, each with its maximum offset, near the middle of its length. The largest observable offset on a single fault within this system is about 80 feet. Cumulatively, the fault system creates a maximum of 120 feet of structural relief.

The third fault system, an east-west to southeast-northwest trending splay of vertical and near vertical normal faults, is located north of Highway 24. This fault system is one of the dominant structural features in the quadrangle. Beginning as a single fault in the western part of the adjacent Fruita quadrangle, this fault system creates a quasi-triangular splay that opens to the northwest. Faults in this system range from 8 km to less than a kilometer in length with offsets ranging from nearly 300 feet (north of Chimney Rock) to a few feet. Anderson and Barnhard (1986) suggest that there is a minor strike-slip component associated with these faults, although reliable kinematic indicators found in this study were sparse and inconclusive in this area.

The fourth system of faults is represented by two nearly north-south trending near-vertical faults that are associated with and in some cases are intruded by 4 Ma mafic dikes (Anderson and Barnhard, 1986). Maximum offset along these faults in the map area is 15-20 feet. These faults represent an east-west extensional stress field that post-dates the other three fault systems that are interpreted to be associated with Laramide compression.

Detailed structural and kinematic analysis of the area is included as the second chapter of this thesis.

CONCLUSIONS

The geologic map contained in this thesis summarizes the stratigraphic, structural and Quaternary geology of the Twin Rocks quadrangle, including the following features:

- Bedrock mapping of recognized stratigraphic formations, including the division of the Chinle and Moenkopi Formations into their component members
- Mapping of the Page Sandstone as a formation separate from the Navajo and Carmel Formations
- Division of the Navajo Sandstone into basal and upper members
- Detailed mapping of Quaternary units, including division of volcanic boulder terrace deposits according to height above present stream level
- Structural contour map showing broad homoclinal structure, dipping between 2° and 20° to the northeast, and an asymmetrical, southwest verging anticline bounded on the southwest by a vertical fault. This antiform is located in the northeast part of the quadrangle.

Linear terrace patterns over a broad area and modern boulder-filled and abandoned channels in Sulfur Creek suggest a new model for terrace development in this area. Fluvial terraces within the Sulfur Creek drainage developed as boulder-filled channels were abandoned and the stream downcut preferentially through the softer surrounding bedrock, stranding the deposit above the present stream level. While Pazzaglia's (1998) model for fluvial terrace development focuses primarily on the role of climate, this study shows that the bedrock type, and its resistance to erosion, also plays a key role in controlling the development of and style of terrace preservation. Analysis of terrace deposits in the Sulfur Creek drainage shows spatial changes in the location of the stream through time, recording a general northeastward migration followed by a relatively recent southward shift into its present location.

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CHAPTER 2

PALEOSTRESS AND DEFORMATION ANALYSIS OF THE BACKLIMB OF THE MINERS MOUNTAIN UPLIFT, CAPITOL REEF NATIONAL PARK, UTAH

ABSTRACT

Kinematic analysis of structures in the backlimb of the uplift show a principle compressive stress orientation nearly perpendicular to the uplift axis and rotated 30° counter clockwise from the stress indicated by deformation bands measured in the forelimb. These data suggest that stress transmitted through the basement is partitioned and rotated in the backlimb, likely due to decoupling and differential slip in strata with low shear strength. Such decoupling would allow the stress to be rotated perpendicular to the resisting fold axis, rather than parallel to the far-field stress transmitted through the basement. Sandbox models produced in this study display boundary perpendicular structures similar to those measured in the backlimb of the Miners Mountain uplift.

INTRODUCTION

The Late Cretaceous-early Tertiary Laramide orogeny exhibits a deformational style drastically different from that of the partly contemporaneous Sevier orogeny (Schmidt et al., 1993). Laramide contractional deformation consists mainly of fault bounded, basement-cored uplifts, varying in size, orientation and structural relief (Davis 1999). Much of the research concerning basement involvement and geometry of Laramide uplifts has been focused on the Rattlesnake Mountain and other uplifts in Wyoming as well as in the Grand Canyon, where uplift-bounding faults and basement contacts are exposed at the surface (Huntoon et al., 1993; Schmidt et al., 1993; Timmons et al., 1993). Throughout the Colorado Plateau, however, uplift-coring faults are either buried and/or expressed as fault-propagation folds in which the fault did not propagate to the present surface (Bump, 2003).

The Laramide orogeny is generally characterized as thick-skinned, suggesting that far-field stresses were transmitted primarily through the rigid basement and major deformation is only observed above areas where the basement failed and stresses were transferred into the overlying sedimentary strata (Erslev, 1993; Davis 1999). Bump and Davis (2003) assert that as long as the overlying sedimentary strata are welded to the basement, stress preserved in the sedimentary cover reflects basement strain, meaning that the "direction of greatest shortening in the basement was parallel to the maximum compressive stress direction in the cover." This assumption of "welded" sedimentary cover is supported by the observation of oblique-reverse slip along the East Kaibab monocline and Miners Mountain uplift (Anderson and Barnhard, 1986; Tindall and Davis, 1999; Davis, 1999) suggesting that the basement did not move laterally independent of the overlying sedimentary cover (Bump and Davis, 2003).

The observation of oblique motion on Laramide structures indicates that uplift-scale decoupling from the basement was not a controlling factor during the development of these uplifts. This paper, however, focuses on the local stress-field on the backlimb of the Miners Mountain uplift and evidence for small-scale decoupling away from the highly deformed forelimb.

PREVIOUS WORK

A great deal of detailed structural and kinematic research has been directed toward Laramide structures in the Colorado Plateau. Anderson and Barnhard (1986) used fault slip and trend data to calculate paleostress fields for Laramide and post-Laramide deformation in the Capitol Reef area. George Davis and Alex Bump (Davis, 1999; Davis, et al., 2000; Bump and Davis, 2003, 2005) reconstructed Laramide paleostress based on kinematic data obtained from Riedel deformation bands preserved in the structural forelimbs of the major Laramide uplifts in the Colorado Plateau. These data were further combined to show a remarkably consistent stress field in the Colorado Plateau during the Laramide. Most recently, Bump (2003) and Bump and Davis (2005) have shown evidence that many Laramide structures are cored by reactivated extensional faults.

Modeling of Laramide uplift structures focused on cross section balancing (Suppe, 1983; Mitra, 1990) and essentially geometric solutions using simple shear algorithms (e.g. Suppe et al., 1992) until Allmendinger (1998) created a computer program allowing graphical implementation of the two-dimensional Trishear fault propagation folding concepts of Erslev (1991). Bump (2003) used Trishear software to model deformation in Laramide uplifts throughout the Colorado Plateau, finding the most success in reconstructing the Circle Cliffs uplift, located south and adjacent to the Miners Mountain uplift.

Previous kinematic studies of the Miners Mountain uplift (as well as the other related structures) focus on the highly deformed fold forelimb, due to the abundance of preserved kinematic indicators, giving little attention to the kinematics and deformation of the comparatively undeformed backlimb. Although the total amount of structural deformation is much less, the backlimb of the Miners Mountain uplift contains a suite of reliable kinematic indicators including faults, small-scale folds, and fracture sets.

