STRUCTURAL OBSERVATIONS AND STRATIGRAPHIC VARIABILITY IN JURASSIC STRATA, UPHEAVAL DOME, CANYONLANDS NATIONAL PARK, UTAH, USA

by

Patrick J. Geesaman
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Golden, Colorado

Date ________________

Signed: ____________________________
Patrick Geesaman

Signed: ____________________________
Dr. Bruce D. Trudgill
Thesis Advisor

Golden, Colorado

Date ________________

Signed: ____________________________
Dr. Paul Santi
Professor and Interim Head of Department of Geology and Geological Engineering
ABSTRACT

Upheaval Dome is a structurally deformed topographic depression located in Canyonlands National Park, southeast Utah. Multiple hypotheses for its origin have been proposed by various scientists over many years of research. The two remaining viable hypotheses are at opposite ends of the geologic spectrum, one proposing long-term deformation of the structure, while the other proposes a catastrophic meteorite impact. (1) The seminal paper by Jackson et al. (1998) suggests that Upheaval Dome was created due to the growth and subsequent pinch-off of a salt diapir sourced from the Pennsylvanian Paradox Formation. Their conclusions were based on various growth geometries in Jurassic age strata. (2) Perhaps the most influential paper proposing a meteorite impact at Upheaval Dome is by Buchner and Kenkmann (2008), titled “Upheaval Dome, Utah, USA: Impact origin confirmed”. In this paper only two grains of shocked quartz are identified, out of 120 standard thin sections. Based on these thin sections comprising medium-coarse sand grains, only ~0.00043% of grains displayed evidence of high-pressure deformation. For shocked quartz to confirm a meteorite impact there must be abundant shocked grains (2-5%), and ~0.00043% cannot be considered abundant (French and Koeberl, 2010).

Prior to this study there has been no attempt made to combine an in depth stratigraphic investigation of exposed, accessible formations with structural and lithologic observations in the Upheaval Dome area. Analysis of stratigraphic field data for Triassic to Jurassic-aged strata reveals: (1) stratigraphic thicknesses from measured sections range from 7 meters to 224 meters in the Kayenta Formation, and projected thicknesses in cross sections can exceed 400 meters; (2) distinct changes in facies distributions in relation to mapped structural features; (3) localized angular discordances, such as angular unconformities and onlaps, at the contact between
formations or within individual formations.

Analysis of structural features at Upheaval Dome reveals: (1) synclinal axes and associated depositional centers shift throughout the Jurassic; (2) stratigraphic thicknesses across normal faults from hanging to footwall blocks are unequal on the scale of meters to tens of meters; (3) thrust faults verge dominantly to the southeast regardless of the side of the dome they are located on; (4) blocks of Triassic Chinle Formation encased in the younger Jurassic Wingate Sandstone adjacent to dog tongues suggests the involvement of a brief period of allochthonous salt break out after the deposition of the Chinle. Petrographic analysis was inconclusive, as there were no shocked grains, nor any clasts of the Paradox Formation present in younger formations.

The research presented in this study strongly indicates that long-term deformation occurred at Upheaval Dome during the Early Jurassic and possibly in older less well exposed units. Evidence supporting long-term deformation includes growth strata, changes in facies distributions, shifting formation depocenters, angular discordances, and growth faults. Sparse indicators of catastrophic are also present in the form of sparse shocked quartz grains and poorly developed shatter cones. To accommodate these juxtaposing deformational regimes an evolution of Upheaval Dome is presented here that relies on an early meteorite impact to initiate active diapirism leading eventually to a passively growing salt diapir. This explanation would account for the petrographic evidence supporting meteorite impact, as well as the growth geometries in the Triassic-Jurassic aged strata surrounding Upheaval Dome.

Upheaval Dome has historically been one of the most controversial geologic features in the United States. It is important for geologists to understand the genesis for this structure as it is an extremely well exposed field example of a meteorite impact, pinched-off salt diapir, or a combination of the two, and can help further understand similar structures found around the
world at the Earth's surface, or in the subsurface.
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CHAPTER 1

INTRODUCTION

The geology of Canyonlands National Park is for the most part very predictable, displaying flat-lying to low dipping strata with negligible structural deformation. This pattern of geologic tranquility changes radically at the structure known as Upheaval Dome. Upheaval Dome is structurally deformed topographic depression located about 36 kilometers to the southeast of Moab (Figure 1.1).

The genesis of Upheaval Dome has been studied and scrutinized for decades, with scientists from various backgrounds postulating different hypotheses for its origin. These hypotheses include: cryptovolcanic explosion (Bucher, 1936), doming of the underlying Paradox Formation (McKnight, 1940), fluid escape from an over-pressured fault system (Kopf, 1982), a pinched-off salt diapir (Jackson et al., 1998) and a catastrophic meteorite impact (Boone and Albritton, 1938; Kriens et al., 1999; Huntoon, 2000; Kenkmann, 2003; Scherler et al., 2006; Buchner and Kenkmann, 2008). Most scientists presently believe that the structure is either the eroded root of a large scale meteorite impact crater (Boone and Albritton, 1938; Kriens et al., 1999; Huntoon, 2000; Kenkmann, 2003; Scherler et al., 2006; Buchner and Kenkmann, 2008), or the remnants of a pinched off salt diapir (Jackson et al., 1998), or a combination of the two (Daly, 2010).

Over the years, Upheaval Dome has been intensively studied, but much of the research undertaken has focused on structural deformation of the surrounding rocks (Kriens et al., 1999; Huntoon, 2000; Kenkmann, 2003; Scherler et al., 2006; Daly, 2010), or on specific petrographic features of rocks or grains in thin section (Koeberl et al., 1999; Okubo and Schultz, 2007; Buchner and Kenkmann, 2008; Key and Schultz, 2011). The goal of this study was to determine
the genesis of Upheaval Dome in an integrative manner by chiefly focusing on the collection and interpretation of stratigraphic data, along with the collection and analysis of structural and petrographic data, collected in the field.

In order to best address the goal of this study a series of objectives were generated: (1) complete meter scale stratigraphic measured sections through accessible portions of the Kayenta Formation to test whether there is significant thickening and thinning of the formation, or if there are shifts in stratigraphic facies related to the proximity to the dome center; (2) record examples of angular truncations or terminations (angular unconformities and onlapping strata) within units or at the contacts between formations around the dome; (3) record examples of structural deformation (normal faults, thrust faults, reverse faults, folds), especially if there appears to be discrepancy in thickness between the hanging and footwall blocks of normal faults; (4) collect samples of Kayenta Formation conglomerate and distinctive sandstones for petrographic analysis, specifically to inspect them for shocked minerals or clasts from older units that would have been entrained in mobile salt through a possible diapir throat; (5) record any other distinct lithologies or geologic features.

Through working towards these objectives this study has documented various geologic phenomena that support long-term deformation at Upheaval Dome including: significant stratigraphic thickness variations in the Kayenta and Wingate Formations, multiple examples of angular unconformities and onlapping strata, numerous normal faults displaying stratigraphic thickness discrepancies between the hanging wall and footwall blocks, and several examples of distinct lithologies that imply shifting of formation depocenters, synclinal axial traces, and long-term deformation.
Figure 1.1: Location maps for Upheaval Dome. (A) Outline of the United States with the state of Utah and its capital, Salt Lake City highlighted. (B) State of Utah with the location of Upheaval Dome and Moab outlined. (C) Location map highlighting Upheaval dome in relation to Moab and other structural features (Modified from Huntoon, 2000).
CHAPTER 2

GEOLOGIC SETTING AND PREVIOUS WORK

Upheaval Dome is located in the southwest part of the northern Paradox Basin (Trudgill, 2011), so its formation and current appearance could be intricately associated with Paradox Basin structural and stratigraphic history. Therefore, a brief review of Paradox Basin geology including its structure, stratigraphy and salt related features is necessary to preface the discussion of the geologic feature that is Upheaval Dome.

2.1 Paradox Basin

During Late Pennsylvanian to Permian time extensive mountain building events extended from southern Idaho to central Texas, known today as the Ancestral Rocky Mountain (ARM) uplands (Figure 2.1) (Barbeau, 2003). Thick-skinned, amagmatic basement cored thrusts and arches formed far from plate margins, and displayed many different structural trends (Kluth and Duchene, 2009; Trudgill, 2011). The Uncompahgre Uplift is a well known and documented Ancestral Rocky Mountain Uplift directly influencing the formation of the Paradox Basin. The Uncompahgre uplift, is a 50-km wide, northwest to southeast trending structure (Figure 2.1) defined by a stack of southwest directed thrust-faulted basement blocks extending from northeast Utah into southern Colorado (Barbeau, 2003).

Intrinsically associated with, and locally adjacent to the Uncompahgre Uplift, are thick successions of coarse-grained syntectonic sediments (Condon, 1997). The mechanism for creating the accommodation necessary for the deposition of these thick sedimentary packages is interpreted as crustal loading from the growing basement cored ARM uplift (Barbeau, 2003). Crustal loading resulted in significant amounts of flexural subsidence in the footwall of the thrust bounding the mountain front, providing the accommodation required for thick accumulations
of syntectonic sediments in the basin foredeep (Barbeau, 2003). The thick accumulation of sediments to the southwest of the Uncompahgre front is now known as the Paradox Basin.

The strata of the Paradox Basin fill proper are comprised of three conformable lithostratigraphic units including, from oldest to youngest, the Pennsylvanian Paradox Formation, Pennsylvanian Honaker Trail Formation, and the Permian Cutler Group (Figure 2.2) (Barbeau, 2003). Of these three formations the Paradox is the most significant for this study as it may have played a direct role in the genesis of Upheaval Dome due to its high concentration of the evaporite halite and its ability to flow over geologic time scales (Jackson and Vendeville, 1994).

In the thickest part of the Pennsylvanian Paradox Formation (~3 kilometers) 29 dolomite-evaporite cyclothsms have been identified by Hite and Buckner (1981). These evaporite-carbonate cycles have been interpreted to have been deposited in a restricted marine basin, which filled and subsequently dried repetitively due to glacio-eustatic sea-level changes (Peterson and Hite, 1981). In the medial to distal basin the evaporite rich, shale and biohermal carbonate facies of the Paradox Formation inter-finger with the coarse grained deposits of the Cutler Formation shed from the active Uncompahgre Uplift. Differential loading from the progradation of clastic Cutler Group sediments loaded the salt layers, contributing to halokinetic rise of salt walls and growth structures in the northeastern part of the basin near Moab, Utah (Ge et al., 1997; Kluth and Duchene, 2009).

The stratigraphic thickness and facies of the basin-fill units found stratigraphically above the Paradox Formation (Lower Cutler Beds, Halgaito Formation, Cedar Mesa Sandstone, Organ Rock Formation, and the White Rim Sandstone) were all greatly affected by the halokinetic rise and movement of salt within the Paradox Formation (Trudgill, 2011). These formations (excluding the White Rim Sandstone) are not exposed in the outcrops surrounding Upheaval
Dome, and therefore will not be described in detail here.

The Permian White Rim Sandstone is rightly named for its characteristic white color and commonly forms a cliff and bench between the finer-grained Organ Rock and Moenkopi Formations. The White Rim Sandstone was deposited as an eolian sand in a coastal environment as the final fill of the Paradox Basin (Steele, 1987). The deposition of the White Rim Sandstone was followed by a major depositional hiatus at the end of the Permian (Jackson et al., 1998).

Formation thickness estimates referred throughout the rest of this chapter are based on the regional stratigraphy of the northern Paradox Basin (Figure 2.3). The next stratigraphically younger formation exposed at Upheaval Dome is the fine grained, fluvial to shallow marine Lower Triassic Moenkopi Formation (~80-150 meters thick) (Jackson et al., 1998). This interval was deposited during a marine transgression as the sea encroached from the west (Jackson et al., 1998). The characteristics of the Moenkopi Formation are extremely variable, but is generally described as chocolate brown, thin and evenly bedded siltstone and fine-grained sandstone with lesser amounts of conglomerate, gypsum, and claystone (Doelling et al., 1988; Jackson et al., 1998) (Figure 2.3). The deposition of the Moenkopi Formation was followed by another significant depositional hiatus.

Stratigraphically above the Moenkopi Formation lies the Upper Triassic, continental Chinle Formation (~110 meters thick). This formation blanketed the topographic expression of the Uncompahgre Uplift, removing it as a physiographical feature (Jackson et al., 1998). Throughout the Colorado Plateau the Chinle Formation can be split into four different members. The basal sandstone-conglomerate Moss Back Member commonly crops out as a prominent gray ledge. The younger Petrified Forest Member is a shale which weathers to a bluish-gray or lavender color. The Black Ledge sandstone crops out as a prominent ledge consisting of a pebble
conglomerate (Jackson et al., 1998). The final unit within the Chinle is the Church Rock Member, which is a recessive red, brown, orange-red siltstone (Jackson et al., 1998).

A hiatus followed the deposition of the Chinle Formation (~210-206 million years, J-0 unconformity) (Pipiringos and O’Sullivan, 1978; Jackson et al., 1998). After this pause in sedimentation the thick, homogenous Wingate Sandstone was deposited from a continental erg, or eolian sand sea, which once blanketed much of the Colorado Plateau (Blakey, 1988; Jackson et al., 1998). The Wingate Sandstone forms a continuous and uniform cliff with a consistent thickness of between 90 to 100 meters throughout the Canyonlands of southeast Utah (Blakey et al., 1988; Doelling, 1988; Jackson et al., 1998).

The Jurassic Kayenta Formation accumulated stratigraphically above the Wingate Sandstone. The rocks of the Kayenta Formation record a fluvial plain that extended from the Uncompahgre Uplift to the west and southwest, covering vast portions of western Colorado, northeastern Arizona, southern Nevada, and southeastern Utah (Miall, 1988; Stevens, 1994). The stratigraphic thickness of the Kayenta Formation varies across its areal extent, from approximately 40 meters in the east near Dove Creek in Colorado, thickening to roughly 300 meters down paleo-flow to the southwest towards central Arizona (Miall, 1988). In the Paradox Basin the thickness of the Kayenta Formation is approximately 70 meters, when unaffected by the halokinetic rise of salt bodies (Doelling, 1988; Jackson et al., 1998).

The upper part of the Kayenta Formation interfingers with the eolian deposited Jurassic Navajo Sandstone as the paleo-climate shifted toward more arid conditions (Miall, 1988). The Jurassic Navajo Sandstone of the western United States is one of the most voluminous erg deposits in the rock record (Blakey, 1988). The regional stratigraphic thickness of the Navajo varies across its areal extent. It thins from west to east, but the thickness of the Navajo in the Paradox region
and near Upheaval Dome is approximately 120 meters. The Navajo is the youngest unit that crops out adjacent to Upheaval Dome and the top of the unit is never exposed at Upheaval Dome. Therefore, units stratigraphically younger than the Navajo Sandstone will not be mentioned or described in this paper (Figure 2.3).

2.2 Upheaval Dome

Upheaval Dome is located in Canyonlands National Park near the junction of the Green and Colorado Rivers in southeast Utah, USA, in the southwestern portion of the northern Paradox Basin (Figure 1.1). The dome is defined by a topographic basin, cutting into the regional stratigraphy to a depth of approximately 300 meters. Formations exposed across the dome include the Moenkopi, Chinle, Wingate Sandstone, Kayenta and Navajo Sandstone (Koeberl et al., 1999). The White Rim Sandstone is not present as beds of strata, but instead is preserved near the center of the dome as a series of interconnected clastic dikes (Kenkmann, 2003).

The structural characteristics of Upheaval Dome are defined by distinct features that change with increasing distance from the center of the dome (Figure 2.4). The interior of the dome is defined by a central uplift (Jackson et al., 1998; Scherler et al., 2006a; Sherler et al., 2006b). Outside of the central uplift the dome is encircled by a depressed dome-encircling syncline (DES) with a diameter of approximately 3.6 kilometers (Koeberl et al., 1999). Further from the center of the dome an inward dipping dome-encircling monocline (DEM) is present; this feature has a diameter of about 5.2 kilometers (Koeberl et al., 1999). Outside of the monocline, beds return to near flat lying, with regional dips common to Canyonlands National Park (Figure 2.5 for cross section displaying many of these features).
2.2.1 Disproved Hypotheses

For decades, geologists and planetary scientists alike have studied Upheaval Dome in order to better understand the origin of this geologic feature in southeast Utah. An early study of the area by Bucher (1936) led him to believe that the circular depression was formed by a cryptovolcanic explosion. He postulated that this type of feature formed due to the upward explosion of volcanic gases from a hidden igneous source, such as a lava-plug (Bucher, 1936; McKnight, 1940). Further studies of the area surrounding Upheaval Dome have shown that there are no igneous rocks within approximately 45 kilometers of the dome center, largely disproving Bucher’s hypothesis (Jackson et al., 1998).

McKnight (1940) proposed that Upheaval Dome formed by doming of the underlying, halite rich, mobile Paradox Formation. McKnight’s hypothesis was based on the moderate depth of Paradox salt, and that the structure-contour surface of the strata around the dome is practically identical to the curved surface of the theoretical shape of a salt dome (McKnight, 1940). McKnight’s hypothesis seems unlikely as there is strong evidence for lateral constriction in the dome center rather than extension, which would be expected in conjunction with a buried salt dome and it fails to explain the presence of overturned beds (Jackson et al., 1998).

Kopf (1982) attributed the structural deformation at Upheaval Dome to the sudden upward release of a fluid slurry from a tectonically over-pressured deep fault system; there is little evidence to support this hypothesis (Jackson et al., 1998).

The two hypotheses that are still considered possible, and have yet to be disproved for the origin of Upheaval Dome, are a meteorite impact and a pinched-off salt diapir. These proposed explanations for the structure of Upheaval Dome are discussed briefly in the following sections. A diagrammatic comparison between these two processes is visited in Figure 2.6 (modified from...
Jackson et al., 1998).

