PRE-LARAMIDE SALT TECTONISM IN THE WESTERN EAGLE BASIN OF CENTRAL COLORADO

by
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ABSTRACT
Located west of the Front Range and situated between the Sawatch Range to the southeast and the Piceance Basin to the west, the Eagle Basin of central Colorado is a flexural foreland basin originally formed in the footwalls of the converging Uncompahgre and Front Range Ancestral Rocky Mountains Uplifts. Previous studies of this area highlight Laramide orogenic events as the main phase of tectonic deformation in this region. However, a closer evaluation of the complex array of structures in the Eagle Basin, along with the Pennsylvanian Eagle Evaporite Formation and adjacent and overlying Late Pennsylvanian to Jurassic strata provide evidence for a period of salt tectonics in the region pre-dating the Laramide Orogeny. Building on recent work completed by two Colorado School of Mines graduate students, this research seeks to provide further evidence of pre-Laramide salt tectonics and associated halokinetic deformation in the western part of the Eagle Basin. Field work completed in the western portion of the Eagle Basin demonstrates that sedimentary layers of varying thickness and the presence of folding, faulting, and overturned beds point to the growth of a series of Late Pennsylvanian to Early Permian salt walls and associated minibasins that may have been overlooked in the past. The western Eagle Basin contains diapiric salt walls, tongues, and canopies that were welded between minibasins during more recent, Laramide-aged shortening events. Salt diapirism explains the dramatic formation thickness variations and local overturning seen in the Late Pennsylvanian Eagle Valley and Permian Maroon Formations. A modern examination of the Eagle Basin provides insight into current salt tectonics theories and serves as a field analog of salt structures and minibasins in other comparable salt basins.
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CHAPTER ONE

INTRODUCTION

1.1 Purpose and Objectives

The purpose of this research is to provide new insight into salt tectonics in the western Eagle Basin and supply valuable field derived analogs that are key in understanding salt tectonism. The main objectives of this project are to understand the age, extent, and impacts of salt tectonism in the western Eagle Basin. With new mapped areas and structural data, cross sections will be refined for reconstruction to investigate the relative impacts of Laramide shortening versus salt-related deformation. Previous research completed in the eastern Eagle Basin provides context for this current research in the western Eagle Basin (Figure 1.1 and 1.2). Well defined salt wall structures and minibasins in the Paradox Basin in southwest Colorado and southeast Utah, are well defined (Kluth and Duchene, 2009; Trudgill, 2011) and provide a framework to compare the salt tectonic geometries and associated growth strata sequences throughout the Eagle Basin. This research will focus on field mapping structures and stratigraphic units in order to: 1) Locate and confirm the presence of salt walls and minibasins throughout the western Eagle Basin, 2) Understand the timing of salt related structures associated with minibasin formation, 3) Determine the temporal and spatial extent of salt diapirism across Central Colorado, 4) Highlight key differences between pre- and post-Laramide deformation events, 5) Identify and compare reactivated, post Laramide-aged evaporite mobility with pre-Laramide salt tectonics, and 6) Build a framework for a greater understanding of salt tectonics as applied to the regional geologic history of Central Colorado. Field mapping and analyses of complex structures, such as folding and faulting, and stratigraphic sequences in relation to salt structures, such as salt walls and welds, will further explain influences of evaporites on overlying
structural and sedimentological geometries and deformation. Expected results of this study will suggest a more complex, pre-Laramide evolution of the previously oversimplified structural and deformational history of the western Eagle Basin.

Figure 1.1. Location map of the study area in west-central Colorado, USA. The red box highlights the western Eagle Basin, the focus of this research (modified from Pearigen, 2019; Rice, 2021).
Figure 1.2. Map of the Eagle Basin highlighting previous and new research areas (gray and black, dashed lines respectively), interpreted salt walls, and named minibasins. These are key to determining structural and stratigraphic evolution of the Eagle Basin (modified from Pearigen et al., 2019). Minibasin color scheme: Pink = Eagle Valley (Early Pennsylvanian), Red = Maroon (Late Pennsylvanian), Orange = Maroon and State Bridge (Late Pennsylvanian-Permian), and Yellow = State Bridge (Permian-Triassic).
1.2 Theory of Salt Tectonics

The complex topic of salt tectonics is fundamental in understanding the deformation and tectonism of several basins throughout the world. As a crystalline aggregate of the mineral halite, salt acts as a viscous fluid in rock form (Archer et al., 2012). Evaporites such as halite, anhydrite, and gypsum are common constituents in evaporite basins around the world creating various structural and sedimentological anomalies. Salt tectonics, or halokinesis, is responsible for some of the world’s most intricate geology as seen in basins such as the Gulf of Mexico, the North Sea, the Paradox Basin (Kluth and Duchene, 2009; Trudgill, 2011) and Flinders Ranges, South Australia (Hearon, 2013). An understanding of diapiric salt and minibasin formation are key to developing a better understanding of the pre-Laramide tectonic evolution of the Eagle Basin.

Passive diapirism as defined by Rowan and Giles (2021), is “the ongoing, near-surface, syndepositional growth of a diapir” (Figure 1.3). Expanding on and refining historical definitions, passive diapirism is a long-lived process after salt breaks through the thin roof of a preexisting structure (Jackson and Vendeville, 1990; Vendeville and Jackson, 1991; 1992; Jackson, 1995; Rowan and Giles, 2021). Diapirs that result from passive diapirism may be emergent at the surface or slightly to completely covered by a thin onlapping roof of sediments (Rowan and Giles, 2021). The interplay between salt and sediment aggradation produces salt-withdrawal structures such as minibasins that have been studied for decades. The term “minibasin” was first used by Worrall and Snelson in 1989 (Hudec, 2009), but the concept dates back further; the first illustration was by Lehner in 1969 on salt in the Gulf of Mexico of synclinal minibasins sinking off the coast (Hudec et al., 2009). Salt-withdrawal minibasins have been defined as “synkinematic basins subsiding into thick, allochthonous or autochthonous salt”
Passive diapirism may also occur in the absence of sedimentation and minibasin subsidence during shortening events as salt becomes inflated (Rowan et al., 2003). Diapirism may also be triggered by extension and reactive diapirism (Vendeville and Jackson, 1992), breaching of contractional detachment folds or progradational loading (Coward and Stewart, 1995; Ge et al., 1997). Minibasin formation may initiate due to one or several of the following: A) density driven subsidence, B) diapir shortening, C) extensional diapir fall, D) decay of salt topography over a single sheet or salt canopy, E) sedimentary loading above salt, and F) subsalt deformation (Figure 1.5) (Hudec et al., 2009).

Figure 1.3. Examples of passive diapirs where gray is salt, orange are older strata, and yellow are younger strata: A) exposed diapir with no roof, B) partially exposed diapir with onlapping strata, C) exposed diapir on topographic high of salt-cored anticline, D) diapir with removed roof by way of erosion, E) fault-bounded diapir roof exposing diapir flanks, F) covered diapir with local exposure due to slumped roof from mass wasting, G) diapir with thin roof sediment coverage and hook halokinetic sequences (HS) forming tabular composite halokinetic sequences (CHS) of each side, H) diapir with thicker roof and wedge HS formed by two tapered CHS on flanks (Rowan and Giles, 2021), reprinted with permission of the AAPG whose permission is required for further.

Figure 1.4. Seismic section displaying a minibasin subsiding into thick allochthonous salt of the northern Gulf of Mexico, V.E. is vertical exaggeration. (Modified from Hudec et al., 2009).
Active diapirism as redefined by Rowan and Giles (2021) occurs in two specific circumstances of diapir rise: the first is a transitional phase of active diapirism in a single, short lived phase after salt in the precursor structure breaks through its thin roof; this is followed by
passive diapirism. The second is compressional active diapirism that occurs when an inactive diapir buried beneath a relatively thick roof is squeezed during shortening and uplift of the roof resulting in salt rise (Vendeville and Jackson, 1992; Schultz-Ela et al., 1993; Rowan et al., 2003, Rowan and Giles, 2021) (Figure 1.6). Active piercement or passive rise of salt diapirs may result in stratal faulting, folding, thinning of strata, the overturning of beds, and local unconformities (e.g. Bornhauser, 1969; Johnson and Bredeson, 1971; Giles and Lawton, 2002; Rowan et al., 2003). Rowan et al. (2003) discuss the termination of passive diapirism, which occurs when the source salt layer has depleted and salt flow cannot match sedimentation rates, a feeder closes off or welds, or shortening ceases.

Figure 1.6. Examples of active diapirism from Rowan and Giles, 2021: A-C) brief phases of active diapirism where precursor salt structure breaks through its roof and is followed by lengthy period of passive diapirism, D) shortening followed by rejuvenation of buried and inactive diapir, reprinted with permission of the AAPG whose permission is required for further.

The identification of megaflaps is key in determining geometries associated with early halokinesis. A megaflap is a “steeply dipping folded or upturned strata located on the steep flank of a diapiric salt wall or a salt weld” (Figure 1.7) (Rowan et al., 2016). The megaflap contains the oldest suprasalt sediment which are folded with vertical relief of multiple kilometers (Rowan and Giles, in press, 2022). Typically, megaflaps can have multiple-kilometer fold widths with distinct structural relief which differentiate them from smaller-scale hereafter defined minibasin tectonostratigraphic successions and even smaller-scale composite halokinetic sequences (Rowan et al., 2016, Rowan and Giles, in press, 2022).
Minibasin tectonostratigraphic successions (MTS) are defined by Rowan and Giles (in press, 2022) as “large-scale geometries of strata subsiding in salt” and are categorized by layer MTS, thinning-wedge MTS, and thickening wedge MTS (Rowan and Giles, in press, 2022) (Figures 1.8 and 1.9). The stratal successions with lateral dimensions of multiple kilometers have distinct three-dimensional thickness patterns such as minibasin bowls, minibasin troughs, minibasin wedges, and minibasin layers (Figure 1.8) (Rowan and Giles, in press, 2022). Further defined by Rowan and Giles (in press, 2022), layer MTS contain strata with consistent thickness approaching the diapir, thinning-wedge MTS have convergent bounding surfaces approaching the diapir, and thickening-wedge MTS contain expanding strata near the diapir (Figure 1.9).
Composite halokinetic sequences (CHS) are of importance in determining the structure and stratigraphy of minibasins. As defined by Giles and Lawton (2002), “halokinetic sequences are relatively conformable growth strata influenced by near surface or extrusive salt movement and
are bounded at the top and base by angular unconformities that may become disconformable with increasing distance from the diapir” (Figure 1.10). Additional terminology associated with halokinetic sequences are the two endmembers, hook and wedge halokinetic sequences, which are responsible for facies changes in stratigraphy adjacent to diapirs (Giles and Rowan, 2012). Hook halokinetic sequences are characterized by narrow and steep drape folds, beds that fold and thin over 50-200 meters from the diapir with unconformity rotation up to 90°, and abrupt facies change near the diapir (Giles and Rowan, 2012). Wedge halokinetic sequences are those that have broad, gentle drape fold geometries, strata folding and thinning that occurs 300-1000 meters from the diapir with angular unconformity rotation up to 30°, and gradual facies changes over a broad area (Giles and Rowan, 2012).

**Figure 1.10.** Endmembers of halokinetic sequences, (a) hook halokinetic sequence and (b) wedge halokinetic sequence, these are smaller scale drape fold geometries with angular discordance at the boundaries of unconformities. (Modified from Giles and Rowan, 2012)

Hook and wedge halokinetic sequences stack vertically to form tabular and tapered composite halokinetic sequences (CHS), respectively (Figure 1.11) (Giles and Rowan, 2012). These composite sequences can range up to hundreds of meters in thickness and they correspond in duration to third-order depositional sequences with a range of several hundred thousand years to several millions of years (Giles and Rowan, 2012). These tabular and tapered sequences have been analyzed in both field exposures and seismic data (Giles and Rowan, 2012).
Figure 1.11. Schematic cross sections of stacked composite halokinetic sequences (CHS). (a) stacked tabular CHS, (b) stacked tabular and tapered CHS, (c) stacked tapered CHS, and (d) stacked tapered and tabular CHS. (Modified from Giles and Rowan, 2012)

Tabular CHS have parallel to sub-parallel bounding surfaces, narrow zones of thinning near the diapir, and a zone of stacked monoclinal surfaces parallel to the diapir margin; tapered CHS have gradually converging boundaries toward the diapir, broad zones of thinning toward the diapir, and a zone of stacked monoclinal surfaces inclined away from the diapir margin. (Giles and Rowan, 2012). Figure 1.12 shows the relationship between the smallest to largest components of minibasin stratal packages from the roof to depocenter of the minibasin. Each of these components is identifiable within the minibasins of the Eagle Basin and are crucial in unravelling the evolution of salt tectonics within the basin (Pearigen, 2019; Rice, 2021).
Numerous basins around the world are sedimentary basins in which salt plays a key role (Archer et al., 2012). These basins have been studied over time to create a basis upon which geologists can view the Eagle Basin and define key structures. The evolution of a minibasin is crucial in understanding stratigraphic and structural deformation in a basin containing evaporites.

Archer et al. (2012) discuss the evolutionary complexities of basins which contain salt such as the halokinetic processes associated with the history of a basin that can drastically change the architecture and geometry of a basin. The importance of salt tectonics is key to the petroleum industry as many of the world’s largest hydrocarbon systems are in salt-related basins (Archer et al., 2012). The process of halokinesis can lead to structural traps, counter regional dips on continental margins, and may entrain adjacent lithologies via rafting (Archer et al., 2012). As noted by Archer et al. (2012), salt may also play a key role in future technologies beyond petroleum as it may hold potential as a repository for radioactive waste or a top seal to CO$_2$ sequestration.
CHAPTER TWO
GEOLOGIC SETTING AND PREVIOUS WORK

2.1 Central Colorado Tectonic History
Throughout Proterozoic time, Colorado’s continental crust is known to have materialized from accretion of magmatic arcs and inter-arc basins 1.8-1.65 Ga and magmatism from 1.0-1.45 Ga (Whitemeyer and Karlstrom, 2007). Subsequent uplift and erosion removed several kilometers of Proterozoic aged metamorphic and igneous rocks (Scott et al., 1999; Kirkham and Scott, 2002). Areas of unexposed Precambrian rocks presumably make up the basement of central Colorado (Lovering and Johnson, 1933; Tweto, 1977). Extensive work in the Rocky Mountain region interprets a period of sporadic sedimentation in the Cambrian to Mississippian, tectonism of the Ancestral Rocky Mountains throughout the Pennsylvanian and Permian, and onlap and burial of the Ancestral Rocky Mountains in the Late Permian to early Mesozoic as the primary modes of Paleozoic through Mesozoic tectonostratigraphic development (Scott et al., 1999; 2002; Blakey, 2009). Aside from the general structural style and sedimentation throughout central Colorado, there is only a vague discussion of the possibility in west-central Colorado of a phase of tectonism that resulted from evaporite deposition, mobility, and subsequent related structures.

Several early studies have found evidence of salt related deformation such as: 1) abrupt stratigraphic thickness variations of Pennsylvanian to Triassic aged strata, 2) the existence of salt floored minibasins, and 3) the presence of salt walls with subsequent welding between minibasins (Mallory, 1971; Tweto, 1977). Older studies, however, fail to clearly define the tectonic evolution of events pre-dating the Laramide Orogeny.

Recent research in the southern and north-central Eagle Basin (Pearigen, 2019; Rice, 2021) interpreted the Eagle Basin with a focus on salt tectonics and the application of new theories
post 1980s. Pearigen (2019) found Pennsylvanian to Triassic aged salt tectonism as seen in minibasin fills and salt wall structures. Rice (2021) also found distinct pre-Laramide, salt-related deformation. The tectonostratigraphic relationships point to a Pennsylvanian through Triassic aged period of salt tectonics (Rice, 2021). The deformation of central Colorado contains extensive tectonic events, and this field study of the Eagle Basin will further update the geologic and tectonic history of this region of the Rocky Mountains.

2.2 Eagle Basin Tectonics

The documented Phanerozoic tectonic history of this region involves a series of shortening and uplift events during the Ancestral Rocky Mountain Orogeny of Pennsylvanian time, crustal shortening, uplift, and magmatism throughout the Laramide Orogeny (Late Cretaceous to Eocene), extension and uplift during the late Cenozoic, extension and magmatism in Paleogene time, and uplift, extension, and evaporite tectonism during the Neogene (Scott et al., 1999; 2002). Since the landmark publication of Tweto (1977), potential pre-Laramide deformation and salt tectonism in the Eagle Basin of central Colorado has seldom been scrutinized. Much of the Late Paleozoic and Early Mesozoic are sidestepped in literature leaving a gap in the geologic history that has recently been studied by Colorado School of Mines graduate students (Pearigen, 2019; Pearigen et al., 2019; Rice, 2021).

Precambrian influences such as the north-northwest-trending fault and fracture systems in the Gore Range and the northeast-trending Homestake shear zone (Figure 2.1) of the Sawatch Range set a precedent for younger tectonism and deformation (Tweto, 1977; Tweto and Sims, 1963). Reactivation of these Precambrian basement shear zones and faults led to the development of structures such as the Castle Creek fault, the Grand Hogback monocline, White River Uplift and potentially the formation of the Piceance basin (Figure 2.1) (Tweto, 1977; Pearigen, 2019).
The tectonostratigraphy of the Eagle Basin is critical to establishing the timing and distribution of pre-Laramide tectonic events, particularly salt tectonics. The southern Eagle Basin has dramatic overthickening of Pennsylvanian to Permian strata (Pearigen, 2019) and the north-central Eagle Basin has overthickening of Pennsylvanian to Permian and Triassic strata (Rice, 2021) (Table 1). Noting the variable thicknesses and other stratigraphic relationships (unconformities and variable bedding strikes and dips) are key in unraveling the history of the Eagle Basin.
Figure 2.1. Regional location map highlighting key features throughout the study area in the Eagle Basin. Shear zones, regional faults, depocenters and uplifts are key in understanding pre and post salt deformation (modified after Tweto, 1977 and Pearigen et al, 2019).
Table 1. Table modified from Tweto (1977) with rock units of the Eagle Basin, their relative ages, names, maximum thicknesses, and relationships to surrounding stratigraphy.