GEOLOGIC SETTING

The Miners Mountain uplift is located in the northern portion of Capitol Reef National Park on the western edge of the Colorado Plateau. Although historically depicted as the northern expression of the Circle Cliffs uplift, together forming the "Waterpocket Fold," detailed structural analysis (Anderson and Barnhard, 1986; Bump et al., 1997; Bump and Davis, 2003) has shown the Miners Mountain uplift with southwest vergence is a structure distinct from the east-vergent Circle Cliffs uplift (see Figure 6). Bump and Davis (2003) have further shown that in spite of having opposite vergence and non-parallel axes, these two uplifts developed in a very similar stress field during the Laramide Orogeny. The southern end of the Miners Mountain uplift meets the northern tip of the Circle Cliffs uplift in the vicinity of Sheets Gulch (Davis, 1999) (see Figure 6). Similar in gross morphology and Laramide tectonic origin to the nearby Circle Cliffs

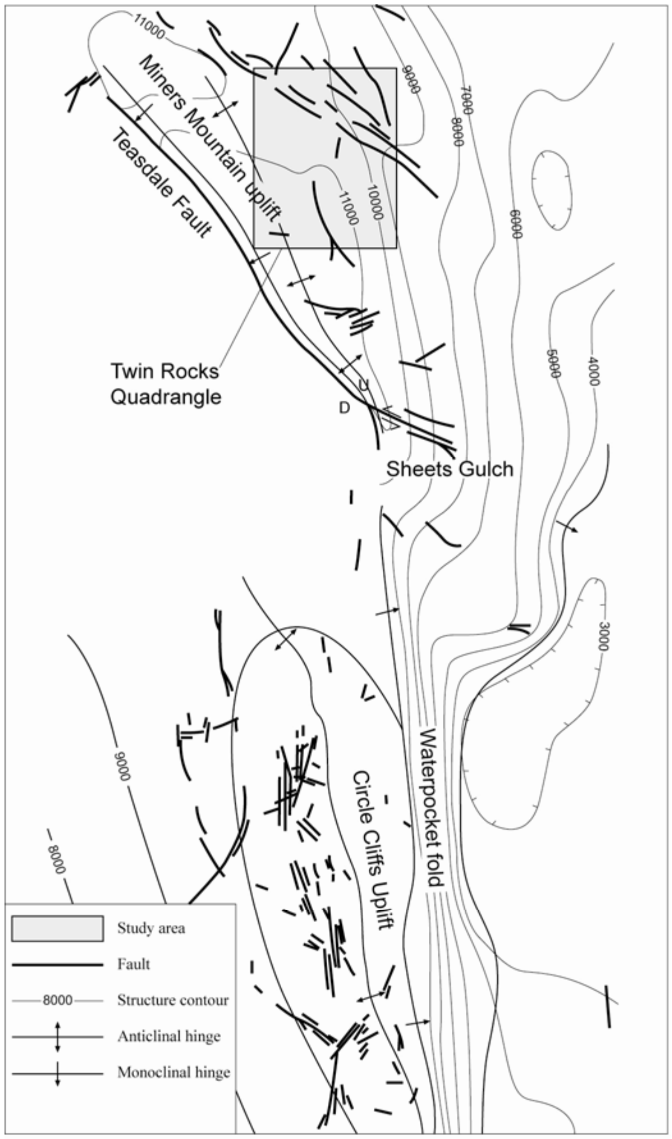

Figure 6. Simplified structure map of the Miners Mountain and Circle Cliffs uplifts showing faults, folds and structure contours. Structure contours drawn on the base of the Dakota Sandstone. Contour interval = 1000 ft. (Modified from Davis, 1999).

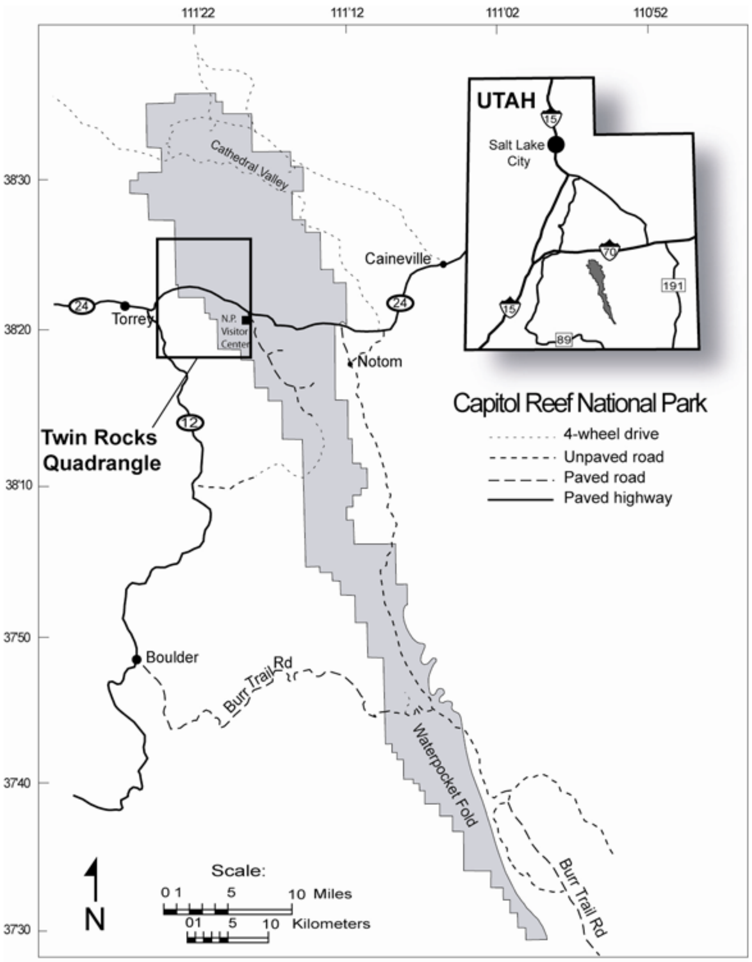

Figure 7. Reference map showing the location of the study area relative to Capitol Reef National Park (Modified from Morris et al., 2000).

uplift and the San Rafael Swell, Miners Mountain is a basement-cored uplift creating an asymmetric, doubly-plunging anticline (Bump et al., 1997). The gently-dipping (~15°) backlimb rises from Highway 24 near Park Headquarters (Figure 7) flattening to form the top topography of the Miners Mountain, with the steeply-dipping forelimb expressed by the Teasdale Monocline (referred to as the Cockscomb Monocline in Anderson and Barnhard, 1986). The fold is cut along much of its length by the Teasdale fault and exhibits approximately 1,500 meters of structural relief (Martin et al., 2006). The fold axis trends NW-SE, forming a triangular outcrop pattern pointing toward the southeast where it meets the Circle Cliffs uplift. The northwestern end of the uplift terminates into Thousand Lake Mountain. Bump and Davis (2003) have proposed that the Miners Mountain uplift formed by sinistral oblique-reverse motion along a basement-cored fault, the fault trending parallel to the NW-SE fold axis.