2.2.2 Impact Hypothesis

Over 70 years ago Boone and Albritton (1938) first proposed that Upheaval Dome formed as a consequence of a meteorite impact. They suggested a meteorite impact hypothesis as Upheaval Dome displays many features that are diagnostic of a meteorite impact crater including: a circular shape, a central dome uplift, peripheral folds, radial faults, and intense deformation (Boone and Albritton, 1938).

Many of the recent published papers supporting the impact hypothesis focus on structural and petrographic components of Upheaval Dome. For those scientists who prefer the impact hypothesis, Upheaval Dome is classified as an eroded core of a small complex (with multiple rings) impact crater (Kriens et al., 1999; Huntoon, 2000). Complex impact craters are created in a three step process: (1) contact and compression (Figure 2.7A), (2) excavation (Figure 2.7B), and (3) modification (Figure 2.7C) (Grieve, 1987; Huntoon, 2000; McCall, 2009). Certain geologic features from Upheaval Dome could be used as evidence for each stage. These cratering processes and their associated features present at Upheaval Dome are explored further below.

During the contact and compression stage of impact the kinetic energy from the impactor is translated into the target (Figure 2.7A). This stage lasts less than a second, or as long as it takes for the shock wave leaving the point of contact to travel through the impactor, return off of its trailing surface, and arrive back at the point of impact. The large magnitude shock wave produced by the impact then propagates into the target producing near surface, distinctive and diagnostic indicators of meteorite impact, including melt features, shattercones, high pressure phases of quartz (coesite, stishovite), and planar deformation features (Huntoon, 2000; Buchner and Kenkmann, 2008).
Rocks from Upheaval Dome display extremely sparse and questionable examples of these impact indicators both at microscopic and outcrop scale. However, Kriens et al. (1999) reported some weakly developed shatter cones in thin sandstone beds of the Moenkopi near the center of the dome (Figure 2.8). Okubo and Schultz (2007) studied deformation bands within the Wingate Sandstone and concluded that the mean stress for their nucleation would have to exceed 0.7 Gpa. This level of stress is indicative of a meteor impact, as stresses produced by diapirism and tectonic stress would not generate deformation bands within the Wingate Sandstone (Okubo and Schultz, 2007). Thin sections from the clastic dikes of the White Rim Sandstone also show planar microstructures in quartz grains, but alone cannot be considered to be diagnostic of shock deformation (Kriens et al., 1999). Subrounded quartzose fragments were previously interpreted by early researchers as “impactites”, but have been proven to show no evidence of a high-temperature history diagnostic of impacts (Koeberl et al., 1999). The “smoking gun” for a meteorite impact was identified by Buchner and Kenkmann (2008), when they reported two grains of shocked quartz with planar deformation features out of more than 120 standard polished thin sections (Figure 2.9).

During the second stage of the cratering process, known as the excavation stage (Figure 2.7B), a hemispheric shock wave compresses and accelerates the target material to velocities of several kilometers per second. Rarefaction wave fronts are generated by the original shock wave on available free surfaces such as the ground surface. These rarefaction waves are not parallel to the compressional wave, and lead to the upward and outward motions of the target material, creating a depression known as a transient cavity (Grieve, 1987). The excavation stage is over in seconds to minutes, even for the largest of impactors (Huntoon, 2000).

There are several structural features commonly produced by impactors during the
excavation stage; multiple examples of these are present at Upheaval Dome. Clastic dikes are created during this stage of crater formation due to stress waves over-pressuring aquifers and petroleum reservoirs. The rocks surrounding these over-pressured liquids cannot withstand the increased stress field, which results in the hydraulic fracturing of surrounding strata (Huntoon, 2000). As fractures open, rock fragments become mobilized into the newly opened fractures and become preserved as clastic dikes. Clastic dikes composed of White Rim Sandstone are common in the central uplift of Upheaval Dome, and are interpreted to have been emplaced during the excavation stage of impact cratering (Kriens et al., 1999; Huntoon, 2000; Kenkmann, 2003). The frequency of clastic dikes decreases away from the center of the dome (Kriens et al., 1999). Roberts Rift has also been attributed to hydraulic fracturing from the hypothetical Upheaval impact (Huntoon, 2000), however, this outcrop is over 20 kilometers from the dome and has yet to be conclusively linked to a meteor impact at Upheaval Dome.

Other structural features generated during the excavation stage of impaction are outward verging thrust faults. These form in response to stresses released radially from the impact. Within the Wingate Sandstone there is possible evidence of ductile and mechanical thickening interpreted to have been caused by the excavation stage of impaction (Huntoon, 2000). Wingate “dog tongue” structures have also been interpreted to have been the product of strain accumulation and disintegration of grains due to micro-fracturing during concentric shortening (Scherler et al., 2006a; Scherler et al., 2006b).

Various structures present at Upheaval Dome are attributed to the collapse stage (Figure 2.7C) of a meteorite impact. In this stage gravitational processes are dominant as the transient crater collapses into itself (Huntoon, 2000). As the transient crater collapses inward movement of strata takes place on low angle listric normal faults, which are located around the rim of the
Upheaval crater (Scherler et al., 2006a; Scherler et al., 2006b). The inward movement from these listric normal faults impinges on the center area of the crater, producing a series of outward dipping thrust faults. Thrust faults impinge upon one another in the center of the dome and form slices that are analogous to a camera diaphragm mechanism. This fault geometry allows for the significant amounts of concentric shortening in the dome center (Scherler et al., 2006a; Scherler et al., 2006b).

Even though there has been a significant amount of work done on Upheaval Dome by planetary scientists and impact geologists, there is still no agreed date for when an impact may have occurred. Alvarez et al. (1998) proposed a Jurassic impact, based on convolute bedding and syndepositional folds in the Jurassic aged Carmel, Slickrock, and Entrada Sandstones of Arches National Park. These authors claim that the large scale liquefaction and soft-sediment deformation in the formations would be difficult to explain without a catastrophic event such as large earthquake, or meteor impact. Other dates that have been proposed for the impact at Upheaval Dome range from Cretaceous to Paleogene time (Shoemaker and Herkenkoff, 1984; Kenkmann, 2003). These proposed dates for impact are based on the reconstruction of eroded material that has been removed since impact, or the deformation of the Navajo Sandstone. The data presented suggest that there was 1.5-2 kilometers of strata removed since the creation of Upheaval Dome, placing the timing of impact in the Late Cretaceous (Shoemaker and Herkenkoff, 1984; Kenkmann, 2003; Jackson et al., 1998). Okubo and Schultz (2007) and Huntoon (2000) place the impact simply as post Jurassic, based on deformation in Jurassic units.

From the brief discussion above, it is clear that there is a body of evidence that potentially supports the meteorite impact hypothesis. However, to this date, there has been no conclusive evidence showing when that impact occurred, or that movement of the underlying halite rich
Paradox Formation was not at least partially involved in the genesis of Upheaval Dome.

2.2.3 Pinched-off Salt Diapir Hypothesis

In 1998, Jackson et al. put forth a new hypothesis of a pinched-off salt diapir to explain the formation of Upheaval Dome. This hypothesis proposes that Upheaval Dome formed by an overhanging diapir of a semi-extrusive salt being pinched off from its feeder stem, and subsequently being dissolved and eroded (Jackson et al., 1998). The authors believed that a new hypothesis was necessary to explain Upheaval Dome due to overwhelming evidence of long-term deformation including angular truncations, onlapping geometries and thickness variations within the Chinle, Wingate and Kayenta Formations caused by a laterally shifting peripheral sink from underlying salt flow in the Pennsylvanian Paradox Formation (Jackson et al., 1998).

Deformation and thickness changes within the Chinle Formation are difficult to discern because much of the formation is covered by Wingate Sandstone talus within the interior depression of Upheaval Dome. However, angular discordances of as much as 90 degrees have been recorded (Trudgill and Hearon, pers. comm., 2012). Although the origin of the truncations is speculative, their presence suggests a doming of topography during the deposition of Chinle strata (Jackson et al., 1998).

Unlike the Chinle Formation, the exposure of the Wingate Sandstone is close to 100%, but is still difficult to gather stratigraphic data as it is most commonly a steep cliff face. Jackson et al. (1998) documented evidence of synsedimentary deformation in the form of internal diastems and growth folds within the Wingate. An example of an internal diastem is located west of Holeman Springs Alcove (Figure 2.10). There the Wingate strata thin dramatically, from 75 meters in the east to approximately 50 meters in the west (Jackson et al., 1998). This change in stratigraphic thickness and presence of a small scale intraformational erosional contact is interpreted to have
been caused by the shifting of the diapir-flanking peripheral sink (Jackson et al., 1998) (see Figure 2.11 for a schematic reconstruction).

Further evidence of long-term (non-catastrophic) deformation is growth folds in the Wingate cliffs that surround the central depression of Upheaval Dome. These folds are present around the entire structure, and display wavelengths with intervals of between 150 an 190 meters. As a typical Wingate Sandstone section is approximately 100 meters thick, the wavelength to thickness ratio is far smaller than what is commonly observed in nature, or in theoretical experiments on lithified sandstone (Jackson et al., 1998). This ratio infers the folds in the Wingate surrounding Upheaval were not formed by the buckling of a single layer of lithified rock. Other evidence for long-term deformation within the Wingate strata is present in strata thickening over synforms, and thinning over antiforms, a common diagnostic feature of growth folds (Jackson et al., 1998). These observations gathered in the field by Jackson et al. (1998) indicate syndepositional deformation during Wingate deposition.

Intraformational diastems are present within the stratigraphically younger Kayenta Formation. In the Kayenta Formation near the axis of the present DES south of Upheaval Canyon, are three individual truncation surfaces. Each of these surfaces has been interpreted to have been formed by the shifting of the rim syncline as fluvial deposition and erosion continued (Jackson et al., 1998) (Figure 2.11).

Further evidence supporting long-term deformation at Upheaval Dome is present in the form of growth faults within the Kayenta Formation. Many of the faults in well exposed areas of the Kayenta die out up section abruptly, a representative feature of growth faults. Stratigraphic separations on faults measured by Jackson et al. (1998) displayed differences of about 5 to 10 meters. Although the authors did not correlate meter scale packages across faults, the
observations of thickness changes across faults were abundantly clear to the unaided eye (Jackson et al., 1998).

A structural feature that the impact hypothesis supporters have not been able to explain satisfactorily is the presence of doubly curved synformal radial lobes, or “dog tongues”. These three dimensional lobate structures of the lower part of the Wingate Sandstone drape over significant parts of the underlying Chinle Formation unconformably. Scherler et al. (2006a, b) claim that these structures are the product of increased internal strain accumulation and grain disintegration due to microfaulting during concentric shortening. However there is little evidence to support this claim. Jackson et al. (1998) interpret the “dog tongues” as being the remnant flap, that welded to older stratigraphy after the dissolution of an extrusive salt flange. As the salt dissolved, the flap of sediment was slowly dropped into contact with the lower formation forming a mini-salt weld. Overall, there are structural and stratigraphic features of Upheaval Dome which cannot, or have not, been fully explained by a catastrophic meteorite impact; therefore the geologic features displaying long-term deformation must be explained more thoroughly.

Authors who adamantly argue against the involvement of salt in the development of Upheaval Dome commonly cite a seismic survey performed near the dome by Kanbur et al. (1999). This seismic survey shot two lines, one sub-tangential and the other radiating obliquely from the structure generally following the road away from Upheaval Dome. Both surveys were shot over a kilometer from the dome center. These seismic sections show less than 100 meters of relief on the top of the evaporite-rich Paradox Formation. The data provided from the seismic survey however, are not entirely convincing. The processed seismic data was shot into shallow rocks, has poor resolution, and was performed a kilometer away from the dome center. Salt deformation due to the growth of a passive diapir only deforms strata less than a kilometer from
Figure 2.1: Pennsylvanian-Permian paleogeographic map of the Western United States displaying the Ancestral Rocky Mountain uplifts and their associated basins. Uncompahgre Uplift and associated Paradox Basin are highlighted in red. Red star displays location of Upheaval Dome within the Paradox Basin (Modified from Trudgill, 2011).

Figure 2.2: Tectono-stratigraphic chart displaying the basin fill units of the Paradox Basin. Chart shows units proximal to the Uncompahgre Uplift to the right, and more distal units on the left side of the figure. The basin fill is defined by three conformable lithostratigraphic units including the Paradox Formation, the Honaker Trail Formation and the Cutler Group. The Paradox Formation is important to this study due to its high percentage of halite and ability to flow over geologic time periods (Modified from Barbeau, 2003).
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<td>Moenkopi Formation (80-150 m)</td>
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<td>Permian</td>
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Formations exposed at Upheaval Dome

Figure 2.3: Stratigraphic section of rock units in the northern Paradox Basin. Formations exposed at Upheaval Dome are highlighted in color, units above the Navajo Sandstone are eroded at Upheaval Dome, and units in the subsurface are from data extracted from the Buck Mesa #1 well. Average thicknesses are based on stratigraphy of northern Paradox Basin (Modified from Jackson et al., 1998).
Figure 2.4: Aerial photo of Upheaval Dome displaying the significant structural features including the DES with a diameter of 3.6 km, DEM with a diameter of 5.2 km and the central uplift located in the center of the topographic depression defined by a series of imbricated thrust faults. (X-X’ marks the cross section line from Figure 2.7 (Utah AGRC).
Figure 2.5: Cross section of Upheaval Dome field area, location on Figure 2.4. Figure displays present day syncline, shifting rim synclines, the dome-encircling monocline, white rim sandstone dikes, thickening and thinning of Jurassic strata (Modified from Jackson et al., 1998)
Figure 2.6: Schematic diagrams of the two viable hypotheses discussed in this paper. (A) Cross sectional view of a Upheaval Dome as a deeply eroded impact crater. The present day topographic profile is highlighted in red. (B) Schematic diagrams of the diapir in map and cross sectional view both before and after pinch-off. Faults in cross sectional view after pinch off are extremely simplified. Diagrams highlight that these two deformation mechanisms can leave many of the same distinctive features (central uplifts, inward dipping normal faults, inner constrictional zone, rim syncline etc.) (modified from Jackson et al., 1998).
Figure 2.7: Figure displaying the stages of deformation from a meteorite impact including (A) compression with the approximate size of the hypothetical impactor at Upheaval Dome (Kriens et al., 1999), (B) excavation, and (C) gravity modified collapse, leading to the (D) final form of a complex impact structure (EC=Excavation, TC=Transient Cavity) (modified from Grieve et al., 1981).
Figure 2.8: One of two poorly-developed shatter cones collected in the crater depression from thin sandstone beds within the Moenkopi (From Kriens et al., 1999).

Figure 2.9: Photo-micrographs of two shocked quartz grains found from 120 thin sections displaying planar deformation features (PDFs) in the Kayenta Formation. A-B are taken from quartz grain 1 and display two dominant sets of decorated planar deformation features. C-D are from quartz grain 2 and show three planes of more decorated lamellae (From Buchner and Kenkmann, 2008). PDFs are features commonly used as diagnostic indicators of meteor impacts.
Figure 2.10: Schematic reconstruction of Holeman Spring outcrop displaying synsedimentary deformation of the Wingate Sandstone due to the shifting of the formational depocenters through time (From Jackson et al., 1998)

Figure 2.11: Schematic restoration of the Kayenta Formation on the south side of Upheaval Canyon displaying shifting patterns of subsidence and tilting. These patterns are evidence of long-term deformation caused by shifting peripheral sinks during the growth of a passive diapir (From Jackson et al., 1998).
CHAPTER 3

METHODS

Structural and stratigraphic data were collected in the areas surrounding Upheaval Dome in order to address the goals of this study. Field work spanned from Spring 2011 to Fall 2012 totaling approximately four weeks. Field mapping was completed using ortho-rectified aerial photos at a scale of 1:7000, a Brunton Compass, and a hand held Garmin GPSMAP 60CSx. Mapping was assisted by the use of numerous published references and previously published maps (Kriens et al., 1999; Jackson et al., 1998). A final map of Upheaval Dome was drafted using a combination of Global Mapper 13, and Adobe Illustrator CS6 (Base Map 3, 4, 5, 6). Six geologic cross sections (Figures 3.1-3.7) were compiled in a radiating pattern across the dome flanks (Base Map 3) to include, from youngest to oldest, the Navajo Sandstone, the Kayenta Formation, the Wingate Sandstone, the Chinle Formation and the Moenkopi Formations. Cross section D (Figure 3.2) integrates subsurface data from the Buck Mesa #1 well by projecting it into the section ~500 meters from the south (Base Map 3), in order to interpret older units not exposed at the surface including the Paradox Formation, Hermosa Group, and the Cutler Group. Cross sections were drafted using stratigraphic and structural data collected in the field during this study and from previously published literature (Jackson et al., 1998; Kriens et al., 1999) (Figures 3.1-3.7). Structural bedding strike and dip data were projected onto cross section lines along strike, and are red dashes in the final cross sections. Cross sections were drafted using a combination of Global Mapper 13, 2D MOVE, and Adobe Illustrator CS6.

Fifteen stratigraphic sections (Appendix A) totaling approximately 1430 meters were measured within the halo of structural deformation surrounding Upheaval Dome (Base Map 3) (inside the DEM). Stratigraphic sections were measured using a 1.5 meter Jacob Staff, a Brunton
Compass, and when necessary a folding two meter ruler. Measured sections were logged at sub-meter scale and record grain size, sedimentary structures, color, weathering, bed contacts, and other noteworthy characteristics. The base of Section 12 north of the dome (Base Map 3) was a steep cliff, and therefore its lower thickness was based on photo-interpretation. Photos were taken with a high resolution SLR camera. Sections were measured stratigraphically upwards from the top of the Wingate Sandstone to the base of the Navajo Sandstone across the entire stratigraphic section of the Kayenta Formation in areas lacking evidence for structural thickening or thinning (unfaulted). Sections were measured in accessible areas from inside of the DES to near the DEM in order to collect data on thickness of the Kayenta Formation around the structure (Base Map 3). A separate stratigraphic section was measured away from the structural deformation defined by the dome for regional stratigraphic context approximately ten kilometers to the west along the Shafer Trail. This section measured from the base of the Chinle Formation to 30 meters into the Navajo Sandstone. The entire Shafer Trail section (Chinle Formation-Lower Navajo Sandstone) was found to be approximately 340 meters thick (Appendix A). Measured thicknesses gathered in the field were compared to regional stratal thicknesses from previously published material, and well data from the Utah Division of Oil, Gas and Mining website.

