THE STRUCTURAL EVOLUTION OF THE HAMILTON CREEK-DRY CREEK ANTICLINE AND ITS RELATIONSHIP TO THE SOUTHEAST TERMINATION OF PARADOX VALLEY, SW COLORADO

by

Elizabeth P. Wilson
A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Geology).

Golden, Colorado

Date: _________________

Signed: ________________________

Elizabeth P. Wilson

Signed: ________________________

Dr. Bruce Trudgill

Thesis Advisor

Golden, Colorado

Date _________________

Signed: ________________________

Dr. M. Stephen Enders

Professor and Interim Department Head

Department of Geology and Geological Engineering
ABSTRACT

The Hamilton Creek-Dry Creek anticline lies to the southeast of the Paradox Valley salt wall termination, near Naturita, Colorado in the northeast region of the Paradox Basin, southwest of the Uncompahgre Front. Integration of subsurface well data, 2D and 3D seismic, and field data collected across the Dry Creek anticline provide a more comprehensive understanding of the structural evolution of the Hamilton Creek-Dry Creek anticline in relation to Paradox Valley salt wall. At outcrop, the Dry Creek anticline appears to be a very different structure from other salt anticlines in the Paradox Basin, and could be used as an analog for shortened or pinched-off salt ridges. 2D seismic profiles trending NE-SW across the Uncompahgre Front into the Paradox Basin near the Hamilton Creek structure show thrust faults of the Uncompahgre Front emplacing Late Proterozoic basement over Pennsylvanian aged evaporites in the vicinity of the Hamilton Creek anticline. A close study of the relationship between faulting and evaporite cycles of the Paradox Formation constrains the timing of movement of the Uncompaghre Front in southwestern Colorado to late Pennsylvanian-earliest Permian. In addition, tying the seismic data to field exposures of Mesozoic stratigraphic units in the Dry Creek anticline, northwest of the Hamilton Creek 3D volume and southeast of the termination of Paradox Valley, allows for reconstruction of the Hamilton Creek-Dry Creek anticline through time, further helping to constrain the timing of the regional tectonics associated with the Uncompahgre Front and Laramide deformation of the Colorado Plateau. Interpretation of 3D and 2D seismic data calibrated to extensive well datasets across the Hamilton Creek field will allow the field to be assessed for future petroleum development. A better understanding of the salt anticline will help assess the feasibility of future petroleum exploration in the Hamilton Creek field, and constrain regional tectonics of the Uncompahgre Front and Laramide deformation of the Colorado Plateau.
TABLE OF CONTENTS

ABSTRACT ........................................................................................................... iii

ACKNOWLEDGMENTS .................................................................................. xvii

LIST OF FIGURES ...................................................................................... viii

LIST OF TABLES .......................................................................................... xvi

CHAPTER 1 INTRODUCTION ........................................................................ 1

1.1 Research Objectives ................................................................. 3

1.2 Study Area & Dataset ........................................................... 4

  1.2.1 Field Data .............................................................. 4

  1.2.2 Seismic .............................................................. 6

  1.2.3 Wells .............................................................. 6

  1.2.4 Software .......................................................... 8

CHAPTER 2 GEOLOGIC BACKGROUND .............................................. 9

  2.1 Tectonics ................................................................. 9

  2.2 Structural Geology ........................................................ 11

  2.3 Stratigraphic Framework .................................................. 15

  2.4 Salt Movement .......................................................... 22

  2.5 Salt Terminology ........................................................ 24

CHAPTER 3 METHODOLOGY ............................................................. 26

  3.1 Field Work .............................................................. 26

  3.2 Seismic Interpretation ..................................................... 26

  3.3 Cross Section Construction ............................................. 29
3.4 Dry Creek Cross Sections .................................................. 29
3.5 Hamilton Creek Cross Sections ........................................... 31
3.6 Restorations ............................................................... 32
3.7 Result Assessment ......................................................... 35