The principle compressive far-field stress was oriented NE-SW, 25° clockwise from normal to the fold axis (see Figure 9).

FIELD ANALYSIS

Methodology

The approach used in this study focuses on mapping and determining the principle stress direction indicated by small-scale structures within the backlimb of the Miners Mountain uplift. These structures include small-scale folds, slickenlines, and fracture sets, which provide reliable paleostress data (Hancock, 1985; Gray and Mitra, 1993).

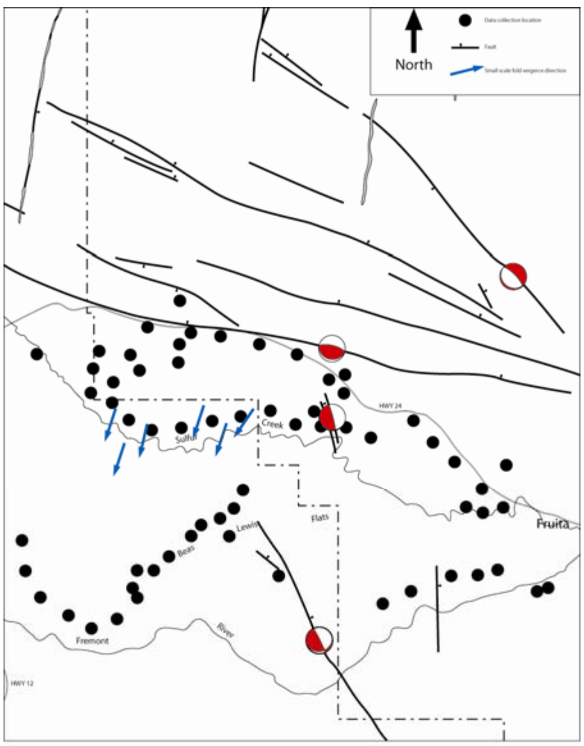

Figure 8. Reference map of the study are showing data collection locations and fault-plane solutions for faults with measured slip data. Blue arrows indicate vergence direction of small-scale folds, black dots show data-collection locations. Red fields in fault-plane solutions represent compression regions.

Small-scale folds

Compressive folds have long been utilized as an indicator of paleostress, with the direction of greatest shortening representing the maximum principle paleostress axis (σ_1). Defined as small-scale folds, those used in this study are compressive, highly asymmetric, fault-propagation folds. In the study area these folds occur in competent sandstone or limestone layers sandwiched between incompetent mudstone layers. Strain was accommodated by folding in the rigid rocks and by flexural flow in the more ductile rocks above and below. A compass was used to measure the direction of greatest shortening.

Fracture sets

Mode 1 fracture or joint sets are found throughout the more brittle portions of the Torrey and Sinbad members of the Moenkopi Formation on Miners Mountain (see Chapter 1 and Appendix A, this thesis). In a compressional regime such fractures propagate parallel to the principle stress, recording the direction of σ_3 in brittle rocks. Joint sets are also known to develop in extensional stress regimes, with the fracture propagating perpendicular to extensional direction. Such a stress field could also develop following the cessation of compression during relaxation of the rocks, producing secondary, non-systematic joints. Figure 9 shows the two dominant joint sets measured within the study area. Ambiguous abutting relationships between the two joint sets preclude a simple determination of the sequence of fracturing. At some outcrops, northeast-southwest trending fractures dominate and appear to be systematic, while the northwest-southeast trending fractures appear to be non-systematic cross joints. In other locations, however, both fracture sets are equally prominent, and determination of systematic and non-systematic joints is impossible.

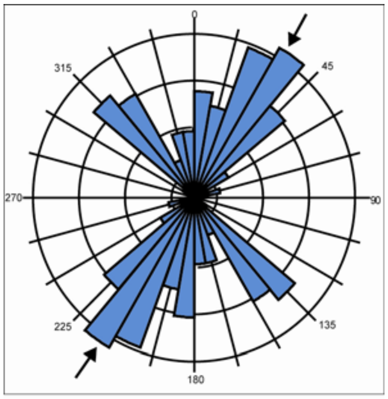

Figure 9. Rose diagram showing the orientation of mode-1 fractures (bi-directional) (n=89). Paired arrows show the principle shortening direction of small-scale folds located on the backlimb of the Miners Mountain uplift (shown in Figure 8).

Slickenlines

Slickenlines, as well as other various grooves and striations found within fault planes help define the precise direction of slip along the fault. Strike and dip of fault-planes and the rake of slickenlines and grooves were measured where possible, and fault-slip data are shown in Figure 8 as fault-plane solutions. Measurements show essentially vertical to high-angle normal movement along faults within the study area and give little clear insight into the Laramide stress regime in the area.

Synthesis

Kinematic data from folds and fractures in the backlimb of the Miners Mountain uplift (Figure 9) indicate a local σ_1 oriented ~35° and 215° azimuth, nearly perpendicular to the uplift axis and 30° counter-clockwise from the far-field σ_1 from Bump et al. (2003) which was measured in the forelimb of the uplift. Relationships between the kinematics of the forelimb and backlimb relative to the uplift axis are shown in Figure 10. Assuming that both data sets accurately indicate the paleostress during the Laramide, these data suggest a rotation or partitioning of the strain field between the two parts of the fold.

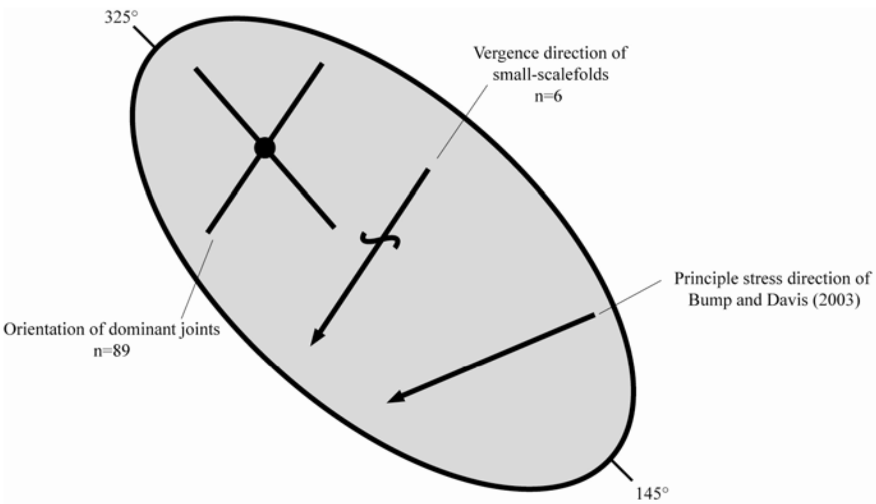

Figure 10. Synoptic diagram of small-scale structures on Miners Mountain. Ellipse represents the Miners Mountain uplift with structural symbols within the ellipse showing average orientations of structures measured in the backlimb relative to the far-field stress measured in the forelimb by Bump and Davis (2003).