Due to the nature of the cliff forming landscape in the Canyonlands region, photographs are commonly the only data type that could be collected for interpretation from certain areas. Therefore, photos of pertinent geologic features (faults, truncation surfaces etc.) were taken in order to create photo-mosaics and associated photo interpretations. Photo-mosaics were stitched in Adobe Photoshop CS6, and subsequently interpreted and annotated in Adobe Illustrator CS6.

Hand samples were collected as prescribed by the National Park Service’s collection permit from the field area for petrographic analysis. 18 hand-samples were collected and thin sectioned
in order to search for shocked minerals, or anomalous grains such as carbonate clasts or fossils which may have been sourced from older units and shed from a passive diapir. Each thin section was cut to standard thin section size, impregnated with epoxy, half dyed for potassium feldspars, and applied with a cover slip. Of the 18 thin sections, eight were cut from conglomerates within the Kayenta Formation, six are sandstones from the Kayenta Formation, two are finer grained samples with strange features, and two are fossiliferous samples from formations older than the Kayenta. Four of the six sandstone samples are from two channelized sandstone beds, one from near the dome (within the DES) and one away from the dome (Shafer Trail). Each channel was sampled from the base of the channel and the top of the channel-form. These sandstone samples were point counted to test for any type of statistical difference in their compositions. Five other hand-samples were collected, but not thin sectioned for petrographic analysis.
Base Map 3: Geologic map of Upheaval Dome with cross section and measured section locations. Map of Utah in lower right corner shows the location of Upheaval Dome. (Field mapping completed by author with data from Jackson et al., 1998; Kriens et al., 1999).
Figure 3.1: Geologic cross section A-A’ from Base Map 3. Note the Kayenta and Wingate Formations thicken towards the dome center, and formational depocenters do not align. Thin, solid black lines are formation contacts, short red lines are dip symbols, thin black dashed lines represent form lines projected from strike and dip data, and thin black dashed closely spaced dashes are formation contacts projected into the air. Dome center is to the right. Jn, Navajo Sandstone; Jk, Kayenta Formation; Jw, Wingate Sandstone.
Figure 3.2: Geologic cross section D-D’ of Base Map 3. Note the Kayenta and Wingate Formations thicken towards the dome center, and formational depocenters do not align. Thin, solid black lines are formation contacts, short red lines are dip symbols, thin black dashed lines represent form lines projected from strike and dip data, and thin black closely spaced dashed lines are formation contacts projected into the air. Dome center is to the right. D-D’ uses subsurface data from the Buck Mesa #1 well to draft older formations to the base of the Paradox Formation. Jn, Navajo Sandstone; Jk, Kayenta Formation; Jw, Wingate Sandstone; Trc, Chinle Formation; Trm, Moenkopi Formation; Pc, Cutler Group; IPl, Hermosa Group; IPp Paradox Formation.
Figure 3.3: Geologic Cross section F-F' of Base Map 3. Note the Kayenta and Wingate Formations thicken towards the dome center, and formational depocenters do not align. Thin, solid black lines are formation contacts, short red lines are dip symbols, thin black dashed lines represent form lines projected from strike and dip data, and thin black closely spaced dashed lines are formation contacts projected into the air, thick black dashed lines are inferred contacts in the subsurface. Dome center is to the right. Jn, Navajo Sandstone; Jk, Kayenta Formation; Jw, Wingate Sandstone; Trc, Chinle Formation; Trm, Moenkopi Formation.
Figure 3.4: Geologic Cross section G-G’ of Base Map 3. Note the Kayenta Formation thickens towards the dome center, and formational depocenters do not align. Thin, solid black lines are formation contacts, red dashes are dip symbols, thin black dashed lines represent form lines projected from strike and dip data, and thin black closely spaced dashed lines are formation contacts projected into the air, thick black dashed lines are inferred contacts in the subsurface. Dome center is to the right. Jw displays a “dog tongue” feature. Jn, Navajo Sandstone; Jk, Kayenta Formation; Jw, Wingate Sandstone; Trc, Chinle Formation; Trm, Moenkopi Formation.
Figure 3.5: Geologic cross section I-I’ of Base Map 3. Note the Kayenta and Wingate Formations thicken towards the dome center, and formational depocenters do not align. Thin, solid black lines are formation contacts, short red lines are dip symbols, thin black dashed lines represent form lines projected from strike and dip data, and thin black closely spaced dashed lines are formation contacts projected into the air, thick black dashed lines are inferred contacts in the subsurface. Dome center is to the right. I-I’ displays shifting depositional axis between Jw and Jk. Jn, Navajo Sandstone; Jk, Kayenta Formation; Jw, Wingate Sandstone; Trc, Chinle Formation; Trm, Moenkopi Formation.
Figure 3.6: Geologic cross section K-K’ of Figure Base Map 3. Note the Kayenta and Wingate Formations thicken towards the dome center, and formational depocenters do not align. Thin, solid black lines are formation contacts, short red lines are dip symbols, thin black dashed lines represent form lines projected from strike and dip data, and thin black closely spaced dashed lines are formation contacts projected into the air, thick black dashed lines are inferred contacts in the subsurface. Dome center is to the right. Jn, Navajo Sandstone; Jk, Kayenta Formation; Jw, Wingate Sandstone; Trc, Chinle Formation.
Figure 3.7: Cross sections A-A', D-D', F-F', G-G', I-I' and K-K' (Figures 3.1-3.6) at the same scale. Figures 3.1-3.6 displayed sections at different scales for better display, this figure (next four pages) allows for one to one comparison between each separate cross section.
Buck Mesa #1 (projected ~550 m from the south)

Top Cutler Group (~538 m drill depth)

Top Hermosa Group (~902 m drill depth)

Top Paradox Formation (~1360 m drill depth)

Base Paradox Formation (1810 m drill depth)

Log data indicates overthickened Jw (~250 m) and thinned Jw (~250 m)
DEM

Jk ~20 m thick

Jk ~450 m thick

Jn

Jk thickening

Dog Tongue

Dome Center

H=V
Depositional sinks between Jw and Jk do not match (shifting synclines?)

Dome Center

W

meters

1750

Bighorn Mesa

Jw

Tc

Tm

H=V

NW

meters

1700

Buck Mesa

Jw

Jc

Jn

Syncline Valley

Jk depositional sink ~150 m

Dome Center

H=V

SE

meters

1700

Jk depositional sink ~250 m

Dome Center

H=V

Thickened Jw

Jk ~250m

Syncline Butte

Jn

DES

DEM

Jw

Jk

Jw

Jk
CHAPTER 4

STRATIGRAPHIC FEATURES

4.1 Kayenta Formation: Outcrop Description, Facies and Facies Associations

Due to the accessibility and cliff forming tendencies of the majority of the stratigraphic units surrounding Upheaval Dome, this project primarily focused on the Kayenta Formation, which forms a series of benches and ledges between the more resistant eolian Wingate and Navajo Sandstones (Stevens, 1994). Previous studies have interpreted the Kayenta Formation as a braided stream deposit dominated by sandstone with less common conglomerates, siltstones and shales (Doelling, 1988). The lithofacies (Table 4.1) reported in this study from the Kayenta Formation around Upheaval Dome are dominated by sandy channelized deposits, and are consistent with previously published descriptions of facies from the Kayenta Formation in southeast Utah (Stephens, 1994; Miall, 1988). The lithofacies recognized in the Kayenta surrounding Upheaval Dome are described in Table 4.1, and are photographically displayed in Figure 4.1.

The lithofacies from Figure 4.1 and Table 4.1 have been further categorized into facies associations and their respective depositional environments (Table 4.2). Each measured section has separated rock units into distinct facies associations in order to test if there are patterns in changing depositional environments around the dome, proximity to the dome center, or vertically through time in individual measured sections (Appendix A).

4.2 Thickness Variations Within the Kayenta

The Kayenta Formation regionally thickens from 40 meters near the Uncompahgre Uplift, to roughly 300 meters down paleo-flow to the southwest in central Arizona (Miall, 1988; Bromley, 1991). Data from boreholes, previously published measured sections and the Shafer Trail section (this study), show that the Kayenta in close proximity to Upheaval Dome, but outside
of this area of structural deformation is consistently 70-80 meters thick (Figure 4.2). Although
the Kayenta seems to have been deposited relatively evenly over areas affected by salt growth,
there are boreholes (Conoco #1 Salt Valley) adjacent to the Salt Valley salt structure (Figure
4.3), that record the entire stratigraphic section from the Honaker Trail Formation to the base
of the Carmel Formation as missing entirely. Other stratigraphic units near salt walls are over-
thickened compared to regional thicknesses in the Paradox Basin (Doelling et al., 1988). Variation
of Kayenta thicknesses adjacent to Salt Valley anticline are shown in Table 4.3 and Figure 4.3
(Redrafted from Doelling et al., 1998).

Clearly, from the data provided in Table 4.3, there can be significant variation in the
Kayenta Formation thickness adjacent to salt walls, tens of kilometers to the northeast of
Upheaval Dome. Similar stratigraphic thickness changes within the Kayenta have been recognized
in this study by measuring stratigraphic sections and compiling structural cross sections around
Upheaval Dome. In order to simplify the discussion of the variations between stratigraphic
sections measured around Upheaval Dome the sections have been grouped into the structural
zone they were measured in: (1) those measured inside the DES, (2) near the axis of the DES,
and (3) outside of the DES, near the DEM. Structural zones are defined by mapped surficial
structural features; for example the axis of the DES is located where there is a mapped reversal
in dip measurements (Base Map 4). (Individual detailed stratigraphic sections with meter-scale
descriptions are presented in Appendix A).

Stratigraphic sections 1, 3, 5, 6, 7, 13, 14, and 15 are sections measured inside of the DES;
the most easily accessible part of the Kayenta. These range in thickness from 69 to 224 meters.
Stratigraphic sections 2, 8, 9, and 10, measured near the axis of the DES and range in thickness
from 7 to 34 meters. Finally, sections 4, 11, and 12, measured near the DEM range in thickness
from 54 to 117 meters. The exact locations of these stratigraphic sections are shown on Base Map 4. These measured sections highlight that there is not only significant thickness variation from proximal to distal areas radiating out from the dome center, but also concentrically within distinct structural zones around the dome. Stratigraphic thickness variations are displayed visually in the fence diagram in Figure 4.4.

Due to the three dimensionality of the field area, a fence diagram was constructed to visually portray thickness variations within the Kayenta Formation around Upheaval Dome (Figure 4.4). In Figure 4.4 an oblique Google Earth image from the south of Upheaval Dome was used as a base map. Each section measured in the field area was then hung from the base Navajo at the section location. Sections 2 and 9 were omitted due to high concentration of other stratigraphic sections from that area. To see the stratigraphic sections and their associated thickness changes, and stratigraphic relationships better, the base Google Earth image was removed from the figure. There is an approximate 4:1 vertical exaggeration between the vertical measured sections and the horizontal measured map length. To effectively portray the stratigraphic thicknesses from the various structural zones around the dome, panels fully circumscribe the sections within the DES where the highest concentrations of measured sections were recorded. Panels then radiate outwards from sections within the DES to sections measured near the DES axis, and finally to the outer part of the dome where sections were measured near the DEM.

Figure 4.4 illustrates the obvious thickness variations in the Kayenta around Upheaval Dome. The stratigraphic sections within the DES have relatively consistent thicknesses on the eastern side of the dome; all are thicker than 150 meters and are commonly over 200 meters thick. It is important to note that these eastern sections are over twice the regional thickness of the
Kayenta in this part of the Paradox Basin. On the western side of the dome on the inside of the DES the two measured sections are 69 and 90 meters thick; closer to the regional thickness of the Kayenta.

The Kayenta Formation near the axis of the DES is only exposed to the northwest and southwest of the dome center where the outcrop has been eroded down to the Kayenta on opposite sides of Upheaval Canyon. Measuring sections to the northwest was impossible due to issues with accessibility. Sections measured from the Kayenta Formation to the southwest of the dome center display significant thinning, down to a surprising minimum of seven meters (Section 2), and a maximum measured thickness of 34 meters. All sections measured from near the axis of the DES were less than half the regional thickness of the Kayenta. Further from the dome center and close to the DEM the stratigraphic sections show significant variability (54 to 117 meters), but not enough sections could be measured in these areas (due to cliffs) for complete 360 degree stratigraphic control around Upheaval Dome.

Geologic cross sections (Figures 3.1-3.7) illustrate stratigraphic thickness variations that simple measured stratigraphic sections cannot record. Each of the six cross sections depicts drastic thickening of the Kayenta from outside of the DEM to inside of the DES, or towards the center of the dome. In addition to the thickness changes in the Kayenta a number of the cross sections display thickness variations in the Wingate Sandstone. The Kayenta in cross section A-A’ (Figure 3.1) thickens from about 100 meters away from the dome center to a projected thickness of 400 meters, or approximately five times the regional thickness of the Kayenta. Cross section D-D’ (Figure 3.2) shows the Kayenta thickening from ~70 meters outside of the DES to a projected stratigraphic thickness of over 200 meters. The older Wingate shows thickness variation in cross section D-D’ (Figure 3.2), thickening towards the dome center from less than 100 meters.
outside of the DES to approximately 250 meters, 2.5 times the regional thickness. The Kayenta Formation in cross section F-F’ (Figure 3.3) displays less radical thickness changes than in the other cross sections from this study; however there still is a 150 meter discrepancy in thickness from opposite limbs of the DES (~100 m thick outside of the DES), ~250 m projected thickness inside of the DES). There appears to be a slight thickening of the Wingate Sandstone towards the dome center in cross section F-F’ (Figure 3.3).

The Kayenta illustrated in cross section G-G’ (Figure 3.4) undergoes the most extreme thickness change recorded from cross sections in this study. The Kayenta near the DEM is only ~20 meters thick before it expands by over an order of magnitude to a projected thickness of ~450 meters towards the center of the dome. 450 meters is over five times the regional stratigraphic thickness of the Kayenta. Cross section I-I’ (Figure 3.5) cuts through Syncline Butte and records a thickness change from ~100 meters outside of the DES to ~250 meters within the DES. The Wingate in I-I’ (Figure 3.5) thickens towards the dome as well, from less than 100 meters outside of the DES to ~300 meters within the DES, or about three times its regional thickness. The thickness of the Kayenta in cross section K-K’ (Figure 3.6) is relatively thin on the outside of the DES at less than 50 meters thick, and becomes substantially thicker on the inside of the DES to a projected thickness of about 150 meters. It is clear from these six cross sections (Figures 3.1-3.6) that the thickness of the Kayenta is extremely variable within the deformed area surrounding Upheaval Dome, but is consistently and radically, thicker on the inside of the DES than the strata found on the outside of the DES (Figure 4.4).

4.3 Stratigraphic Surfaces

Stratal terminations, such as truncation and onlap, are classified by the relationship between the strata and the stratigraphic surface against which they terminate (Catuneanu,
Truncation is defined by strata terminating against an overlying erosional surface (Boggs, Jr., 2006; Catuneanu, 2006). Onlap is defined by the termination of strata against a steeper stratigraphic surface (Boggs, Jr., 2006; Catuneanu, 2006).

### 4.3.1 Angular Discordances within Kayenta Formation

Truncation surfaces in the Kayenta Formation that are larger in scale than what would be expected from fluvial channel erosion are rare across its regional extent; however, there are a number of examples of localized angular discordances present in the Upheaval Dome field area. The most impressive angular discordance (although somewhat difficult to locate) is located to the southwest of the False Kiva overlook, south east of the dome center (Base Map 4). Figure 4.5 is an annotated outcrop photo-mosaic of this stratigraphic feature. The surface truncates a minimum of three meter scale packages of sandstone, and a number of recessive mudstone beds. From a visual estimate there has been at least ten meters erosionally removed from this part of the Kayenta section. The angle between the truncation surface and the beds terminating against its base in the area of greatest dip discordance measured in the field was found to be 19 degrees. The dip discordance decreases to the southwest until the surface becomes conformable with overlying strata. The truncation surface itself is onlapped to the northeast by Late Kayenta beds, and possibly some lower Navajo Sandstone beds, although this is difficult to determine due to cover (See Figure 4.5).

Upon further inspection of this truncation surface and its related beds it was noted there was no evidence of faulting such as fault gauge, or slickenlines (Figure 4.6). Instead, evidence supporting that this surface was stratigraphic in nature was found in a distinctive bed above the truncation surface. The bed was found to be a unique bed of Jurassic aged fresh water clams, most likely from a species of *Unio* (McKnight, 1940). This was the only bed of *Unio* fossils found in the
Upheaval Dome field study area, although similar fossils have been described at Salt Valley within the Kayenta Formation (McKnight, 1940).

4.3.2 Other Angular Discordances (Navajo-Kayenta, Wingate and Chinle)

Angular discordances and truncation surfaces are present within formations other than the Kayenta and at the contacts between formations around Upheaval Dome. Adjacent to the Alcove Spring Trail at the contact between the Kayenta Formation and the Navajo Sandstone is a localized angular discordance (Figure 4.7). This particular contact is important as the surface between the Kayenta Formation and the Navajo Sandstone is conformable, and commonly is gradational as fluvial deposits grade into reworked eolian beds in the Canyonlands and areas near Moab, Utah (Jackson et al., 1998).