CHAPTER 4 DRY CREEK SALT ANTICLINE ........................................ 37
4.1 Introduction ............................................................... 37
4.2 Stratigraphy ............................................................... 40
  4.2.1 Paradox Formation (Pennsylvanian) ................................ 41
  4.2.2 Cutler Group (Penn-Permian) ...................................... 42
  4.2.3 Triassic Formations .................................................. 43
  4.2.4 Jurassic Formations .................................................. 45
  4.2.5 Cretaceous Formations ............................................. 50
4.3 Field Observations and Mapping Results ................................ 50
  4.3.1 Stratigraphic Observations ......................................... 50
  4.3.2 Structural Observations ............................................ 52
  4.3.3 Northeast Flank ...................................................... 54
  4.3.4 Southeast Flank ...................................................... 54
  4.3.5 Northwest Flank ...................................................... 56
  4.3.6 Southwest Flank ...................................................... 56
  4.3.7 Southeastern Termination .......................................... 60
  4.3.8 Northwestern Termination ......................................... 60
4.4 Restorations ............................................................... 65
4.4.1 Assumptions and Potential Sources of Error ......................................... 66
4.4.2 Cross Section A .................................................................................... 68
4.4.3 Cross Section B .................................................................................... 72

CHAPTER 5 HAMILTON CREEK SALT PILLOW ........................................... 75

5.1 Overview ......................................................................................... 75
5.2 Stratigraphy ...................................................................................... 76
5.3 Seismic interpretation ........................................................................ 82
  5.3.1 Basement Architecture Interpretation ........................................... 82
  5.3.2 Salt Interpretation .......................................................................... 84
  5.3.3 Minibasin Interpretation ................................................................. 84
5.4 Seismic Horizon Structure and Isochron Mapping Results ................. 88
  5.4.1 Major Horizon Maps ..................................................................... 88
  5.4.2 Minibasin Horizon Maps .............................................................. 91
5.5 Structural Restorations ...................................................................... 94
  5.5.1 Assumptions and Potential Sources of Error ................................. 94
  5.5.2 Section 1 ...................................................................................... 96
  5.5.3 Section 2 ...................................................................................... 100

CHAPTER 6 DISCUSSION .......................................................................... 103

6.1 Regional Structural Framework .......................................................... 103
  6.1.1 Basement Architecture ................................................................. 103
  6.1.2 Timing the movement along southwest dipping basement thrusts .... 109
  6.1.3 Influence of Basement Architecture on Salt Diapir Locations ......... 109
6.2 Salt System Evolution ................................................ 113

6.2.1 Salt Flow Mechanism ............................................. 116

6.2.2 Halokinetic Sequences and Timing of Diapirism ............ 118

6.3 The Argument for Laramide-aged Compressional Tectonics in the Paradox Basin . 119

6.3.1 Laramide Shortening in the Western United States ........... 119

6.3.2 Compressional Salt Diapir Analogs .............................. 122

6.4 Salt Structure Termination Geometries .......................... 125

6.4.1 Termination Geometry Observations from the Paradox Basin .... 127

6.4.2 Possible Scenarios for Development of Termination Geometries .... 129

CHAPTER 7 CONCLUSION ................................................ 131

7.1 Recommendations for Future Work ................................ 132

REFERENCES .............................................................. 134

APPENDIX A ............................................................... 139
LIST OF FIGURES

Figure 1.1: Regional map of the Paradox Basin and Uncompahgre Uplift, highlighting major salt walls, salt anticlines, and Laramide uplifts (modified after Doelling, 1983). .......................................................... 2

Figure 1.2: Map of study area showing the location of the field study area, well dataset, and 2D and 3D seismic data. .......................................................... 5

Figure 1.3: Maps showing well control and section lines across the Dry Creek field study area and the Hamilton Creek 3D seismic volume. (A) Subsurface well control across Dry Creek salt anticline. Wells are located on the southwestern flank, Sawtooth Ridge, and Naturita Ridge. (B) Wells drilled on and around the Hamilton Creek dry gas field, with synthetic seismogram wells colored in the seismic. ............................................................ 7

Figure 2.6: Interpreted cross sections along the southwestern Uncompahgre Front from northwest to southeast, after White and Jacobson (1983). Cross sections reveal a change in structural style from a single, steeply dipping fault plane in the northwest to imbricate thrust faults on the southeastern end of the uplift. . . . . . 14