<table>
<thead>
<tr>
<th>Age</th>
<th>Formation</th>
<th>Maximum Thickness (ft)</th>
<th>Maximum Thickness (m)</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paleocene and Late Cretaceous</td>
<td>Intrusive rocks</td>
<td>Variable</td>
<td>Variable</td>
<td>Many bodies from Aspen northeastward; ages mainly 55-70 m.y.; possible use as a “paleoflat” for reconstruction purposes</td>
</tr>
<tr>
<td>Late Cretaceous</td>
<td>Pierre Shale</td>
<td>5,300</td>
<td>1,615.44</td>
<td>Upper part missing; eroded by unconformities or faults</td>
</tr>
<tr>
<td>Late Cretaceous</td>
<td>Mesaverde Group</td>
<td>6,100</td>
<td>1,859.28</td>
<td>Thins southward by intertonguing with Mancos Shale</td>
</tr>
<tr>
<td>Late Cretaceous</td>
<td>Niobrara Fm.</td>
<td>600</td>
<td>182.88</td>
<td>Thins westward and becomes tongue in lower Mancos Shale</td>
</tr>
<tr>
<td>Late and Early Cretaceous</td>
<td>Benton Shale</td>
<td>400</td>
<td>121.92</td>
<td>Frontier SS and Mowry Sh. Equivalents at top; passes westward into lower Mancos Sh.</td>
</tr>
<tr>
<td>Late and Early Cretaceous</td>
<td>Mancos Shale</td>
<td>6,000</td>
<td>1,828.8</td>
<td>Thickens southward; includes lower Pierre, Niobrara, Benton, Frontier, and Mowry equivalents</td>
</tr>
<tr>
<td>Early Cretaceous</td>
<td>Dakota Sandstone</td>
<td>250</td>
<td>76.2</td>
<td>Thins eastward</td>
</tr>
<tr>
<td>Early Cretaceous</td>
<td>Burro Canyon Fm.</td>
<td>225</td>
<td>68.58</td>
<td>Only present in Aspen-Basalt area</td>
</tr>
<tr>
<td>Late Jurassic</td>
<td>Morrison Fm.</td>
<td>500</td>
<td>152.4</td>
<td>Thins at Gore fault and eastward where it overlaps Precambrian rocks</td>
</tr>
<tr>
<td>Middle Jurassic</td>
<td>Curtis Fm.</td>
<td>&lt;100</td>
<td>&lt;30.48</td>
<td>Mainly in CO. River area near McCoy; overstepped eastward by Morrison</td>
</tr>
<tr>
<td>Middle Jurassic</td>
<td>Entrada Sandstone</td>
<td>100</td>
<td>30.48</td>
<td>Truncated beneath Morrison near Gore fault and west of Aspen</td>
</tr>
<tr>
<td>Early Jurassic and Late Triassic</td>
<td>Glen Canyon Sandstone</td>
<td>75</td>
<td>22.86</td>
<td>Equivalent to Navajo Sandstone; southern limit is near New Castle</td>
</tr>
<tr>
<td>Late Triassic</td>
<td>Chirle Fm.</td>
<td>1,200</td>
<td>365.76</td>
<td>Thicknesses &lt;150 m in most areas but 365 m in Hardscrabble Mountain area; truncated beneath Entrada or Morrison in Elk Mountains and Gore Range</td>
</tr>
<tr>
<td>Early Triassic and Permian</td>
<td>State Bridge Fm.</td>
<td>5,000</td>
<td>1,524</td>
<td>Thickness &lt;200 m in most areas but 1,525 m in Hardscrabble Mountain area; equivalent to Moenkopi-Park City; depositional edge near Gore fault; truncated beneath Chirle or Entrada in southern Grand Hogback and Elk Mountains</td>
</tr>
<tr>
<td>Permian and Pennsylvanian</td>
<td>Weber Sandstone</td>
<td>100</td>
<td>30.48</td>
<td>From northern Grand Hogback, thins to east and south by facies change into Maroon Fm. and by truncation beneath State Bridge</td>
</tr>
<tr>
<td>Permian and Pennsylvanian</td>
<td>Maroon Formation (Upper and Lower)</td>
<td>15,000</td>
<td>4,572</td>
<td>Thins eastward and northward from Aspen area to depositional margin along Gore Range and east of Breckenridge; lower part intertongues with Eagle Valley Evaporite</td>
</tr>
<tr>
<td>Pennsylvanian</td>
<td>Eagle Valley Evaporite Fm.</td>
<td>Variable</td>
<td>Variable</td>
<td>Basinal evaporitic and color-transitional facies; intertongues with Maroon, gothic, and Belden Fms.; uppermost clastic units likely transitional facies into Minturn fm.</td>
</tr>
<tr>
<td>Pennsylvanian</td>
<td>Minturn Fm. And Gothic Fm.</td>
<td>6,600</td>
<td>2,011.68</td>
<td>Coarse clastic facies that grades into and intertongues (?) with Eagle Valley Evaporite; eastern depositional margin near Gore fault and Breckenridge</td>
</tr>
<tr>
<td>Pennsylvanian</td>
<td>Belden Fm.</td>
<td>900</td>
<td>274.32</td>
<td>Thins eastward to depositional margin west of Gore fault</td>
</tr>
<tr>
<td>Pennsylvanian</td>
<td>Molas</td>
<td>75</td>
<td>22.86</td>
<td>Discontinuous along pre-Belden unconformity</td>
</tr>
<tr>
<td>Early Mississippian</td>
<td>Leadville Limestone</td>
<td>275</td>
<td>83.82</td>
<td>Truncated beneath Belden near Gore Range and at Treasure Mountain</td>
</tr>
</tbody>
</table>

There is debate on whether the Mississippian Leadville limestone (Table 1) was deposited throughout the Ancestral Rockies, or selectively deposited (Brill, 1942, Tweto, 1977). An accepted interpretation from Brill (1942) is that Mississippian rocks did not extend throughout
the entire Front Range as the Uncompahgre highland was an area of non-deposition during the Mississippian, there is thinning and onlap of the limestones that flank of present-day uplifts. Tweto (1977) described a period of deposition and erosion that resulted in various unconformities throughout Cambrian, Ordovician, Devonian, and Mississippian rocks. These unconformities establish the stratigraphy underlying the formations now present throughout the Eagle Basin. Between the Cambrian and Mississippian, there is thought to have been relative tectonic stability until Early to Middle Pennsylvanian uplift from Ancestral Rocky Mountain crustal shortening (Pearigen, 2019; Scott et al., 1999).

Blakey (2009) studied the formation of the northeast-southwest-trending Transcontinental Arch that uplifted and eroded during Late Mississippian to Early Pennsylvanian time (Figure 2.2). Pennsylvanian-Permian uplift of the Ancestral Rocky Mountains had a northwest-southeast-trend, perpendicular to that of the Transcontinental Arch (Blakey, 2009; Mallory, 1972; Sloss, 1988). There are several hypotheses pertaining to the cause of the Pennsylvanian Ancestral Rocky Mountain Uplift (Blakey, 2009). These include transmittal forces from the Gondwanan-Laurussian collision (Kluth and Coney, 1981; Kluth, 1986; Dickinson and Lawton, 2003), wrench faulting and pull-apart basin generation of southwestern North America (Stephenson and Baars, 1986), and shallow-slab Cordilleran subduction from the southwest (Ye et al, 1996).
Figure 2.2. Reconstruction of The Ancestral Rocky Mountain region with uplifts and basins labeled (Blakey, 2009). Dashed lines show the location of the Transcontinental Arch. Key areas of interest for the proposed research are denoted by letters: CCT – Central Colorado Trough, EB – Eagle Basin, FRU – Front Range Uplift, PaB – Paradox Basin, and UnU – Uncompahgre Uplift.

Two elements that originated during the uplift throughout Middle Pennsylvanian and persisting through Jurassic time are the Eagle and Paradox Basins (Figure 2.3) (Kluth and Coney, 1981; Casey, 1980; Kluth, 1986; Blakey, 2009). During this time (specifically Atokan time) the formation and uplift of the ancestral Front Range Uplift and the Uncompahgre Uplift created flexural troughs (foreland basins) between the highlands in central Colorado (DeVoto, 1986;
Mallory, 1971; Tweto, 1977). The adjacent lowlands, or basins, created accommodation for thick sediment accumulation to fill the structural lows of this region. In Middle to Late Pennsylvanian time, the Eagle Basin was filled with clastic rocks of the Minturn, Gothic, and Maroon, and Eagle Valley Formations (Table 1). The center of the basin contains the Eagle Valley Evaporite (Formation) overlain by the Maroon Formation, while the flanks of the basin consist of Minturn, Gothic, and Maroon Formations (Table 1). (Tweto, 1977).

Figure 2.3. Paleogeography of the Paradox and Eagle Basins of west-central Colorado in Middle Pennsylvanian time (Modified from Rice, 2021).
Evidence of erosion is found in the regional unconformities throughout the Eagle Basin. The Middle Permian-Lower Triassic State Bridge Formation (Table 1) rests unconformably atop the Maroon and Weber Formations, all of which can lie unconformably below the Upper Triassic Chinle Formation (Freeman, 1971; De Voto, 1972). These unconformities are evidence of the stratigraphic and structural evolution of the Eagle Basin but overprinting of Laramide and more recent tectonic events create an obstacle for defining Late Paleozoic to Early Mesozoic tectonism.

The base Chinle and base State Bridge unconformities locally truncate steeply dipping Maroon minibasin sequence, while salt controlled accommodation also explains thickness variations in areas such as Hardscrabble Mountain (Figures 1.2 and 2.1) and the Fryingpan River area (Freeman 1971a; Tweto, 1977). Accommodation related to salt withdrawal provides reasoning as to why there is no indication of widespread erosion of these formations throughout the Eagle Basin (Tweto, 1977). The Sloane Peak member of the State Bridge (Table 1) is a consistent lithology and readily identifiable across both thick and thin sections of State Bridge. Tweto (1977) attributes these thickness variations of the Maroon and State Bridge (Table 1) to localized and rapid subsidence of the basement in response to sediment loading, or large-scale flowage of evaporites creating the depocenters (Figure 2.4). The Maroon and State Bridge-Chinle depocenters explain localized deposition triggered by subsidence, sediment load, and evaporite flowage (Tweto, 1977).
Tweto (1977) explored the possibility of a phase of salt tectonism that occurred during the Late Paleozoic to Early Mesozoic. Several areas of the Eagle Basin provide evidence of this lengthy salt movement including: a) the Permian syncline at the site of Red Table Mountain (Figures 1.2 and 2.1) which is now a west-northwest-trending anticline, b) the absence of evaporites from the Red Table Mountain #1 (Figure 2.1) well below the Red Table Mountain Permian syncline that were later squeezed into contiguous anticlines, c) salt-cored anticline between Red Table and Hardscrabble Mountains, and the diapiric anticline of Cattle Creek south of Glenwood Springs (Tweto, 1977; Freeman, 1971b; 1972a). These areas of interpreted evaporite flowage are hypothesized to occur beneath the Maroon and State-Bridge depocenters (Figure 2.4), causing abnormal thickness accumulations, rapid thinning, and unconformable surfaces (Freeman, 1971a, b; Tweto, 1977).
Evaporite flowage and resultant halokinetic deformation in areas such as the Cattle Creek diapiric salt wall (Figure 1.2) may have initiated as early as Late Pennsylvanian time based on work done in the Paradox Basin that suggests diapir formation soon after deposition in Late Paleozoic (Mallory, 1966). With evaporite deposition as early as Middle to Late Pennsylvanian, there is reason to hypothesize that evaporite flowage and associated deformation may have developed as early as Late Pennsylvanian to Early Permian time (Mallory, 1966; Tweto, 1977). The orogenic events during the Laramide likely reactivated these evaporitic flow structures causing overprinting deformation relationships.

Renewed uplift of the Uncompahgre uplift is thought to have begun again in Middle Triassic time as evidenced by the unconformity at the base of the Chinle that truncates the State Bridge found in the southern Grand Hogback and the eastern Elk Mountains (Tweto, 1977). The record of Triassic uplift was erased by the unconformity at the base of the Entrada Sandstone, which Tweto (1977) wrote records differential uplift of the Uncompahgre and Front Range uplifts.

The Laramide Orogeny of the Southern Rocky Mountains in west-central Colorado began with the uplift of the Sawatch Range (Figure 1.2) (Tweto, 1977). The Sawatch Range contains Cretaceous and Tertiary rocks that have been uplifted and deformed to create a large anticline. Tweto (1977) described dated ammonites found in the upper Mancos Shale and basal Mesaverde Formation to be 71-72 Ma; by 69-70 Ma, fault-controlled porphyries were being emplaced into sedimentary rocks on the flanks of the anticline. According to Tweto (1977), the early Laramide tectonic spasm is indicated by structures of igneous and sedimentary structural relationships. The Sawatch Range was eroded into abundant volcanic and igneous intrusive material that contributed to the Wasatch Formation of the southern Piceance basin (Tweto, 1977).
Soon after the erosion of the highland of the Sawatch Range, the Gore and Front Ranges (Figure 1.2) saw renewed uplift near the end of the Cretaceous (Tweto, 1977). The western flank of the Sawatch anticline is the location of present-day Elk Mountains where Bryant (1966) interpreted the range to be a thrust fault from gravity slide postdating the Sawatch structure. The last structures associated with the major Laramide uplift are the structural dome of the White River uplift and the long, steep monocline of the Grand Hogback (Figure 1.2) (Tweto, 1977).

A series of igneous intrusions began in late Cretaceous and lasted through the Paleogene giving rise to much of the mineral belt in Colorado (Tweto and Sims; 1963, Tweto, 1977). Throughout Neogene, there were events of rifting and block faulting that are related to the previously mentioned volcanism (Tweto, 1977). This rifting is a northern extension of the Rio Grande rift and controlled much of the topographic relief in this area of Colorado (Steven et al., 1995, 1997; Scott et al., 1999). Kirkham and Scott (2002) discuss two evaporite collapse centers; one that includes the lower Roaring Fork River and the Grand Hogback monocline, the other includes lower areas between Minturn, the White River uplift, Dotsero, and the Sawatch uplift. These Cenozoic collapse centers are identified at Eagle and Carbondale (Figure 2.5) (Kirkham and Matthews, 2000).
Figure 2.5. Map showing the location and extent of the Eagle and Carbondale collapse centers (after Scott 1997, written communication). These collapse features are thought to be a result of evaporite flowage due to overburden (Kirkham and Matthews, 2000).

The geologic features of Cenozoic time include volcanism, evaporite deformation and dissolution, collapse, and deep incision of stream valleys (Kirkham and Scott, 2002). The incision of valleys and deformation are attributed to collapse and anomalous evaporite tectonism that resulted in evaporite flow and diapirism in the Eagle Basin (Kirkham and Scott, 2002). The following sections will discuss the known structural and stratigraphic components of the Eagle Basin and the key areas of focus for this research.
2.3 Stratigraphy of the Western Eagle Basin

Attempts to unravel the complex structural history of the Eagle Basin requires an understanding of the stratigraphy within the basin. Sedimentary records in various areas throughout the basin along with paleogeographic reconstructions provide context for stratigraphic relationships between units, their associated thickness variations, and regional depositional trends. Until recently, much of the field work in this area defined stratigraphic relationships without regard for modern salt tectonic theories. This section will define the stratigraphic units of importance within this field area to set the stage for approaching this field work within the scope of modern salt tectonics (Table 1, Figure 2.6).
Figure 2.6. Correlation chart of units in various locations within the Eagle Basin (modified from Pearigen, 2019; Rice, 2021). Left column, the Horse Mountain-New Castle Region column, contains the key stratigraphy for this research in the western Eagle Basin.
Pre-Pennsylvanian constituents are the Cambrian Sawatch quartzite, the lower Ordovician Manitou limestone, Middle Ordovician Harding sandstone, upper Devonian Chaffee Formation containing the Parting quartzite and Dyer dolomite, and the Mississippian Leadville limestone, which lies unconformably below the Pennsylvanian rocks (Table 1) (Brill, 1942).

Early Pennsylvanian formations such as the Molas and Belden formations pre-date the salt in the basin. The Molas Formation is discontinuous, but the Belden is widely present throughout the basin, and thins to the east (Tweto, 1977). The Minturn and Gothic formations are mostly coarse clastics and intertongue with the Eagle Valley Evaporite (Table 1, Figure 2.6).

The Eagle Valley Evaporite deposited during Atokan-Desmoinesian time is an accumulation of evaporite rocks such as massive to laminated gypsum, anhydrite, halite, and beds of light-colored mudstone and fine-grained sandstone, thin limestone and dolomite, and black shale (Table 1, Figure 2.6) (Kirkham et al., 2008). This Middle Pennsylvanian formation was deposited in a marine evaporitic basin that formed as a restricted outlet of the Central Colorado Trough. (Mallory, 1971; Kirkham et al., 2008). As observed by Bryant et al. (2002), diapirism may affect the thickness of this formation making original thickness uncertain. Mallory (1971) gives a range of total thickness of the Eagle Valley Evaporite from 365 meters (1,200 feet) to as great as 2,750 meters (9,000 feet) (Table 1).

The Eagle Valley Formation locally intertongues with the Eagle Valley Evaporite. The Middle Pennsylvanian Eagle Valley Formation consists of interbedded reddish-brown, gray, reddish-gray, and tan siltstone, shale, sandstone, gypsum, and carbonate rocks (Table 1, Figure 2.6) (Kirkham et al., 2008). Kirkham et al. (2008) describe this formation as a conformable and intertonguing formation deposited in the Eagle Basin at the margin of the evaporitic basin. This formation is thought to be deposited more specifically at the distal end of a merging alluvial fan.
complex and a submarine environment of the evaporite basin (Kirkham et al., 2008). Kirkham et al. (2008) give the thickness range from 152 meters (500 feet) to 309 meters (1,000 feet) as thickness of this formation is quite variable across the Eagle Basin (Table 1). There is an interpreted contemporaneous deposition of the Eagle Valley, Minturn, and Gothic Formations that were deposited at the same time in different parts of the Eagle Basin (Schenk, 1992; Pearigen, 2019, Rice, 2021).

The Lower Permian and Pennsylvanian Maroon Formation is a fluvial deposit with eolian environment influences in the Central Colorado Trough (Figure 2.6) (Kirkham et al., 2008). Kirkham et al. (2008) describe the Maroon as a formation comprised of red beds of sandstone, conglomerate, mudstone, siltstone, and claystone with thin beds of gray limestone (Table 1). In the western Eagle Basin, the Maroon Formation can be split into the Lower and Upper Maroon. The Lower Maroon as described in the Storm King Mountain quadrangle unit descriptions, consists of grayish-red to reddish brown sandstone and siltstone with few distinct dark gray to medium gray limestone beds (Table 1) (Bryant et al, 2002). The Upper Maroon contains white to grayish, gray-red, and pale reddish-brown, very fine grained to coarse sandstones and less common pebble to cobble conglomerate (Bryant et al, 2002). The Schoolhouse Member or Weber Sandstone caps the Maroon Formation and has wide variety of feldspathic sandstone and conglomeratic sandstones (Table 1). (Kirkham et al., 2008). The Weber is most prevalent in the northwestern Eagle Basin and was deposited in a dominantly eolian system. (De Voto et al., 1986) The thickness of the Maroon Formation varies from 915 meters (3,000 feet) to 4,572 meters (15,000 feet) thick including the Schoolhouse Member and the variations adjacent to salt structures in the basin (see Table 1).
The State Bridge Formation is a Permian to Lower Triassic deposit from a fluvio-lacustrine environment with dominantly lacustrine processes (Table 1). The lithology consists of pale-red, grayish-red, reddish-brown, and greenish-gray, micaceous siltstone, clayey siltstone, shale and sandstone with prominent, thin sandy dolomite and sandy limestone (Kirkham et al., 2008). Johnson and others (1988) suggest an angular unconformity between the Schoolhouse Member of the Maroon and the red beds of the State Bridge Formation. There is a carbonate bed named the South Canyon Creek Dolomite Member (Figure 2.6) which can be used to divide the State Bridge Formation in the western and central Eagle Basin into three distinct members: the upper and lower State Bridge separated by the South Canyon Creek Member. (Bass and Northrup, 1950; Murray, 1958; Kirkham et al., 2008). The South Canyon Creek is interpreted as being laterally equivalent to the Phosphoria Formation and of Permian age (Bass and Northrop, 1980). The presence of the South Canyon Creek Member suggests a short-lived environment favorable for carbonate deposition. (Kirkham et al., 2008). The top of the State Bridge is time equivalent to the base of the Gartra Member of the Chinle Formation which is locally unconformable on the State Bridge/Sloane Peak.

The upper Triassic Chinle Formation lies unconformably atop the State Bridge Formation (Figure 2.6) (Freeman, 1971a, Kirkham et al., 2008). Scott et al. (2001) observed the contact of the Chinle and underlying State Bridge is often difficult to locate due to the discontinuous nature of the Gartra Member. Kirkham (2008) describes the Chinle as thin, even-bedded, and structureless red beds with dark-reddish-brown, orangish-red, and purplish-red, calcareous siltstone and mudstone with occasional thin lenses of limestone and pebble conglomerate (Table 1). Dubiel (1992) suggested the upper Chinle red siltstone beds formed by lateral accretion and floodplain deposits with a basal conglomerate and sandstone Gartra Member in areas of active
channel-fill and valley-fill deposits. Dubiel (1992) also observed a thin, basal sandstone in the Chinle Formation and correlated this to the Gartra Member (Kirkham et al. 2008).