The angular discordance displayed in Figure 4.7 is extremely localized, only continuous laterally for tens of meters. Approximately five sub-meter scale sandstone beds separated by thin units of mudstone within the Kayenta Formation are truncated at the base of the Navajo Sandstone at an angle of approximately ten degrees. There is no evidence of faulting along the truncation surface such as slickenlines and fault gouge. Based on visual estimations of bed thicknesses there seems to have been less than 10 meters of total section from the top Kayenta Formation removed by erosion, although it is possible that more section may be missing.

On the southwest side of the dome near the axis of the DEM there are more angular discordances between the Kayenta Formation and Navajo Sandstone (Figure 4.8). This photo-panorama displays no less than four meter-scale sandstone beds terminating at the base of the Navajo Sandstone. Although Figure 4.8 displays structurally complex deformation throughout the Glen Canyon Group (Wingate SS, Kayenta Formation, Navajo SS), the truncations at the base of the Navajo Sandstone appear to be stratigraphic, as there is no visual indication of brittle
deformation.

Similar localized angular discordances and truncation surfaces are present at the base of the Wingate Sandstone on the northeast side of Syncline Butte (Figure 4.9), and west of Holeman Spring (Figure 4.8). The contact between the Chinle Formation and the Wingate Sandstone has been recognized from previous work as a regional unconformity (J-0, from 210 Ma to 206 Ma) (Blakey et al., 1987; Jackson et al., 1998), although angular discordances are rare (Banbury, 2006; Molenaar, 1981). Therefore, even though the surface is a well known disconformity, it is important to note angular discordances between the two formations.

In Figure 4.8 (Base Map 4) multiple beds of varying composition of the Chinle Formation are truncated at the base of the Wingate Sandstone. These truncations vary from very low angle (<5 degrees) up to approximately 15 degrees. The overlying Wingate Sandstone and Kayenta Formation are extensionally faulted in this area, but the faults are not interpreted to have played a part in the formation of the stratal discordance, although a close inspection of the surface for evidence of faulting was not completed. Figure 4.9 displays a similar localized unconformity between the Chinle Formation and the Wingate Sandstone. These are two low angle truncations on opposite limbs of a broad synformal fold in the Chinle Formation at the base of the Wingate Sandstone cliff. Close inspection of the terminations in Figure 4.9 was impossible as they are located at the base of a steep cliff.

Additionally, intraformational angular discordances have been noted from the Chinle Formation within the central depression of the Upheaval Dome structure. These angular discordances were found to have differences of up to 90 degrees (Figure 4.10).

4.3.3 Onlaps

In certain locations stratigraphic units from around Upheaval Dome including the
Wingate Sandstone, Kayenta Formation, and the Navajo Sandstone display onlapping stratal geometries. Figure 4.11 is a textbook example of onlap just above the base of the Wingate Sandstone (location Base Map 4). Figure 4.11A is a photo of the location of this feature within the dome center. These particular onlapping geometries are found on the perimeter of the depression in the dome center, at the base of the Wingate Sandstone where it folds into a symmetric, outward-plunging antiform. The folded strata are isopachous. Figure 4.11B shows the left hand, or western portion of the antiformal fold. Within the frame of 4.11B there are four sandstone beds that thin dramatically towards the fold and terminate on the upper surface of the folded strata. There are two beds that thin from about a meter to centimeters thick within a few lateral meters of the fold. Figure 4.11C shows the opposite, or eastern limb of the fold. This figure displays two beds thinning towards the other limb of the antiform thinning and onlapping onto the folded layers. It is notable that the beds on either side of the fold display different geometries and lithologies.

The beds that thin and onlap in Figure 4.11B and C are also distinctive in that they display lithologic characteristics and bedding styles that are rarely displayed by the Wingate Sandstone. Some of the beds have a tabular pock marked texture, which is interpreted to have been caused by preferentially eroded rip-up clasts. Other beds display cm-scale bedding laminations. Certain beds in Figure 4.11 are entirely muddy in composition. These lithologic and bedding characteristics from this locality are unlike what is exhibited throughout the rest of the homogeneous eolian Wingate Sandstone.

As mentioned in a previous section there are onlaps within the Kayenta Formation and Navajo Sandstone located south west of the False Kiva overlook (Figure 4.4, Figure 4.12). There are approximately five sandstone beds that onlap the top of a truncation surface with an angular
discordance beneath it. The onlaps are defined by youngest Kayenta and the base of the Navajo Sandstone. There appears to be minor thinning in some of the beds onlapping the surface (Figure 4.12).

Strata at the base of the Navajo Sandstone in Figure 4.8 onlap a high in the Kayenta Formation. The onlapping strata in Figure 4.8 are not overwhelmingly thick, but are geologically significant.
Base Map 4: Map displaying section locations and photo locations referred to in Chapter 4 (Field mapping completed by author with data from Jackson et al., 1998; Kriens et al., 1999).
Table 4.1: Table listing descriptive characteristics and interpretations of seven lithofacies recognized in the Kayenta Formation surrounding Upheaval Dome. Colors in facies column correspond with the colors used in described stratigraphic sections (Appendix A). Photographic examples are provided in Figure 4.1.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Facies Name</th>
<th>Grain size</th>
<th>Description</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Structureless sandstone</td>
<td>Very fine to medium grained sand</td>
<td>Sandstone beds displaying no sedimentary structures. Bed thickness varies from centimeter to meter scale. Grain size, sorting, and roundness vary from bed to bed.</td>
<td>N/A</td>
</tr>
<tr>
<td>B</td>
<td>Planar laminated channelized sandstone</td>
<td>Very fine to medium grained sand (predominantly lower fine)</td>
<td>Sandstone predominantly laminated by sub-cm to cm scale laminations. Laminations most commonly alternate between red-purple to more buff colored. Rarely displays ripples. Grains are most commonly moderately sorted, sub-rounded to sub-angular.</td>
<td>Braided stream deposit, lower to upper flow regime; low to high energy</td>
</tr>
<tr>
<td>C</td>
<td>Cross-stratified channelized sandstone</td>
<td>Very fine to medium grained sand (predominantly lower fine)</td>
<td>Channel form sandstones displaying trough and tabular cross-stratification. Bases are commonly erosive.</td>
<td>Braided stream deposit, lower flow regime, tractive deposition, high energy</td>
</tr>
<tr>
<td>D</td>
<td>Channelized conglomerate</td>
<td>Granule to cobble sized clasts, matrix grain size varies</td>
<td>Conglomerates immediately above the erosive base of channelized beds. Conglomerate clasts are homogenous in some cases and polymictic in others. Most commonly found to be matrix supported but in some cases are clast supported.</td>
<td>Braided stream, upper flow regime, tractive deposition; lower flow regime with high sedimentation rates.</td>
</tr>
<tr>
<td>E</td>
<td>Red to purple mudstone</td>
<td>Clay to silt</td>
<td>Fissile to non-distinct bedding, commonly are exposed as recesses.</td>
<td>Overbank flood deposits</td>
</tr>
<tr>
<td>F</td>
<td>Multi-colored mottled mudstone</td>
<td>Clay to silt</td>
<td>Non-distinct bedding. Commonly deformed by the presence of paleo-roots. Distinctive coloration due to reduction and oxidation zones.</td>
<td>Paleosol</td>
</tr>
<tr>
<td>G</td>
<td>Trough to tabular cross-stratified to planar laminated non-channelized sandstone</td>
<td>Very fine to fine grained sand</td>
<td>Non-channelized, cross-stratified sandstones. Grains are fine to very fine grained are well sorted, well rounded and frosted.</td>
<td>Eolian, transport and deposition due to wind</td>
</tr>
<tr>
<td>H</td>
<td>Alternating clastic and carbonate laminations</td>
<td>Very fine to medium grained sand (predominantly lower fine)</td>
<td>Alternating mm-scale siliciclastic and carbonate laminations with polygonal fractures</td>
<td>Algal/bacterial mats</td>
</tr>
<tr>
<td>A: Structureless sandstone</td>
<td>B: Planar laminated channelized SS</td>
<td>C: Cross stratified channelized SS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------------</td>
<td>-----------------------------------</td>
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<td></td>
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</tr>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>D: Channelized conglomerate</strong></td>
<td><strong>E: Red to purple to mudstone</strong></td>
<td><strong>F: Multicolored mottled mudstone</strong></td>
<td></td>
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</tr>
<tr>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>G: Cross stratified non-channelized SS</strong></td>
<td><strong>H: Alternating clastic and carbonate lams</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.1: Photographic examples of lithofacies described in Table 4.1.
Table 4.2: Facies associations and descriptions based on lithofacies listed in Table 4.1. Colors of facies associations match those displayed in the detailed stratigraphic sections (Appendix A).

<table>
<thead>
<tr>
<th>Facies Association</th>
<th>Association description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Braided Channels</td>
<td>Includes facies A, B, C and D. Depositional processes are dominated by traction transport. Grain sizes range from very fine sand to cobble clasts. Geometry of beds are most commonly channel form to lenticular. Most common sedimentary structures are planar laminations and cross-stratification</td>
</tr>
<tr>
<td>2. Overbank/flood deposits</td>
<td>Includes facies E. Deposition of sediments is due primarily to suspension settling. Grain sizes vary from clay to silt. The geometry of these beds is most commonly tabular to sheet-like. These deposits are commonly fissile, and lack any noticeable sedimentary structures.</td>
</tr>
<tr>
<td>3. Paleosol</td>
<td>Includes facies F. Lacks sedimentary structures, often displays oxidation and reduction zones. Many paleosols display paleo-rootlets, or desiccation cracks.</td>
</tr>
<tr>
<td>4. Eolian</td>
<td>Includes facies A, G. Deposition is dominated by eolian processes. Grain sizes vary from silt to fine sand. Sedimentary structures are dominated by trough cross stratification and planar laminations.</td>
</tr>
<tr>
<td>5. Algal Mats/Laminations</td>
<td>Includes facies H. Deposition of this facies occurs near the capillary fringe of the water table. Surface damp during wetter times forming algal and bacterial mats, during dry times likely influenced by evaporation concentrating salts in the water forming early evaporite cements.</td>
</tr>
</tbody>
</table>
Figure 4.2: (A) Graph/stratigraphic profile of Kayenta thickness running SW to NE with respect to Upheaval Dome. Red bar represents measured thicknesses at Upheaval Dome. This chart displays the constant thickness of the Kayenta in the Paradox Basin away from Upheaval Dome. Data comes from sections measured in this study, previously published data, or subsurface data from publicly available well bores. (B) Gamma ray curve is a type log for picking the base and top of the Kayenta Formation with subsurface data. (C) Location map of measured sections, previously published data and well bores. Upheaval is designated by a star (UTM coordinates) (next page) (Satellite imagery from GoogleEarth).
Table 4.3: Table showing the thickness variations of the Kayenta Formation from well bores in close proximity to the Salt Valley salt structure. Note the Conoco #1 Salt Valley well where the Kayenta is completely absent, and Union #1 P-2 State well where the Kayenta is 170 meters thick, clearly displaying the variability of Kayenta thickness adjacent to salt structures. Locations are given in Township and Range and UTM coordinates (redrafted from Doelling et al., 1988).

<table>
<thead>
<tr>
<th>Location</th>
<th>Name of Borehole</th>
<th>Kayenta Thickness (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NENW 22-22S-19E S 603295 E 4300455</td>
<td>Conoco #1 Salt Valley</td>
<td>0</td>
</tr>
<tr>
<td>NESE 36-23S-19E S 607683 E 4291379</td>
<td>Equity #1 State</td>
<td>50</td>
</tr>
<tr>
<td>SWSW 6-23S-20E S 607736 E 4299000</td>
<td>Conoco #1 Hall</td>
<td>79</td>
</tr>
<tr>
<td>SESE 2-23S-21E S 624555 E 4299305</td>
<td>Union #1 P-2 State</td>
<td>170</td>
</tr>
<tr>
<td>SWSE 5-23S-21E S 619551 E 4299122</td>
<td>Union #1 Devils Garden</td>
<td>57</td>
</tr>
<tr>
<td>SWNE 12-24S-20E S 616531 E t 4288850</td>
<td>Shell #1 Legger Courthouse</td>
<td>70</td>
</tr>
<tr>
<td>SWSE 36-24S-20E S 616557 E 4281492</td>
<td>Union #1 State</td>
<td>132</td>
</tr>
</tbody>
</table>
Figure 4.3: Map of well locations from Table 4.3 (from Doelling et al. 1988) around the Salt Valley salt structure. Salt Valley salt anticline is displayed in a transparent pale blue. Kayenta thickness for each well is listed after well name in parentheses. Map clearly displays thickness variation of the Kayenta Formation in close proximity to salt structures (Satellite imagery from GoogleEarth).
Figure 4.4: Fence diagram displaying stratigraphic thickness of the Kayenta Formation in the Upheaval Dome field area using measured sections from this study hung from the base of the Navajo Sandstone. This diagram is viewed obliquely from the south, and the white oval represents the center of the Upheaval Dome structure. The panels closest to the center, measured from the inside of the DEM, circumscribe the structure. Other panels radiate outwards towards the axis of the DES and the DEM to show thickness variation from proximal parts of the dome to distal parts of the dome. Note the thickest measured section here is over 220 meters thick (Section 14) and the thinnest is less than 30 meters thick (Section 8). All measured sections completed in the Upheaval Dome field area are displayed in this figure except for Sections 2 and 9.
Figure 4.5: Panoramic photo of angular discordances, looking southwest from the False Kiva Overlook. A) Photo-pan without interpretation, B) photo-pan overlain by geologic interpretation, C) geologic interpretation alone. This exposure displays a stratigraphic surface that is both a localized angular discordance and an onlap surface. Thick black lines are formation contacts, thin black lines are stratigraphic form lines, bold red line is surface of angular discordance, red line becomes dotted where it becomes conformable with underlying units. Jn, Navajo Sandstone; Jk, Kayenta Formation; Jw, Wingate Formation.
Figure 4.6: Close up of Figure 4.5. A) Outcrop location of angular discordance and *Unio* bed, B) close up of angular discordance with onlapping *Unio* bed above it, white lines outline bedding contacts (pencil for scale) C) close up of distinctive concave *Unio* shell fossils (pencil for scale).
Figure 4.7: Photo interpretation of angular discordance between the Kayenta Formation and Navajo Sandstone exposed near the top of the Alcove Spring Trail, looking approximately to the south (Base Map 4). White lines outline bedding terminations at the red truncation surface. Boulder labelled for scale. Jn, Navajo Sandstone; Jk, Kayenta Formation.
Figure 4.8: Photo-panorama of outcrop near the DEM southwest of the dome center. This figure displays angular discordances at the base of the Wingate Sandstone, the base of the Kayenta Formation, and another possible angular discordance within the Wingate Sandstone. The lowest Navajo Sandstone beds onlap the top Kayenta Formation. Each of these stratigraphic surfaces suggest long term deformation of units through the Jurassic. Jn, Navajo Sandstone; Jk, Kayenta Formation; Jw, Wingate Sandstone; Trc, Chinle Formation. (For structural interpretation of this outcrop see Figure 5.6).
Figure 4.9: Outcrop photo and interpretation of angular discordance between the Chinle Formation and the Wingate Sandstone (J-0 Unconformity (Pipiringos and O'Sullivan, 1978)). There are multiple beds of variable rocks within the Chinle truncating at the base of the Wingate. Bold lines are formation contacts, thin white lines are stratigraphic form lines highlighting where the strata truncate against the contact. Jw, Wingate Sandstone; Trc, Chinle Formation.
Near Flat lying stratigraphy

Figure 4.10: Photo interpretation of 90 degree angular discordance in the Chinle Formation within the topographic depression. Near vertical beds of sandstone are truncated at the base of a near flat lying sandstone. This surface is interpreted to be stratigraphic.
Figure 4.11: Outward-plunging antiformal fold at the base of the Wingate Sandstone. A) Photo showing general location of fold B) western limb of antiform, with multiple meter-scale beds that onlap the structure C) multiple meter-scale beds thin and onlap the eastern limb of the fold.
Figure 4.12: Close up photo of from Figure 4.4 illustrating the shift of the surface from a truncation surface to an onlap surface within the Kayenta Formation and earliest Navajo Sandstone. Red line represents the stratigraphic surface that is both an angular unconformity and an onlap surface. This feature is interpreted to have evolved over long periods of geologic time. The distinctive *Unio* bed has an arrow highlighting its location in the section just above the truncation surface. Jn, Navajo Sandstone; Jk, Kayenta Formation.
CHAPTER 5

STRUCTURAL FEATURES

The structural characteristics and features within the study area are important for understanding the geologic history of Upheaval Dome. The structural geology of Upheaval Dome is complex, but analyzing the different structural forms and attitudes of faults and folds from formations exposed at the surface helps to work towards a more comprehensive interpretation for the origin of Upheaval Dome. For this study, faulting in the Wingate Sandstone and the Kayenta Formation is described and discussed separately. Folds are discussed on a sub-regional scale, and will then focus on the dog-tongue features located at the base of the Wingate Sandstone on the perimeter of the central depression of the dome.

A geologic map (Base Map 5), six cross sections (A-A’, D-D’, F-F’, G-G’, I-I’, and K-K’) (Figures 3.1-3.7), and photo-interpretations were compiled in order to better portray the important structural characteristics. The geologic map covers the entire extent of structural deformation associated with Upheaval Dome, an area of approximately 36 square kilometers. Each cross section was compiled in a radiating fashion around the dome perimeter to include the Navajo Sandstone, the Kayenta Formation, the Wingate Sandstone, the Chinle Formation and the Moenkopi Formation. Cross sections extend from the inside of the DES to the outside of the DEM (Base Map 5, Figures 3.1-3.7).