DISCUSSION

Penetrative deformation is concentrated in the forelimb above the basement fault in basement-cored uplifts such as Miners Mountain (Erslev, 1991, Tindall and Davis, 1999). Oblique-reverse slip observed in the fold forelimb by Bump et al. (2003) indicates that the basement could not move obliquely without recording that motion in the sedimentary cover, suggesting that the kinematics of the forelimb accurately represent the far-field stress being transmitted through the rigid basement. Key to this model is the assumption that the sedimentary strata mechanically connected to the basement are passive, and that all stress is transmitted into the cover by traction, rather than being "pushed" horizontally.

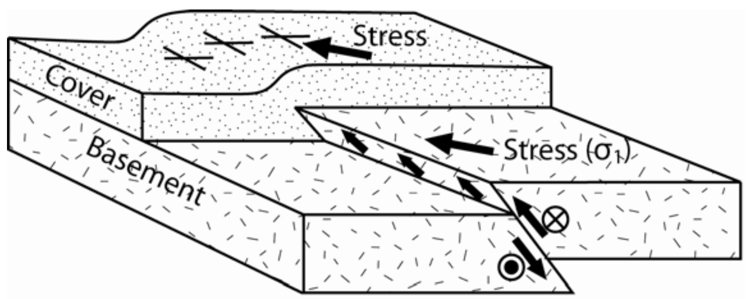

Figure 11. Schematic block diagram showing the relationship between basement and cover strain. Slip in the basement is oblique left-lateral reverse. Penetrative deformation in the cover is localized above the basement fault and reveals principle stress directions parallel to basement strain (modified from Bump and Davis, 2003).

Assuming that the stress being transmitted through the basement is accurately recorded in the forelimb (σ_1=65° and 245° azimuth, see Figure 11), the 30° counterclockwise stress-field rotation observed in the backlimb (σ_1=35° and 215° azimuth) likely represents decoupling within the sedimentary strata and rotation of the stress field in response to resistance perpendicular to the uplift axis.

The assumption that cover strain accurately represents basement stress (Bump et al., 2003) is only accurate when the cover strata are effectively welded to the basement and no differential movement can occur between stratal layers. While this assumption is likely true in the highly deformed forelimb, the kinematic data in this study provides evidence for backlimb decoupling. Although the presence of a large-scale detachment in this area is unlikely (Bump et al., 2003), small scale detachment and multiple partial detachment horizons could easily occur in weak shales present in many underlying formations. The assumption that basement strain is transferred into the cover by traction suggests that any weak layer would lead to imperfect transmission of stress, decreasing vertically through the stratigraphic section. The backlimb strain field recorded at the surface today likely represents the combined effect of multiple weak horizons where partial decoupling takes place, rather than a single detachment surface.

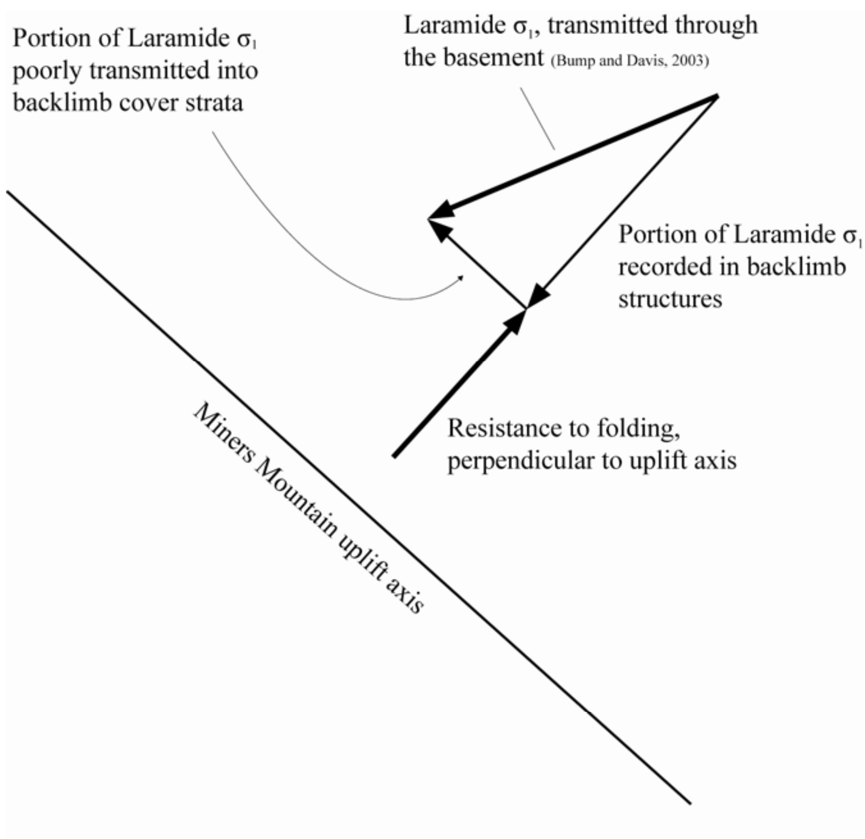

Figure 12. Stress vector diagram showing the relationships between the Laramide σ_1 being transmitted through the basement and the stress recorded in the backlimb of the Miners Mountain uplift. Note that resisntance to deformation perpendicular to the fold axis controls the orientation of the backlimb stress field. Within the fold forelimb, however, a higher degree of deformation allows the full σ_1 to be expressed.

Backlimb stress-field partitioning (Figure 12) can be conceptually thought of in terms of stress vectors. As sedimentary cover folds above the basement fault, the developing fold exerts a resistance force against the backlimb strata that are otherwise passively riding on the rigid basement. Assuming that decoupling in the sedimentary strata does occur, the localized stress field in the decoupled sedimentary strata is oriented perpendicular to the resisting fold axis, rather than parallel to the stress in the basement.

MODELING

Numerical and physical analogue modeling techniques have been used to better understand the structural complexities of the Miners Mountain uplift, each with limited success.