Figure 2.7: Regional stratigraphic chart modified after Doelling (2001) and Trudgill (2011). Formations found in the study area are colored, those missing are white. Note that salt may control deposition of younger Jurassic formations in the study area. ..................................................................... 16

Figure 2.8: Wolfcampian paleogeography and depositional environment for the Cutler Group. Alluvia fan and fluvial environments in the NW transition to dune fields and marginal marine environments to the SW. From Condon (1997). . . . . 18

Figure 2.9: Cross sections showing the evolution of a salt system above a stepped basement where salt evacuation is initiated by differential loading and overburden progradation (modified after Ge et al., 1997). Progradation forces salt to evacuate in the direction of sedimentation and salt diapirs rise where there are changes in basement elevation. .................................................. 23

Figure 2.10: Diagrams of the halokinetic sequences end-members: (a) hook halikentic sequences, and (b) wedge halokinetic sequences (from Giles and Rowan, 2012). .......................................................... 24

Figure 3.1: Geologic map of Dry Creek salt anticline showing the location of structural measurements. ...................................................... 27

Figure 3.2: Map of study area showing the distribution of subsurface well control, 2D seismic, and 3D seismic, .......................................................... 28

Figure 3.3: Map of subsurface well control (well tops) across Dry Creek anticline and the section lines used for 2D structural restorations. The stereonet shows the distribution of measurements taken across the structure, colored by unit, and the preferred orientation for the section lines shown in the map. . . . . 30

Figure 3.4: Map of Hamilton Creek 3D seismic volume showing the location of the wells used for depth conversion and restoration section lines overlain on the Top
Salt time structure map. .................................................. 31

Figure 4.1: Map showing the location of Dry Creek anticline relative to the southeastern termination of Paradox Valley (Google Maps, 2017). ......................... 37

Figure 4.2: Geologic map of Dry Creek with wells and representative structural measurements. Four of the six subsurface control wells are seen at this scale (Sawtooth 1-22 and Martin Mesa 1 A 12 are not shown. ......................... 38

Figure 4.3: Map showing the naming conventions for Dry Creek anticline. (Google Maps, 2017) .......................................................... 39

Figure 4.4: Photos of Paradox caprock (Phpc) on the NE flank of Dry Creek anticline. (A) Paradox caprock at the base of the NE flank, approximately 40 m thick. Thin layers of Cutler and Chinle crop out above the caprock. (B) Fairly continuous layer of black shale at the base of the caprock unit. (C) Bedding planes visible in the shale layer, indicating that at least the base of the caprock is Paradox age. ............................................................... 41

Figure 4.5: (A) Deep red, purple Cutler outcrop in a ravine at near the base of the NW flank. The formation is bleached proximal to fractures seen in clusters along the outcrop. (B) Close up of matrix-supported conglomeratic texture. Grain size ranges from small pebbles to small cobbles. ............................ 42

Figure 4.6: Google Earth satellite imagery of the NW flank showing continuous conglomeratic benches near the top of the Cutler Group. Red box shows the location of the images in Figure 4.5. ........................................ 43

Figure 4.7: Angular unconformity seen on the NW flank in the Chinle that could define the contact between Triassic Moenkopi and the overlying Triassic Chinle. There is no lithological difference in the rock across the unconformity, but the units below the unconformity have undulating beds. .............................. 44

Figure 4.8: Chinle outcrop images. (A) Close up of characteristic bright-red color of the Chinle with fine-grained sand to silt laminations. (B) Contact between the top of the Chinle and base Wingate. The Chinle coarsens upward, but remains more thinly bedded than the Wingate. .......................................... 45

Figure 4.9: Wingate outcrop images. (A) Wingate forms cliffs on the anticline flanks approximately 30 meters thick. (B) Close up of the stratigraphic architecture of Wingate. Thick sandstone beds with up to 3 meter thick cross-strata... 46

Figure 4.10: Kayenta outcrop of red interbedded sand and silt units on the NW flank. The beds steeply dip at approximately 55° to the southwest. The southeastern termination and southern flanks are annotated in the background. The high dips can be seen on the annotated SW flank, locally defining a halokinetic hook sequence adjacent to the core of the structure. ......................... 47

Figure 4.11: Satellite imagery of the contact between the Kayenta (Jk) and Entrada (Jec) on the NW flank. Jk is the bright red slope former and Jec forms a pink bench above the slope. The contact is demarcated by a change in color and end of vegetation. Note the bleaching in the Upper Jec and close to the axis. .............. 48

Figure 4.12: Entrada Sandstone outcrops on the NW flank. (A) Close up of Jec showing
the basal pink "member" capped by the bleached upper "member" of the formation. (B) Google Earth satellite imagery photo of bleaching through the entire Jec thickness near the axis of the anticline. Note the high dips in the Jk and Jec, locally defining a halokinetic hook sequence adjacent to the core of the structure.