Across most of the Eagle Basin, the Triassic Chinle Formation is unconformably overlain by the Upper Jurassic Entrada Sandstone and Morrison Formation. The Entrada-Chinle contact is sharp and unconformable presenting an erosional surface (Figure 2.6) (Kirkham et al., 2008). The Glen Canyon Sandstone is only present in the western Eagle Basin as an eolian sandstone (Scott and others, 2001). The Glen Canyon is described as yellowish-gray to light gray, fine to very fine grained eolian sandstone with cross beds that are on the meter to 10-meter scale (Scott and others, 2001). Kirhham et al. (2008) describe the Entrada as a light-gray to light-orange, cross-bedded, medium to very fine-grained, well sorted sandstone (Table 1). The cross beds are large scale leading to interpretations of eolian processes. The base of the Entrada includes pebbles and coarser sands which are accumulations of an eolian lag deposited on the Chinle Formation (Kirkham et al., 2008). The Morrison Formation conformably overlies the Entrada with a sharp contact. Lithologic descriptions by Kirkham et al. (2008) present pale-green and maroon mudstones and shale with thin beds of silty sandstone and thin, gray beds of limestone. Thickness of both formations vary over distances; the Entrada averages about 6-30 meters (20-100 feet) thick and the Morrison is nearly 122 to 152 meters (400-500 feet) thick (Table 1).
Figure 3.1. Simplified regional map of the western Eagle basin locating quadrangle names, well locations, cross section lines, and logged sections (modified from Scott et al., 2002).
3.1 Field Work

During the Spring of 2021 and Fall of 2021, structural and stratigraphic data collection commenced for this research project. Throughout the western extent of the Eagle Basin, field work included detailed structural mapping and stratigraphic logging within previously mapped quadrangles from the USGS and new mapping in the Deep Creek Point quadrangle (Figure 3.1). Structural data were collected in the field using FieldMove Clino in addition to digitized data from previously published USGS quadrangle maps. New contacts and stratigraphic relationships were mapped across the western Eagle Basin. FieldMove Clino and digitized data were imported into GoogleEarth Pro and GlobalMapper21.1 where the structural data could be visualized in spatially accurate x, y, z locations. Within GlobalMapper21.1, geologic contacts and maps were digitized for import into Move2019.1 software. Through a combination of new data from this field work and previously published work, new geologic maps and cross sections were created using GlobalMapper21.1, Move2019.1, and Adobe Illustrator 2021.

Two stratigraphic logged sections were measured using a 1.5-meter Jacob’s staff combined with field data to depict accurate thicknesses and descriptions of the key stratigraphic units. The first logged section was measured at the meter scale and specifically measured an overturned section of the Pennsylvanian-Permian-aged Upper and Lower Members of the Maroon Formations overlying the evaporite in the Storm King Mountain USGS quadrangle map (Figure 3.1). A published stratigraphic section (Bass and Northrop, 1950) along the South Canyon Creek was digitized and added to the logged section to obtain a full stratigraphic thickness of the Maroon Formation in the western Eagle Basin (Figure 3.1 and Appendix A). The second logged section measured the interpreted Neogene-aged Canyon Creek Conglomerate at a half meter scale in the Storm King Mountain quad (Figure 3.1). These new measured sections in
addition to previously measured and published sections in the western Eagle Basin give an accurate base-line logged section of the post evaporite formations.

Well data from the Colorado Oil & Gas Conservation Commission of the Department of Natural Resources were used in addition to logged sections to constrain depths of the evaporite in the subsurface in two key wells within the western Eagle Basin: the Elk Camp #12-22-05-91 and Rifle Creek Hatchery #1 (Figure 3.1). The formation depths associated with specific wells along cross section lines give accurate formation depths of the evaporite and overlying formations in the subsurface. The thicknesses of formations can be integrated in the reconstruction process to utilize accurate thickness within the model in Move2019.1.

3.2 Cross Section Construction

The construction of four structurally restored cross sections along with several smaller scale geologic cross sections provide two-dimensional views of key structural features throughout the western Eagle Basin. With several parallel sections perpendicular to key structural features, the cross sections, combined with detailed new maps collaboratively unravel the three-dimensional complexity of the salt-related features in the field area. The cross sections were created in Adobe Illustrator 2021 using a combination of all digital field data in Global Mapper 21.1 and Move 2019.1. All structural measurements from the Spring and Fall 2021 field season, USGS geologic quadrangle maps (Storm King Mountain, New Castle, Rifle Falls, Horse Mountain, and Silt) were digitized in Global Mapper. New and previously digitized geologic contacts were exported from Global Mapper and placed into Move 2019.1. Global Mapper 21.1 was used to assign elevation points to all data using elevation profiles from the USGS 10-meter
resolution National Digital Elevation Model (DEM). All data were exported from *Global Mapper* to then be utilized for structural modeling in *Move 2019.1*.

Georeferenced data input into *Move* allows for visualizing of the data in three-dimensional space and map view which are then projected into cross-section view. With structural measurements, contact data, and key well data, cross sections were drawn perpendicular to the significant structures throughout the field area. Faults and folds along each cross section were interpreted and constructed based on field data and observations made during the 2021 field season along with previously mapped and published geologic maps and cross sections (Scott and others, 1997; Scott and others, 2001; Bryant et al., 2002; Scott et al., 2002; Perry and others, 2003). Reinterpretations of structural features were made in the construction of each cross section to give a more accurate representation of subsurface structures and geometries related to pre-Laramide, salt-related deformation.

### 3.3 Structural Restorations

*Move 2019.1* was used to restore each cross section in the western Eagle Basin to interpret the evolution of the salt derived tectonism in the region. These cross sections were restored using a combination of workflows from the 2016 Midland Valley Move Tutorials (*Move 2019.1* Petroleum Experts), workflows from Pearigen (2019) and Rice (2021), and restoration methodologies after Rowan and Ratliff (2012). Cross sections were first interpreted using collected structural measurements, previously published and digitized measurements, and data from wells within the field area. Cross sections were then unfaulted, unfolded, and reconstructed to reflect pre-Laramide conditions (flattened to base Entrada at ~0m elevation); then, decompaction was run in the software using Table 2 to restore all pre-Laramide layers to original
thickness; lastly, isostatic adjustments and model conditioning were performed. These outlined workflows were repeated for each post-salt interval to reconstruct the Pennsylvanian aged structures and geometries (Figure 3.7). Rowan and Ratliff (2012) note the importance of restorations as a more qualitative analysis of individual and regional structures. Although salt introduces ambiguity in the restoration process, measures such as decompaction and isostatic adjustment help constrain the reconstructed salt-derived geometries.

3.3.1 Unfaulting

The first step in the restoration process is to unfault the section along all major faults. The tool used within *Move 2019.1* is the “2D Move-on-Fault” module. The seven algorithms offered in Move are simple shear, fault parallel flow, fault bend fold, fault propagation fold, trishear, detachment fold, and elliptical fault flow.

For the purposes of this research, fault parallel flow was the most applicable method based on its ability to model hanging wall movements in restoring deformation and forward modelling (Figure 3.2) (*Move 2019.1* Petroleum Experts). The fault parallel flow algorithm is based on Egan et al. (1997) and the analysis of particulate laminar flow over a fault ramp; the algorithm is used for modelling faults from fold and thrust belts as it divides the fault plane into dip domains. Flow lines are used to connect points to translate along a fault plane at a defined distance (*Move 2019.1* Petroleum Experts).
Figure 3.2. Cartoon of fault parallel flow module that unfolds based on flow lines along horizons associated with a fault.

Trishear was the second method used during the unfaulting stage of the restoration as it is suitable for forward modelling and restoring basement-involved deformation. This algorithm was developed to forward or reverse model fault related folds (Move 2019.1 Petroleum Experts). The trishear unfaulting uses a workflow that deforms beds in triangular zones of shear where the magnitude of slip is user-defined and the direction of slip is either parallel to the fault dip or parallel to the angle of the base of the zone (Figure 3.3) (Move 2019.1 Petroleum Experts).

Figure 3.3. Cartoon of trishear module that unfolds based on the triangular zone of shear associated with a fault.
3.3.2 Unfolding

There are three methods of unfolding within the Move 2019.1 modules: flexural slip, simple shear, and line length.

The flexural slip model is applied to concentric, layer parallel folds and rotates the limbs to a set datum (Figure 3.4). This algorithm of unfolding maintains line length of each horizon being unfolded and maintains orthogonal bed thickness and unit area as unfolding occurs. Flexural slip unfolding in Move uses a pin and a slip system parallel to a template bed as a control on unfolding (Move 2019.1 Petroleum Experts). Template beds within this algorithm are the bed or beds to be unfolded, passive objects are the underlying beds. Unfolding using the flexural slip method was sequentially preformed throughout the restoration process.

![Figure 3.4. Simple cartoon of the flexural slip module which unfolds based on a defined template bed to unfold to horizontal.](image)

Simple shear unfolding within Move is applied to geologic horizons when restoring to a pre-deformed state. The simple shear, or vertical, unfolding is used; this algorithm is best for flattening regional dips that have shallow dips (Figure 3.5). Unlike the flexural slip method, the
simple shear unfolding does not preserve line length of the formations, therefore the area is not preserved. Distortions may be present if a steeper dipping layer is restored using simple shear (Move 2019.1 Petroleum Experts). The simple shear method was used when correcting for any restoration artifacts throughout the unfolding and decompaction process.

Figure 3.5. Cartoon of the simple shear module that unfolds based on a defined bed to flatten to horizontal.

The line length unfolding module within Move 2019.1 may be applied to any folded strata within the program to unfold the stratigraphy to an undeformed state. The unfolding does not maintain area of formations as the module uses a pin and defined line to unfold to a horizontal, straight line (Figure 3.6). The line length method was periodically applied during the restoration process to accommodate for any restoration artifacts.
3.3.3 Reconstruction of salt geometries and assumptions

When restoring cross sections that involve salt, there is a level of ambiguity that must be considered. Based on previous restorations containing salt and the associated uncertainties, the list of limitations includes (Rowan and Ratliff, 2012; Pearigen, 2019; Rice, 2021):

- Salt area/volume decrease over time, attributed to three-dimensional flow of salt in and out of the plane of interest and the ability of salt to dissolve and collapse when introduced to liquids, namely meteoric waters

- Rotation of minibasins and salt-flanking strata about a horizontal and/or vertical axis during shortening

- Original salt thickness and amount of diapir growth, stretch, and squeeze

Due to these uncertainties, there are assumptions made in the restoration process based on a 3D approach and geologic reasoning derived from field work. Assumptions throughout this study were made using guidelines provided by Rowan and Ratliff (2012). When removing the effects of Laramide-aged deformation, the amount of shortening in the pre-salt and post-salt
sections were used to estimate the width of diapiric salt predating the Laramide deformation. Salt collapse and dissolution were restored by using volumetric analyses based on studies around collapse centers in the Eagle Basin by Lidke et al. (2002). The removed salt (by way Laramide or younger faulting and dissolution) was restored by estimating the fault throw and dip to re-inflate salt structures pre-existing the younger faulting and dissolution (Lidke et al., 2002; Rice, 2021).

3.3.4 Decompaction

Following the unfaulting and unfolding of Laramide related deformation, the 2D Decompaction module was used in Move. This tool is used to model the effects of rock volume change due to porosity loss associated with burial depth (Move 2019.1 Petroleum Experts). The isostatic effects and burial history are also calculated together with the changes in porosity. This workflow is developed from Sclater and Christie (1980) and the model assumes that porosity decreases with increasing depth, whereas porosity increases with decreasing burial depth (Move 2019.1 Petroleum Experts; Sclater & Christie, 1980). The following formula from Sclater and Christie (1980) represents this porosity and depth relationship:

\[ f = f_0 (e^{-cy}) \]

Where:
- \( f \) is the present-day porosity at depth
- \( f_0 \) is the porosity at the surface
- \( c \) is the porosity-depth coefficient (km\(^{-1}\))
- \( y \) is depth (m)

Sclater and Christie (1980) defined typical surface porosities and rates of porosity decay with increasing depth, these values and associated lithologies that are shown in Table 2. Note that salt is considered incompressible during the decompaction process, the incompressible depth coefficient assigned is zero porosity (Move 2019.1 Petroleum Experts).

Table 2. Lithology, surface porosity, and depth coefficient based on Sclater and Christie (1980) used during the decompaction module of the restoration process. The formations and color
codes correspond to the geologic formations represented in each 2D restoration and cross section.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Lithology</th>
<th>Surface Porosity ($f_0$)</th>
<th>Depth Coefficient ($c$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kwf: Williams Fork Sandstone</td>
<td>0.49</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>Kbs/Km: Bowie and Mancos Shales Shale</td>
<td>0.63</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>Kd: Dakota Sandstone Sandstone</td>
<td>0.49</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>Jm: Morrison Fm Sandstone</td>
<td>0.49</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>Je: Entrada Sandstone Sandstone</td>
<td>0.49</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>TrPcs: Chinle-State Bridge Shaly Sandstone</td>
<td>0.56</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>Pw: Maroon Fm Sandstone Schoolhouse Mbr</td>
<td>0.49</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>PPm: Maroon Fm Sandstone</td>
<td>0.49</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>Pe: Eagle Valley Fm Limestone/Shale</td>
<td>0.41</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>Pee: Eagle Valley Evaporite Salt</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Pb: Belden Fm/Pre-salt Limestone</td>
<td>0.41</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>M-pCq: Basement Basement</td>
<td>n/a</td>
<td>n/a</td>
<td></td>
</tr>
</tbody>
</table>

The 2D Decompaction module in *Move 2019.1* includes an isostatic relief tool. There are two methods of isostatic rebound correction to account for isostatic response to loading or unloading, Airy Isostasy or Flexural Isostasy. The chosen method for this study is the Airy Isostasy method in the decompaction module, based on practices set forth my Rowan (1993), Rowan and Ratliff (2012), Pearigen (2019), and Rice (2021). Airy isostasy is a suitable algorithm for restoring salt related deformation as it assumes a brittle crust is supported and allowed to move on a fluid layer. The crust is assumed to be of finite strength and cannot support its own weight. This means that when overburden is added, the response is to compact or decompact and isostatically adjust. The adjustments are vertical movements relative to the basement or defined basal surfaces (Move 2019.1 Petroleum Experts). This method is best suited for salt restoration because the isostatic response is calculated to bulk shift the entire
section based on the formation attributes above the defined salt layer (Move 2019.1 Petroleum Experts). The alternative method, flexural isostasy, is not used in this study based on the section length recommendations. In extensional and compressional systems, the flexural isostatic deflection should be accounted for and modeled in those sections with a length of ~25 kilometers or longer.

3.3.5 Model Conditioning and Quality Check

Through the decompaction and isostatic adjustment stages of the restorations, conditioning of the cross-section interpretations was done to compensate for geologically unreasonable artifacts in the restorations. Some artificial errors were created while decompacting and making isostatic adjustments such as variations in thicknesses of the salt and surrounding formations. Due to restoration derived errors, deformed horizons were periodically smoothed before proceeding to the next phase of decompaction and isostatic adjustment. Additionally, slight modifications were occasionally made to structural interpretations of geometries associated with salt. The model conditioning step occurred sequentially to allow for more accurate and geologically reasonable restorations.
Figure 3.7. Workflow of restoration of Section A-A’ in Move 2019.1. (A) Present day reconstruction of all horizons and geometries, (B) Unfault and unfold of all Laramide related deformation, (C) and (D) Decompaction to last stratigraphic unit above the evaporite. Note, model conditioning was performed sequentially.
CHAPTER FOUR
SALT-RELATED TECTONOSTRATIGRAPHY

4.1 Tectonostratigraphy

4.1.1 Leadville and Belden (pre-salt)

The pre-salt section is not widely present in the western Eagle Basin due to deep burial along the Laramide-aged Grand Hogback monoclinal structure. Basement and pre-Eagle Valley Evaporite strata are exposed over the White River Uplift, but the pre-salt formations that are visible in the western extent of the Eagle Basin are primarily the Leadville Limestone and Belden Formation (Figure 2.6). These formations have been uplifted and crop out at the top of basement-cored features in the field area. For the purposes of this study, the Leadville and Belden will not be described in detail aside from when they are in direct contact with the Eagle Valley Evaporite in key locations. As described by Perry and others (2003), the Leadville Limestone is predominantly a massive bioclastic limestone that is oolitic near the top with a thickness of 84 m (275 ft). The Belden Formation comprises of finely crystalline limestone, locally fossiliferous (Figure 4.1), and dolomite with black shales near the base and top (Perry and others, 2003) and has a maximum thickness of up to 274 m (900 ft). The thickness of the Belden formation across the western Eagle Basin is up to 130 m thick (426 ft) (Scott and others, 2001; Bryant and others, 2002; Perry and others, 2003). For the purposes of this study, the pre-salt is assumed topographically flat at the time of deposition in a marine environment.
Figure 4.1. Fossils (circled in red) in the Belden Formation in the Horse Mountain quad.

4.1.2 Eagles Valley Evaporite (salt)

The stratigraphy of the Eagle Valley Evaporite is variable across the western Eagle Basin field area. The evaporite is characterized in the field by white to medium gray, laminated gypsum and anhydrite with moderately to highly contorted beds. The evaporite crops out more commonly in the eastern extent of the mapping area versus that of the west (Figure 3.1). There are extensive, thick exposures of the Eagle Valley Evaporite in the Storm King Mountain quadrangle while there are less extensive, and thinner exposures in the Horse Mountain quadrangle adjacent to the White River Uplift. The evaporite contains limestone and poorly sorted, medium grained sandstones interbedded with the gypsum and anhydrite. The caprock in
the western Eagle Basin is massive, laminated, and microlaminated gypsum. Locally, the stratigraphic level of the Eagle Valley Evaporite is comprised of a coarse, intraformational breccia, interpreted as an autochthonous salt remnant (described in more detail below).

In the Storm King Mountain and Deep Creek Point quadrangles (Figure 3.1), the evaporite contains distinctive local lenses of massive gray limestone. The evaporite also contains some dark gray to black shales interbedded with gypsum, anhydrite, and limestone (Figure 4.2). As also noted by Bryant and others (2002), the evaporite cuts across bedding of the Eagle Valley Formation and affects the thickness and bedding configuration of the Eagle Valley and Maroon Formations. The evaporite also has a peculiar relationship with the Neogene (?) aged Canyon Creek Conglomerate (discussed later in this section).