Trishear Modeling

Attempts to use Allmendinger's (1998) Trishear software to model the Miners Mountain uplift have been unsuccessful, primarily due to 1) a lack of control along the forelimb and 2) oblique-reverse slip during deformation. Trishear algorithms are strictly two-dimensional, and cannot account for the oblique component of motion in the Miners Mountain uplift. Although algorithms for pseudo three-dimensional (Cristallini and Allmendinger, 2001) and true

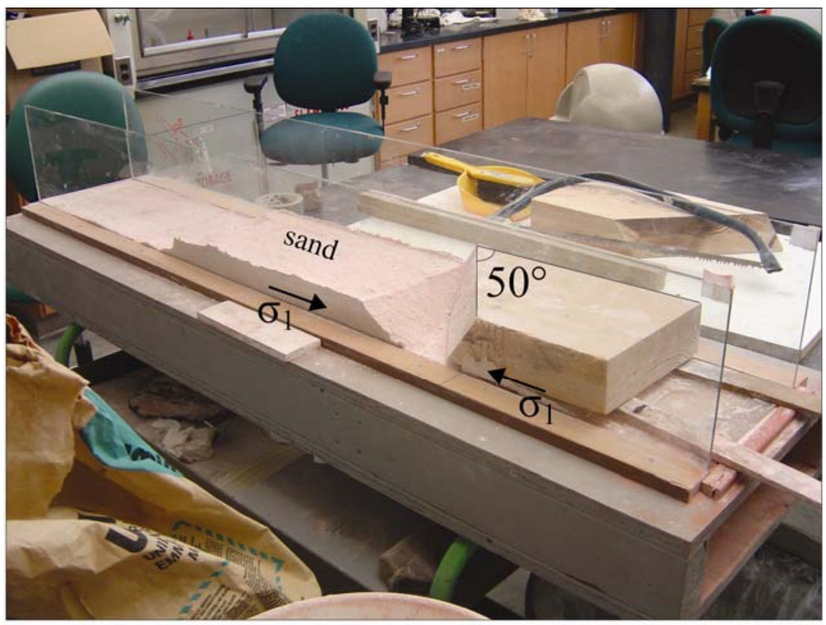

Figure 13. Photograph of pre-deformation sandbox analogue model setup. Sand was pushed against a stationary wood block cut at a 50° angle to σ1, recreating the stress field of the backlimb of the Miners Mountain uplift.

three-dimensional trishear (Cristallini et al., 2004) models have been presented in the literature, neither has been released in a usable graphical format.

Analogue Modeling

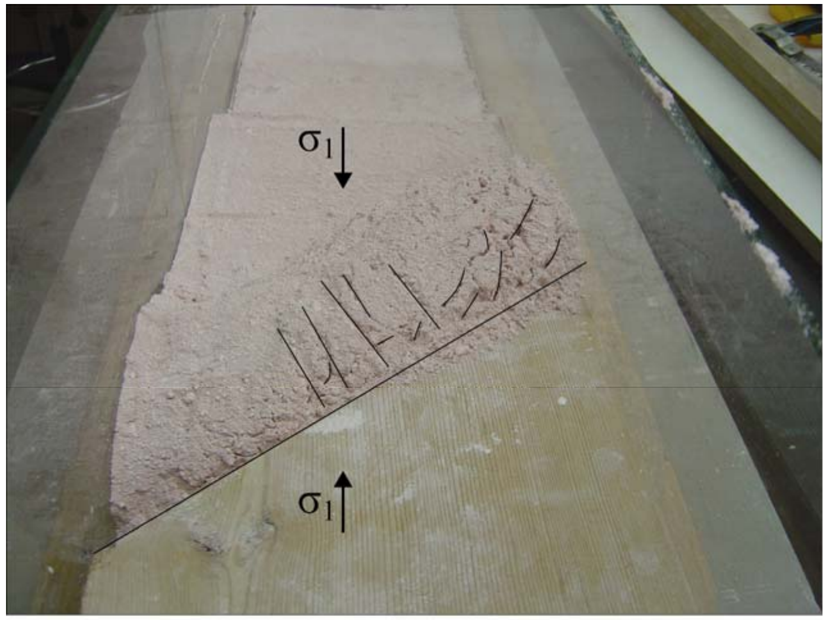

Figure 14. Structures created by sinistral oblique convergence in the sandbox model. Note the perpendicular orientation of fractures relative to the stationary block, rotated counter clockwise from the far-field principle compressive stress.

In an attempt to better understand the deformational kinematics of Miners Mountain, we created a physical analogue sandbox model in which sand was pushed against a stationary block representing the uplift axis as shown in Figure 13. The block was cut at an angle to the compressive axis in order to recreate the oblique convergence in Miners Mountain. In the model, the sand is resting on a sheet sandpaper that is pulled beneath the stationary block. Figure 14 shows the strain developed near the surface in the sand, with boundary-perpendicular structures analogous to those observed on the backlimb of Miners Mountain.

CONCLUSIONS

The principle compressive stress recorded in the backlimb of the Miners Mountain uplift (35° and 215° azimuth) is nearly perpendicular to the fold axis, 30° counterclockwise of the 65° and 245° azimuth Laramide σ_1 measured in the forelimb of the structure (Bump and Davis, 2003). The σ_1 of Bump and Davis (2003) represents Laramide strain being transferred though the basement during deformation, while the σ_1 observed in the backlimb (this study) suggests a local stress field rotation perpendicular to the fold axis. This local stress field is created in the backlimb may be due to decoupling of sedimentary strata and imperfect transmission of basement strain vertically through the sedimentary cover. Boundary perpendicular structures were created in an analogue sandbox model which supports the data gathered in the field but does not increase our understanding of the mechanism by which the stress field is rotated.

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APPENDICIES

APPENDIX A

APPENDIX A—Plate 1. Geologic Map of the Golden Throne quadrangle

APPENDIX A—Plate 2. Legend for the map of the Golden Throne quadrangle including the following:

- A description of map units
- A geologic cross-section
- A lithologic column depiction of mapped units
- A diagram showing correlation of map units age
- A key explaining map symbols

APPENDIX B

APPENDIX B—Data CD containing the following information:

- Geologic Map of the Twin Rocks quadrangle, Wayne County, Utah, GIS Data (ESRI ArcGIS 9.3)
- Map Legend and Key of the Geologic map of the Twin Rocks quadrangle (Adobe Illustrator CS 2)
- Digital version of this thesis (Adobe PDF)