5.1 Faults

The following sections review brittle deformation of exposed units at Upheaval Dome. These sections include normal faults in the Wingate Sandstone and Kayenta Formation, and thrust faults exposed in the Kayenta.
5.1.1 Wingate Faults

The Wingate Sandstone is a massive, homogenous, 100 meter thick eolian sandstone with very few well defined bedding planes, making it difficult to discern faults in this formation in a field setting. The few Wingate faults recognized and described in this study are extensional, and are most commonly listric in nature (Figures 5.1, 5.3, 5.4). The faults presented in Figures 5.3 and 5.4 both propagate into the overlying, younger Kayenta Formation, and will be described in more detail in the Kayenta fault section. The fault detailed in Figure 5.1, on the other hand, seems to have only deformed the Wingate Sandstone. It is a large scale listric fault striking approximately north to south, with the down-thrown side on the east side of the fault, obliquely towards the dome center. The footwall is relatively undeformed and the strata in the hanging wall block is moderately folded.

Figure 5.2 (location Base Map 5) displays an entirely different style of normal fault in the Wingate Sandstone. It offsets the base of the Wingate Sandstone and top Chinle Formation, displays a near vertical dip surface, and is a planar fault surface rather listric. The fault strikes approximately northwest to southeast and dips to the southwest. Although the fault surface is difficult to trace upward into the homogeneous Wingate Sandstone, there are obvious cutoffs present in both the footwall block of the Chinle Formation as well as in the hanging wall of the Wingate Sandstone. An upturned fold present in the hanging wall of the Wingate Sandstone adjacent to the surface is a kinematic indicator of the normal movement along the surface (Hamblin, 1965). The hanging wall block of the fault is at least 10 meters thicker than the footwall block. The fault heals before Kayenta time, but had an affect on the deposition of sediments during the Early Kayenta as there are Kayenta beds onlapping a topographic high above the faulted surface at the top of the Wingate. Locations of these features are illustrated in Base Map 5.
5.1.2 Kayenta Normal Faults

The Kayenta Formation displays both extensional and contractional fault features. Extensional features, such as normal faults, are located outside of the DES, compressional features on the other hand, such as thrust faults and compressional folds, are found inside of the DES in the outward dipping strata. This section will focus on the extensional features observed at Upheaval Dome in the Kayenta Formation.

Figures 5.3 and 5.4 display a fault that is interpreted as the same surface exposed on opposite sides of Syncline Butte (Base Map 5). Figure 5.3 is shot from Buck Mesa looking east and Figure 5.4 was shot from a Kayenta tongue north of Syncline Butte. Both show a fault surface striking approximately northeast-southwest and dipping to the northwest, obliquely away from the dome center. The fault cuts from near the top of the Kayenta Formation, down through the base Kayenta and Wingate Sandstone where it soles out listrically at the Chinle-Wingate contact. There is an onlapping stratal relationship present in the upper part of the Kayenta on the northeast side of Syncline Butte (Figure 5.4), but is either covered or absent on the southwestern side of Syncline Butte. The Wingate Sandstone strata adjacent to the fault surface is somewhat thinner than the regional thickness of 100 meters expected for the Wingate Sandstone, but on either side of the fault appear to be relatively equal in stratigraphic thickness and could be restored. However, the younger Kayenta Formation strata are significantly thicker in the hanging wall block (>10 meters) of the fault than the strata in the footwall block. The fault heals within the formation late in Kayenta time, and does not deform the overlying Navajo Sandstone.

Figure 5.5 displays a fault surface looking northwest from the road on the way into Upheaval Dome. There are two distinct fault surfaces in this figure. The first cuts the entire Kayenta Formation before soling out listrically at the top of the Wingate Sandstone. The
second surface is stratigraphically above the fault mentioned above, is contained entirely in the Kayenta Formation and is listric in nature similar to the fault immediately below it. The Kayenta Formation is less than 10 meters thick in the footwall of the fault adjacent to where the Navajo outcrop noses out. In the hanging wall the Kayenta is approximately four times that thickness. It is important to mention that this fault is not exposed directly in strike view, and there is likely movement in and out of the plane of view. This movement is interpreted to have been going into the plane of view in the hanging-wall and out of the plane of view in the footwall. This inferred slip would make the fault dip obliquely towards the center of Upheaval Dome.

Figure 5.6 displays a number of faults within the Kayenta Formation, including some that offset the Kayenta and Wingate Sandstone. On the far left (west end) of the photo there are two small scale listric normal faults offsetting the Kayenta and the Wingate. Further to the right (east) there are two similar listric faults dipping opposite of each other leaving a horst of resistant Wingate Sandstone. Within the Kayenta Formation there are a number of normal faults with their hanging-wall block on the west side of their particular fault surfaces. All of the fault surfaces in this figure appear to strike obliquely towards the center of Upheaval Dome, rather than dipping towards its center; this however may simply be a byproduct of the outcrop view. Locations of these features are presented in Base Map 5.

5.1.3 Thrust Faults in the Kayenta Formation

Although this is by no means a comprehensive study of the compressional fault features from Upheaval Dome, there are a number of structural features worthy of description and interpretation. The first to be described in this study is a duplex fault zone within the crater complex on the face of the steep cliff on the northwest side of the dome (Figure 5.7). The faulting in this area affects both the Kayenta Formation and Wingate Sandstone, although most of the
smaller scale faulting took place in the Kayenta. There are a number of horse-blocks contained within a floor thrust and a partially eroded roof thrust. The main detachment surface of the duplex is the Kayenta-Wingate contact. The largest fault in this location penetrates into the Wingate through the main detachment of the duplex feature. This large fault splays into two separate surfaces as it propagates into the overlying Kayenta formation. Another smaller fault to the east penetrates into the Wingate, but not as far as the previously described fault surface. Data gathered by Jackson et al. (1998) indicates that the faults within the duplex verge to the southeast towards the dome center.

Figure 5.8 displays a separate thrust fault located east-northeast of the dome center, in the Kayenta Formation. This thrust fault is defined by a series of ramps and flats, unlike the duplex zone in Figure 5.7. This fault has an un-deformed footwall and a deformed hanging-wall forming a series of folds. Where the fault dies out it forms a leading anticline and syncline. This fault verges approximately to the east. Locations of these features are illustrated in Base Map 5.

5.2 Folds

Around Upheaval Dome the scale of folding varies from small scale folding within singular units (antiform from Figure 4.9); to macroscopic, or larger scale of folding forming the syncline and monocline surrounding Upheaval Dome. This study will focus on the large scale folding in the syncline and monocline as well as the doubly curved synformal radial lobes (dog tongues) found at the base of the Wingate Sandstone surrounding the perimeter of the topographic depression.

5.2.1 Large Scale Folds

This section refers back to the cross sections from the methods section of this paper. In general, the axial traces of the synclinal folds in Figures 3.1-3.7 is located consistently in the
same area through the formations drafted from surface data. The same cannot be said for the
depositional axial traces (part of the unit measured perpendicular to bedding with the thickest
stratigraphic thickness) of various stratigraphic units.

For each cross section drafted (Figures 3.1-3.7) for this study the depositional axial trace
of the Kayenta Formation is not only offset from the present day structural synclinal axial trace,
commonly by hundreds of meters, but is consistently offset towards the dome center. Where
reliable stratigraphic and structural data were collected for the Wingate Sandstone a similar
phenomenon can be observed. The depositional axial trace of the Wingate Sandstone does not
always align with either the regional structural synclinal axial trace, or the depositional axial
trace of the Kayenta Formation; but is offset even further towards the center of the dome than the
depositional axial trace of the Kayenta. The offset depositional axial trace in the Wingate is only
truly apparent in cross sections D-D’, F-F’, and I-I’ (Figures 3.2, 3.3, 3.5), with some minor offset
in A-A’ (Base Map 5).

5.2.2 Dog Tongues and Associated Features

Surrounding the perimeter of the inner depression of Upheaval Dome, at the base of
the Wingate Sandstone there are ten doubly curved synformal radial lobes, or dog tongues
(previous discussed in Chapter 2). These are curious structural features that geologists have
attempted to explain by a number of different processes (Jackson et al., 1998; Kriens et al., 1999;
Huntoon, 2000; Scherler et al., 2006a; Scherler et al., 2006b). In order to try to better understand
these features two dog tongues and their adjacent flanks located on the south side of the inner
dome were investigated (Figure 5.9), and this investigation identified a number of key geologic
features. The older Chinle Formation provided little data or geologic information in this location
as much of it is covered in its own, or by debris from the Wingate Sandstone debris. It was noted
that the Chinle terminated disconformably against the base of the Wingate flap (See cross section G, Figure 3.5). Adjacent to the main flaps of the dog tongues there are features that have yet to be described in previous literature. These features are documented in Figure 5.9 B and C.

The photo-pan in Figure 5.9B was taken at the base of the Wingate Sandstone cliff on the south side of the Upheaval Dome central depression, and is situated to the east of Figure 5.9C, and to the west of Dog Tongue #1 (Figure 5.9A). In this photo-pan there are two slightly tilted, meter scale, sub-rectangular shaped, blocky-boulders of dark red, fine grained sandstone to mudstone. Due to their lithology and appearance these boulders are interpreted to be sourced out of the Chinle Formation. In between these two tilted rocks, and possibly surrounding them, is a seam of fine grained orange-tan Wingate Sandstone. This strange phenomenon of angular Chinle blocks tilted into the Wingate Sandstone has not been documented elsewhere in the Upheaval Dome field area.

Figure 5.9C is a photo from the eastern flank of Dog Tongue #2. This photo illustrates that there is a near vertical thrust fault that offsets the base of the Wingate Sandstone at the upper limit of the dog tongue. The top of the Chinle underneath the base of the Wingate Sandstone fold displays a greenish-gray, orthogonal pattern in between the dominant deep red color of the Chinle. The pattern is not likely due to sedimentological features such as desiccation cracks, as their lines form sub-right angles whereas mud-cracks most commonly form obtuse angles and a crude polygonal pattern (Boggs Jr., 2006). The orthogonal pattern is interpreted to have been caused by the stress field felt in this particular area during deformation. The color could have been caused by diagenesis or alteration due to the presence of evaporite-rich fluids during folding and faulting.
Base Map 5: Map displaying photo and figure locations from Chapter 5 (Field mapping completed by author with data from Jackson et al., 1998; Kriens et al., 1999).
Figure 5.1: Photo interpretation of listric normal fault in the Wingate Sandstone from Syncline Loop Trail southeast of the dome center. Fault strikes approximately north-south and dips off to the east. Dome center is back and to the left of this fault in this image.
Figure 5.2: Photo and interpretation of Wingate Sandstone normal fault north of Alcove Spring Trail (southeast of dome center), looking ~north (see Base Map 5 for location). Photo of outcrop taken from an oblique angle.

A) Photo without interpretation  
B) Photo with structural and stratigraphic interpretation  
C) Interpretation without photo.

This figure displays deformation through exposed Triassic and Jurassic units. The fault to focus on in this figure crosses from the Chinle into the Wingate Sandstone. It is apparent in this figure that the hanging wall block of this fault is tens of meters thicker than the footwall block. This thickness discrepancy is diagnostic of faults propagating over time with continued sedimentation. Further evidence of long-term deformation is present at the top of the Wingate where the Kayenta onlaps a localized high above the previously mentioned fault surface.
Figure 5.3: Photo and interpretation of structural and stratigraphic features of the southwest side of Syncline Butte. (1) Pre-fault deposited Wingate (2) Lower Kayenta deposited pre-faulting (3) Initiation of faulting and main growth package (4) Upper Kayenta where faulting ceases. Darker red in the Kayenta Formation (3) highlights the main growth package. A) Photo-panorama without interpretation B) photo-panorama overlain by structural and stratigraphic interpretation C) interpretation without photo-panorama. Jn, Navajo Sandstone; Jk, Kayenta Formation; Jw, Wingate Sandstone; Trc, Chinle Formation.
Figure 5.4: Photo and interpretation of structural and stratigraphic features of Syncline Butte. Figure displays same fault surface as seen in Figure 5.5 from opposite side of Syncline Butte. Dark red within Kayenta Formation highlights the main growth package of the normal fault. Unit 3 is onlapped by Unit 4 further suggesting long-term processes. A) Photo-panorama without interpretation B) photo-panorama with photo overlain by structural and stratigraphic interpretations C) interpretation without photo-panorama. Jn, Navajo Sandstone; Jk, Kayenta Formation; Jw, Wingate Sandstone; Trc, Chinle Formation.
Figure 5.5: Photo-panorama and interpretation of structural and stratigraphic features of a normal fault outside of the DES, approximately south of the dome center. Red package highlights the main growth package associated with this fault where normal faulting was most active in conjunction with deposition. A) Photo-panorama without interpretation B) Photo-panorama overlain by structural and stratigraphic interpretations C) interpretation without photo. Jn, Navajo Sandstone; Jk, Kayenta Formation; Jw, Wingate Sandstone; Trc, Chinle Formation.
Figure 5.6: Photo-panorama and interpretation of structural and stratigraphic features west of Holeman Spring outside of the DES. Figure displays angular discordance between the Chile and Wingate, within the Wingate, and between the Kayenta and the Navajo. A) Photo-panorama without interpretation B) Photo-pan overlain by interpretation C) Interpretation without photo background. Jn, Navajo Sandstone; Jk, Kayenta Formation; Jw, Wingate Sandstone; Trc, Chinle Formation.
Figure 5.7: Photo-panorama and structural interpretation of compressional fault feature on the northwestern side of the cliff surrounding the inside of the dome depression. Feature is a duplex fault and verges to the southeast. The fault blocks steepen in the direction of vergence. The fault transitions from compressional to extensional to the west. A) Photo-panorama overlain by structural and stratigraphic form lines B) geologic interpretation with out photo-panorama. Jn, Navajo Sandstone; Jk, Kayenta Formation; Jw, Wingate Sandstone.
Figure 5.8: Photo and annotated interpretation of a low angle thrust fault east of the dome center inside of the DES. This fault displays a ramp flat geometry and verges to the east. The hanging wall is deformed into a series of folds, and the footwall is largely undeformed. A) Photo with structural and stratigraphic form line interpretations B) interpretation of fault without photo.
Figure 5.9: Dog tongues and associated features at the base of the Wingate Sandstone cliff surrounding the Upheaval Dome impression. A) Photo of dog tongues, boxes marked B and C refer to the other photos in this figure on south side of topographic depression B) Tilted Chinle blocks encased in the Wingate Sandstone C) steep thrust offsetting the Wingate Sandstone and the Chinle Formation where the flap of dog tongue #2 intersects with the vertical cliff face.
CHAPTER 6
PETROGRAPHIC AND LITHOLOGIC FEATURES

6.1 Thin Sections

Multiple samples of Kayenta and older stratigraphic units were collected for petrographic analysis. These samples were collected and analyzed in order to verify whether or not there was petrographic evidence for either a meteor impact (shocked grains) or salt diapirism at Upheaval Dome. Sandstones were collected to test whether there was significant difference in samples from close to the dome and samples further away from the structural influence of the dome. Pebble conglomerates were collected from the Kayenta Formation and older units to test whether they contained anomalous clasts such as fossils, evaporite minerals, carbonates or shales, which may have been sourced from the older and unexposed Paradox or Honaker Trail Formations (Lawton and Buck, 2006). Conglomerates were collected at Upheaval Dome, and ~10 km away from the structural deformation associated with Upheaval Dome, in order to determine if they are distinctive from conglomerates around the basin.

6.1.1 Sandstones

Sandstone samples were collected from two different channels in the field from the Kayenta Formation. Each channel was sampled from the base and from the top. One channel was located within the confines of structurally deformed area of Upheaval Dome (Sample 22.1), and the other channel form was located on the Shafer Trail ~10 km to the west of Upheaval Dome (Sample 22.6, location Figure 1.1). The other two sandstones were collected because of odd features displayed by the outcrop that were not observed in other rocks around Upheaval Dome.

Sample 22.1 Base (Upheaval Dome Sample)

Sample 22.1 base is a subarkose, cemented predominantly by quartz, with small
percentages of both carbonate and clay in the matrix. The sand grains are predominantly fine-grained, moderately to well sorted, and subrounded. Many grains have a minor iron coating (Figure 6.2). See pie charts for simplified point count data (Figure 6.1).

*Sample 22.1 Top (Upheaval Dome Sample)*

Sample 22.1 top is a subarkose with minor percentages of carbonate grains and pore-filling clays. A majority of the quartz and potassium feldspar grains are fine grained, sub-angular to sub-rounded, and moderately to well sorted (Figure 6.3). Point count data located in the appendix. See pie charts for simplified point count data (Figure 6.1).

*Sample 22.6 Base (Shafer Trail)*

Sample 22.6 base is a subarkose with minor percentages of carbonate grains, chalcedony, muscovite, and opaque minerals. Pore spaces are filled with a combination of clay minerals and quartz overgrowth cement. Grains are predominantly fine grained, sub-rounded to sub-angular, and moderately to well sorted (6.4). See pie charts for simplified point count data (Figure 6.1).

*Sample 22.6 Top (Shafer Trail)*

Sample 22.6 top is a subarkose with minor percentages of chalcedony, carbonate grains, mica, chert, and opaques. The sample is cemented by quartz overgrowths. The grains are predominantly fine grained, sub-rounded, and moderately sorted (Figure 6.5). See pie charts for simplified point count data (Figure 6.1).

*Sample 13.7 (Syncline Butte)*

Sample 13.7 is a gravelly sandstone. A large majority of pebble clasts within this sample are calcareous, and range in size from 2 mm up to 5 mm. Many of these carbonate clasts have undergone pressure dissolution leaving a reddish, iron-rich insoluble residue. The sand grains are 95% quartz, with 5% potassium feldspar and other minerals, and are cemented by carbonate.
Sand grain sizes range from fine to medium and are rounded to sub-rounded (Figure 6.6).

*Sample 15.4 (Syncline Butte)*

Sample 15.4 is a fine grained subarkose. The grains are approximately 90% quartz grains, 8% potassium feldspar and 2% other grains such as muscovite and opaques. The cement of this sandstone is dominated by granular carbonate cements. Within this sample there are thin laminae of fine grained material, probably mud fragments, or insoluble residue left by pressure dissolution of carbonates.