The Eagle Valley Evaporite is mapped as medium gray to brownish-gray laminated gypsum and anhydrite in the New Castle quadrangle (Figures 3.1). The Deep Creek Point, unmapped quadrangle north of the New Castle quad, has vuggy caprock found adjacent to a contact with the Maroon Formation. 10-25m thick gray to brownish-gray limestones are interbedded with the evaporite in this area. The Elk Camp #12-22-05-91 well (Figure 3.1) drilled in the New Castle quadrangle constrains the depths and thicknesses of the units in the subsurface. The first visible halite bed of the Eagle Valley Evaporite was drilled at 4,928m (16,168ft) and the well reached its total depth in the evaporite at 5,312m (17,430ft) below surface (Figure 4.3).
Figure 4.2. Field photo from Bear Wallow Ranch (Storm King Mountain quadrangle) of evaporite with local fold and clastic siltstone to fine sandstone beds above (bedforms are noted with black dashed lines).
Figure 4.3. Gamma ray and sonic log through the Elk Camp #12-22-05-91 well in the New Castle quadrangle. Depth interval shown on the log is from 4,928m (15,780ft) to the total depth of the well at 5,312m (17,430 ft). The halite beds are highlighted in light blue where gamma ray is low and sonic is fast (around 60 microseconds per foot). The dashed black line marks contact between Eagle Valley Formation base and the Eagle Valley Evaporite top (modified from unpublished well log).
The Rifle Falls quadrangle has a greater amount of exposed Eagle Valley Evaporite (Figure 3.1). In this quadrangle, there is highly contorted, bedded gypsum and anhydrite (Table 1 and Figures 2.6). With cross cutting contacts between the evaporite and Eagle Valley Formation. Minor limestone, shale, and siltstone layers are found within the evaporite in this quadrangle (Scott and others, 2001). The Rifle Creek Hatchery #1 well is directly adjacent to the C-C’ cross section line in the Rifle Falls quadrangle (Figure 3.1). The total depth of this well is 101.5m (332ft) where the wellbore reached the first halite layer in the Eagle Valley Evaporite at around 20m (68ft). This gives an accurate subsurface data point along with the structural data to constrain the depth of the evaporite. The presence of halite in the wellbore at this shallow depth implies the Eagle Valley Evaporite has undergone dissolution leaving behind only gypsum in outcrop.

Puma Paw Ranch (Figure 3.1) within the Horse Mountain quadrangle contains an abundance of exposed evaporite (Figures 4.4 and 4.5). There are large, coarse, massive gypsum beds with some limestone and sandstone clasts found within the evaporite. Vuggy beds of gypsum were primarily found at or near the contact with the overlying Eagle Valley and Maroon Formations (described in the Eagle Valley Formation section). There was also a zone of heavily brecciated evaporite with clasts of gypsum, sandstone, and limestone (Perry and others, 2003). Throughout the field area, the evaporite has previously been interpreted to have diapirically injected contacts with the overlying Eagle Valley Formation and in some areas, the Maroon Formation (Figure 4.5) (Bryant and others, 2002).
Figure 4.4. Gypsum of the Eagle Valley Evaporite seen in the Horse Mountain quadrangle.

Figure 4.5. Eagle Valley Evaporite underlain by flat lying to gently dipping Eagle Valley Formation in the Horse Mountain quadrangle.

4.1.3 *Autochthonous Salt level Breccias (local to Horse Mountain Quad)*
In the Horse Mountain quadrangle, an in-situ boulder breccia overlies the Belden Formation (Figures 4.6 and 4.7). This breccia consists of large (up to ~1 m), angular clasts of cobble to boulders of sandstone and unfossiliferous limestone. The clasts and boulders of sandstone are characterized by planar laminations and cross beds of all orientations situated in a sandy matrix. Dark blueish-gray limestone cobbles to boulders are found in the sandy matrix and are predominantly angular to subangular (Figure 4.6B). Along the northern extent of the Horse Mountain quadrangle, this boulder breccia is found atop the steeply dipping beds of Belden Formation with a thickness of ~3-7 meters (~10-23 feet). In several areas, the breccia is found in tower-like outcrops (Figure 4.7), with poorly sorted limestone and sandstone boulders. This breccia is located at the original, autochthonous level of the evaporite, and is associated with both the Eagle Valley Evaporite and Eagle Valley Formation. The in-situ autochthonous breccia is interpreted to be formed by the evacuation and dissolution of salt.
4.1.4 Eagle Valley Formation (post-salt)

The Eagle Valley Formation is coeval with the Gothic and Minturn formations of the eastern and southern extent of the Eagle Basin (Pearigen, 2019; Rice, 2021) (Figure 2.6) and is seen in all the quadrangles of the study area. This formation is characterized by dark to medium gray limestones and yellowish-gray, pale orange, light olive gray, greenish gray to light greenish-gray sandstone, siltstone, and gypsiferous mudstone intervals (Scott and others, 2001; Perry and others, 2003; Scott and others, 1997). Variable thicknesses ranging from 0 m to ~50 m of white to light-gray gypsum are found throughout the Eagle Valley Formation in the western Eagle Basin. The sandstones within the Eagle Valley contain local cross beds and channel-type bedforms. Upper limestone beds locally exhibit, Middle Pennsylvanian aged fossils (Figure 4.8) (Scott and others, 2001; Perry and others, 2003; Scott and others, 1997).
Massive beds of vuggy gypsum and limestone are found adjacent to salt bodies in the field area. “Salt hopper” vugs are seen in these massive beds; the vugs have a cubic form indicating the weathering and consequent dissolution of halite crystals that were once present in the formation adjacent to salt bodies (Figure 4.9). Exposure of the Eagle Valley Formation is largely found in stream beds and valleys and in contact with the Eagle Valley Evaporite across the field area.
Figure 4.9. Vuggy diapir-adjacent limestone as seen in (A) the Storm King Mountain quad and (B) the Horse Mountain quad.

The Eagle Valley Formation is locally brecciated and tightly folded as evident in the Horse Mountain quadrangle in the western portion of the field area. The autochthonous level breccia (Figure 4.6 and 4.7) locally overlying the Belden is associated with the tight, intraformational antiforms and synforms found in the Eagle Valley Formation at Puma Paw Ranch. The Eagle Valley Formation represents the oldest post salt section across the field area and consequentially demonstrates the salt associated geometries in much of the western Eagle Basin.
4.1.5 Lower and Upper Members of the Maroon Formation (post-salt)

The Maroon Formation is informally subdivided into the Lower and Upper members of the formation in the western Eagle Basin (Scott and others, 1997; Scott and others, 2001; Bryant and others, 2002). This subdivision is only made in certain quadrangle maps but is extended into all areas of this study. This distinction is based on grain size and sorting distributions, color changes, and amount of limestone and calcareous silt and sandstone mapped in the upper and lower members of the formation (Figures 4.10 and 4.11) (Scott and others, 1997; Scott and others, 2001; Perry and others, 2003).

The Lower Maroon member as shown on the geologic map from Storm King Mountain (Figure 4.10 and Appendix A) has variable grain sorting and size from well- to poorly sorted sandstones and siltstones with fine to coarse grains (Figure 4.11A and B). The color of the lower Maroon Member varies from pale-red, grayish-red, light pinkish-red, and purplish red to grayish-white and gray. There are distinct limestone beds found at the top of the Lower Maroon and one or two more dispersed within the middle potion of the Lower Maroon. An uppermost limestone bed is near the contact between the Lower and Upper Maroon members and can be mapped throughout the western Eagle Basin. The last limestone bed in the lower Maroon Formation marks the transition into the upper member of the Maroon Formation.
Figure 4.10. Geologic map with the transect in red locating the Storm King Mountain logged section from the field work done in this project and the additional section logged by Bass and Northrop (1950) to the southeast along Canyon Creek.

The Upper Maroon Member, as characterized in the Storm King Mountain logged section (Figure 4.10 and Appendix A) is more consistent medium to coarse grained sandstones with a color range of red, moderately red, dark to medium pink, and reddish-maroon beds (Figure 4.11 C and D). The key difference from the Lower Maroon Member is the complete absence of limestone beds. There are coarse lag and pebble conglomerates towards the top of the Upper Maroon Formation. There are a greater number of cross beds and a moderate occurrence of planar beds within the upper portion of the Maroon.
The Upper and Lower Maroon members have variable thickness and exposure throughout the western portion of the Eagle Basin as the Maroon tends to thin overall from the east to the west. The total thickness of the Maroon Formation as logged in the Storm King Mountain quad is \( \sim 652.5 \text{m} \) (~2,140ft) (Appendix A). The thicknesses noted in the quadrangle maps indicate a thinning of the Maroon Formation from up to \( \sim 1,150 \text{m} \) thick in the easternmost quadrangle to \( \sim 450 \text{m} \) in the westernmost quadrangle (Scott and others, 1997; Scott and others, 2001; Bryant, 2002; Perry and others, 2003). This variability is attributed to both the relationship to the evaporite tectonism along with the uplift and the regional thinning across the Eagle Basin, amplified by the subsequent erosion adjacent to the White River Uplift.

Figure 4.11. Maroon Formation in outcrop: Lower member of the Maroon Formation cross beds in (A) the Storm King Mountain quad and (B) the Rifle Falls quad; the Upper member of the Maroon Formation (C) along Canyon Creek, and (D) in the Storm King Mountain quad (overturned).
4.1.6 Schoolhouse Member - Weber Sandstone (post-salt)

The Schoolhouse member of the Maroon Formation (Table 1 and Figure 2.6) (also known as the Weber Sandstone) is a white to grayish-black and grayish red sandstone unit that was deposited at the top of the Maroon Formation (Figure 4.12). The Schoolhouse as seen in the Storm King Mountain quadrangle is characterized by eolian and fluvial cross beds (Bryant and others, 2002). The primary sedimentary structure seen in the South Canyon Creek area were eolian cross beds (Figure 4.12). The exposed Schoolhouse in the Storm King Mountain quadrangle is up to 50m in thickness as measured and described previously (Stewart and others, 1972a; Bryant and others, 2002).

Figure 4.12. Weber sandstone with wind-blown cross beds along Canyon Creek.
4.1.7 State Bridge Formation (post-salt)

The State Bridge Formation (Table 1 and Figure 2.6). is predominantly exposed in the Storm King Mountain quadrangle to the southeast part of the study area. This formation consists of moderate red, grayish-red, and pale reddish-brown, very fine to very coarse-grained sandstone and less prevalent pebble and cobble conglomerate (Bryant and others, 2002). The unit has a sharp contact with the overlying Chinle Formation and a sharp basal contact with the Weber Sandstone. Within the basal 5 meters of the State Bridge is a dark gray to dark greenish gray dolomite known as the South Canyon Creek Dolomite. The dolomite contains hydrocarbon staining and grain coating (Bryant and others, 2002). The Canyon Creek dolomite member splits the State Bridge into upper and lower members (Bryan and others, 2002; Kirkham and others, 2008). Previously logged sections (Bass and Northrop, 1950) from South Canyon Creek and Main Elk Creek (Figure 4.10 and 4.13) have consistent thicknesses compared to other parts of the basin (Appendix A). The southern Eagle Basin has thickness ranging from ~300m up to ~730m; the north-central Eagle Basin has up to 1,525m of State Bridge on Hardscrabble Mountain (Figure 3.1) (Pearigen, 2019; Rice, 2021).
Figure 4.13. Logged section by Bass and Northrop (1950) of the upper part of the Maroon Formation through the Jurassic Entrada. Note the South Canyon Creek dolomite member found near the top of the Maroon Formation has later been identified as the State Bridge Formation (Kirkham and others 2008).

4.1.8 Chinle Formation, Glen Canyon Sandstone, and Entrada Sandstone (post-salt)

These formations are key to the mapping area as all are regionally mapped and are interpreted as deposited across a nearly flat surface at ~0m elevation before the uplift and deformation brought on by the Laramide Orogeny. Due to the consistent thicknesses and little facies variations, these formations are interpreted as deposits in a relatively flat paleogeographic setting with no significant influence of salt tectonics. The Chinle Formation is primarily a moderate-red, moderate-reddish-orange, and pale-red-purple siltstone and calcareous siltstone with a thickness of up to 130 meters (Scott and others, 1997). The “Glen Canyon” as seen in the
Rifle Falls quadrangle is exposed as yellowish-gray, grayish pink to light gray fine-grained sandstone with maximum thickness of ~20m (Scott and others, 2001). The Glen Canyon has prominent cross beds, and the formation locally creates steep cliff faces (Figure 4.14 A). In contrast, the overlying Entrada Sandstone creates smooth, rounded cliffs of light gray to grayish-orange-pink very fine-grained and well sorted sandstones. The Entrada exhibits large scale crossbedding (Figure 4.14 B) and has a sharp unconformable contact with the underlying Chinle (Scott and others, 2001) where the Glen Canyon is absent. The Entrada is interpreted as being deposited after the pre-Laramide salt tectonic phase. Thicknesses of the Entrada across the western Eagle Basin range from 25m to 35m (Scott and others, 1997; Scott and others, 2002; Bryant and others, 2002), and as thick as 55m in the Horse Mountain quad (Perry and others, 2003).
Figure 4.14. (A) Fluvial cross beds of the Glen Canyon (small wallet for scale) and (B) Wind-blown cross beds of the Entrada (Rifle Falls quadrangle).

4.1.9 Canyon Creek Conglomerate (Tcc) (localizeds to the New Castle and Storm King Mountain quads)

The Canyon Creek Conglomerate as described by Bryant and others (2002), is a light-brown, white, and very pale gray, clast supported and locally matrix supported, cobble to pebble
conglomerate (Figures 4.15-4.17). The conglomerate contains local lenses of pale red, medium to coarse grained sandstone and pebble lags as identified in the Canyon Creek Conglomerate measured section (Figure 4.15 and Appendix A). The outcrops of the Canyon Creek Conglomerate are restricted to the Storm King Mountain quadrangle only. As noted by Bryant and others (2002), and the measured stratigraphic section from this study, most clasts found in this conglomerate are sandstones and limestones. Sparse amounts of granite, quartzite, and dolomite clasts are found in this conglomerate. The total measured thickness of the conglomerate is 392 meters (Appendix A). The conglomerate is interpreted a result of a close to the source deposit from high gradient streams during the Miocene or Pliocene (Bryant and others, 2002). The relationship between the Tcc Conglomerate and outcrop of the Eagle Valley Evaporite is discussed in more detail in Chapter Five.

Figure 4.15. Geologic map with the transect in red locating the Canyon Creek Conglomerate logged section from the field work done in this project in the Storm King Mountain quadrangle.
Figure 4.16. Detailed view of the Canyon Creek Conglomerate outcrop in the Storm King Mountain quadrangle. Note angular cobbles to boulders of sandstone and limestone.

Figure 4.17. Outcrop of Canyon Creek Conglomerate on the southern exposure in the Storm King Mountain quadrangle.
4.1.10 Boulder conglomerate above Eagle Valley Formation (localized to unmapped Deep Creek Point area north of New Castle quadrangle)

A previously unmapped boulder conglomerate was discovered north of the New Castle quadrangle in the Deep Creek Point quadrangle (Figure 4.18). This conglomerate contains pebbles, cobbles, and boulders of dominantly sandstone, limestone, and chert in a clast supported matrix of very coarse sandstone. The boulder conglomerate is exposed directly overlying beds of the Eagle Valley Formation (Figure 4.19). The boulder conglomerate was determined to have a prominent angular unconformity at the sharp basal contact with upturned Eagle Valley Formation strata (Figure 4.20). The exposure of the conglomerate is not extensive, and the boulder conglomerate is most likely a Quaternary aged river terrace deposit on folded and eroded Eagle Valley Formation and Evaporite. This boulder conglomerate is not age equivalent to the Canyon Creek Conglomerate due to the differing structural elevation and a different composition and degree of lithification.
Figure 4.18. Location map of the boulder conglomerate in the Deep Creek Point quadrangle (highlighted with red star) where local angular unconformity is found below at the contact with the Eagle Valley Formation.
Figure 4.19. (A) Contact between the Eagle Valley Formation (below) and the boulder conglomerate (above) in the Deep Creek Point quad, (B) detailed view of contact with coarse layers throughout fine to coarse grained sand and silt.
Figure 4.20. View of the angular unconformity in the Deep Creek Point quad at the location of the boulder conglomerate overlying and truncating the Eagle Valley Formation.
4.2 Thickness Variations Basin wide

Throughout the western Eagle Basin, there are significant thickness and facies variations within the Eagle Valley Evaporite, Eagle Valley Formation, and Maroon Formation. The Eagle Valley Evaporite in the Storm King Mountain and New Castle quadrangles is widely exposed in the northern extent of each quadrangle, whereas in the Rifle Falls and Horse Mountain quadrangles, there is less extensive surface exposure of the evaporite (Figures 3.1, 5.1, and 5.2). There are lenses of exposure moving west through the Rifle Falls and Horse Mountain quadrangle with the overlying Eagle Valley Formation presenting variable dips from right way up to vertical to locally overturned. Throughout the western Eagle Basin, both the evaporite and Eagle Valley Formation are exposed in a west-northwest trend (Figure 3.1).

Previously studied in the Aspen region (Pearigen, 2019) and measured by Bryant (1954) and Freeman (1953), an approximate stratigraphic thickness of 3,200 meters of Maroon Formation is exposed along a section near the Maroon Bells. In addition, a total thickness of the Maroon Formation is measured at 4,500 meters along Woody Creek near Lenado (Figure 3.1) (Bryant, 1979; Pearigen, 2019). There is abrupt thinning of the Maroon Formation to as little as 100 to 500 meters in the subsurface as seen in the Eagle area of the northeastern Eagle Basin (Rice, 2021). In the Storm King Mountain quadrangle in the western Eagle Basin, the Maroon Formation is measured in a north-south section at up to 652.5 meters. As evident along various measured section, the Maroon Formation is of variable thickness throughout the whole of the Eagle Basin.

In the Aspen and Eagle region of the south and northeast Eagle Basin, the overlying section of the Weber and State Bridge also exhibit significant thickness variations. These formations tend to thicken and thin adjacent to the flanks of salt bodies and are dramatically
overthickened in the Hardscrabble minibasin (>1,500m) (Rice, 2021) (Figure 1.2 and 3.1). But in the western Eagle Basin, these overlying formations remain consistent with little to no thickness variability. The stratigraphy overlying the Maroon in the western Eagle Basin has consistent dips as seen along the Grand Hogback in the southern extent of this field area. In the western portion of this field study, these younger, right-way-up, south dipping strata contrast drastically with the Maroon and Eagle Valley Formations that range from steeply dipping to sub-vertical to locally overturned in exposures adjacent to the Eagle Valley Evaporite (Figure 3.1).
CHAPTER FIVE
STRUCTURAL COMPONENTS

5.1 Regional Geologic Map

Construction of the regional geologic map of the Eagle Basin (Figure 5.1 and Appendix C) combines data from the USGS geologic maps: Storm King Mountain, New Castle, Silt, Rifle Falls, and Horse Mountain (Scott and others, 1997; Scott and others, 2001; Bryant et al., 2002; Perry and others, 2003), previously published maps by Scott et al. (2002) (Figure 3.1), previous field work by Pearigen (2019) and Rice (2021), and data collected during the 2021 field season for this research.

The field work completed by Pearigen (2019) is the southeastern extent of the regional map that encompasses the Aspen region. The Aspen region of the Eagle Basin includes four quadrangles including the Woody Creek quad, Ruedi quad, Highland Peak quad, and Aspen Quad. The Laramide aged Sawatch Uplift bounds this area to the southeast, the minibasins mapped by Pearigen (2019) are the Woody Creek Minibasin, Snowmass Minibasin, and Red Table Mountain Minibasin. Additional structural features of the Aspen region include the Woody Creek salt wall, the Basalt Mountain fault zone, and the Ruedi Salt Diapir (Pearigen, 2019; Rice, 2021).

The northeastern region of the Eagle Basin includes work by Rice (2021) and includes the Gypsum, Eagle, and Wolcott quadrangles. Rice (2021) completed analysis on structural features including the Gypsum Creek salt wall, the Hardscrabble minibasin, the Eagle River salt wall, and the Bellyache, Red Canyon, and Wolcott minibasins.
The data mapped in the western extent of the regional map are found in the Storm King Mountain, New Castle, Deep Creek Point, Silt, Rife Falls, and Horse Mountain quadrangles (Figures 3.1, 5.1, and Appendix C). The structural features in the western Eagle Basin include the Grand Hogback, Rifle Falls minibasin, Bear Wallow diapir, East Elk Creek diapir, New Castle Arch, Rifle Creek diapir, Puma Paw salt complex, and White River Uplift. The structural data of strikes, dips, folds, faults, salt structures and associated geometries throughout the Eagle Basin are displayed on this regional map. Also presented in the western field area on the regional map are the locations of key wells, logged sections, and city locations for reference.
Figure 5.1. Regional geologic map of the Eagle Basin.
5.2 Western Eagle Basin Geologic Map

The geologic map of the western Eagle Basin (Figure 27 and Appendix C) includes sections A-A’, B-B’, C-C’, and D-D’ along with detailed cross-sections constructed along the eastern- and western-most section A-A’ and D-D’. The following sections will include a more detailed look along each cross-section line moving from east to west through the quadrangles.