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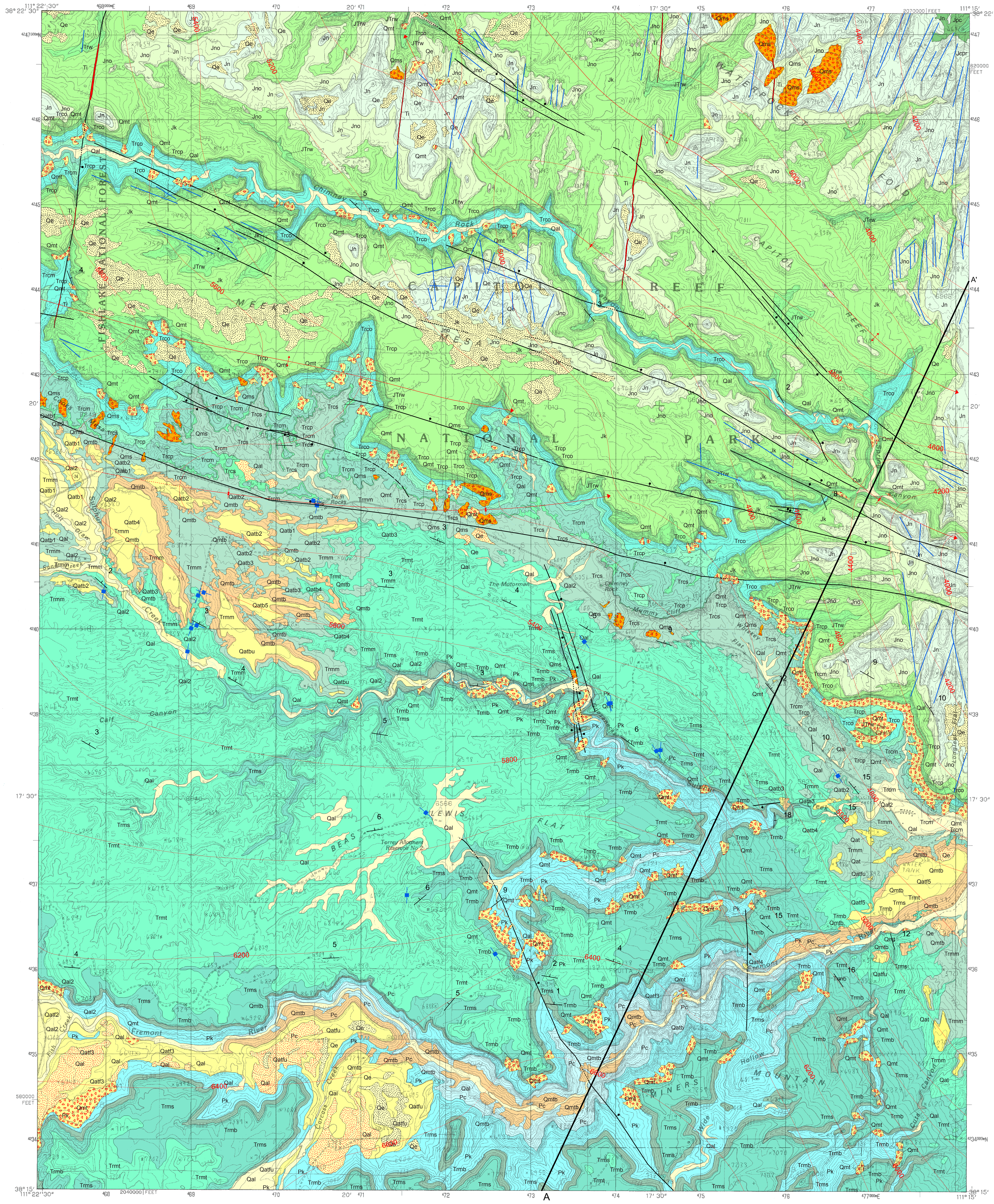

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SCALE 1:24,000
Contour Interval 40 feet

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Geologic data in NAD 1927; base map in NAD 27.
Field mapping by authors, 2005
Cartographic assistance by J. Buck Ehler

Geologic Map of the Twin Rocks Quadrangle, Wayne County, Utah

by
Samuel C. Sorber[1], Thomas H. Morris[1], and Jeremy M. Gillespie[1]
2006

[1]Brigham Young University, Department of Geological Sciences, Provo, UT

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DESCRIPTION OF MAP UNITS

QUATERNARY DEPOSITS

Qal Alluvial and floodplain deposits - Poorly to moderately sorted material in modern stream and river channels. Includes clay-to-boulder size sediments composed of mudstone, siltstone, sandstone, and limestone particles. Includes low terrace deposits up to 10 feet (3 m) above the active channel. 0-10 feet (0-3 m).

Qal2 Alluvial and floodplain deposits of a former river level - Located 10 to 20 feet (3-6 m) above current floodplain. Clay-to-boulder size sediments composed of mudstone, siltstone, sandstone, and limestone particles. 0-20 feet (6 m).

Qatv Qatf Volcanic boulder terrace deposits - Sediments overlying river-cut strath terraces sourced from volcanic covered highlands to the west. Composed of pebble-to-boulder size extrusive (basaltic and andesitic) igneous rocks as well as clay-to-boulder size locally-derived material consisting of mudstone, siltstone, sandstone, and limestone. Terraces have an easily recognized dark coloration due to the presence of weathered black volcanic boulders. Terrace deposits have been divided according to the methodology of Eddleman (2005) according to their associated drainage and height above present stream level as follows:

Qatv - Terrace deposits associated with stream drainages other than the Fremont River. Qatv1 represents deposits 0-60 feet above the present stream level, Qatv2 - 60-120 feet, Qatv3 - 120-180 feet, Qatv4 - 180-240 feet, Qatv5 - 240-340 feet, Qatvu (undifferentiated) - >340 feet.

Qatf - Terrace deposits associated with the Fremont River drainage. Qatf1, Qatf2, Qatf3, Qatf4, Qatf5, and Qatfu (undifferentiated) represent deposits divided in the same manner as Qatv (above). 0-50 feet (0-16 m).

Qatlo Old locally derived terrace deposits - Terraced fluvial remnants derived from local, non-volcanic sources composed of clay-to-boulder size particles of mudstone, siltstone, sandstone, and limestone. Typically very well cemented. Equivalent to Qatv4 (180-240 feet above the present stream level). Located in the southeast part of the quadrangle. 5-30 feet (1.5-9 m).

Qmt Talus deposits - Mass movement talus deposits. Rock falls and rock slides. Composed of clay to boulder size particles. Commonly found where an easily erodible rock layer is located directly under a more resistant rock layer. For example, talus deposits composed of the Sinbad Member of the Moenkopi Formation overlie the Black Dragon Member in many areas and talus deposits composed of the Wingate and Kayenta Formations overlie the Owl Creek Member of the Chinle Formation. Rarely applies to deposits over pediment-like surfaces. 0-30 feet (0-9 m).

Qmtv Volcanic boulder colluvial deposits - Predominantly composed of talus and colluvial material weathered from volcanic boulder terraces. Includes large extrusive (basaltic to andesitic) igneous boulders as well as other locally derived material. In the Fremont River canyon the unit includes volcanic boulder containing material stranded along the canyon sides during ancient floods not associated with overlying, bedded terrace deposits. 0-5 feet (0-1.5 m).

Qms Landslide deposits - Semi-coherent mass movement slump blocks and landslide deposits composed of Chinle, Moenkopi, and the lower portion of the Navajo Formation, which have slid at low-angle onto underlying strata. Slide-planes in Navajo slumps correspond to bedding surfaces within the red mudstone at the Kayenta-Navajo contact. While basal slide-planes are commonly seen, scarps at the head of the slump are not mappable due to subsequent erosion. 20-80 feet (6-24 m).

Qe Eolian deposits - Very well-sorted, fine-grained, well-rounded, commonly frosted wind-blown sand size particles. Commonly associated with outcrops of Navajo Sandstone, but also present in other areas. 0-10 feet (0-3 m).

Qea Eolian-alluvial deposits - Windblown, fine-grained sand to silt locally mixed with alluvial sand, gravel and clay. 0-10 feet (0-3 m).