The most interesting part of this sample is a fossil shell fragments displayed in the thin section. Figure 6.7 shows a broken off tip of a bivalve which was recrystallized and pressure dissolved.

**6.1.2 Conglomerates**

*Sample 5.7 (Kayenta, within Upheaval Dome)*

Sample 5.7 is a clast supported, carbonate dominated, pebble conglomerate. Clast sizes range from less than one millimeter up to 1.5 centimeters, and are rounded to sub-rounded. Roughly 90% of the pebble clasts in this thin section are either entirely calcareous, or are calcareous containing at most 50% quartz and potassium feldspar grains cemented interspersed throughout the clasts. A large portion of the carbonate crystals within the pebble clasts display a rhombic morphology, but in a small number of other grains the carbonate is micritic. Many of the grain boundaries are pressure dissolved, and are easily recognizable by their iron stained boundaries. A majority of the matrix is defined by recrystallized, sparry carbonate cement (Figure 6.8).

*Sample 13.5 (Kayenta, within Upheaval Dome)*

Sample 13.5 is a matrix supported, carbonate- pebble conglomerate with grain sizes up to
1.3 cm. The clasts in this sample range from sub-angular to sub-rounded. Some of the larger clasts of carbonate display rinds of finer crystal sizes with cores of rhombic coarse grained crystals. A small percentage of the carbonate grains appear to be iron rich, as they exhibit a distinctive red-brown stain. The matrix in this sample is a mixture of carbonate cement and medium to fine grained quartz sand with subordinate potassium feldspar grains. The quartz sand in the matrix is dominantly rounded with some sub-rounded grains (Figure 6.9).

*Sample 20.2 (Kayenta, within Upheaval Dome)*

Sample 20.2 is a clast supported, carbonate-pebble conglomerate. The pebble clasts range in size from 2 mm to greater than 2.3 cm (clast larger than thin section). A large majority of the pebbles in this thin section are entirely calcareous. The clast that is over 2.3 cm across is over 80% carbonate, but also contains ~15% quartz and 5% potassium feldspar grains with minor amounts of chert and muscovite. A small number of clasts are made up entirely of clay.

The matrix of this conglomerate is predominantly fine to medium, sub-rounded quartz sand with a little subordinate potassium feldspar cemented by micritic carbonate (Figure 6.10).

*Sample 22.4 (Shafer Trail)*

Sample 22.4 was collected ~10 km from the center of Upheaval Dome to compare conglomerates from near the dome to one collected far from structural deformation associated with the dome. Sample 22.4, is similar to the conglomerates collected from around Upheaval dome as it is a matrix supported, carbonate-pebble conglomerate. This sample is dominated by a couple of different carbonate morphologies making up ~90% of the clasts present. These morphologies are separated by how much quartz and other minerals are found inside of them. About 40% of the clasts in this sample are clean carbonate pebbles, the other 60% have some percentage of their composition made up of siliceous minerals.
The matrix of this sample is fine to medium quartz sandstone with some subordinate grains of potassium feldspar. The cement of this sample in carbonate and is optically continuous in many areas. This type of optically continuous cement is not present in samples from near Upheaval Dome.

6.2 Hand-sample and Outcrop-Scale Lithologic Features

In the Upheaval Dome field area a large majority of the exposed Jurassic aged rock is fine grained sandstone. This abundance of fine grained sandstone is no surprise considering that a large portion of the stratigraphy is defined by thick eolian deposited units such as the Wingate and Navajo Sandstones. The braided channel deposit of the Kayenta Formation that separates the two thick eolian units is also very sandy, albeit with a higher percentage of feldspars and lithics than either the clean Wingate or Navajo Sandstone. Despite the significant amount of monotonous fine-grained sandstone at Upheaval Dome there are examples of distinct, and important lithologies and lithologic features within samples collected adjacent to Upheaval Dome.

In the center of Upheaval Dome and in the alluvial deposits in Upheaval Canyon there are significant amounts of gypsum and gypsum clasts (Figure 6.11). At other salt extrusions in the Paradox basin to the northeast of Upheaval Dome (e.g., Onion Creek), the Paradox Formation, where exposed at the surface, is a jumbled mass of gypsum, black shale and dolomites that have been leached out of the Pennsylvanian Paradox Formation (Baars and Doelling, 1987). It is possible that the gypsum found in the center of the dome is a remnant of dissolved Paradox salt.

In the Navajo Sandstone there are interbeds located in the axis of the present day synclinal axis. These interbeds are either flat-lying carbonates in conjunction with irregular tubular shaped sandstone casts that protrude out of the Navajo, or the tube shaped sandstone casts alone without the carbonate surface (Figure 6.12). The calcareous interbeds display v-shaped fractures with a
Base Map 6: Map displaying sample and important lithologic feature locations (Field mapping completed by author with data from Jackson et al., 1998; Kriens et al., 1999).
Figure 6.1: Pie charts from sandstone point counts displaying relative percentages of quartz, feldspars and lithic fragments from samples collected at Upheaval Dome (Top) and away from Upheaval Dome at the Shafer Trail (Bottom) from the Kayenta Formation. Point counts showed that sandstones from Upheaval Dome were similar to sandstones away from the structure. Blue quartz, yellow potassium feldspars, green lithics.
Figure 6.2: Photo-micrographs taken at a 10X magnification of sample 22.1 Base from the Kayenta Formation within Upheaval Dome. Cross polars on left, plain polars on right. Petrographically similar to Figures 6.3 and 6.4 (samples collected at Shaffer Trail).

Figure 6.3: Photo-micrographs taken at a 10X magnification of sample 22.1 Top from the Kayenta Formation within Upheaval Dome. Cross polars on left, plain polars on right. Petrographically similar to Figures 6.3 and 6.4 (samples collected at Shaffer Trail).
Figure 6.4: Photo-micrographs taken at a 10X magnification of sample 22.6 Base from the Kayenta Formation at Shafer Trail. Cross polars on left, plain polars on right. Petrographically similar to Figures 6.1 and 6.2 (samples collected at Upheaval Dome).

Figure 6.5: Photo-micrographs taken at a 10X magnification of sample 22.6 Top from the Kayenta Formation at Shafer Trail. Cross polars on left, plain polars on right. Petrographically similar to Figures 6.1 and 6.2 (samples collected at Upheaval Dome).
Figure 6.6: Photo-micrographs taken at a 10X magnification of sample 13.7 from Syncline Butte. Lower left is a pebble sized carbonate clast. Cross polars on left, plain polars on right.

A

B

Figure 6.7: (A) Photo-micrographs taken at a 4X magnification of sample 15.4. Cross polars on left, plain polars on right. Photo displays a pressure dissolved tip of a shell fragment from Syncline Butte. (B) Photo-micrographs taken at a 10X magnification of sample 15.4. Cross polars on left,
Figure 6.8: Kayenta conglomerate samples, displaying an abundance of carbonate and morphologies of carbonate clasts. (A) Photo-micrographs taken at a 10X magnification of sample 5.7. Cross polars on left, plain polars on right. (B) Photo-micrographs taken at a 2.5X magnification of sample 5.7.
Figure 6.9: Photo-micrographs taken at a 2.5X magnification of sample 13.5, this Kayenta conglomerate was composed of pebble sized carbonate clasts. Cross polars on left, plain polars on right.

Figure 6.10: Photo-micrographs taken at a 10X magnification of sample 20.2, a Kayenta conglomerate. Cross polars on left, plain polars on right. Image is one large clast made predominantly of quartz grains and carbonate cement.

Figure 6.11: Clasts of the evaporite mineral gypsum present in the Moenkopi in the dome center. In addition, gypsum alluvium is present in the drainage of Upheaval Canyon. Gypsum is a common component of caprock facies in other salt structures around the basin.
Figure 6.12: Irregular tubular sandstone castes associated with the Navajo Sandstone interbeds, located in the axis of the DES.

Figure 6.13: Photo of carbonate interbed located in the axis of the DES. Folding of this bed suggests deformation continuing into Navajo time. Inset photo displays the plan view of a Navajo, carbonate interbed. Note the polygonal pattern on the top surface.
7.1 Stratigraphic Features

The stratigraphic features recorded in the strata surrounding Upheaval Dome are important for understanding and unraveling its structural history. Analysis of stratal stacking patterns, lithofacies distribution, variations in formation thickness (growth strata) and different types of stratigraphic surfaces (onlap and angular truncations) provide insights for interpreting the geologic history and development of Upheaval Dome (Aschoff and Giles, 2005).

7.1.1 Facies Analysis

The Kayenta Formation displays various siliciclastic facies and subordinate carbonate facies (Tables 4.1, 4.2, and Figure 4.1), including structureless sandstone, planar laminated channelized sandstone, cross-stratified channelized sandstone, channelized conglomerate, red to purple mudstone, multi-colored mottled mudstone, non-channelized trough to tabular cross-stratified sandstone, and alternating clastic and carbonate laminations. These facies are grouped into facies associations including braided channel deposits, overbank or flood deposits, paleosols, eolian, and algal or bacterial mats or laminations (Tables 4.1, 4.2, and Figure 4.1). Objectives of facies analysis were to investigate measured sections for any specific vertical stacking patterns, or specific facies distributions in relation to the structural zones they were measured from (such as inside the DES, near the axis of the DES and near the DEM).

The investigation of vertical stacking patterns within particular measured sections yielded no solid conclusions. The data gathered in the field reflected that there was no organized stacking pattern, such as coarsening upward or fining upward packages, within individual measured sections. For example, sections measured within the DES displayed randomly stacked facies of
braided channels, overbank deposits, and sporadic eolian deposits. Sections measured outside of the DES displayed similarly unpredictable stacking patterns, but with different fractions of similar facies present inside of the DES (see Appendix A).

There is a good correlation, however, between stratigraphic facies associations, and the structural zones within which they were measured. The measured sections from inside of the DES (Sections 1, 3, 5, 6, 7, 13, 14, 15) were dominated by braided channel deposits, with common overbanks and recessive beds.

Sections measured near the axis of the present day DES (2, 8, 9, 10) were distinctly thinner than sections measured inside the DES, they display unique facies not present in other localities in the field area, and exhibit a much lower percentage or complete absence of sandy-braided channel deposits. The facies not observed in other structural zones of the field area are laminated algal mats alternating with fine-grained sandstones (Figure 4.1). Algal mats present in the axis of today’s DES are interpreted to have been deposited near the capillary fringe of the water table. During wetter times the surface would be damp or have standing water, leading to the growth of algal or bacterial mats (Kocurek et al., 2006; Fryberger, 1983). The most dominant type of deposition in these times occurs by a process of sediment trapping and mat growth due to a rise of the capillary fringe (Kocurek et al., 2006). During dryer periods the surface would be more influenced by evaporation, thus concentrating ions in solution and forming early evaporite cements causing cohesion of the grains. Dry periods were also vulnerable to wind scour because the loss of cohesion from a moist surface from a shallow capillary fringe, and are displayed as small unconformities in outcrop (see Facies H from Figure 4.1) (Collinson, 1986; Crabaugh and Kocurek, 1993).

Mature paleosol beds are present in some of the measured sections near the present
day axis of the DES and have been noted at the base of Syncline Butte at the top of the Kayenta Formation and other locations near the axis of the present day DES.

Sections measured outside of the DES (Sections 4, 11, 12) are dominated by sandy-braided stream type deposits, with very minor input from overbank and flood deposits. These observations of facies variations from different structural zones allow us to make a few interpretations of the depositional history of the Kayenta Formation surrounding Upheaval Dome.

The beds measured from inside of the DES and towards the dome center are interpreted to have been deposited in the axis of a Kayenta aged paleo-minibasin and associated depocenter. This interpretation is based on the substantial thickness of the measured sections (69-224 meters) and the high percentage flood deposits and braided channel deposits that were focused towards the axis of the subsiding minibasin. The sediments from near the axis of the present day DES are interpreted to have been deposited on a paleo-high or flank of the mini-basin (Figure 7.1). This interpretation is based on their relatively thin measured thicknesses (7 to 34 meters) and the facies preserved in these areas. The rare occurrence of channelized strata, combined with the presence of fragile algal mats and mature paleosols indicates that the strata recorded in these sections were located in an area that was rarely, if ever, exposed to fluvial erosion and sedimentation. This interpretation agrees with the conclusion made by Prochnow et al. (2006) that, ‘paleosol maturity is inversely related to stratal thickness, and decreases towards the minibasin where episodic burial by fluvial sediment was more frequent’. The sections outside of the DES reflect more closely the Kayenta Formation in its regional appearance, and were likely deposited in a similar braid plain environment.

Based on these facies interpretations, there is a disconnect between the paleo-synclinal
and depositional axis, and the synclinal axis perceptible in the surface geology today. The measured sections from near the present day synclinal axis display facies that would be found on a paleo-high that was not regularly influenced by high energy fluvial deposition and erosion. The inside limb of the present day DES displays facies that would more likely be found in the axis of an actively subsiding synclinal axis (Prochnow et al., 2005). These interpretations of facies and their location within a structural zone indicate that there has been shifting of synclinal axial traces and depocenters through geologic time (Figure 7.1).

7.1.2 Formation Thickness

This study clearly demonstrates that the stratigraphic thickness of the Kayenta Formation is extremely variable within the halo of deformation of Upheaval Dome (6 meter minimum thickness, 224 meter maximum thickness). The variability in stratigraphic thickness around Upheaval Dome is inconsistent with other areas of the basin unaffected by halokinesis, as the Kayenta Formation has a very consistent regional thickness in the northern Paradox Basin of 70-80 meters.

As previously mentioned, the sections measured within the Kayenta Formation have been separated into distinct groups based on where they were measured in relation to structural features. The sections measured from within the DES were found to be frequently thicker than sections measured in other zones of the dome with an average thickness of 160.25 meters. The sections measured within this structural zone also display distinct variation in relation to what side of the dome they were measured from. For example, the two most westward sections (6 and 13) were found to be the thinnest (69 and 90 meters respectively), and sections measured to the north, south or east of the dome were much thicker (over 150 meters thick). This asymmetric deposition around the dome is interpreted to have been caused by shifting synclinal axes and
depocenters asymmetrically on opposing sides of the diapir during the downbuilding process of a salt diapir (Schultz-Ela, 2003).

The few sections measured from near the axis of the DES were consistently the thinnest stratigraphically when compared to measured sections in other zones, with an average thickness of 24 meters. Because of exposure issues some sections from around the dome were impossible to collect. It is reasonable to assume, however, that if sections could be measured away from the southwestern side of the dome there would likely be significant variability in thickness similar to the sections measured near the DES.

Sections measured near the DEM displayed significant variability (minimum of 55 meters, maximum of 117 meters) but reflect the regional stratigraphic thickness of the Kayenta Formation more closely than the other zones mentioned above, with an average thickness of 92 meters.

Perhaps the more important thickness changes are those that occur with changing distance from the dome center. The sections are at the thickest inside of the DES, thin to almost nothing in some places near the axial trace of the present day DES, and finally begin to return to regional thickness at the DEM. If these thicknesses are considered relative to today’s structural orientation they do not make geologic sense. Why would the thinnest part of the Kayenta be located in the axis of the syncline, where the synclinal axis should be a depocenter, and therefore the thickest stratigraphically? It is because the synclinal axial trace, and thus the formation depocenter through the Jurassic shifted over geologic time. During Kayenta time the synclinal axis was located closer to the center of the dome than it is today; therefore the thickest depositional units were located nearer the dome center. The thinnest part of the Kayenta Formation was likely deposited over some type of high, such as a flexed margin of the mini-basin or depositional sink, leading to the deposition of a thin Kayenta section (Figure 7.1).
Based on the observations of asymmetric thickness distributions within distinct structural zones, and the thickness pattern of the Kayenta from proximal parts of the dome to distal parts of the dome, we conclude that there was long-term deformation of the area surrounding Upheaval Dome during the deposition of the Kayenta Formation (199.3 Ma-182.7 Ma or 16.6 million years) at a minimum (Tykoski et al., 2002). This long-term deformation is interpreted to have been caused by syndepositional movement of mobile salt in the underlying Paradox Formation as salt movement has long been known to cause significant and asymmetric thickness variations in the Paradox Basin and other basins influenced by salt movement (Jackson et al., 1998; Rowan et al., 2003; Schultz-Ela, 2003; Banbury, 2005; Rowan et al., 2012). There are no other structures of sufficient scale to explain the dramatic changes in thickness of these Kayenta growth strata.

7.1.3 Angular Truncations

Throughout the northern Paradox basin the presence of localized angular unconformities and onlapping strata are rare or absent unless associated with the growth of salt structures (Bromley, 1991; Hazel, 1994; Prochnow et al., 2005, Prochnow et al., 2006 Lawton and Buck, 2006; Matthews et al., 2007). At Upheaval Dome there are a number of examples of these surfaces, and their presence is significant for the interpretation of Upheaval Dome as they infer long-term processes (Boggs, Jr., 2006).

Localized angular unconformities and onlapping stratal relationships that represent long-term deformation are present in a variety of areas of the stratigraphy surrounding Upheaval Dome from the Chinle Formation to the base of the Navajo Sandstone (Figures 4.5, 4.6, 4.7, 4.8, 4.9, 4.10). Truncation surfaces (from now on to be considered localized angular unconformities) are present both at the contact between formations and within a single formation (intraformational unconformity). Each of these stratigraphic features are interpreted to have formed by
a combination of either localized deformation and erosion, or deformation in conjunction with continued sedimentation and deposition. These surfaces and their significance to the genesis of the Upheaval Dome structure will be described below from oldest to youngest.

The oldest angular unconformities present at Upheaval Dome are located in the central depression within the Chinle Formation. These angular unconformities were found to have angular discordances up to 90 degrees (see Figure 4.10). Further examination of these stratigraphic discordances revealed that if they were restored to horizontal the truncated beds would dip regularly outward from the dome (Jackson et al., 1998). This radially symmetric tilting cannot be explained by regional tectonics, and therefore is most likely associated with the formation of Upheaval Dome (Jackson et al., 1998). Although the origin of the truncations is speculative, their presence suggests a doming of topography during the deposition of Chinle strata (Jackson et al., 1998).