Figure 4.13: Updated geologic map of Dry Creek anticline

Figure 4.14: Close up map of the NE flank of Dry Creek. Dips range from 75° to 7°. The dips generally decrease away from the axis, quickly shallowing from 75° in the Paradox to <40° dips in the Chinle and younger units.

Figure 4.15: Sketch of dip changes along NE flank showing gradual dip changes from SW to NE. Dips consistently above 20° until the Jmb.

Figure 4.16: Close up map of the SE flank of Dry Creek. Dips range from 75° to 7°. Measurements on this flank are highest closest to the fault in the southeastern termination, and quickly decrease to <30° values less than 100 meters from the axis.

Figure 4.17: Close up map of the NW flank of Dry Creek. Dips range from 88° to 3°. Measurements on this flank are high through Js on the flank near the axis. The dips rapidly steepen towards the anticline axis, increasing from 13° to >50° in under 100 meters in the Jec.

Figure 4.18: (A) Rapid steepening of dips seen in the halokinetic hook sequence in the Jec and Jk on the NW flank in measurements and bed rotation on the flank close to the axis. Jurassic units wrap around the flank to the NW termination. Although perspective in the photo does not show this, the Jec, Js, Jms, and Jmb units continue to the NW towards the NW termination, and do not rise in elevation towards the structure axis, which is why the sketch in 4.18B shows the flank profile. (B) Sketch showing dips across the outcrop from the base of the flank along Dry Creek, to the rotated units in the axis at the Jec-Jk cliff. The dips are <20° across the flank and abruptly increase to >50° close to the axis. The sketch combines data from the top of the NW flank, along the Jec outcrop, with data taken at the base of the flank along the creek bed to show the orientation of beds across the western flank of the structure.

Figure 4.19: Map of the SW flank showing steep dips in the axis center near the Pc outcrop. The dips quickly shallow in the Trc on the flank. No measurements were taken in the Jk and Jec to compare to the NW flank.

Figure 4.20: Map of the SE termination. Dips are very shallow near the termination <20°, except for measurements proximal to Fault SE_01 which are >70°. The sense of fault slip is difficult to determine on SE_02, SE_03, and SE_04. Fault SE_01 is a steep, down-to-the-northeast normal fault.

Figure 4.21: Annotated photo of the SE termination. Fault SE_01 divides the SW and SE flanks, down dropping the SE flank. 3 faults in the SE flank (SE_02, SE_03, and SE_04) crosscut the SE flank, connecting to fault SE_01 in the anticline axis. Note the rapid steepening of beds, like the NW flank (Figure 4.18), is seen in the Jk and Jec on the SW flank.
Figure 4.22: Map of the NW termination. The folded Phpc, PC, and Trc units in the termination have highly variable dip ranges and strike directions. Measurements in the Jec and Js shallow from the NW flank. Strike values do not change much, but are controlled by fault movement.

Figure 4.23: Ramp and fold from the NW flank to the NW termination. The ramp is clearly visible in the Jec.

Figure 4.24: Photo showing the relationship between the faults and units in the NW termination. Faults NW_01 and NW_02 connect in the Trc. Faults NW_03 and NW_04 connect in the Pc. The Jk pinch out is visible on the NW flank against Fault NW_03.

Figure 4.25: Map of section line locations and subsurface well control across Dry Creek anticline.

Figure 4.26: Mapping data and subsurface well control constrain the shape of the salt wall. The Dry Creek salt diapir is a narrow salt wall connected to autochthonous salt 4,000 meters below the surface. Salt may or may not be welded out under Coke Oven Syncline to the NE, and there is no control over salt depth and thickness to the SW of Dry Creek anticline.