TERTIARY ROCKS

Ti Intrusive igneous dikes - Dark gray trachybasalt to basanite with diabasic textures. Locally highly altered and easily eroded with poorly-defined margins. Intruded along north-south trending near-vertical fractures in the Glen Canyon Group. Pliocene. 4.35±0.04 Ma ($^{40}Ar/^{39}Ar$) (Doelling and Kuehne, 2005). Referred to as shonkinite in Delaney and Gartner, 1997. 2-10 feet (0.5-3 m).

JURASSIC ROCKS

Jcpr Paria River Member of the Carmel Formation (Middle Jurassic) - Moderate-reddish-brown mudstone and siltstone, yellowish-gray siltstone, and light-gray to white gypsum. Forms ledges. 150-200 feet (45-60 m).

Jpc Page Sandstone (Middle Jurassic) - The Page Sandstone in this area is composed of two members; Harris Wash Member (lower), and Thousand Pockets Member (upper), which are separated by the Judd Hollow Tongue, a member of the overlying Carmel Formation that is included in the Page map unit. The Harris Wash Member is 92 to 113 feet (28-35 m) thick. It is composed of very-pale-orange to pale-yellowish-orange, fine- to medium-grained, cross-bedded sandstone. The Judd Hollow Tongue has been divided into two units based on pollen ages: the upper portion contains the Crystal Creek Member and the lower portion contains the Judd Hollow Member (Sprinkel and Doelling, personal communication). It is composed of ripple-laminated, moderate-reddish-brown to dark-reddish-brown mudstone and sandstone with local interbeds of limestone. The Judd Hollow Tongue forms a slope and ranges from 10 to 17 feet (3-5 m) thick. The Thousand Pockets Member is composed of very-pale-orange to pale-yellowish-orange, fine- to medium-grained, cross-bedded sandstone with planar and contorted beds. It is 17 to 32 feet (5-9 m) thick. The Page Sandstone can be distinguished from the underlying Navajo Sandstone by the abrupt change in weathering styles. The lower portion of the Page Sandstone forms a sheer cliff above the rounded expression of the Navajo Sandstone. 130-150 feet (40-45 m).

Navajo Sandstone (Lower Jurassic) - Mapped as upper and basal members, divided by a locally continuous thin (5-10 feet (2-3 m)) reddish-brown to reddish-orange slope-forming mudstone.

Jn Upper Member - Very-pale-orange to pale-gray, large-scale cross-bedded fine to very fine-grained sandstone. Localized soft sediment deformation observable in the top 200 feet (61 m). Forms cliffs and rounded domes. Base is marked by sharp contact with underlying mudstone in the basal member. 450-550 feet (135-170 m).

Jno Basal Member - Same as Upper Member, except contact with underlying Kayenta Formation is gradational. Upper portion includes the mudstone that separates basal from upper member. Forms prominent cliff at the base. 110-150 feet (35-45 m).

Jk Kayenta Formation (Lower Jurassic) - Moderate-reddish-brown to moderate-reddish-orange irregularly bedded sandstone siltstone, and mudstone. Forms stepped topography composed of ledges (occasional cliffs) and slopes. Upper 50-80 feet locally contains blocky, cliff-forming very fine-to-fine-grained cross-bedded sandstone. 200-300 feet (60-90 m).

JURASSIC - TRIASSIC ROCKS

JTRw Wingate Sandstone (Lower Jurassic to Triassic(?)) - Light-brown to moderate-reddish-brown cross-bedded to massive, very fine- to fine-grained, calcite-cemented sandstone. Forms the sheer cliffs of the western escarpment of the Waterpocket Fold. Cliff faces are commonly highly fractured and covered with black to brown desert varnish. 260-310 feet (80-95 m).

TRIASSIC ROCKS

TRco Owl Rock Member of the Chinle Formation (Upper Triassic) - Orange and purple mudstone, siltstone, and sandstone with 1 to 3 feet (0.5-1 m) thick interbeds of mottled dusky-red to pale-yellowish-green limestone representing highly bioturbated paleosols with abundant rhizoliths and large burrows (up to 2 in. (5 cm) diameter). Member commonly covered by talus deposits of the overlying Wingate and Kayenta sandstones. 150-200 feet (45-60 m).

TRcp Petrified Forest Member of the Chinle Formation (Upper Triassic) - Moderate-reddish-brown mudstones and siltstones interbedded with carbonate nodule horizons 2 feet (0.6 m) thick interpreted to be paleosols. Basal portion contains a locally continuous dark-reddish-brown, ledge-forming, medium-to-coarse-grained sanstone called the "Capitol Reef Bed." Contains petrified wood. Most of the member forms a slope. 110-135 feet (35-40 m).

TRcm Monitor Butte Member of the Chinle Formation (Upper Triassic) - Light-olive-gray to greenish-gray bentonitic claystone with thin dusky-brown to dark-yellowish-orange, medium- to coarse-grained, cross-bedded, channelized sandstone beds. Forms a slope. Contact with overlying Petrified Forest Member is poorly defined and approximated in this map. 120-150 feet (40-45 m).

TRcs Shinarump Conglomerate Member of the Chinle Formation (Upper Triassic) - Grayish-orange to very-pale-orange, medium- to very coarse-grained cross-bedded sandstone and conglomerate. Contains petrified wood. Shinarump beds are discontinuous and commonly channelized due to its fluvial depositional history. The basal unconformity is scoured with 0-5 feet (0-1.5 m) of relief and is typically overlain by a gravel lag. The unconformity is regionally continuous and is found even where no Shinarump accumulation is present. The member contains uranium that has been historically mined within the quadrangle. Forms ledges and cliffs. 0-30 feet (0-9 m).

TRmm Moody Canyon Member of the Moenkopi Formation (Lower Triassic) - Moderate-reddish-brown to moderate-reddish-orange laminated mudstone and siltstone with sparse very fine-grained ripple-laminated sandstone beds. Small-scale soft-sediment deformation common in silt and sandstone beds. Bedding-parallel gypsum veins and stringers common throughout. Typically forms a slope but can be cliff-forming where overlain by the Shinarump Conglomerate. 220-280 feet (65-85 m).

TRmt Torrey Member of the Moenkopi Formation (Lower Triassic) - Moderate-reddish-brown to moderate-reddish-orange mudstone, siltstone and very fine-grained sandstone. Contains the "ripple-rock" and reptilian trackways found in the park. Bedding thickness ranges from 1-15 feet (0.5-5 m). Forms ledges and slopes. 190-210 feet (60-65 m).

TRms Sinbad Limestone Member of the Moenkopi Formation (Lower Triassic) - Very-pale-orange to grayish-orange limestone and dolostone with interbeds of calcareous siltstone and sandstone and algal boundstone. Upper beds commonly contain oolitic grains and bivalve fragments. Forms a cliff above the Black Dragon Member. 50-90 feet (15-25 m).