Stratigraphically higher there are a number of examples of angular unconformities at the contact between the Chinle Formation and the Wingate Sandstone (Figures 4.8, 4.9). The contact between the Chinle Formation and the Wingate Sandstone is a regional unconformity (J-0, from 210 Ma to 206 Ma) (Pipiringos and O'Sullivan, 1978; Jackson et al., 1998), but in the northern Paradox basin it rarely displays visual indicators of long term exposure and erosion such as angular unconformities (Banbury, 2006; Molenaar, 1981). Therefore, it is important to note where this formational contact is unconformable and consider possible reasons why.

These unconformable contacts between the Chinle and the Wingate are found in a variety of locations surrounding Upheaval Dome, display varying degrees of discordance, and are interpreted to have been emplaced due to localized uplifts caused by underlying salt evacuation, and subsequent erosion of the localized highs of the Chinle Formation before the deposition of
the Wingate Sandstone.

Intra-formational unconformities within the younger Wingate Sandstone are hard to discern simply because the formation is very homogenous, and is difficult to see individual bedding planes. However, Jackson et al. (1998) interpreted an outcrop from southeast of the dome center as an intra-formational unconformity caused by synsedimentary deformation during the deposition of the Wingate Sandstone (Figure 2.10; Jackson et al., 1998 interpretation, Figure 4.9 for outcrop interpretation this study). From what is displayed in outcrop, Jackson and other's (1998) reconstruction is highly interpretive. However, there is significant thinning of the Wingate in this location, and there are faint bedding planes that appear to truncate at a surface within the Wingate. Based on these observations, Jackson et al. (1998) interpretation of synsedimentary deformation during Wingate time adequately explains geometries exposed in outcrop today.

A surface that is very telling in terms of long-term and synsedimentary deformation is located in the Kayenta Formation and is located to the southwest of the False Kiva overlook (Figure 4.5). This surface is both an intra-formational unconformity within the Kayenta Formation, and an onlap surface with onlapping beds extending from the Upper Kayenta into the Lower Navajo Sandstone. In order to create this surface there would have had to have been multiple events of deformation, erosion, and deposition, requiring a significant time frame (Figure 7.2 schematic restoration). Based on field analysis and photo-interpretation there was first deposition of the Kayenta Formation over a deformed surface. This uneven surface then underwent general tilting towards the center of the dome, leading to an erosional truncation of localized flexed marginal uplifts. This was followed by an episode of tilting away from the dome, and subsequent onlap of sediments from the Upper Kayenta and Lower Navajo.

One of the onlapping beds is a fossiliferous sandstone bed composed of *Unio* fresh water
clams (Figure 4.6). To create an environment that supported a community of fresh water clams and deposit a relatively thick bed of their shells, there would have had to have been a long period of time with specific living conditions allowing these clams to flourish. It is interpreted that specific tilting and deformation felt in this particular location must have created paleotopography and a small basin with standing water where these fossil mollusks to burgeon. Thus, the presence of this fossil mollusk bed further suggests that this stratigraphic truncation surface was created over significant geologic time scales, and not in a catastrophic event.

Younger localized unconformities are present at the contact between the Kayenta Formation and the Navajo Sandstone (Figures 4.7, 4.8). These formations around the basin are conformable, and commonly inter-finger in a gradational contact (Blakey, 1988; Blakey et al., 1988; Jackson et al., 1998; ). Again, these angular unconformities are located in an assortment of areas within the area of structural deformation around Upheaval Dome, and display various angles and attitudes of discordance. These angular unconformities are interpreted to have been caused by the same process as those mentioned previously: long-term deformation of strata combined with erosion of localized uplifts, followed by the deposition of the subsequent formation.

There are numerous examples of localized angular unconformities in the stratigraphy surrounding Upheaval Dome, there are also numerous examples of structures that are onlapped by younger stratigraphic units. The best example of onlapping strata in Figure 4.11 is at the base of the Wingate Sandstone on the perimeter of the topographic depression. The onlaps present in this figure are interpreted to be syndeformational features, and to have deposited and thinned onto the steadily growing antiformal feature within the early Wingate Sandstone. Other less impressive examples of onlap are mentioned previously in this study, but are interpreted similarly
as products of syndeformational sedimentation and deposition.

The best interpretation for the presence of angular unconformities and onlapping stratigraphy present in outcrop surrounding Upheaval Dome relies on a mechanism that supports long-term deformation. Because Upheaval Dome is located within a known salt basin, and these stratigraphic features are only present within the deformation halo of Upheaval Dome and other known salt structures northeast of the Dome, the best explanation for these long term deformation features is the lateral movement, diapiric rise and subsequent evacuation of the underlying, halite rich, Pennsylvanian Paradox Formation.

7.2 Structural Features

The structural components present at Upheaval Dome are key in providing a further understanding of Upheaval Dome as a complicated geologic feature. The structural features that will be discussed in depth here include normal faults, reverse faults, and folds.

7.2.1 Normal Faults

A large portion of the normal faults observed in the Jurassic aged strata in the Upheaval Dome field area have stratigraphic thickness discrepancies from the footwall block to the hanging wall block across the fault surface (Figures 5.2, 5.3, 5.4, 5.5). Faults displaying this type of geometry are interpreted to have propagated steadily upward as sediment accumulated in the accommodation created on the hanging wall side of the fault; characteristics of growth faults (Van der Pluijm and Marshak, 2004).

The oldest growth fault identified in the field area propagates from the Triassic Chinle Formation upwards into the younger Jurassic Wingate Sandstone (Figure 5.2). The Lower Wingate Sandstone deposited over the top of the Triassic Chinle Formation with little to no deformation. Later, during the Early Jurassic there was enough extension in the area to initiate
a steep, planar normal fault in the Chinle and the Wingate sandstone (Figure 5.2 and schematic reconstruction 7.3). This fault continued to propagate up-section through much of the Early Jurassic in conjunction with coeval deposition of eolian sediments. The sediments deposited during this time of continued slip along the fault were preferentially preserved in the hanging wall due to the localized accommodation created through normal faulting. The deformation along this fault continued through late Wingate time, as there is distinctive localized uplift above the fault surface at the top of the Wingate leading early beds of Kayenta to onlap the local high.

The field observations and interpretation of this structure leads to the conclusion that this entire fault surface was not created in seconds to minutes (as would be expected from a catastrophic event), but actually was actively growing and propagating with continued sedimentation for millions of years (~20 million years based on current age dates).

Normal growth faults are present in the younger Kayenta Formation (Figures 5.3, 5.4, 5.5). The fault surface in Figures 5.3 and 5.4 is a normal fault located at Syncline Butte documented from opposite sides of the butte. The major fault located at Syncline Butte is listric in nature, and propagates upward from the Wingate-Chinle Contact into the Upper Kayenta (Figure 7.4). During the deposition of the Wingate Sandstone there may have been some minor deformation of the Chinle, causing slight thinning in the Wingate. It appears that early in Kayenta time the fault had not yet initiated, as the unit 2 restores across the fault surface. However, later in time, unit 3 displays a distinct stratigraphic thickness difference across the fault surface, and it is because of this thickness difference that it is interpreted that the faulting in this location initiated in early during unit 3 time. Unit 3 on the hanging wall block pinches out as the local accommodation created by the normal faulting gradually lessens away from the fault. The fault continues to propagate through early 4, as there is a minor displacement in the basal part of the unit, and
slight thickening of the unit on the hanging wall side of the fault. Onlaps are documented in the
growth package present on the opposite side of Syncline Butte. The evidence from this outcrop
strongly indicates long-term growth of the fault (millions of years) in conjunction with continued
sedimentation.

The third growth fault feature to be discussed here is visible from the road driving into
Upheaval Dome, and is located on the south side of the dome outside of the DES (Figure 5.5).
This fault displays two main normal fault surfaces. The first propagates through the entire Kayenta
and soles out at the contact with the Wingate Sandstone. The second major fault surface is isolated
within the Kayenta entirely. The rock units marked 2, are distinctly thicker on the hanging-wall
block, and unit 3 does not have an equivalent rock package on the footwall side of the block.
Based on this photo interpretation, these faults propagated over long periods of geologic time in
conjunction with continued deposition, and thus are interpreted as a growth faults.

It is important to mention the various attitudes that normal fault surfaces strike around
Upheaval Dome. In a meteorite impact listric normal faults are modeled to dip towards the center
of the impact due to the collapse of a transient crater (Grieve, 1987; Kriens et al., 1999 Huntoon,
2000). Some of the fault surfaces strike tangentially around the dome and dip towards the dome
center, but there are numerous faults that dip either away from the dome center, or obliquely away
from the dome. These structural data suggest that extension in the area around Upheaval Dome
was not simply focused towards the center of the dome, but in a variety of directions relative
to the dome center. Extension of this type could be caused by asymmetric evacuation of the
underlying Paradox Formation.

7.2.2 Thrust Faults

Probably the first structural feature people see at Upheaval Dome is the thrust duplex
located on the Wingate and Kayenta cliff northwest of the topographic depression (Figure 5.7). This fault array displays fault spacing that decreases and folding associated with the fault increases in its direction of vergence (Jackson et al., 1988). This type of geometry associated with this duplex suggests either out of sequence thrusting, or the beds in the front of the duplex were folded and oversteepened prior to thrusting. This fault zone also displays portions along its surface that have normal offset. A single fault plane that shows both reverse and normal offset implies multiple displacements over geologic time periods (Jackson et al., 1988). Fault duplexes that exhibit smooth roofs, no hanging-wall anticlines and relatively small offsets commonly evolve due to facies or thickness changes that resist thrust-propagation (Jackson et al. 1988). With this in mind, the mechanism behind the formation of this duplex may have been caused more by upward flexure than by inward contraction (Jackson et al., 1998). Upward flexure in this area would be caused by the evacuation of salt from the autochthonous level in the rim syncline, leaving this area of the Kayenta and the Wingate on the flexed margin of the evacuating sink. The stresses caused by this upward flexure could then initiate strain by shortening the Kayenta into the duplex fault present on the southeast facing cliff of the Kayenta Formation and Wingate Sandstone.

The second fault to be discussed here has a similar eastward vergence that is consistent with the duplex fault zone discussed above, but is located on the eastern side of the dome. The fault here, unlike the fault discussed above, does not have a series of horse blocks. The fault formed east of the dome instead has a series of ramps and flats. The leading and trailing anticline of the hanging-wall block have been eroded, but the front limb of the leading anticline is preserved and in the field and is exposed as a series of hook like geometries. A mechanism is necessary to thrust the Kayenta over itself. The mechanism for the emplacement of this fault is interpreted as basal shear at or near the base of extrusive salt, and more particularly, this fault is
interpreted as a roof-edge, peripheral thrust fault associated with an allochthonous salt sheet that was active for at least part of Kayenta time (Figure 7.5) (Hudec and Jackson, 2009).

A majority of thrusts surrounding Upheaval Dome verge to the southeast. Consistent vergence direction is not expected from an impact event as thrust faults verge away from the dome center during the excavation stage of impact, and do not form thrusts that verge in the same direction regardless of the side of the structure they are located (Huntoon, 2000).

7.2.3 Folds

This section discusses features of various scales including the DES, DEM, and smaller more localized dog-tongue features at the base of the Wingate Sandstone on the periphery of the central depression. The depositional axes of the Kayenta Formation (thickest stratigraphic part of the unit), and commonly the Wingate Sandstone do not align with the present day axial trace of the DES (Figures 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7). The realization that different formations have different depositional axes implies that the synclinal axis around the dome shifted positions through geologic time. This shift in synclinal axes and depositional axes is common during passive growth of salt diapirs (Rowan et al., 2012) (Figure 7.6). The synclinal axis depicted in the cross sections (Figures 3.1-3.7) shift away from the dome center through time. This is the opposite from what is normally in seismic examples of salt diapirs, as synclinal axes commonly shift towards the diapir throat (Figure 7.6). This difference in synclinal axial migration could be caused by a salt first evacuating from close to the diapir throat before mobile salt being sourced from more distal areas of the autochthonous Paradox Formation. Synclinal axial traces also shift away from the neck of a diapir at the front of a ramping salt allochthonous salt sheets.

The formation of the Wingate dog-tongues (doubly-curved radial lobes), and their associated features are a completely different story, but an altogether very interesting and telling
one. This study interprets the formation of the dog-tongues in the same way as Jackson et al. did in 1998. Dog-tongues are considered to have formed by Wingate sands onlapping emergent salt, that obstructed the deposition of Wingate in this locality. Salt would then be evacuated from the relatively small salt flange, leading to the formation of a weld between the Chinle Formation and Wingate Sandstone.

Adjacent to dog tongues above the Wingate-Chinle contact blocks of the Chinle Formation encased in the Wingate Sandstone are present. This phenomenon is not noted in other places around the dome. The presence of these Chinle blocks inside the Wingate does not make sense when first considered. How does an older unit become detached and completely surrounded by a younger unit? It is possible that during the growth of a diapir there the older Chinle was plucked from the flanks of the diapir, and were abandoned in the Wingate Sandstone as the salt flange was either dissolved or evacuated out. However, salt is mechanically weak compared to other rocks, and it is unlikely that salt was mechanically plucking a stronger rock into the mobile diapir throat (Alsop et al., 2000; Hudec and Jackson, 2007). A preferred model involves a thin roof of Chinle over a predominantly passively growing salt diapir (Figure 7.7). During a time of active salt growth the Chinle roof began to extend and develop a series of normal faults. Eventually the mobile salt would take advantage of one of the weaknesses caused by normal fault zones, and break out overriding the adjacent Chinle strata. At this point the deposition of the Wingate began, and onlapped both the salt flange, and the rafted Chinle blocks. Salt then evacuated or dissolved, causing the partially lithified Wingate to lie on top of the Chinle and encase the abandoned rafted carapace blocks of Chinle Formation (Figure 7.7).

Under this model, both the Chinle blocks and the dog-tongues are explained by a small salt extrusion between the Wingate and the Chinle Formations. Furthermore, no model exists in
the meteorite impact literature that could account for the presence of older rigid blocks of strata preserved in younger sedimentary units.

7.3 Petrographic and Lithologic Discussion

Point counts comparing sandstones from inside of the structurally deformed area defined by the dome to sandstones from outside of the structurally deformed area did not reveal any significant petrographic variability that could be associated with meteor impact or salt diapirism. Each point counted sandstone was identified as a subarkose, whose percent potassium feldspar ranged from eight to fourteen percent. The samples from outside Upheaval Dome did contain a variety of grains not present in the samples from inside of the dome including: chalcedony, muscovite and opaque grains. This slight variation in grain distribution is likely due to localized depositional patterns, but the sample size from this study is far too small to make any broad reaching statements.

Sandstone samples 13.7 and 15.4 were collected for their unique appearance when compared to the common Kayenta sandstones around Upheaval Dome. Both samples were collected on opposite sides of Syncline Butte at or near the contact between the Kayenta and the Navajo Sandstone. Sample 13.7 has carbonate clasts of pebble size, but this is not uncommon in the Kayenta as the formation is commonly calcareous (Doelling et al., 1988).

Sample 15.4 displays a fragment of a shell fragment, likely from a bivalve, that then underwent pressure dissolution. This sample was collected from just inboard of the present day dome encircling synclinal axis in the Kayenta Formation. The Kayenta paleo-depositional axis was located inboard (towards dome center) of the present day synclinal axis, and coincides with where this sample was located. There may have been an environment near the axis of deposition in the Kayenta that fostered the growth of these types of bivalves. However, as it is a fragment
of a shell it is more likely that it was transported to this location by fluvial action. No planar deformation features (PDFs) or petrographic evidence of meteorite impact were noted in any of the sandstone samples.

Conglomerates were identified to be either a matrix or clast supported a carbonate-pebble conglomerate, displaying variable matrices. It is possible that the carbonate clasts were sourced from older units such as the Paradox or Honaker Trail Formations, however there are no fossil or time indicators to support the presence of Paradox or Honaker Trail Formation carbonates in these samples. Thus, it is more likely that the carbonates in the collected conglomerates are simply sourced from within the Kayenta itself.

Overall, this petrographic study sheds little light on the genesis of Upheaval Dome. There were no apparent planar deformation features diagnostic of a catastrophic shock (Buchner and Kenkmann, 2008; French and Koeberl, 2010), and no fossils or other rock fragments sourced from older unexposed rock units present in the Kayenta Formation conglomerates analyzed petrographically (Lawton and Buck, 2006).

Outcrop-scale lithologies and rock fabrics present around the dome are more helpful in discussing Upheaval Dome history than petrographic analysis from thin sections. A possible important occurrence of gypsum is present in the central uplift of the dome in the Moenkopi Formation, and in alluvial float in Upheaval Canyon. When the Paradox Formation is exposed at the surface in other salt walls located to the northeast of Upheaval Dome, there are jumbled masses of gypsum, black shale and dolomites that have been leached out of the Pennsylvanian Paradox Formation (Baars and Doelling, 1987). Therefore, it is possible that this gypsum is a more resistant facies left over after the dissolution of the main portion of the halite rich Paradox Formation. It is more likely, however, that the gypsum present in these locations was sourced
from the Moenkopi Formation, which has subordinate amounts of gypsum (Doelling et al., 1988).