Figure 4.27: Dry Creek restoration of Section A. See text for detailed description of each restoration.

Figure 4.28: Dry Creek restoration of Section B showing the difference in line length and salt wall shape created by fault restoration orders. Restoration Version 1 (A-C) restores Fault NW_01 (B) before fault NW_02 (A). The restoration results in folded units on the NE flank and a rotated salt wall in Mancos time (C). There is also a 2-1% loss in length of all units after the fault restoration. Restoration Version 2 (D-F) restores Fault NW_02 (E) before NW_01 (D). The restoration results in folded bed orientations that are similar to the restorations in Figure 4.27.

Figure 5.1: Map showing the location of the Hamilton Creek salt pillow in relation to Dry Creek anticline and Paradox Valley.

Figure 5.2: Surface geology above Hamilton Creek 3D seismic volume shows no structural topography.

Figure 5.3: Time structure map of Top Paradox Salt across the Hamilton Creek salt pillow, revealing a low relief structure with a NNE-SSW strike. Salt minibasins are interpreted N and E of the salt pillow.

Figure 5.4: (A) Synthetic seismogram of HC Federal 5-21 showing the correlation between the synthetic seismic and well top picks. (B) Well location (time projected) on the SE edge of seismic volume. (C) Well location on seismic drilled through the upper fault tip of B_01, showing the correlation of the synthetic seismogram to the seismic character of the Paradox Salt.

Figure 5.5: (A) Synthetic seismogram of Hamilton Creek State 36-23 showing the correlation between the synthetic seismic and well top picks. (B) Well location on the W edge of the salt pillow. (C) Well location on seismic. The well is not drilled through the salt (time projection), but shows the correlation between
Figure 5.6: Map and 3D view of six basement thrust faults (B_01-B_06) interpreted across the seismic volume. B_01 and B_02 are the largest faults with the greatest throw. B_03 is a minor thrust between B_01 and B_02. B_04 and B_05 are imbricates off B_02. B_06 is on the SW edge of the seismic and is omitted from the restorations. Note: Hamilton Creek salt pillow sits above B_01 and B_03, and the northern minibasin sits in the basement low created by the offset of B_02. 

Figure 5.7: Seismic interpretation of basement faults B_01-B_05, Hamilton Creek salt pillow, and minibasin intervals. Axial surfaces in the Mississippian interval define the folds in the strata near the upper fault tips. The line also illustrates the low, broad relief of the salt pillow.

Figure 5.8: Seismic lines showing the interpretation of the Cutler minibasins above the Hamilton Creek salt pillow. (A) Northern rollover minibasin off the northern edge of the salt pillow. The minibasin welds out the salt north of the salt pillow, and is bounded by supra-salt fault S_02 to the east. (B) Faulted minibasin on the eastern edge of the salt pillow. The minibasin is bounded by supra-salt faults S_01 and S_02 and welds out the salt east of Hamilton Creek salt pillow.

Figure 5.9: Map of supra-salt faults S_01 and S_02. Fault S_01 is a down-to-the-southeast normal growth fault that strikes NNE-SSW on the eastern edge of the salt pillow. Fault S_02 is a down-to-the-west normal fault that curves along the western edge of the salt pillow interpreted on the eastern edge of the seismic volume.

Figure 5.10: Time structure maps of the major horizons: Basement, Base Salt, Top Salt, Ismay, P06 (top Cutler), and Chinle. The basement thrusts are imprinted in the Basement and Salt_Base maps. Salt_Top, Ismay, and P06 are influenced by the shape of the underlying salt and the post-salt faults. The Chinle map does not reflect any of the underlying faults or salt structures.

Figure 5.11: Time thickness maps of the Paradox salt (A) and total Cutler (P06-P01) (B). Thicks are purpler and thins are red. (A) The Hamilton Creek salt pillow and pillow on the eastern edge of the seismic volume are the thickest regions. There are two thins, on basement faults, in the northern area of the seismic volume. (B) Total Cutler isochron highlights post-salt depocenters across the seismic, flanking the salt pillow. The two minibasins analyzed in this study are outlined by what dashed lines.