TRmb Black Dragon Member of the Moenkopi Formation (Lower Triassic) - Moderate-reddish-brown to moderate-reddish-orange interbedded mudstone, siltstone, and sandstone with gypsum stringers throughout. Forms a slope. In many areas undercuts, and is commonly covered by talus, composed of the overlying Sinbad Limestone. 80-120 feet (25-35 m).

PERMIAN ROCKS

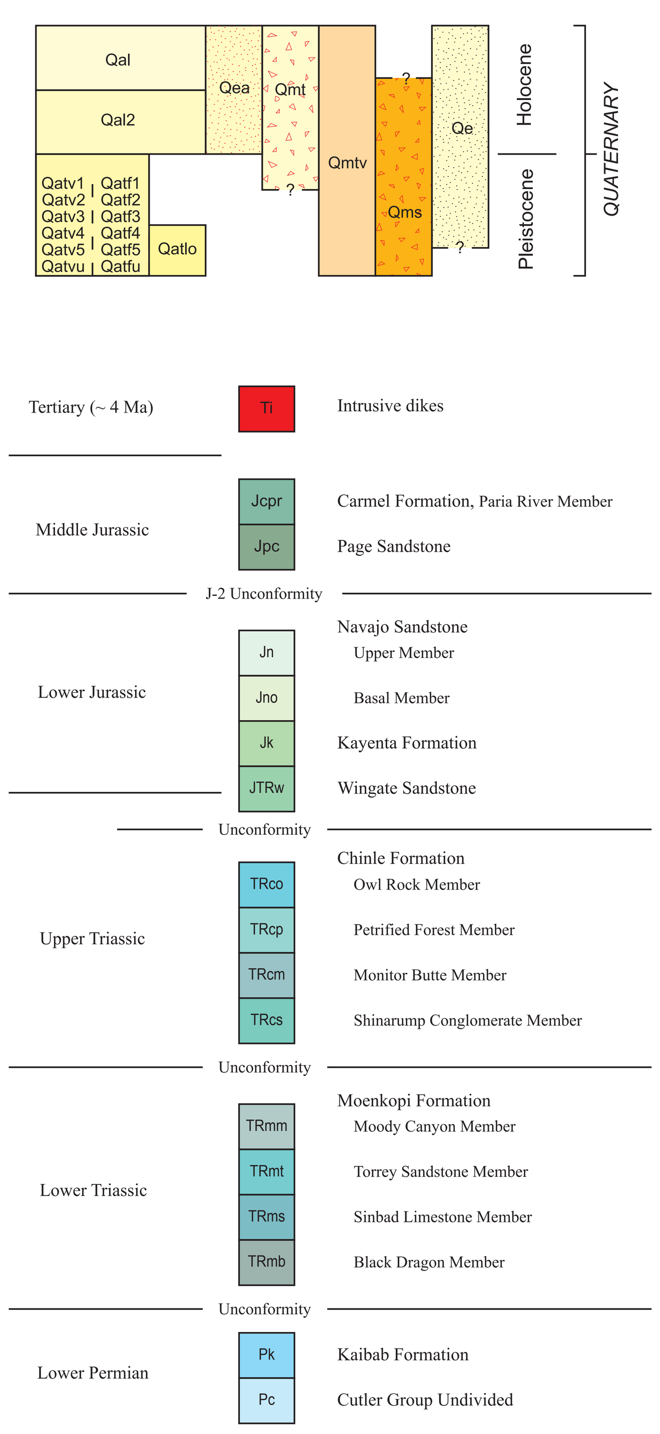
Pk Kaibab Limestone (Lower Permian) - Upper 100 feet (30 m) is composed of very light-gray to yellowish-gray shale and limestone beds with carbonate and silicate nodules. Lower portion is composed of interbedded pale-gray limestone and calcareous sandstone beds. Locally sandstone beds contain glauconite grains. Lower Kaibab interfingers with Cutler Group, creating a gradational contact. Contact is drawn at the base of the the lowest limestone bed. Forms slopes and ledges. 400-500 feet (120-150 m).

Pc Cutler Group Undivided (Lower Permian) - Very pale orange to yellowish-gray, medium- to fine-grained, trough cross-stratified sandstone. Distinguished from the overlying Kaibab Limestone by the absence of carbonate beds. Undivided in this locality due to the absence of the Organ Rock Shale between the White Rim Sandstone and Cedar Mesa Sandstone. Base not exposed within the quadrangle. Forms a cliff. Greater than 1000 feet (300+ m).

Pu Paleozoic and Precambrian Undivided - Subsurface rocks, cross section only.

SYSTEM		FORMATION	Member	THICKNESS feet (meters)	MAP SYMBOL	LITHOLOGY	ENVIRONMENT
JURASSIC		Carmel Formation, Paria River Member		150-200 (45-60)	Jcpr		marine
JURASSIC		Page Sandstone		130-150 (40-45)	Jpc		eolian
JURASSIC	Glen Canyon Group	Navajo Sandstone	Upper Member	450-550 (135-170)	Jn		eolian
JURASSIC	Glen Canyon Group	Navajo Sandstone	Basal Member	110-150 (35-45)	Jno		eolian
JURASSIC	Glen Canyon Group	Kayenta Fm.		200-300 (60-90)	Jk		fluvial
JURASSIC / TRIASSIC	Glen Canyon Group	Wingate Sandstone		260-310 (80-95)	JTRw		eolian
TRIASSIC		Chinle Fm.	Owl Creek Mbr.	150-200 (45-60)	TRco		lacustrine/ fluvial
TRIASSIC		Chinle Fm.	Petrified Forest Mbr.	110-135 (35-40)	TRcp		
TRIASSIC		Chinle Fm.	Monitor Butte Mbr.	120-150 (35-45)	TRcm		
TRIASSIC		Chinle Fm.	Shinarump Cgl. Mbr.	0-30 (0-9)	TRcs		
TRIASSIC		Moenkopi Fm.	Moody Canyon Mbr.	220-280 (65-85)	TRmm		coastal plain & tidal flat
TRIASSIC		Moenkopi Fm.	Torrey Mbr.	190-210 (60-65)	TRmt		
TRIASSIC		Moenkopi Fm.	Sinbad Ls. Mbr.	50-90 (15-25)	TRms		marine
TRIASSIC		Moenkopi Fm.	Black Dragon Mbr.	80-120 (25-35)	TRmb		
PERMIAN		Kaibab Limestone		400-500 (120-150)	Pk		marine
PERMIAN		Cutler Group Undivided		1000+ (300+)	Pc		eolian

CORRELATION OF MAP UNITS



MAP SYMBOLS

Contact

Fault - bar and ball on the downthrown block; dashed where approximate, dotted where covered

6000 Structural Contours - drawn on the top of the Cutler Group. Units are feet above sea level. Contour interval: 200 feet. Dashed where projected above ground surface.

Anticline - showing anticlinal axis

Syncline - showing synclinal axis

A — A' Line of Cross Section

10 Strike and Dip of Bedding

Joints - showing trend of prominent joint sets

Joints - showing location of major near-vertical joints in the Glen Canyon Group

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GEOLOGIC CROSS SECTION