In the Navajo Formation, located in the present day synclinal axis, are beds of tubular shaped sandstone casts that are commonly associated with carbonate interbeds (Figure 6.12, 6.13). These casts are interpreted to be the burrows of sand wasps, or another type of burrowing insect (Ahlbrandt et al., 1978). Sand wasps are very selective about the kind of surface they choose to burrow in based on texture of the sand present (Ahlbrandt et al., 1978). Because these burrowers are selective in the type of surface they dig in, it seems reasonable that the two locations that are burrowed were similar in terms of environment of deposition, and as the burrowed surface is also associated with a carbonate interbed with abundant mudcracks it also is presumable that this surface was intermittently damp (Boggs Jr., 2006). Because these burrows and interbeds are located only in the synclinal axis of the Navajo Formation, and display evidence of a having been a damp surface it seems likely that the present day structural synclinal axis may have developed as early as Navajo time allowing for a more damp environment to exist in the paleotopographic low created by the axis of the syncline during Navajo time. Lenticular interbeds of carbonate within the Navajo Sandstone have been linked to the presence of salt anticlines in the Paradox basin (Doelling et al., 1988). Based on observations of lithologic features in the Navajo, the synclinal axis shifted away from the center of the dome due to lateral migration of underlying Paradox Salt.

7.4 Interpretations and Comparisons to Previous Work

From previous research it appears there is evidence for a catastrophic meteorite impact at Upheaval Dome (Shoemaker and Herkenkoff, 1984; Shoemaker et al., 1993; Kriens et al., 1999; Kanbur et al., 1999; Huntoon, 2000; Kenkmann, 2003; Scherler et al., 2006; Buchner and Kenkmann, 2008; Key and Schultz, 2011), and evidence for long-term deformation in the exposed
units surrounding the structure (this paper, Jackson et al., 1998).

The most robust evidence supporting an impact is the presence of two quartz grains displaying planar deformation features out of 120 thin sections cut from samples from all stratigraphic layers exposed at Upheaval Dome (Buchner and Kenkmann, 2008). Assuming that the grains from the thin sections petrographically analyzed in this study were medium to coarse sand (as stated in the study) there would be approximately 3,872 grains on each standard petrographic slide. Multiply that by the 120 thin sections analyzed and there would be somewhere near 464,640 grains of sand. That makes the two grains of sand a mere 0.00043% of the grains analyzed. The lack of shocked quartz grains brings the meteorite hypothesis into question, since in other reported impacts indicate ~4% of the quartz grains analyzed displayed shock features (Clymer et al., 1996). Ray Anderson of the Iowa Geological Survey and expert on the Manson impact structure located in Iowa has been quoted saying, “...Scattered quartz in any deposit may contain planar deformation features as detritus from the weathering of other impact sites, so rocks must be found containing abundant [shocked] quartz grains” (Chamot, 2003). French and Koeberl (2010) stated that 2-5% of grains at an impact must display PDFs to be considered diagnostic of a meteorite impact. Thus, the figure of 0.00043% of shocked grains calculated from the Buchner and Kenkmann (2008) study cannot be considered abundant, and therefore cannot be considered as diagnostic indicators of impact. It is very possibly that the two grains are relicts from distal impact sites, or reworked grains from an early impact (pre-Chinle) at Upheaval Dome.

Other evidence suggesting the possibility of an impact is the presence of sparse, weakly developed shatter cones from thin sandstone beds of the Moenkopi near the central uplift (Shoemaker et al., 1993, Kriens et al., 1999). Other geologic features of Upheaval Dome, such as its circular shape and structural deformation features (faults, folds, central uplift, DES, dikes) are
consistent with meteorite impact (Huntoon, 2000; Kenkmann, 2003), but that is not to say that other processes could not be responsible for their presence (French and Koeberl, 2010).

Evidence for long term deformation is recorded in Jurassic aged strata in the form of thickness changes in the Kayenta Formation and Wingate Sandstone, the shifting of synclinal axial traces, angular truncations of strata, and growth faults (See also Jackson et al., 1988).

There is strong evidence for both meteorite impact and localized and focused long term deformation at Upheaval Dome. The hypothesis that best supports the evidence of deformation over opposing time scales (catastrophic vs. millions of years) is the combination of both a meteorite impact, and a pinched-off salt diapir (Figure 7.8).

In this interpretation there is a meteorite impact in the during Moenkopi time (~227-215 Ma). This timing of an impact would leave the diagnostic indicators of a catastrophic deformation that are present in the Dome today, including the poorly developed shatter cones, as well as remove and weaken the stratigraphic units overlying the Paradox Formation. Based on the formula for the depth of excavation for terrestrial complex craters (Depth of excavation=0.06 (Final or apparent diameter)1.1) (Grieve et al., 1981) there would be approximately 735 meters of strata removed from an impact with a minimum diameter of ~5.2 kilometers (present day DEM diameter). This would leave approximately 100 meters (cross section D, Figure 3.2) of fractured and weakened rock preserved above the halite-rich Paradox Formation. The impact would thus initiate active piercement of the salt through the weakened overburden, leading eventually to the passive growth of a salt diapir out of the center of the crater (Figure 7.8).

This proposed evolution would account for impact features present at Upheaval Dome. An impact during the Moenkopi would account for Moenkopi aged shatter cones, grains of shocked quartz displaying PDFs in the Kayenta, and sandstone dikes of the White Rim Sandstone. Here
we interpret that the shocked quartz grains were reworked from the Moenkopi impact, and re-deposited in the Kayenta. If the impact happened at a later time, such as in the Cretaceous or Tertiary, as has been previously hypothesized, (Shoemaker and Herkenhoff, 1984; Kenkmann, 2003) there would presumably be a significantly higher frequency of diagnostic shock indicators. There was no shortage of quartz sand deposited in the Paradox basin in the Jurassic, and it is expected that a higher percentage of quartz grains would show shock features had the impact taken place after the sediments were already deposited.

This explanation also can account for growth geometries in the stratigraphy exposed around Upheaval Dome. Salt migrating laterally towards the diapir throat out of the autochthonous level would lead to thickness changes, shifting synclinal axial traces, angular truncations, and growth faulting in the Jurassic strata.

Many of the growth geometries present around Upheaval Dome (thickness changes, shifting depo-centers) have also been noted around the other salt structures in the Paradox basin (Trudgill, 2011; Paz et al., 2009). The salt structures to the northeast however are very different from the potential pinched off salt-diapir at Upheaval Dome for multiple reasons. Firstly, the sizes of the salt anticlines are drastically larger than the structure of Upheaval Dome. Secondly, the salt anticlines are northwest to southeast elongate features in map view, and Upheaval is circular, representing the only potential circular salt structure in the basin. Finally, the location of Upheaval Dome is over 32 kilometers away from the other salt structures grouped further to the northeast part of the basin.

The question remains as to why there is this small, circular feature, far away from other previously described salt structures? The answer likely lies in different trigger mechanisms for the growth of the salt walls to the northeast and Upheaval Dome. For the salt anticlines to the
northeast, faults at the top of the Mississippian localized the development of vertical salt growth (Trudgill, 2011), but this mechanism does not apply to Upheaval Dome, as it is neither linear nor aligned with Mississippian fault features. A trigger to initiate the flow of salt at Upheaval could logically be a meteorite impact from above. The structure would be circular, relatively small compared to the salt anticlines, and its location would be purely accidental.

There are certain problems that arise from interpretations that depend on a pinched-off salt diapir, as it is difficult to think of a reasonable mechanism leading to the pinch-off of the salt diapir throat. Compression is necessary to fully pinch-off a diapir throat (Vendeville and Nilsen, 1995), and no compressional event is apparent from the overall basin tectonic history. Jackson et al. (1998) postulated that the diapir became entirely pinched-off due to gravity gliding of the country rocks down an inward dipping surface towards the relatively weaker salt within the diapir throat.

There are other interpretations that could explain the genesis of Upheaval Dome. One of these possible explanations is isostatic rebound of the central peak after an impact. Melosh and Ivanova (1999) maintain that impact craters are originally out of isostatic equilibrium, and that there is an associated viscous relaxation of the crater to move towards equilibrium. These authors explain further that the viscous relaxation times for craters with diameters of 10-100 km are on the timescale spanning more time than the age of our solar system (Melosh and Ivanova, 1999). Although Upheaval Dome is only 5 km across, viscous relaxation could still be a significant process operating over millions of years, perhaps contributing to the growth geometries exposed at the dome today.

The research presented in this study strongly indicates long-term deformation of exposed Jurassic-aged units surrounding Upheaval Dome. Stratigraphic and structural data collected at
Upheaval Dome display thickness variations, facies changes, angular discordances and growth geometries. These features are consistent with deformation associated with the presence of a passively growing salt diapir. Age constraints for a hypothetical triggering-impact initiation of a vertically growing salt body are yet to be determined, but based on this research the deformation began in pre-Chinle time (Table 7.1 for observations supporting the presence of a pinched-off salt diapir, or a meteorite impact crater).
Figure 7.1: Schematic reconstruction of shifting synclinal axes and depocenters through the Glen Canyon Group (Jurassic). Figure displays how certain facies were preserved in particular areas in relation to the synclinal axis during the deposition of the Kayenta Formation.
Figure 7.2: Schematic restoration of deformation and stratigraphy exposed southwest of the False Kiva Overlook displaying angular discordances (truncation and onlap) within the Kayenta Formation and the Lower Navajo Sandstone (Figure 4.5 and 4.12 for outcrop interpretation).

(A) Deposition of flat-lying sediments, (B) localized uplifts and tilting of stratigraphy to the north and the center of the dome due to the lateral migration of the underlying Paradox Formation, (C) erosional truncation of localized highs, (D) deposition of Kayenta Formation and lower Navajo Sandstones onlapping the former erosional surface. This figure displays a stratigraphic feature that would take millions of years to develop as there must have been multiple phases of deposition, deformation, and erosion.
Figure 7.3: Schematic restoration of Chinle Formation-Wingate Sandstone normal growth fault from Figure 5.2. (A) Flat-lying deposition of lower Wingate Sandstone over Chinle Formation. (B) Initiation of a steep-planar normal fault from Chinle Formation into the Wingate Sandstone. (C) Continued sedimentation and propagation of normal fault in conjunction with continued eolian deposition. (D) Normal fault dies out up section, but deformation continues until at least early Kayenta time, when beds within the Kayenta onlap the localized high in at the top of the Wingate Sandstone. This schematic reconstruction suggests that there was long-term deformation of Triassic and Jurassic units at Upheaval Dome.
Figure 7.4: Schematic restoration of Syncline Butte normal growth fault from Figures 5.3 and 5.4.
(A) Deposition of Wingate Sandstone over paleo-high in Chinle Formation as the Wingate is locally thin in this location. (B) Deposition of Lower Kayenta Formation before initiation of normal faulting. (C) Initiation of listric normal fault soling out at the contact between the Chinle Formation and Wingate Sandstone. Time unit 3 represents the time of maximum growth along the fault with continued deposition. (D) Continued propagation of listric normal fault into upper Kayenta Formation where it dies out into Unit 4. (E) Present day photograph of Syncline Butte from the southwest with overlain outcrop interpretation.
Figure 7.5: Interpreted photo-mosaic of thrust fault located on the east side of the dome. Inset diagram (lower left) is a schematic diagram the structural feature of a fault-bend fold exposed in outcrop (redrafted from Suppe, 1983). Inset (lower right) displays seismic and associated interpretation that is an analog for the fault exposed in outcrop of an roof-edge, peripheral thrust fault associated with an allochthonous salt sheet (From Hudec and Jackson, 2009). The leading and trailing anticline have been eroded from this fault feature leaving a leading syncline that now look like a series of hooks in outcrop.
Figure 7.6: Seismic profile from the Gulf of Mexico displaying a shifting depositional axial traces (green dashed lines). In this example of a pinched off salt diapir the depositional axial traces shift towards the center of the dome through time. At Upheaval dome the depositional axial traces shift away from the dome center, this difference could be caused by the salt being sourced from close to the dome before being sourced from further away. Here the pinched-off salt diapir shown in light blue.
Figure 7.7: Schematic diagram and model for the formation of dog tongues and the emplacement of Chinle blocks within the younger Wingate Sandstone. (A) Growth of salt diapir with a thin, drape of Chinle sediments. (B) Salt initiates active piercement by reactivating a normal fault formed over the diapir. The Chinle roof is extended further due to the minor allochthonous break out of salt. (C) Shift in depositional environment to eolian sand leads to the burial of the allochthonous salt and rafted Chinle roof blocks. (D) Zoomed in diagram of final welding process, where the Chinle and Wingate Formation meet in the area that was previously occupied by salt. Dissolution or evacuation leads to the flap of Wingate to weld to the older Chinle formation. Chinle blocks are thus preserved in the younger Wingate Sandstone. See Figure 5.9 for field example of Chinle Formation preserved in Wingate Sandstone (Modified from Rowan et al. 2003).
Figure 7.8: Schematic reconstruction of a salt diapir triggered by meteorite impact at Upheaval Dome. Starting in late Cutler to early Moenkopi time (Permian to Triassic) and proceeding through to Navajo time (Jurassic). (A) Meteorite impact in Early Moenkopi. (B) Excavation and deformation of overlying strata due to meteorite impact removes and weakens strata leading to active piercement of the salt. (C) Diapir develops into a passively growing diapir from starting in the Moenkopi and continuing through Chinle time. (D) Possible allochthonous break out during the deposition of the Wingate, Kayenta and Navajo Formations. Green dashed lines represent the formational depocenters, and illustrate how they shift through time due to evacuation of the Paradox Formation at the autochthonous level.
Table 7.1: Observations recorded at Upheaval Dome supporting the pinched-off salt diapir hypothesis, the meteorite impact hypothesis, or both. Data provided here suggest the possibility that there was a meteorite impact that spurred the passive-growth of a salt diapir. (* Indicate observations that were volumetrically insignificant) (Modified from (Jackson et al., 1998))

<table>
<thead>
<tr>
<th>Observation</th>
<th>Pinch-off</th>
<th>Impact</th>
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<tbody>
<tr>
<td><strong>Positive evidence</strong></td>
<td>Incompatable with impact</td>
<td>Compatible with pinch-off</td>
</tr>
<tr>
<td>Circularity</td>
<td></td>
<td>×</td>
</tr>
<tr>
<td>Central uplift</td>
<td></td>
<td>×</td>
</tr>
<tr>
<td>Clastic dikes</td>
<td>×</td>
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<tr>
<td>Crushed quartz grains</td>
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<tr>
<td>Inner constrictional zone</td>
<td>×</td>
<td>×</td>
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<tr>
<td>Outer extensional zone</td>
<td>×</td>
<td>×</td>
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<tr>
<td>Radial flaps (dog tongues)</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Presence of underlying salt</td>
<td>×</td>
<td>×</td>
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<tr>
<td>Gravity and magnetic anomalies</td>
<td>×</td>
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</tr>
<tr>
<td>Contiguous anticline</td>
<td>×</td>
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<tr>
<td>Nearby salt structures</td>
<td>×</td>
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<td>Growth folds</td>
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<td>Shifting rim synclines</td>
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<td>Truncations and channeling</td>
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<td>Onlap</td>
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<td>Multiple fracturing and cementation</td>
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<td>Shatter cones*</td>
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<td>PDF's*</td>
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| Negative evidence                          |          |                    |
| Lack of salt at the surface                | ×         | ×                  |
| Lack of nearby piercing diapirs            | ×         | ×                  |
| Lack of meteoritic material                | ×         | ×                  |
| Lack of melt                               | ×         | ×                  |
| Lack of in-situ breccia                    | ×         | ×                  |
| Lack of shock-metamorphic minerals         | ×         | ×                  |
| Lack of outer fault terracing              | ×         | ×                  |
| Lack of overturned peripheral flap          | ×         | ×                  |
CHAPTER 8

CONCLUSIONS

Documentation of stratigraphic and structural variation at Upheaval Dome, Canyonlands National Park Utah was used to determine the following:

1. Stratigraphic facies around Upheaval Dome display distinct variability, possibly caused by local paleo-highs and lows due to lateral migration of Paradox Formation salt.

2. There are significant thickness changes in the Kayenta Formation in the following areas:
   A) Within distinct structural zones, such as inside the dome-encircling syncline (Maximum measured thickness ~220 meters and a minimum measured thickness of ~69 meters).
   B) Increasing distance from dome center (Within dome-encircling syncline ~90 meters, near axis of present day dome-encircling syncline ~7 meters, and near the dome-encircling monocline ~44 meters thick).

3. Geologic cross sections illustrate the offset between synclinal axial traces, representing shifting depositional centers between the Wingate Sandstone and the Kayenta Formation due to underlying salt movement.

4. Angular truncations, including angular unconformities and onlapping strata, record long-lived deformation in the Jurassic stratigraphic units surrounding Upheaval Dome.

5. Interpretation of listric normal growth faults implies long-lived deformation of the Jurassic aged rocks surrounding Upheaval Dome.
6. Data from the petrographic study of sandstones and conglomerates from the Kayenta Formation did not lead to any conclusive information supporting either meteorite impact or the passive growth of a salt diapir.

7. Boulder sized blocks of Chinle Formation present in the Wingate Sandstone adjacent to Wingate dog tongues are interpreted to have been caused by the allochthonous breakout of salt carrying a thin roof of Chinle. In this model salt flow would progress until the salt welded out, abandoning the Chinle roof blocks in the younger Wingate Sandstone.

Overall, there is abundant stratigraphic and structural evidence for long-term deformation of Early Jurassic aged units surrounding Upheaval Dome, with specific geometries that are compatible with halokinesis. However, age constraints for the timing of the hypothetical salt diapirism-triggering impact, and the potential geometry of the resultant salt diapir, are still to be determined.

However, based on previous research and research completed in this study, a pre-Chinle impact is proposed. This proposed impact would remove and weaken overlying strata leading to active piercement, and subsequent passive diapiric growth of the halite-rich Paradox Formation.
REFERENCES CITED


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The supplemental files include oversized figures that could not be included in the main thesis and include measured sections. These sections were measured inside of the halo of deformation defined by Upheaval Dome, and a regional section measured at Shafer Trail.

<table>
<thead>
<tr>
<th>Appendix A: Measured sections, cross sections, and large Upheaval Dome map</th>
<th>15 measured sections total sections measuring over 1430 meters in total, and one measured section measuring 340 meters from Shafer Trail for regional context. Cross sections on same artboard for easy comparison.</th>
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