Figure 5.12: Time structure and isochron maps for Cutler seismic horizons P01-P03. On the structure maps, red is high and purple is low. On the isochron maps, red is thin and purple is thick. See text for detailed description of each map.

Figure 5.13: Time structure and isochron maps for Cutler seismic horizons P04-P06. On the structure maps, red is high and purple is low. On the isochron maps, red is thin and purple is thick. See text for detailed description of each map.

Figure 5.14: Section lines used for the Hamilton Creek salt pillow restorations. Line locations can be seen on the Top Salt time structure map. The section lines were based on time seismic interpretations of the three lines shown in figures.
5.7 & 5.8. Section 1 transects the basement back thrusts and salt pillow. Section lines 2 and 3 are roughly perpendicular to the two minibasins focused on in this study. .......................................................... 95

Figure 5.15: Hamilton Creek Section 1 restoration. See text for detailed description of each restoration level. .......................................................... 98

Figure 5.16: Hamilton Creek Section 2 restoration. See text for detailed description of each restoration level. ................................................. 101

Figure 6.1: Map over the study area showing seismic coverage and location of 2D composite seismic lines. Basement thrust faults, dipping northeast and southwest are interpreted across the Uncompahgre Front to the southwest of the Uncompahgre salient. The northeast dipping faults are closest to the Uncompahgre Uplift, and the southwest dipping faults sit further in the basin. Diapiric salt (>0.25 secs TWT thick) was interpreted at the northwestern edge of the salient and in the basin on trend with the four major salt wall lineations. Remnant salt (<0.25 secs TWT thick) was interpreted on the eastern half of the study area. In general, the amount of salt and thickness of salt decreases to the southeast. Isochron map of the Cutler Group reveals the location of the primary depocenter in the study area between the salt against the Uncompahgre thrusts and the Paradox Valley salt trend. .................. 104

Figure 6.2: Interpretation across Sawtooth Ridge composite line. Imbricate thrust faults extend from the Uncompahgre Uplift into the Paradox Basin. A relict salt pillow is trapped against the deepest thrusts, and salt is welded out on the SW end of the line. Expulsion rollover geometry is seen within the Cutler SW of the relict salt pillow and the edge of the main Cutler minibasin (Figure 6.1) is on the SW edge of the line. The Mississippian and Basement horizons were difficult to interpret in the northeastern most thrust blocks, but seismic reflection character suggests that the Mississippian horizon extends across the composite line. Refer to Figure 6.1 for line location. .................. 105

Figure 6.3: Interpretation across Naturita Ridge composite zigzag line. Changes in direction along the zigzag line are noted above the seismic. The line starts in the thrust salient at the NE end, cut by two shallowly dipping thrust faults. Back thrusts are interpreted basinward of the Uncompahgre thrust front where folding of the Mississippian unit and minor basin uplifts are seen. Salt is trapped in the lows around the basement uplifts. A welded Cutler minibasin is interpreted at the SE end of the line on the NE flank of the Naturita Ridge salt ridge, barely imaged on the edge of the composite line. Refer to Figure 6.1 for line location. .......................................................... 106

Figure 6.4: Interpretation across Hamilton Creek composite line. Imbricate thrust faults, with steeper dips than those in Figures 6.2 and 6.2, extend from the Uncompahgre Uplift into the Paradox Basin. Thrust faults obliquely cut by the composite line are shown at the base of the Uncompahgre Front. Paradox salt is welded or not deposited against the Uncompahgre Uplift. A Cutler minibasin sits basinward of the uplift on the northern end of Hamilton Creek salt pillow. The salt is locally welded on the upper tips of back thrusts underneath the salt pillow. Refer to Figure 6.1 for line location. ............... 107

Figure 6.5: Interpreted controlling basement fault zone based on gravity gradient map from Trudgill (2011). Salt wall locations interpreted to be controlled by the location
of the NW and NE trending faults at the top Mississippian level, inherited from PreCambrian basement architecture. ........................................ 110

Figure 6.6: Observed gravity from Banbury (2005) (on the left) and the University of Texas El Paso PACES Gravity Database (on the right) show basement trends. The gravity boundary of the Uncompahgre Uplift extends further SW into the basin than the seismic fault interpretation. The gravity response south of Hamilton Creek suggests that the basement is shallower SE of the salt system, and that the system is close to the basin margin. Note that the maps have different scales so the color gradients do not match. ........................... 111