Figure 5.2. Regional geologic map of the western Eagle Basin.
5.3 Cross Sections and Detailed Geologic Maps

5.4 Storm King Mountain Quadrangle

5.4.1 Geologic Map

Figure 5.3. Detailed geologic map of the Bear Wallow diapir in the Storm King Mountain quadrangle. The seven cross sections along the Bear Wallow diapir are notated on the map along with the logged sections of the Maroon Formation and the Canyon Creek Conglomerate (refer to Figures 4.10 and 4.15 in Chapter Four for a detailed map view of the logged sections). (Inset as noted on Figure 5.2)

Cross section line A-A’ and the associated detailed cross-section lines are generally oriented north to south through the main salt bodies across ~6 kms in the Storm King Mountain quad (Figure 5.3). The salt crops out at the surface along an east-southeast to west-northwest trend. A sequence of cross sections adjacent to the main A-A’ section give an along strike view of the evolving geometries associated with the salt and overlying Eagle Valley and Maroon Formations. The logged section through the Maroon Formation is also noted in this geologic map (Figure 5.3).
5.4.2 *Additional cross sections and 3D Area view*

5.4.3 *Cross section A1-A1’*

In the east, the Eagle Valley Evaporite is interpreted to be welded near the surface with little to no exposure at the surface along cross section A1-A1’ (Figure 5.5). In the absence of salt, there are steeply dipping to overturned beds of Eagle Valley and Maroon Formations at dips of around 85° right-way-up to the south, to 45° overturned to the north (Figure 5.4 and 5.5). With little salt exposed in the easternmost portion of Storm King Mountain with adjacent steeply dipping to overturned beds, the interpreted salt weld once fed a salt tongue to the south that led to local overturning of the beds within the Eagle Valley and Maroon Formations (Figure 5.5).

Figure 5.4. Detailed geologic map locating cross sections A1 and A2; note the overturned dips on the southern portion of both section lines and right way up dips on the northern part of the section lines. A2 crosses the Canyon Creek Conglomerate (Tcc) at the easternmost edge of the syncline.
Figure 5.5. Detailed view of the Bear Wallow diapir along the main cross section A1-A1’. The Maroon (PPm) and Eagle Valley Formations (Pe) overturned on the southwest side of the diapir and gradually flatten to right way up on the southwestern most portion of the section line. The Eagle Valley Formation dips right way up on the north side of the salt weld which creates a fault between the south and north side of the salt weld.

5.4.4 Cross section A2-A2’

Moving 1.5 km west of A1-A1’, cross section A2-A2’ (Figure 5.6) runs parallel to the main cross section line A-A’ (Figures 5.3). Like A1-A1’, this cross section shows the overturned beds in the Eagle Valley and Maroon Formations to the south of the salt body that crop out at the surface along this section line (Figure 5.6). The bedding dips range from around 40° to 60° overturned, dipping to the north. This geometry is reminiscent of a tabular composite halokinetic sequences as the upturned strata within the Maroon and Eagle Valley Formations likely terminated against a salt tongue that spread to the south locally overturning the sub allochthonous salt layers. The Canyon Creek Conglomerate is positioned in a syncline along this cross section on top of the Eagle Valley Evaporite (Figures 5.4 and 5.6). The southern limb of the syncline has steeper dips of around 65° to the north, whereas the northern limb has more gentle dips of around 35° to the south.
Figure 5.6. Detailed view of the Bear Wallow diapir along the main cross section A2-A2’. The Maroon (PPm) and Eagle Valley Formations (Pe) are overturned on the southwest side of the diapir. The Eagle Valley Formation dips right way up on the north side below the salt. The Canyon Creek Conglomerate (Tcc) is a narrow, deep syncline that with steep dips on the south and shallower dips on the north; all dips point to the center of the syncline.

Figure 5.7. Field image along the approximate location of cross section A2-A2’ of the Canyon Creek Conglomerate (Tcc) in a syncline with associated dip measurements labeled and bedforms annotated (view to the east).
5.4.5 Cross section A-A’

Cross section line A-A’ is positioned parallel and ~1 km west of A1-A1’ (Figures 5.3 and 5.8). This section line contains right-way-up, steeply dipping beds of the Eagle Valley and Maroon Formations which contrast with previous sections to the east (Figure 5.9). On the south side of the diapir, north dipping bed measurements range from 70° to 85° right way up along this part of the salt structure (Figure 5.8). On the north side of the down-to-the-north fault, Maroon Formation beds are right way up and south dipping. Moving north of the fault mapped along this cross section, there is another salt outcrop. This is more indication of the along strike transformation of the salt wall and salt tongue moving west through each section. Also note the Canyon Creek Conglomerate positioned within the salt as a syncline with dips ranging from ~40°-45° on the north limb and 65°-75° along the south limb (Figure 5.8).
Figure 5.8. Detailed geologic map locating cross sections A2 and A3; note the variability in right way up and overturned dips on the southern portion of both section lines and right way up dips on the northern part of the section lines. A2 crosses the Canyon Creek Conglomerate (Tcc) at the easternmost edge of the syncline.
Figure 5.9. Detailed view of the Bear Wallow diapir along the main cross section A-A’. The Maroon (PPm) and Eagle Valley (Pe) Formations are steeply dipping and right way up on the southwest side of the diapir. The Maroon and Eagle Valley Formations dip right way up on the north side below the salt. The Canyon Creek Conglomerate (Tcc) is a narrow, deep syncline that with steep dips on the south and north; all dips point to the center of the syncline.

5.4.6 Cross section A3-A3’

A3-A3’ is found ~500 m west of A-A’ (Figure 5.3) and has locally overturned beds of Maroon Formation on its southern flank adjacent to the Bear Wallow diapir (Figure 5.10). Overturned dips on the south side of the diapir dip around 60°-80° to the north and the right-way-up dips to the north of the salt have around 50° dips to the south (Figure 5.8). The Eagle Valley Evaporite crops out again to the north as an interpreted low relief diapir/salt pillow. The locally overturned beds along (Figure 5.10) the south side of the diapir contrast with the previous section (A-A’) (Figure 5.9) where no overturned measurements are seen. These change from right way up beds to overturned beds in adjacent sections illustrate the variable geometries along strike of the salt body moving to the west. The same Canyon Creek Conglomerate syncline is
seen along this cross-section line in a broader, more open syncline atop the Bear Wallow diapir (Figure 5.10).

Figure 5.10. Detailed view of the Bear Wallow diapir along cross section A3-A3’. The Maroon Formation (PPm) is steeply dipping, right way up to locally overturned on the southwest side of the diapir. The Maroon and Eagle Valley Formations dip right way up on the north side below the salt. The Canyon Creek Conglomerate (Tcc) has steeper dips on the south and shallower dips on the north with all dip directions to the center of the syncline.
5.4.7 Cross section A4-A4'

This cross section is located ~500 m west of A3-A3' (Figures 5.3 and 5.11) and has steeply dipping, right-way-up to locally overturned beds of Eagle Valley and Maroon Formations on the south side of the salt (Figure 5.12). To the north, there are faulted, right-way-up beds dipping at ~40° to the south. Further to the north along this section line is more evaporite outcrop which is reminiscent a low relief diapir or salt pillow. The Canyon Creek Conglomerate continues along strike in this synformal structure within the salt (Figure 5.12).

Figure 5.11. Detailed geologic map locating cross sections A4 and A5; note the overturned dips on the southern portion cross section A4-A4’ and the right way up dips on the south side of section A5-A5’. Both cross sections intersect the Canyon Creek Conglomerate.
Figure 5.12. Detailed view of the Bear Wallow diapir along cross section A4-A4’. The Maroon (PPm) and Eagle Valley (Pe) Formations are steeply dipping, right way up to locally overturned on the southwest side of the diapir. The Maroon and Eagle Valley Formations dip right way up on the north side below the salt. The Canyon Creek Conglomerate is a narrower, deep syncline that with steeper dips on the south and shallower dips on the north, all dips point to the center of the syncline.

5.4.8 Cross section A5-A5’

Cross section A5-A5’ is ~1 km west of section line A4-A4’ (Figures 5.3 and 5.13) and has similar geometries as the previously described cross sections (A3, A, and A4) (Figures 5.9, 5.10, and 5.12). The Eagle Valley and Maroon Formations to the south of the salt are right-way-up beds dipping around 60° to the south and the dips get gentler (~30°) as they flatten up section away from the salt (Figure 5.11). There are right-way-up Maroon and Eagle Valley beds dipping around 45° to 75° to the south and there is another outcrop of evaporite in the northern part of the section line (Figure 5.13). The northern evaporite outcrop suggests a salt pillow or low relief diapir. Consistent with the previous sections, the Canyon Creek Conglomerate is located in the center of the evaporite in a syncline (Figure 5.13).
Figure 5.13. Detailed view of the Bear Wallow diapir along cross section A5-A5’. The Maroon (PPr) and Eagle Valley (Pe) Formations are steeply dipping, right way up on the southwest side of the diapir. The Maroon and Eagle Valley Formations dip right way up on the north side below the salt. The Canyon Creek Conglomerate (Tcc) is a narrower, deep syncline that with steeper dips on the south and shallower dips on the north, all dips point to the center of the syncline.

5.4.9 Cross section A6-A6’

The western most cross section in the Storm King Mountain quad is located ~2 km west of A5-A5’ (Figures 5.3 and 5.14) and contains overturned beds of Eagle Valley and Maroon Formations on both the south and north sides of the salt body (Figure 5.15). The southern beds dip at angles of ~60° and the northern most beds are heavily overturned with dips of ~40°. This geometry is indicative of a salt canopy that spreads to the north and south (and likely in and out of the plane view) to locally overturn the strata on both the north and south sides of the salt body (Figure 5.15). The Canyon Creek Conglomerate appears in the western extent of this area, still situated in a synform in the evaporite, but is a thinner deposit with lower dips of ~10°-15° on each limb the syncline (Figure 5.14).
Figure 5.14. Detailed geologic map locating cross section A6. Both the southern and northern portion of the map have overturned beds. This cross section traverses the westernmost part of Canyon Creek Conglomerate filled syncline where the dips are shallow and the syncline is broad and shallow.
Figure 5.15. Detailed view of the westernmost extent of the Bear Wallow diapir along cross section A6-A6’
. The Maroon (PPm) and Eagle Valley Formations (Pe) are overturned on the southwest side of the diapir. The Eagle Valley Formation is very overturned on the north side below the salt. The Canyon Creek Conglomerate (Tcc) is a wider, shallower syncline that has thinned from the eastern extent of the syncline. Shallow dips point to the center of the syncline.

The three-dimensional view looking west-northwest into the seven cross sections of the Storm King Mountain quadrangle illustrate the evolution of salt-related geometries moving along strike (Figure 5.16). There is a dramatic variability from right-way-up to steeply dipping, to overturned beds along the flanks of the evaporite in this quadrangle. Placing the two-dimensional lines in three dimensions illustrates the structural change from a welded salt structure in the east to a south-verging salt tongue, a north-verging salt tongue, and finally a flared salt stock in the westernmost section line. This view shows the dramatically variable dips along strike along with the evolution of the salt body. Also seen in this three-dimensional view is the Canyon Creek Conglomerate that is positioned in a syncline in all but the easternmost section line. With dip measurements along the syncline, data supports a tight syncline to the east that opens to a wider, shallower syncline with gentler dips in the west (Figure 5.16).
The Canyon Creek Conglomerate found in the Storm King Mountain quadrangle has not been age dated, but the syncline on the top of the evaporite suggests Late Cretaceous to Paleogene, Laramide driven uplift, exposure and dissolution of the evaporite followed by later channelized deposits depositing on the crest of the dissolving and collapsing salt section. Although uncertain, the age of the Canyon Creek Conglomerate is likely Neogene, between ~23Ma and present day (Bryant and others, 2002). Cartoon illustrations suggest a progressive deepening syncline as the evaporite progressively dissolved and collapsed (Figure 5.17). With several pulses of a high gradient channelized flow, the channel cut deeper into the syncline now seen in the Bear Wallow diapir and the shallowing dips up section suggest a growth sequence as older beds were progressively rotated with diapir collapse.
Figure 5.17. Cartoon of Canyon Creek Conglomerate (Tcc) formation from Maroon Formation (PPm) Pennsylvanian-Permian time (bottom) to present day (top). Cartoon illustrates the recent formation of the Canyon Creek Conglomerate filled syncline on top of uplifted, dissolved, and collapsed Eagle Valley Evaporite (Pee).
5.4.10 Structures

There are several normal faults throughout this quadrangle which are attributed to both salt tectonism and later Laramide aged deformation such as the development of the Grand Hogback and White River uplift. As described by Scott et al. (2002), the Grand Hogback is a uniform monocline that dies out to the south into a structural bench north of the Colorado River. Scott et al. (2002) informally defines a structural bench as a “bench-like zones of locally shallowly dipping strata between the more uniform, steeply dipping parts of a monocline.” As mapped by Scott et al. (2002) and seen in this field study, there are a cluster of southern diapirs and a separate string of northern diapirs as seen in the A-A’ cross sections and 3D view (Figure 5.16). The two lineaments of diapirs are locally separated by a north-dipping normal fault presumably driven by late deformation after the Laramide Orogeny. Bryant and others (2002) interpret this extensional feature to be associated with dissolution and collapse of the evaporite. In the northeast section of the Storm King Mountain quad, there is exposed pre-salt strata of Mississippian to Cambrian aged rocks that dip gently southwest off the White River Uplift. A high angle, normal fault offsets these units to place them against Pennsylvanian rocks (Scott et al., 2002).

Scott et al. (2002) focused on three relationships to characterize the complex structural relationships in this quadrangle: 1) the structural bench, 2) the thick, young Canyon Creek Conglomerate that forms a tight syncline, and 3) the low angle normal faults that cut steeply dipping Paleozoic strata against the White River Uplift. They speculated that the structural bench is related to evaporite removal along the White River uplift by flow, diapirism, and later dissolution. Scott et al. (200) also interprets the Grand Hogback as a result of a blind thrust and fault-propagation-fold with sub horizontal movement within the crystalline basement. The
proximity to the structural bench and evaporite led Scott et al. (2002) to relate evaporite flow and dissolution to the later formation of the Laramide aged Grand Hogback.

5.5 New Castle Quadrangle

Cross section B-B’ is a northeast to southwest cross section line that runs through the northern portion of the New Castle quadrangle and the southern part of the Deep Creek Point quad (Figure 5.18). The present-day geometries are shown in Figure 5.19 with the Grand Hogback and White River Uplift in the south and north, respectively. The East Elk Creek diapir, as previously defined by Scott et al. (2002), is mapped in more detail in this project to characterize the Maroon Formation outcrops found on top of the evaporite. This Maroon Formation outlier is explained by the development of a diapiric high during Eagle Valley Formation time that explains the lack of Eagle Valley Formation on top of the diapir (Figures 5.19 and 5.20). The diapir had a thin roof comprised of Lower Maroon (and possible Upper Maroon?). With the onset of post Laramide dissolution, steepened dips in this Maroon section resulted from collapse of the diapir. The section of Maroon encompasses an abnormally thin Lower Maroon sequence, topped by a poorly exposed Upper Maroon Member. Both have variable strikes and dips with a dominant dip direction towards the center of the outlier. This bowl-like, synform of Maroon present on the collapsed crest of the salt is reminiscent of the Canyon Creek Conglomerate collapse in the Storm King Mountain quadrangle (Figure 5.20), albeit a much older roof sequence.
5.5.1 Geologic Maps

Figure 5.18. Detailed geologic map of the East Elk Creek diapir in the New Castle and Deep Creek Point quadrangles. The cross section crosses the Grand Hogback, the New Castle Arch, the East Elk Creek diapir, the Maroon Formation (PPm) outliers found in the center of the Eagle Valley Evaporite (Pee), and the White River Uplift in the northeast. Note the Elk Camp #12-22-05-91 well is along this cross-section line.

The Elk Camp #12-22-05-91 constrains the depths and thicknesses of the mapped units in the subsurface. Well tops from the Elk Camp well log data correlate with the structural field data along cross section B-B’ (Figure 5.19). The first halite bed of the Eagle Valley Evaporite was encountered at 4,928m (16,168ft) and the well reached its total depth in the evaporite at 5,312m (17,430ft) (Figure 4.3). Other key well tops include the Dakota Sandstone at 985.7m (3,234ft),
Entrada Sandstone at 1,087m (3,567ft), Chinle-State Bridge at 1,258m (4,130ft), and Maroon Formation at 1,492m (4,898ft) (Figure 5.19).

Figure 5.19. Cross section B-B’ running from south-southwest through the Grand Hogback, the East Elk Creek diapir, and the White River Uplift in the north-northeast. The New Castle arch in the center of the section folds the Maroon Formation (PPm) north of the Grand Hogback. The Elk Camp #12-22-05-91 well drilled along this cross section constrains depths and thicknesses of formations south of the diapir. (Inset is Figure 5.20)
Figure 5.20. Detailed view of East Elk Creek diapir along cross section B-B’. The Maroon Formation (PPm) is found in a synclinal, bowl-shaped outlier. Dip directions all point to the center of the syncline within the collapsed salt as a result of late collapse post the Laramide uplift and erosion. (Inset as noted on Figure 5.19)

The present-day construction of cross section B-B’ crosses the East Elk Creek diapir. The evaporite is seen as the main feature towards the center of the section and a second, more northern occurrence of evaporite interpreted as a small salt diapir that formed early during the deposition of the Eagle Valley Formation. Bedding dips in the Maroon and Eagle Valley Formations are variable on the south side of the diapir ranging from 50° to 60° right way up. The lens of Eagle Valley Formation to the north of the main diapir has dips in the right way up, 40° range (Figures 5.18, 5.19 and 5.20).
5.5.2 Structures

Scott et al. (2002) published an adjacent cross section line through the eastern Maroon outlier that assumes the original thickness of evaporite is ~450 m. The New Castle Arch, the northwest-southeast trending anticline in the New Castle quadrangle (Figure 5.18), is a folded and faulted structure in the absence of the structural bench seen in the Storm King Mountain quad (Figure 5.18) (Scott et al., 2002). Scott et al. (2002) speculates the New Castle Arch to be a result of Laramide deformation first triggered by a blind thrust in the underlying basement rocks. This study asserts pre-Laramide salt tectonism as an additional catalyst of the New Castle Arch formation as salt mobility first activated by differential overburden loading and a basement blind thrust. Diapirism of the Eagle Valley Evaporite at depth could contribute to the folding and faulting observed at the surface in the New Castle quadrangle (Figure 5.18).
5.6 Rifle Falls Quadrangle

Cross section C-C’ is a northeast to southwest line that runs through the Rifle Falls quadrangle (Figure 5.21 and 5.22). The present-day cross section geometries are shown in Figure 5.23 with both the Grand Hogback to the south and White River uplift in the north. C-C’ runs through the south dipping Rifle Falls Fault and another large fault that dips to the north. The Rifle Falls Fault juxtaposes Pennsylvanian strata against Devonian aged rocks (Scott et al., 2002).

5.6.1 Geologic Map

Figure 5.21. Detailed geologic map of the Rifle Creek diapir in the Rifle Falls quadrangle. The cross section crosses the Grand Hogback, the Rifle Creek diapir, and the White River Uplift in the northeast. (Inset is Figure 5.22)
Figure 5.22. Detailed geologic map of the Rifle Creek diapir in the Rifle Falls quadrangle. (Inset as noted on Figure 5.21).

Figure 5.23. Cross section C-C’ running from south-southwest to north-northeast through the Grand Hogback, the Rifle Creek Hatchery #1 well, the Rifle Creek diapir, Rifle Falls fault, and the White River Uplift in the north-northeast. The Rifle Creek Hatchery #1 well drilled ~300 m along strike from this cross section constrains the depth of the top of the Eagle Valley Evaporite (Pee). (Inset is Figure 5.24)
Figure 5.24. Detailed view of cross section C-C’ with the Rifle Creek Hatchery #1 well in the center of the section south of the Rifle Creek diapir. (Inset as noted in Figure 5.23)

The present-day construction of cross section C-C’ as shown in Figure 5.23 displays the main diapir and associated broad salt pillow in the Rifle Falls quadrangle. Detailed construction of cross section C-C’ illustrates a low relief diapir and salt pillow in the subsurface where the Rifle Creek Hatchery #1 well encountered Eagle Valley Evaporite as shallow as 20m (68ft) below the surface (Figure 5.24). Bedding dips in the Maroon and Eagle Valley Formations on the southern side of the diapir range from 8° to 70° upright while the beds of the Eagle Valley Formation on the north side of the diapir are around 30° to 50° (Figure 5.22). The variable dips to the south are the result of upturned strata on the flank of the diapir and over the salt pillow interpreted in the subsurface.

5.6.2 Structures

A similar structural bench to the one seen in the Storm King Mountain quad (Figure 5.9) is present in the Rifle Falls quad. This alludes to a similar diapiric influence as seen in the Storm King Mountain quad where subsurface salt flow contributes to the folding and faulting seen at the surface. The Eagle Valley Evaporite is diapiric against the Eagle Valley Formation with
upturned strata flanking the diapir indicating an Eagle Valley Formation age of passive diapirism.

Scott et al. (2002) discusses the enigmatic structure north of the Rifle Falls Fault along the White River uplift, where Mississippian and Devonian aged rocks dip at ~48° to the north contrary to the ~2° southward dip of the White River uplift (Figure 5.21 and 5.22). The steep northward dip abruptly decreases to match the regional White River uplift dips of the strata underlying the Eagle Valley Evaporite, this suggests a direct relationship to the nearby diapir (Scott et al., 2002). Scott et al. (2002) suggests the proximity of the salt to the footwall of the fault demonstrate a “genetic relation between the two,” which may imply slippage along mobile, dissolving salt.
5.7 Horse Mountain Quadrangle

The Horse Mountain geologic map (Figure 5.25) displays cross section line D-D’ and four adjacent cross sections to illustrate the changing geometries in the westernmost area of this project. The geologic map includes remapped contacts of the Eagle Valley Evaporite as the evaporite proved more extensive than previous maps of this area. Additionally, the anticline originally mapped by Perry and others (2003) on the USGS quadrangle map is extended in the northwest-southeast direction underlying all the evaporite in this region.

5.7.1 Geologic Map

Figure 5.25. Geologic map of the Puma Paw salt complex in the Horse Mountain quadrangle. The cross sections in this quad cross the main salt complexes and the White River Uplift in the northeast. (Inset is Figure 5.26)
Like the cross section in Storm King Mountain, there are five cross sections in this quadrangle to characterize the along strike evolution of the Eagle Valley Evaporite and the adjacent formations (Figure 5.26). With a three-dimensional view, the effects of salt tectonism in the field area are better understood.

Figure 5.26. Detailed geologic map of the Puma Paw salt complex in the Horse Mountain quadrangle. (Inset as noted in Figures 5.2 and 5.25)
5.7.2 Additional cross sections and 3D Area view

5.7.3 Cross section D1-D1’

Cross section D1-D1’ is the eastern most section line in the Horse Mountain quad and this section line crosses through the easternmost salt body that crops out in the quadrangle (Figures 5.26 and 5.27). The Maroon Formation adjacent to the salt in the south has steeply dipping to locally overturned beds (Figure 5.28). The northern extent of the evaporite is defined by an angular boulder breccia that sits on top of the Belden Formation (the pre-salt section.) This breccia sits at the autochthonous, depositional level of the Eagle Valley Evaporite, though the mobile component of the Eagle Valley Evaporite no longer occupies its original position. The autochthonous breccia is a remnant of the mostly evacuated original evaporite level. The Eagle Valley Evaporite is seen in contact with the Maroon to the south and structurally above the Eagle Valley Formation in the form of an interpreted allochthonous salt sheet. The folds seen in between or below the salt bodies present as an antiform and synform pair. The cause of these folds is likely localized shortening within the minibasin brought on by the flowing allochthonous salt. The salt became diapiric in two critical locations which resulted in early formed anticlinal and synclinal structures seen beneath the salt sheet (Figure 5.29).
Figure 5.27. Detailed map locating cross section D1-D1' running from south-southwest to north-northeast through the salt body that crops out at the surface with folded Eagle Valley Formation below the salt in an antiform.

Figure 5.28. Cross section D1-D1' running from south-southwest to north-northeast through the salt body that crops out at the surface with folded Eagle Valley Formation below the salt in an antiform. Note the steeply dipping, right way up Maroon Formation to the south.
Figure 5.29.  A) Field image along cross section D1-D1’ in the Horse Mountain quadrangle. B) Bedding dips and bedforms are drawn in image to show contact relationships between the pre-salt Belden Formation (Pb) through the Maroon Formation (PPm) on the south side. (Note the field images are on a smaller, more detailed scale than that of the constructed cross section in Figure 5.28).
5.7.4 Cross section D-D’

Cross section D-D’ (Figure 5.31) is 1 km west of section D1-D1’ along the second ridge line where salt crops out at the surface (Figure 5.26). This longer section line runs through the Grand Hogback in the southwest and the White River uplift in the northeast. Unlike D1-D1’, there is not one continuous salt outcrop at the surface, rather, there are two distinctly separate salt outcrops with localized folds found between the two (Figures 5.30, 5.31, and 5.32). Possible erosion and dissolution removed the salt section from blanketing the top of the antiform and synform as seen in D1 (Figure 5.28). The southern contact of the salt with the Maroon Formation is characterized by steep to locally overturned dips of ~70° right way up, dipping to the south, to 75° overturned and dipping to the north (Figure 5.30). The autochthonous level boulder breccia is also seen along this section at the northern contact with the Belden Formation (Figure 5.32) (steeply dipping at 80° to the south).
Figure 5.30. Detailed map locating the central portion of cross section D-D’ running from south-southwest to north-northeast through the salt body that crops out at the surface with folded Eagle Valley Formation structurally below the salt in an antiform.
Figure 5.31. Cross section D-D’ illustrating the salt body that crops out at the surface with folded Eagle Valley Formation below the salt in an antiform and adjacent synform. Note the steeply dipping, right way up to overturned Maroon Formation to the south of the southern salt body. Location in Figure 5.30.
Figure 5.32 (A1) Field image along cross section D-D’ looking west in the Horse Mountain quadrangle. (A2) Bedding dips and bedforms are drawn in on the lower image to show contact relationships between the pre-salt Belden Formation through the Maroon Formation on the south side. (B1 and B2) view of cross sections D-D’ and D1-D1’ looking east.
5.7.5 Cross section D2-D2’

Moving along strike ~500 m west of the D-D’ section line (Figure 5.26), cross section D2-D2’ has a similar relationship with the Maroon Formation as the previously described cross sections (Figure 5.33). There are locally overturned beds of Maroon Formation with 89° right way up beds to 74° overturned beds on the south side of the salt complex. The key difference along this cross section is that an abrupt thinning of the interpreted salt feeder is seen in the field on the south side where the Maroon is steeply dipping against the salt. The Maroon Formation strata are truncated or thinned against the dramatically thinned evaporite (Figure 5.34). A thin autochthonous level boulder breccia crops out overlying the Belden Formation (Figure 5.37).

Figure 5.33. Detailed map locating cross sections D2, D3 and D4 running from south-southwest to north-northeast through the salt body that crops out at the surface with folded Eagle Valley Formation below the salt in an antiform.
Figure 5.34. Cross section D2-D2’ illustrating the salt body that crops out at the surface with folded Eagle Valley Formation below the salt in an antiform and adjacent synform. Note the rapid dip change in the Maroon Formation to the south of the southern salt body.

5.7.6 Cross section D3-D3’

The next cross section is positioned ~170 m west of section D2-D2’ (Figure 5.26) and has similar features as seen in the previous cross section lines. The Maroon Formation is steeply dipping to overturned at dips of 55° overturned to 86° right way up (Figures 5.33 and 5.35). Surface dips in the maroon flatten rapidly to the southeast to ~25°, right way up. The local folding found between the northern and southern salt bodies continues along strike to the west but appears to be plunging and opening in a westwardly direction. The tight folds to the east are not seen at the surface below the salt that crops out along this ridge.
Figure 5.35. Cross section D3-D3’ illustrating the salt body that crops out at the surface with folded Eagle Valley Formation below the salt in an antiform and adjacent synform. Note the steeply dipping, right way up Maroon Formation to the south of the southern salt body.

5.7.7 Cross section D4-D4’

The last, westernmost cross section in this area is found ~500 m west of D3-D3’ (Figure 5.26) and contains similar geometries seen along strike. The Eagle Valley Formation is locally folded between the autochthonous level breccia and southern salt body. These folds likely die out further west below the allochthonous salt layer. The evaporite crops out in the south with steeply dipping to overturned beds of Maroon Formation on the southern flank. The Maroon dips are around 85° overturned to 86° right way up and rapidly flatten out moving off the cross-section line towards the southwest. This gives the geometries of an Eagle Valley and Maroon filled minibasin on the south side of the salt (Figure 5.37). The folded Eagle Valley between (or
below) the salt bodies are in a small scale, early minibasin formed before the end of Eagle Valley deposition.

Figure 5.36. Cross section D4-D4’ illustrating the salt body that crops out at the surface with folded Eagle Valley Formation below the salt in an antiform and adjacent synform. There are steeply dipping, right way up Maroon Formation to the south of the southern salt body.
Figure 5.37. A1) Field image along cross sections D2-D2’, D3-D3’, and D4-D4’ looking west in the Horse Mountain quadrangle. A2) Bedding dips and bedforms are drawn in on the lower image to show contact relationships between the pre-salt Belden Formation through the Maroon Formation on the south side.

A three-dimensional view looking west-northwest into the five cross sections in the Horse Mountain quadrangle illustrates the complexity of salt-related geometries moving along strike (Figure 5.38). The evaporite crops out at the surface along the entire sequence; there are two interpreted feeders for the salt sheet overlying the Eagle valley Formation: one from the north, on the ridge close to the original stratigraphic position of the evaporite overlying the Belden Formation, the second is in direct contact with the Maroon Formation to the south.
(Figures 5.29, 5.32, and 5.37). There is a consistent presence of steeply dipping to locally overturned Maroon Formation along the salt flank to the south. Placing the two-dimensional cross section lines into three dimensions demonstrates the relationships of the local, tight folds in the Eagle Valley Formation lying below the allochthonous salt at the surface. The early evolution of the salt sheet throughout this quadrangle consistently folds the Eagle Valley Formation and upturns the Maroon Formation while the salt and associated geometries plunge to the west-northwest.

Figure 5.38. Three-dimensional view of all five cross sections in the Horse Mountain quadrangle. This 3D view illustrates the variable right way up to steep to overturned beds along strike of the Puma Paw salt complex. Also, of note, the variability in folded Eagle Valley Formation in the central part of the salt complex.

These diapir-related folds in the Eagle Valley Formation likely formed early in the diapiric to lateral extrusion stages of salt evolution because they are found only along strike between these two salt bodies and there is no evidence of comparable folding elsewhere in this
quadrangle. All the younger stratigraphy up section dips consistently with the regional dip to the southwest.

### 5.7.8 Regional Structure

As seen on the geologic map and noted by Scott et al. (2002), the Grand Hogback begins to wrap around to the north in the Horse Mountain quad (Figure 5.25). The structural bench seen in this quadrangle correlates to the structural bench seen in the Storm King Mountain and Rifle Falls quad. Atop the structural bench are numerous folds and faults between the Grand Hogback and White River uplift (Scott et al., 2002). Along the flank of the White River uplift, the regional south dip of ~12°-18° is dramatically steepened to ~70° to the south moving up section from the pre-salt Leadville Limestone and Belden Formation into the Eagle Valley Evaporite and Formation. The dramatic dip change is attributed to a large throughgoing fault that displaces the pre-salt section (Scott et al., 2002). Scott et al. (2002) assume an original evaporite thickness of 150m in this quadrangle which becomes diapiric in sheet like and salt wall forms.
6.1 Storm King Mountain – A-A’ Restoration

Restoration A-A’ is a northeast-southwest striking section that crosses through the Storm King Mountain quadrangle (Figures 3.1 and 5.2). The restoration is based on constructed cross sections representing present-day geometries as seen in Figure 6.1. This section is bound by the Grand Hogback to the south and the White River Uplift to the north. A normal, down-to-the-north fault detaches on the top of the salt on the north side of the section line. The standalone restoration does not represent all salt-related geometries throughout the Storm King Mountain quad; therefore, this restoration should be viewed in conjunction with additional cross sections surrounding this restoration cross section line (Figures 5.3-5.16). The restoration steps forward through time starting with Time 1, the deposition of the Eagle Valley Formation and ending with Time 5, the present-day reconstruction of Laramide related and younger deformation (Figures 6.2-6.6). The restorations were performed back through time, but in this section, they will be shown moving forward in time (see methodology in Chapter Three). Note the full section along the present-day reconstruction was restored along the entire section, but for the purpose of this project, a more detailed view is shown to illustrate details around the Bear Wallow diapir throughout the restoration (Figure 6.1).
Present day construction of Restoration line A-A’.

Figure 6.1. Restoration line A-A’ across the Storm King Mountain quadrangle.
Key data points:

- Measured section with associated structural data of the Neogene-aged Canyon Creek Conglomerate found in a syncline on top of the evaporite
- Contact and geometries of the Maroon Formation and Eagle Valley Formation along the section line to the south of the Eagle Valley Evaporite

Key assumptions:

- Geometry and nature of contact relationships are projected along strike on the northeast portion of the section line
- Projected elevations of the Eagle Valley Evaporite and overlying formations on the northern, eroded portion of the section for restoration purposes
- Evaporite weld and associated geometries within the subsurface and projected above the present-day White River Uplift
- Pre-salt (Pb-X) topography is flat at deposition

*Early Eagle Valley Formation (Early Pennsylvanian) – 310 Ma*

Figure 6.2. Time 1. Deposition of the Eagle Valley Formation following the deposition of the Eagle Valley Evaporite. Early onset of salt diapirism as the distribution overlying Eagle Valley Formation creates instability in the Eagle Valley Evaporite. Early stages of salt diapirism ensues as an asymmetric main diapir arises in the center of the section and a southerly salt pillow begins to form.
Later Eagle Valley Formation (Middle Pennsylvanian) – 307 Ma

Figure 6.3. Time 2. The main diapir continues to grow passively with continued deposition of the Eagle Valley Formation. Slight folds in the Eagle Valley Formation begin to form as a salt pillow (to the south) and a salt tongue (to the north) form in the salt. The diapir and attached salt tongue of the Eagle Valley Evaporite create an Eagle Valley Formation filled minibasin.

Maroon Formation (Late Pennsylvanian to Early Permian) – 299 Ma

Figure 6.4. Time 3. With the additional overburden provided by the Maroon Formation, minibasins continue to subside along the flanks of the diapir. The main salt wall produces passive drape folding in the overlying strata. During this time, the salt supply from the south and north both weld as salt movement slows during Lower Maroon time.
Williams Fork Formation (Upper Cretaceous) - ~100 Ma

Figure 6.5. Time 4. All units overlying the Maroon Formation are deposited: The State Bridge through the Cretaceous aged Mancos Shale and Williams Fork Formation which are at or around sea level with stable tectonic conditions. Note the thinning of the Chinle-State Bridge due to differential compaction over the salt.

Laramide Orogeny (Late Cretaceous) - ~72 Ma

Figure 6.6. Time 5. The onset of Laramide deformation in the Late Cretaceous results in a large fold north of the diapir and another fold to the south. The sediments overlying the salt fault and the base of the fault dies out at the top of the salt. Late (?) Neogene time erosion and exposure lead to dissolution and collapse of the roof of salt as evidence by the Canyon Creek Conglomerate resting in a syncline within the main salt diapir.
6.2 New Castle – B-B’ Restoration

Restoration B-B’ is a northeast-southwest striking section that crosses through the New Castle quadrangle (Figures 3.1 and 5.2). The restoration is based on constructed cross sections representing present-day geometries as seen in Figure 6.7. This section is bounded by the Grand Hogback to the south and the White River Uplift to the north. The restoration steps forward through time starting with Time 1, the deposition of the Eagle Valley Formation and ending with Time 6, the present-day reconstruction of Laramide related and younger deformation (Figures 6.8-6.13). The restorations were performed back through time, but in this section, they will be shown moving forward in time (see methodology in Chapter Three).

Present day construction of Restoration line B-B’.

Figure 6.7. Restoration line B-B’ across the New Castle quadrangle.
Key data points:

- Elk Camp 12-22-05-91 well tops: the first recorded halite bed of the Eagle Valley Evaporite was drilled at 4,928m (16,168ft) and the well reached its total depth in the evaporite at 5,312m (17,430ft)

Key assumptions:

- Collapse of Maroon Formation into the Eagle Valley Evaporite of the Elk Creek Diapir is post-Laramide as dissolution occurred after its original deposition as a thinned roof sequence on the crest of the salt wall
- Pre-salt elevation is projected to be closest to the present-day White River Uplift top surface
- Geometry and nature of contact relationships on the northeast portion of the section line
- Surface elevation of the Eagle Valley Evaporite and overlying formations on the northern, eroded portion of the section
- Evaporite weld and associated geometries within the subsurface and projected above the present-day White River Uplift
- Pre-salt (Pb-X) topography is flat at deposition

*Early Eagle Valley Formation (Early Pennsylvanian) – 310 Ma.*

![Diagram](image)

Figure 6.8. Time 1. The deposition of Eagle Valley Formation initiates early onset of salt mobility as a phase of active diapirism followed by passive diapirism. Note a small diapir grows to the north-northeast but ceases development during the deposition of Eagle Valley Formation.
Later Eagle Valley Formation (Middle to Late Pennsylvanian) ~307 Ma

Figure 6.9. Time 2: Passive diapirism continues during Eagle Valley Formation deposition. The diapir becomes more of a salt wall with a southerly salt pillow forming. Two Eagle Valley Formation filled minibasins forming on the flanks of the diapir. The supply of salt begins to thin to the north-northeast and south-southwest.

Lower Maroon Formation (Late Pennsylvanian to Early Permian) ~300 Ma

Figure 6.10. Time 3: As the Maroon formation begins to deposit, the diapir passively grows at or around the surface of the Lower Maroon level. With additional overburden brought on by Maroon deposition, the minibasins continue to form on the flanks of the diapir with Lower Maroon aged strata blanketing the minibasins. Eagle Valley Formation strata are upturned as the diapir grows passively. The salt supply to the south and north begin to thin which starts to cut off the mobile salt supply to the passive diapir.
**Upper Maroon Formation (Early Permian) - ~285 Ma**

Figure 6.11. Time 4: Passive diapirism terminates by early Upper Maroon time as the salt welds to the south and north cutting off the diapir’s salt supply. Salt pillows south of the main diapir present synclinal and anticlinal structures on the flank of the main diapir. Depositional thickness of Maroon Formation is ~2,600m.

**Mancos Shale (Upper Cretaceous) - ~80 Ma**

Figure 6.12. Time 5: The overlying sediments of the Schoolhouse Member, Chinle-State Bridge, Entrada, Morrison, Dakota, and Mancos are deposited compacting the Maroon and Eagle Valley Formations.
Figure 6.13. Time 6: Present day, reconstructed cross section view of the Laramide deformation that created the White River Uplift to the north and the Grand Hogback to the south. The large monocline is produced by the two uplifts that bound the Eagle Basin and the diapir seen in this cross section. Post Laramide deformation also marked a period of dissolution and collapse of the diapir roof which lead to the sinking of the Maroon Formation into the collapsed diapir roof.
6.3 Rifle Falls – C-C’ Restoration

Restoration C-C’ is a northeast-southwest striking section that crosses through the Rifle Falls quadrangle (Figures 3.1 and 5.2). The restoration is based on constructed cross sections representing present-day geometries as seen in Figures 6.14. This section is bounded by the Grand Hogback to the south and the White River Uplift to the north. A normal, down-to-the-north fault detaches on the top of the salt on the north side of the section line. Note the Rifle Falls Fault is a down-to-the-south fault that offsets that strata down through the basement. The restoration steps forward through time starting with Time 1, the deposition of the Eagle Valley Formation and ending with Time 5, the present-day reconstruction of Laramide related and younger deformation (Figures 6.15-6.19). The restorations were performed back through time, but in this section, they will be shown moving forward in time (see methodology in Chapter Three).

Present day construction of Restoration line C-C’.

Figure 6.14. Restoration line C-C’ across Rifle Falls quadrangle.
Key data points:

- Subsurface elevation of salt: The Rifle Creek Hatchery #1 well reached a total depth of 101.5m (332ft) where the Eagle Valley Evaporite was seen at a depth of around 20m (68ft).

- Eagle Valley Evaporite present at the surface of the White River Uplift on the northernmost part of the section

Key assumptions:

- Geometry and nature of contact relationships on the northeast portion of the section line
- Surface elevation of the Eagle Valley Evaporite and overlying formations on the northern, eroded portion of the section
- Evaporite weld and associated geometries within the subsurface and projected above the present-day White River Uplift
- Subsurface elevation of pre-salt formations south of the Rifle Falls diapir
- Thickness and geometry of the Maroon and Eagle Valley Formations flanking the diapir
- The Entrada Sandstone was deposited flat and at or around sea level
- Field interpretations and all digitized data suggest diapir growth ceased as salt supply was welded at the time of Maroon deposition
- Pre-salt (Pb-X) topography is flat at deposition
Early Eagle Valley Formation (Early Pennsylvanian) – 310 Ma.

Figure 6.15. Time 1: Eagle Valley Evaporite was precipitated on top of Belden Formation in a shallow marine setting in the lowland between the Ancestral Rocky Mountain and the Uncompahgre Uplifts, followed by the deposition of the Eagle Valley Formation on top of the evaporite. The loading of the Eagle Valley Formation activated the instability of the salt layer causing the buckling and flow of salt into a low relief, broad salt pillow.

Later Eagle Valley Formation (Middle to Late Pennsylvanian) ~307 Ma

Figure 6.16. Time 2: During the deposition of the Eagle Valley Formation, the salt becomes diapiric as a passive diapir growing at or near the surface of the Eagle Valley Formation. As the overburden of the Eagle Valley Formation increases over time, the south subsides over the thinning salt at a faster rate than the north suggesting the south is supplying a greater amount of flowing salt to the growing diapir. An Eagle Valley Formation minibasin forms to the north of the diapir while the salt supply from the south begins to thin.

Maroon Formation (Early Permian) - ~285 Ma

Figure 6.17. Time 3: Maroon time. The salt to the south of the diapir is welded and the major supply of salt flow that created diapirism ceased. There are two relatively shallow Eagle Valley Formation minibasins flanking the diapir to the north-northeast and south-southwest. Note depositional thickness of Maroon Formation is ~1000m.
Williams Fork Formation (Upper Cretaceous) - ~100 Ma

Figure 6.18. Time 4: The deposition of the Schoolhouse, Chinle-State Bridge, and Entrada were deposited sequentially at or near sea level on top of the Maroon Formation. Note, salt does not compact with the continued deposition of the Mancos Shale, Bowie Shale, and Williams Fork during Cretaceous time.

Laramide Orogeny (Late Cretaceous) ~72 Ma

Figure 6.19. Time 5: The Laramide Orogeny commenced in late Cretaceous time as the Grand Hogback to the south-southwest and the White River Uplift to the north-northeast are uplifted. During uplift, the major Laramide fold is produced along with faulting. The northern Rifle Falls Fault normally faults the units down through the basement as a result of post Laramide extensional collapse. The southern fault detaches on the crest of the diapir along the weak, dissolved areas atop the salt.
6.4 Horse Mountain – D-D’ Restoration

Restoration D-D’ is a northeast-southwest striking section that crosses through the Horse Mountain quadrangle (Figures 3.1 and 5.2). The restoration is based on constructed cross sections representing present-day geometries as seen in Figure 6.20. This section is bounded by the Grand Hogback to the south and the White River Uplift to the north. The standalone restoration does not represent all salt-related geometries throughout the Horse Mountain quad; therefore, this restoration should be viewed in conjunction with additional cross sections surrounding this restoration cross section line (see Chapter Five). The restoration steps forward through time starting with Time 1, the deposition of the Eagle Valley Formation and ending with Time 5, the present-day reconstruction of Laramide related and younger deformation (Figures 6.21-6.25 and 6.26). The restorations were performed back through time, but in this section, they will be shown moving forward in time (see methodology in Chapter Three).

Present day construction of Restoration line D-D’

Figure 6.20. Restoration line D-D’ across the Horse Mountain quadrangle.
Key data points:

- Contact and geometries of the Maroon Formation and Eagle Valley Formation along the section line to the south of the Eagle Valley Evaporite

Key assumptions:

- Maroon Formation is projected into the top of the White River Uplift from the adjacent Rifle quadrangle, ~85 meters of the Maroon Formation is exposed at the top of the White River Uplift
- Pre-salt (Pb-X) topography is flat at deposition

*Early Eagle Valley Formation (Early Pennsylvanian) – 310 Ma.*

Figure 6.21. Time 1: Eagle Valley Formation begins to deposit over the relatively thin Eagle Valley Evaporite. Salt becomes mobile at the start of Pe deposition as two diapirs begin to form passively. A small minibasin forms between the two passive diapirs with slightly upturned strata that has formed as the diapirs rise.

*Early Maroon Formation (Late Pennsylvanian to Early Permian)- ~300 Ma*

Figure 6.22. Time 2: Beginning of Maroon Formation deposition above a thin roof of Eagle Valley Fm. Additional overburden from the Maroon increases the minibasin development on the flanks of both diapirs. The southern diapir becomes slightly unstable and begins to flow laterally to the north as a sheet of salt. The flow of the southern salt sheet combined with the northern diapir result in a shorted minibasin with folded strata.
Late Maroon Formation (Early Permian) - ~285 Ma

Figure 6.23. Time 3: Middle to Upper Maroon Formation deposition where the northern diapir has reached its peak height as the salt supply welds to the north. The salt sheet to the south nearly reaches and comes into contact with the northern diapir when the salt supply from the south is welded. Diapirism shuts down early during Maroon deposition and most of the Maroon blankets the salt structures. Diapirism and allochthonous salt development shut down by Early Maroon deposition.

Williams Fork Formation (Upper Cretaceous) - ~100 Ma

Figure 6.24. Time 4: All strata overlying the Maroon Formation are deposited. Due to the salt withdrawal from the south and north along with compaction, there is a slight fold in the strata through Maroon time. The sediments deposited flat lying above are soon to be dramatically folded in Late Cretaceous time.
Laramide Orogeny (Late Cretaceous) ~72 Ma

Figure 6.25. Time 5: Present day view of the folded and faulted sediments. Note the locally overturned Maroon Formation due to deformation during the Laramide orogeny. Collapse and dissolution of the evaporite leave a smaller salt sheet and diapir seen at the surface.

Figure 6.26. Restoration D-D’ in a detailed view around the Puma Paw salt complex.

Summary

The structural evolution across the western Eagle Basin has great variability from the eastern extent in Storm King Mountain to the western portion of the field area in Horse Mountain. The eastern extent (Storm King Mountain and New Castle quads, (Figure 27) includes primarily salt diapirs with associated right way up to steep to overturned strata in the Maroon and
Eagle Valley Formations. Moving west into the Rifle Falls quad, less extensive amounts of salt crop out and the structures along the salt bodies are primarily right way up. Finally, in the Horse Mountain quad, the salt structures are not large in scale but crop out at the surface as a complex series of salt diapirs, sheets, and a possible feeder. There is a general thinning of original autochthonous salt from east to west in this field area. This implies a lower salt supply from the time of deposition and results in salt welding out during Eagle Valley Formation/Lower maroon time and an earlier cessation of diapiric growth further to the west.
CHAPTER SEVEN
DISCUSSION

7.1 Ancestral Rocky Mountain structural components

After a long period of subaerial exposure, the Eagle Basin began to infill as the Ancestral Rocky Mountains and Ancestral Uncompahgre began to uplift in Late Pennsylvanian time during the collision of Gondwana and Laurentia (Kluth and Coney, 1982; Kirkham et al., 2008; Miller, 2011). The Pennsylvanian aged Ouachita-Marathon Orogeny is most likely responsible for the intraplate mountain building and uplift period that created accommodation and led to evaporite deposition in the adjacent flexural foreland basins (Kluth, 1986). The first sediments eroded from the ancestral uplifts and infilling the basin were the Pennsylvanian-Permian sediments, primarily the Eagle Valley, Minturn, and Gothic Formations flanking the Eagle Valley Evaporite in the basin center (Figure 2.6).

The Paradox Basin is interpreted to have formed contemporaneously with the Eagle Basin with similar depositional and halokinetic processes (Figure 7.1). Pre-existing structural controls of the Paradox and Eagle Basins remains up for debate (Trudgill, 2011). Reconstructions model the geometry and timing of events of the Paradox Basin differently, which suggest that the Paradox Formation and Eagle Valley Evaporite could have been deposited in a continuous evaporite basin before the Uncompahgre Uplift was a positive, subdividing feature (Figure 7.2) (Kluth and Duchene, 2009). Kluth and Duchene (2009) interpret the entire region of west central to central Colorado as a shallow, wide salt basin during middle Pennsylvanian. The reconstructions produced by Kluth and Duchene (2009) along salt walls of the Paradox Basin confirm the presence of fault control beneath the salt walls. Although there is
little subsurface control in the Eagle Basin, a similar implication can be made of the controls on the salt walls of the western Eagle Basin; the salt bodies share a similar trend to those of the Paradox Basin, which points to pre-existing, faults beneath salt bodies – NW-SE trend in the western Eagle Basin possibly inherited from Precambrian then Ancestral Rocky Mountain structures.

Figure 7.1. Paleogeographic map from the Pennsylvanian period. Note the two evaporite basins forming contemporaneously on either side of the Uncompahgre uplift, and the Ancestral Front Range uplift bounding the northeastern extent of the Eagle Basin (Modified from Blakey, 2009; Rice, 2021).
Key differences between the Paradox Basin and the Eagle Basin are likely related to the evolution and structure of the bounding ancestral Rocky Mountain uplift structures. Noteworthy structures include the Uncompahgre uplift to the southwest of the Eagle Basin (northeast of the Paradox Basin) (Figure 7.2) and the Front Range uplift to the northeast of the Eagle Basin (Tweto, 1977; Kluth and Duchene, 2009). Unlike the unidirectional, southwest progradation of...
minibasin development seen in the Paradox Basin (Kluth and Duchene, 2009), the Eagle Basin has a more complex evolution of salt walls and minibasin formation. Looking to Johnson’s (1987) work on paleocurrents in the Maroon Formation, the widely variable paleocurrent measurements further explains asymmetric depositional trends and subsequent minibasin fill in the Eagle Basin (Figure 7.3).

Figure 7.3. Maroon Formation paleocurrent directions as previously measured by Johnson (1987).

The Paradox Basin lacks a southwest bounding uplift while it has the Uncompahgre uplift to the northeast. The duel ancestral uplifts that bound the Eagle Basin may explain the more complex processes of sedimentation and minibasin formation that tend to young towards the central part of the basin as there are two highlands providing sediments from the northeast, southeast, and southwest (Rice, 2021). Although the Paradox Basin formed coevally to the Eagle Basin, the pathways of deposition around the complex pattern of growing salt structures
may have been drastically different, which could explain contrasting magnitude and geometries of the salt diapir and wall structures and minibasins (Figure 7.3 and 7.4).

![Western Eagle Basin research area](image)

Figure 7.4. Map of the Eagle Basin with structural features and predominant ages of minibasins noted. Black, dashed line highlights the area of study for this research project.

### 7.2 Salt structure evolution

The pre-Laramide salt tectonics and subsequent Laramide aged tectonism are affected by depositional and structural processes that occurred throughout geologic time. The evolution of the western Eagle Basin is built with an understanding of these events. Cambrian to Mississippian, pre-salt formations such as the Leadville Limestone were deposited episodically as shelf sequences consisting primarily of limestones (Kirkham et al., 2008) as seen in impressive exposures throughout Glenwood Canyon (Figures 5.1 and 5.2). The Eagle Valley
Evaporite was deposited in the basin during Pennsylvanian time with an unknown depositional thickness.

With continued deposition into the Eagle Basin of overlying sediments such as the Eagle Valley Formation and Maroon Formation in fluvial and fan-type environments, these two highly variable formations created ample overburden for the Eagle Valley Evaporites to mobilize early in the basin history (Kirkham et al., 2008). As mentioned in Chapter Four, the overlying stratigraphy of the State Bridge through the Morrison Formations were deposited in fluvial, eolian, and shoreline deposits and represent the gradual erosion and submergence of the Ancestral Rocky Mountains (Kirkham et al., 2008).

Across the western Eagle Basin, the Eagle Valley Evaporite crops out in varying amounts but with similar stratal geometries throughout the region (Figure 7.5). The eastern extent of this field area in Storm King Mountain is marked by salt walls and salt tongues (See Chapter Five). The New Castle quad is marked by a single large salt wall with associated steeply dipping beds. Into the Rifle Falls quad, the salt begins to thin drastically, and crops out as lenses across the quadrangle. Similarly, in the Horse Mountain quad in the far west of the field area, the evaporite presents itself as a thinner, smaller salt supply that was rapidly exhausted during early diapirism and salt sheet development. (Figure 7.5)
Though the salt is variable across this region, there are similar salt-related geometries seen in the post salt formations of the Eagle Valley and Maroon. Generally, each area of this project has regional gentle dips to the southwest that abruptly steepen and overturn moving northeast toward the diapiric structures. These steepening beds are the halokinetic sequences that flank the minibasins formed between the salt bodies. Until recently, these dip changes and salt adjacent features were attributed to the Cretaceous aged Laramide Orogeny. Though the Laramide Orogeny produced large monoclinal fold structures in this field area such as the Grand Hogback and White River Uplift, this is not the full explanation for all the geometries and
deformation across the western Eagle Basin, as many of these structures and steep to overturned
dips clearly predate deposition of the Jurassic, Entrada, and Morrison Formations.

The results of this field-based study are that the period of basin sedimentation and salt
tectonism is relatively early and short-lived in this part of the Eagle Basin. The timing of the
minibasin formation and diapirism in the western Eagle Basin is Late Pennsylvanian (~310 Ma)
to early Permian (~300 Ma), which contrasts with previously mapped and studied areas of the
Eagle Basin. The north-central Eagle Basin (Rice, 2019) and southern Eagle Basin (Pearigen,
2019) exhibit structures of a longer-lived phase of halokinesis. Table 3 outlines the key
differences between the three key regions of the Eagle Basin and the Paradox Basin (Pearigen,
2019; Rice, 2021).
Table 3. Comparison of size, orientation, age, and evolution of the three regions of the Eagle Basin and Paradox basin (Trudgill, 2011; Pearigen, 2019; Rice, 2021).

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<tbody>
<tr>
<td><strong>Diapir/Salt wall size and orientation</strong></td>
<td>Height: 2,700m to 4,500m tall Width: ~1.5km to 2km</td>
<td>Height: ~1000m to 2,000m Width: ~500m to 2km (shorter diapirs with lateral movement)</td>
<td>Height: Up to 2,500-meter-tall Width: up to ~3km</td>
<td>Height: 2,700m to 4,500m Width: 1.75km to 3.5km</td>
</tr>
<tr>
<td><strong>Minibasin size/orientation</strong></td>
<td>NW-SE orientation Up to ~5km deep</td>
<td>NNW-SSE Up to ~2km (?)</td>
<td>ENE-WSW or NNE to SSW orientation Up to ~3km</td>
<td>NW-SE ~3-5(?) km deep minibasins</td>
</tr>
<tr>
<td><strong>Age and length of diapiric rise and minibasin subsidence</strong></td>
<td>~ 150 Myr (Late Pennsylvanian through Triassic and into Jurassic (?))</td>
<td>~10-20(?) Myr (Late Pennsylvanian to Early Permian)</td>
<td>~80 Myr (Late Pennsylvanian through Triassic)</td>
<td>~50 Myr (Pennsylvanian to Triassic)</td>
</tr>
<tr>
<td><strong>Halokinetic sequences observed and ages</strong></td>
<td>Composite halokinetic sequences, megaflaps</td>
<td>Steeply dipping to overturned strata in the Eagle Valley and Maroon Formations that could be identified as halokinetic sequences (not enough exposure)</td>
<td>Hook composite halokinetic sequences in the Eagle Valley Formation at Hardscrabble Mountain</td>
<td>Gothic and Maroon Formations with megaflap geometries along Castle Creek salt wall halokinetic sequences</td>
</tr>
<tr>
<td><strong>Laramide overprint</strong></td>
<td>None or extremely subtle</td>
<td>Grand Hogback monocline and White River Uplift Rotate and fold salt structures</td>
<td>Front Range, Squeezed diapirs toward eastern margin</td>
<td>Sawatch uplift, minibasin rotation (Castle Creek), secondary welds</td>
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In the southern and north-central Eagle Basin, evidence of a longer-lived phase is seen in the overthickening of the Maroon and State Bridge Formations. These dramatic thickness variations point to continued or reactivated salt tectonism through the Triassic whereas in the western Eagle Basin, no significant thickness variations are seen in the stratigraphy overlying the
Maroon Formation. In the Paradox Basin, an even longer phase of halokinesis persisted than that seen in any region of the Eagle Basin. The diapirism and minibasin subsidence in the Paradox Basin started in Late Pennsylvanian time with the deposition of the Upper Pennsylvanian Honaker Trail, followed by the Permian Cutler Group through the Upper Triassic Chinle Formation (Trudgill, 2011). There is reported thickness variations and unconformities within the Jurassic and Lower Cretaceous adjacent to the salt walls in the Colorado sector of the Paradox Basin which may point to a phase of salt tectonism that continued through the Jurassic (Elston & Landis, 1960; Landis et al., 1961; Cater, 1970; Bromley, 1991; Trudgill, 2011). This longer phase may be due to a greater salt and sediment supply in the Paradox Basin compared to the variable salt and sediment supply across the Eagle Basin.

As seen in the cross sections and restorations of this project (Figure 7.5), diapirism began as early as the initial deposition of the Eagle Valley Formation. In the restoration of C-C’, diapirism shut off by the end of Eagle Valley Formation deposition whereas in restorations A-A’, B-B’, and D-D’ (see Chapter 6) diapirism is thought to have ended during Lower Maroon Formation deposition. By the end of Maroon Formation time and into the younger section, the stratigraphy was deposited continuously and consistently across the region. The salt mobility is thought to have shut off or been buried by Early Maroon Formation time, or Early Permian, in the western extent of the basin.

The minibasins and salt related structures seen throughout the western Eagle Basin are therefore dominantly Late Pennsylvanian to Early Permian aged as those complex salt structures are seen in relation to the Eagle Valley and Maroon Formations. In the eastern portion of this field area, there is a thicker, more widely exposed Eagle Valley Evaporite with Eagle Valley and Maroon Formations abruptly steepening or overturning along the flanks of the salt wall and
associated salt tongue (as seen in the Storm King Mountain quad). While there are consistently complex structures moving in the northwestern direction from Storm King Mountain, there is a decrease in salt volume available (De Voto, 1986; Scott et al., 2002). As the salt supply is thinner in the western Eagle Basin compared to that of the northeastern and southern regions, and the Paradox Basin, the phase of diapirism is shorter lived with shorter diapirs and shallower minibasins (Table 3).

7.3 Laramide Shortening/Overprint

The onset of the Laramide Orogeny in Late Cretaceous time reactivated many ancestral structures. Miller (2011) noted that the main structures of the Laramide are large monoclinal folds (like the Grand Hogback) whereas the ancestral, Ouachita-Marathon Orogeny accommodated shortening primarily by basement-involved thrust faults. The structural styles of the two main orogenic events that affected this area is separate from the halokinetic induced structures seen in the western Eagle Basin. The three separate tectonic events built off each other to produce the present-day complexities seen in the field.

The Laramide Orogeny of Late Cretaceous time uplifted major structures seen in this region of west-central Colorado (DeVoto, 1986; Mallory, 1971; Tweto, 1977). The structures seen in the Eagle Basin produced by the Laramide Orogeny are the White River Uplift, Grand Hogback monocline, Sawatch Uplift, Uncompahgre uplift, and Front Range Mountains (Figure 7.4). Once the gentle to steep, right way up dips along the Grand Hogback and White River uplift are restored and rotated to their undeformed, originally deposited position, steep dips adjacent to salt diapirs and sheets persist throughout the western Eagle Basin (Figure 5.2). This is key in understanding the pre-Laramide phase of deformation triggered by salt tectonism.
The Grand Hogback as noted by Miller (2011) is a broad, basement-cored monoclinal fold that developed from Laramide compression. In the subsurface, the listric reverse fault propagates upward through basement rocks to the lower Wasatch Formation (Miller, 2011). The Grand Hogback monocline is a feature trending at the southwestern boundary of the Eagle Basin with the Piceance Basin to the southwest (Figure 3.1 and 5.1). After assessing dips within the western Eagle Basin, steep to overturned dips do not correlate to the same structural event that produced the monocline or White River uplift.

Notably, in the western Eagle Basin, the White River uplift displaces Cambrian to Mississippian rocks to their present position on the up-thrown side of a series of normal faults, adjacent to Pennsylvanian aged strata. The Laramide-produced White River uplift flanks the western Eagle Basin to the north-northeast and seems to have a structural trend like that of the evaporite outcrops (Figure 5.2). This is likely due to the uplift, subsequent erosion, and downcutting of stream beds that expose the Eagle Valley Evaporite along the margin of the uplift.

As seen in the north-central Eagle Basin (Rice, 2021), Laramide deformation is subtle but presents as shortening seen in squeezed diapirs and rotated minibasins (Table 3). Aside from the major uplifts that bound the Eagle Basin, the lack of Laramide shortening in many parts of the basin could be attributed to salt absorbing compression/shortening, evaporite flowage, and surface dissolution (Rice, 2021). The Laramide overprinting in the western Eagle Basin is characterized by the White River uplift, Grand Hogback, and subsequent erosion and dissolution over time.

**7.4 Late-Stage Collapse and Deposition of the Canyon Creek Conglomerate (Tcc)**
Previous work on attempting to date the Canyon Creek Conglomerate includes an assessment of the cobbles within the conglomerate (Bass and Northrop, 1963); cobbles include red sandstone and siltstone, grey limestone, chert, quartzite, igneous and metamorphic rocks. Bass and Northrop (1963) interpreted that the cobbles originate from the Sawatch, Leadville, Belden, and Maroon Formations, while no cobbles younger than the Maroon Formation were found. Due to the lack of glacial moraine deposits in the conglomerate that are Pleistocene aged, Bass and Northrop (1963) interpret the Canyon Creek Conglomerate as a post Laramide deposit probably late Neogene or Plio-Pleistocene aged.

Studies on dissolution and collapse along faults above salt in the Paradox Basin may be analogous to the Eagle Basin evaporite collapse (Guerrero and others, 2015). The faults related to the Spanish Valley in southeast Utah have been excavated to quantify the amount of salt-dissolution related slip on faults that are driven by dissolution (Guerrero and others, 2015). In trenching along various faults, Guerrero and others (2015) drew conclusions as they found the slip rate to be 3-30 times higher than tectonic driven faults with an average displacement of 3.07 mm/year with an average reoccurrence of ~316 years (Guerrero and others, 2015). A similar study of the Tcc Conglomerate may help in determining the age and rate of subsidence of the Canyon Creek Conglomerate if similar dissolution rates are applied to the Eagle Valley Evaporite below the Canyon Creek Conglomerate. The conglomerate is nearly 400 meters thick and if similar conclusions can be drawn about the amount of dissolved and collapsed evaporite below the Canyon Creek Conglomerate, the conglomerate may be a confirmed to be Plio-Pleistocene aged or marginally older.

However, to add confusion, the evolving paleo topography must also be considered in deliberating the evolution of the Canyon Creek Conglomerate. The present-day elevation of the
Canyon Creek Conglomerate is situated at 2,525 meters (8,287 feet) at its highest and ~2070 meters (~6,800 feet) at its lowest which is above much of the surrounding topography in the immediate area. If the conglomerate sits in a syncline on top of collapsed salt, this implies an elevated paleo topography with drainage off the White River uplift. The age of the Canyon Creek Conglomerate is ambiguous as the present topographic location points to a depositional environment where paleo slopes were higher than those of the present day. The paleo location of the conglomerate deposition would have been on the flank of the White River uplift to then collapse in several subsiding events into its present-day position. The age and evolution of the Canyon Creek Conglomerate therefore remains up for debate.
CHAPTER EIGHT
CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

1) The western Eagle Basin encompasses salt diapirs, tongues and sheets with evidence of salt welds at different levels. The phase of halokinesis is Pennsylvanian to Permian in age as the complex geometries adjacent to salt bodies are exclusive to the Pennsylvanian-Permian aged Eagle Valley and Maroon Formations. The salt bodies throughout the western Eagle Basin trend northwest to southeast along the southern flank of the White River uplift. The abrupt steepening of the Maroon and Eagle Valley Formations throughout the field area produce drape-folded halokinetic sequences that could locally be hook and wedge structures adjacent to the salt and composite halokinetic sequences at a larger scale.

2) Minibasins are primarily filled with Eagle Valley Formation and in some places, an upper minibasin sequence of Lower Maroon Formation. Additionally, there are smaller scale diapirs seen in the lower part of the Eagle Valley Formation (Figures 6.7-6.12) which points to an early onset of salt diapirism in this region that presumably started at the start of Pennsylvanian Eagle Valley Formation time.

3) The Maroon Formation is significantly thinner than that seen in the southern, Aspen region of the Eagle Basin (Pearigen, 2019). As measured in Storm King Mountain at 652.5m (~2,340ft), the Maroon is remarkably thinner than the up to 4,500m (14,763ft) section in the southern Eagle Basin (Pearigen, 2019), but comparable to the ~500m (1,640ft) section of Maroon seen in the northeastern Eagle Basin (Rice, 2021). The thickness variations are probably due to regional flexural accommodation and/or salt controlled minibasin
development of different ages across the Eagle Basin (longer lived, younger salt mobility and minibasin formation toward the center of the basin).

4) More recent deposition of a conglomerate filled syncline within the salt is indicative of salt dissolution and collapse as young as Neogene time (Bass and Northrop, 1963). This recently formed syncline suggests there is much to this story in the Eagle Basin: pre-Laramide salt tectonic processes followed by the Laramide Orogeny with more recent tectonic and depositional processes that affect the salt, which triggers more salt related structures.

8.2 Recommended Future Work

1) There is great ambiguity surrounding the age of the Canyon Creek Conglomerate in the Strom King Mountain quadrangle (Bass and Northrop, 1963; Bryant and others, 2002). To discover the age and processes that deposited this conglomerate could provide a more detailed geologic history to the timing of conglomerate deposition and collapse into the salt. Age dating could be done by locating and dating fossilized wood or possibly volcanic material (16 Ma) eroded off the White River uplift.

2) Measuring additional sections in the central and western part of the syncline could provide a means to trace depositional trends along the syncline in attempts to correlate depositional sequences and generate thickness maps. The first logged section of the Canyon Creek Conglomerate (Figure 4.15 and Appendix A) provides a basis for which other sections could be compared. Though the eastern part of the conglomerate filled syncline is a tight syncline with relatively steep dips, the western part of the syncline begins to broaden, and the dips flatten substantially (Figure 4.15).
3) Similarly, the age and origin of the boulder conglomerate (Figures 4.18-4.20) with a lower angular, unconformable relationship to the Eagle Valley Formation would be worth additional research. There is an interesting relationship with the high energy deposit that is assumed to be of recent deposition. Age dating of the contact between the boulder conglomerate and the underlying angular unconformity should be analyzed.

4) Continued exploration of the salt tectonism in various parts of central Colorado is key to continuing the pre-Laramide salt tectonic history previously overlooked; areas such as Meeker, South Park, and Carbondale would be worth of further investigation.
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Freeman, V. L., 1972a, Geologic map of the Woody Creek quadrangle, Pitkin and Eagle Counties, Colorado: USGS Quadrangle Map GQ-967.

Freeman, V. L., 1972b, Geologic map of the Ruedi quadrangle, Pitkin and Eagle Counties, Colorado: USGS Quadrangle Map GQ-1004


Figure A.1. Measured section of the Maroon Formation (Upper and Lower members) with a digitized copy of Bass and Northrop’s Canyon Creek logged section (Bass and Northrop, 1950).
Figure A.1. continued
Figure A.1. continued
Figure A.1. continued
Figure A.1. continued
Figure A.1. continued
Figure A.2. Measured section of the Canyon Creek Conglomerate in Storm King Mountain.
Figure A.2. continued

boulders of pink granite (in place?)

random large cobbles and boulders
~80 cm clast

75 cm clast of quartzite (includes cross beds)
clasts consist of granite, quartzite, sandstone, and limestone
fining upward cycle
coarse cobbles at base with random boulders
sub angular to sub rounded

Rubble/cover

rounded to sub rounded
cobbles within pebble beds

cobbles composed of limestone and sandstone
Figure A.2. continued
Figure A.2. continued
Figure A.2. continued

course sand to granule sandstone bed
thin sandstone bed
fine to medium sandstone lense
40 cm clast
limestone clasts, red sandstone cobbles, small boulders
fine grained sandstone with cross bedding
fine to medium sandstone bed; 4-5 cm thick, 2 m wide
fine to medium sandstone bed; 2-3 cm thick, 2-3 m wide
mix of limestone, sandstone, and quartzite clasts
large boulder of red-orange, coarse sandstone (resistant)
quartzite clast
quartzite boulder, sandstone cobbles
40 cm random boulders
20-30 cm sandstone lenses: fine to medium, well sorted
angular to sub angular to sub rounded, coarse matrix,
60% L5, 30% S5, 10% quartzite
Elevation: 2110 m, gully after ridge
three and dogleg to fourth ridge
quartzite clast
fines upward, coarse sandstone boulder at base of bed
clast supported, red sandstone clasts, angular
to sub-rounded, dominantly limestone and sandstone
cobble dominant
sandstone lense: ~20-30 cm thick, medium to coarse
~2.5 m of lateral extent, abundance of lithics
layers of coarse cobbles and boulders
20-25 cm boulder size
concentration of limestone and bedded sandstone
boulders
~40 cm boulders
poorly sorted, matrix supported random boulders
angular to sub-rounded
boulder ~60-70 cm
sandstone beds (~20 cm) - conglomerate infills below
lateral extent ~2-3 meters
Figure A.2. continued

random limestone boulders (~30cm)
limestone and sandstone cobbles and pebbles
angular to sub angular grains
boulder sized limestone (up to 50cm)

Rubble/crater
angular to sub rounded
composition: limestone (60%) and sandstone (40%)
quartzite: angular, ~30cm width
higher pebble, cobble, and boulder content
rounded to sub angular clasts
limestone (66%) and sandstone (40%) clasts
poorly sorted: fine to medium (5%), coarse (20%),
very coarse (20%), pebble (5%) to cobble (1%)

Elevation: 2089m, gully after ridge 2

Rubble/crater
matrix supported
limestone pebbles,
sandstone pebbles and cobbles
bed sizes: ~0.5 meters
minimal black chert
primarily limestone clasts
Figure A.2. continued
Figure A.2. continued

- Size range: pebbles to cobbles
- Rubble/cobble
- Predominantly limestone cobbles
- SPARSE sandstone cobbles
- Rubble, dirt, and limestone cobbles
- Grey limestone cobbles
- Higher presence of boulders
- Limestone clasts
- Heavy brush, cover, and rubble

un
Figure A.2. continued
Figure B.1. Map with locations of thin sections.
Sample ID: SKM#1
Location: logged section in Storm King Mountain quadrangle
Formation: Upper Maroon Formation
Notes: Mineralogy includes quartz, plagioclase, microcline, calcite, mica (muscovite and biotite), and opaques. The sample is poorly sorted with sub-angular to sub-rounded grains that are silica cement supported. The grain size ranges from 0.1mm to 1mm and this sample is classified as a subarkosic sandstone.

XPL, 2.5x mag
PL, 2.5x mag

Sample ID: SKM#2
Location: logged section in Storm King Mountain quadrangle
Formation: Upper Maroon Formation
Notes: Mineralogy includes quartz, microcline, muscovite, occasional biotite, and occasional calcite. This sample is moderately to poorly sorted with subangular grains that are cement supported. Many of the quartz grains have hematite rings coating the surface, this indicated hematite cement. Grain size ranges from 0.1 to 1.0mm. This sample is classified as a subarkose sandstone.

XPL, 4x mag
PL, 4x mag
Sample ID: SKM#3  
Location: logged section in Storm King Mountain quadrangle  
Formation: Upper Maroon Formation  
Notes: Mineralogy consists mainly of quartz, sparse muscovite and biotite, some microcline and minimal calcite. The sample is very poorly sorted with sub-angular to sub-rounded grains that are cement supported with hematite. This sample has grains that range from >0.1mm to 0.5mm in size with evidence of coarsening up layers. This sample is classified as a quartz arenite.  
XPL, 4x mag

Sample ID: SKM#4  
Location: logged section in Storm King Mountain quadrangle  
Formation: Lower Maroon Formation  
Notes: Mineralogy consists of quartz and minimal muscovite and biotite. The grains are moderately sorted with sub-rounded to sub-angular grains that are moderately cemented supported. Grain sizes range from >0.1mm to 0.25mm. This sample is classified as a quartz arenite.  
XPL, 10x mag  
PL, 10x mag
Sample ID: SKM#5
Location: logged section in Storm King Mountain quadrangle
Formation: Lower Maroon Formation
Notes: Mineralogy includes very fine-grained quartz and occasional, very fine muscovite grains that are cement supported. The sample is classified as a very fine-grained quartz arenite.
XPL, 4x mag

Sample ID: SKM#16
Location: logged section in Storm King Mountain quadrangle
Formation: Lower Maroon Formation
Notes: Mineralogy is mainly quartz with minimal plagioclase, muscovite, and biotite content. Grains are sub-rounded to angular with a size range of >0.25mm. This sample is classified as a subarkose sandstone.
XPL, 10x mag
Sample ID: EC#1.1
Location: New Castle quadrangle
Formation: Eagle Valley Formation
Notes: The mineralogy of this sample is comprised of calcite grains and clasts of fine-grained mud making parts of this sample brecciated. There appear to be millimeter scale mud drapes that are laminations in the sample. This sample is classified as a carbonate limestone(?) breccia(?).

XPL, 4x mag
PL, 4x mag

Sample ID: EC#1.2
Location: New Castle quadrangle
Formation: Eagle Valley Formation
Notes: Mineralogy of this sample is predominantly calcite and fine-grained mud. The sample is brecciated, and grains consist of finer grained calcite or clasts of mud. Minor quartz in the sample and some hematite between grains. This sample is classified as a carbonate (limestone?) breccia(?).

XPL, 4x mag
PL, 4x mag
Sample ID: EC#2
Location: New Castle quadrangle
Formation: Eagle Valley Formation(?)
Notes: This mineralogy of this sample includes quartz, calcite, hematite, and fine-grained muscovite. The sample has hematite cement (possibly some calcite cement), grains coated with hematite, and the occasional hematite concretion in the sample. The grains are very poorly sorted and angular to sub-angular. Classified as a calcite litharenite sandstone.

Sample ID: PP#1.1
Location: Horse Mountain quadrangle
Formation: Eagle Valley Formation (?) – Diapir adjacent
Notes: Mineralogy consists of quartz, mud, calcite, occasional plagioclase, and sparse muscovite. The sample is matrix supported with mud and hematite and is very poorly sorted. The grains are angular to sub-angular and the size of grains is <0.25mm. Classified as a lithic mudstone.
Sample ID: PP#1.2
Location: Horse Mountain quadrangle
Formation: Eagle Valley Formation (?) – Diapir adjacent
Notes: Mineralogy includes calcite, quartz, mud, and very sparse muscovite. The sample is matrix supported with mud and hematite. The grains are sub-angular to sub-rounded. The sample appears to have void space that was infilled by calcite within the mud. There are very poorly sorted quartz grains in contrast to the calcite filled spaces with calcite grains moderately sorted. This sample is carbonate mudstone.

Sample ID: PP#4.1
Location: Horse Mountain quadrangle
Formation: Eagle Valley Formation (?) – at contact directly below Eagle Valley Evaporite
Notes: Mineralogy included quartz and muscovite with calcite cement. The grains are sub-angular to sub-rounded with sparse elongated muscovite. The sample is a litharenite sandstone.
Sample ID: PP#4.2
Location: Horse Mountain quadrangle
Formation: Eagle Valley Formation (?) – at contact directly below Eagle Valley Evaporite
Notes: Mineralogy of the sample consists of quartz, muscovite, and sparse apatite (?). The cement within the sample is primarily calcite with chlorite coating the grains. Classified as a calcite litharenite.

XPL, 10x mag

PL, 10x mag
APPENDIX C
SUPPLEMENTAL FILES

The supplemental files of this research include oversized figures that were not included in the main text of this thesis. Additional documents include the PDF versions of regional maps and full logged sections.

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<td>Eagle Basin_Regional Map.pdf</td>
<td>Regional map compiling all data from the western, southern, and north-central areas of the Eagle Basin</td>
</tr>
<tr>
<td>Western Eagle Basin_Regional Map.pdf</td>
<td>Geologic map of the western Eagle Basin including all field data from this field study</td>
</tr>
<tr>
<td>Canyon Creek Conglomerate-Logged Section.pdf</td>
<td>Full copy of logged section of Canyon Creek Conglomerate</td>
</tr>
<tr>
<td>Storm King Mtn Logged-Logged Section.pdf</td>
<td>Full copy of logged section from Storm King Mountain quadrangle</td>
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