Figure 6.7: Regional top-based Mississippian horizon shows a steep dip change in the Mississippian under Dry Creek anticline Section A. (A) A normal fault drops the hanging wall block to the NE of the salt wall. (B) A thrust fault (backthrust) folds the hanging wall block, forcing it higher than the footwall block to the NE. ................................................... 112

Figure 6.8: Map highlighting the locations and trends of the salt structures in the study area. Hamilton Creek salt pillow is on strike with Paradox Valley salt wall. Naturita Ridge salt ridge and Dry Creek salt anticline have the same strike but offset to the southeast. The offset of Dry Creek and Naturita Ridge lines up with the location of the Uncompahgre thrust salient. (Google Maps, 2017). ............. 113

Figure 6.9: Interpretation across NR-HC 2D seismic line. Refer to Figure 6.1 for line location. A strike-view of the Dry Creek-Hamilton Creek salt system reveals two salt pillows, Hamilton Creek salt pillow and SE Hamilton Creek salt pillow, separated by a welded, fault-bounded minibasin. The salt also thickens to the NW of Hamilton Creek salt pillow creating a salt ridge under Naturita Ridge. This is the same salt body interpreted at the SE edge of Naturita Ridge composite line (Figure 6.3). The plan view of the salt ridge can be seen on Figure 6.1 ................................................................. 114

Figure 6.10: Comparison of Ge and others (1997) progradational models (A) to seismic interpretation (B) from Kluth and DuChene (2009). The seismic interpretation shows trapped salt and welds against the thrust front, followed by expulsion rollover and the creation of passive salt walls and salt anticlines. .......... 115

Figure 6.11: Map modified from Rasmussen and Rasmussen (2009) showing the distribution of salt structures in the basin. Note the study area sits at the SE extent of diapiric salt in the Fold and Fault Belt. The amount of salt also decreases from NW-SE in the study area, as indicated by the transition from large salt walls to salt anticlines and small salt pillows. ................... 116

Figure 6.12: Restoration levels for Dry Creek and Hamilton Creek for the time of latest salt diapirism. (A) Development of the halokinetic hook sequence on the southwestern margin of the salt wall was complete by Summerville time (166 Ma). (B) Hamilton Creek salt pillow was fully developed by the end of the Triassic (201 Ma). The minibasin is fully developed, but the weld on fault B_02 has not developed. ....................................... 117

Figure 6.13: Regional Laramide compressional tectonics that acted on the Paradox Basin. (A) Modified after Bump (2004). Location of Laramide uplifts on the Colorado Plateau (solid arrows indicate shortening direction). The inset map highlights the location of the Seveir thrust front on the northwestern

Figure 6.14: Guglielmo model for pinched-off salt wall and present day cross section through northwestern termination of Dry Creek. The direction of compression is from left to right on both figures. (A) The Guglielmo model shows steeper dips in the forelimb and an asymmetrical salt anticline at the center. (B) The Dry Creek termination shows steeper dips in the backlimb and a symmetrical salt anticline in the structure’s core.

Figure 6.15: Schematic salt diapir showing the geometric characteristics of late-stage compression from Davison and others (2000).

Figure 6.16: Comparison of folded strata above South Pierce salt diapir, Central North Sea (modified from Davison and others (2000) the Quilitage salt anticlines from Li et al. (2012), and Dry Creek salt anticline. (A) Interpretation of a fold in the Eocene-Oligocene strata above the South Pierce diapir. The direction of compression is unknown. (B) Subsurface interpretation of the Quilitage salt anticlines of the Kuqa Basin projected above ground level. The anticlines are asymmetrical with steeper dips in the forelimbs than backlimbs. (C) Folded strata above Dry Creek anticline showing folded strata in the faulted units. Note there is no control in folding in the latest Cretaceous and younger strata.

Figure 6.17: Rotation in strike along the NE flank, part of Coke Oven Syncline, to the southeastern termination fo Paradox Valley, marked by the white dashed lines. The change in strike suggests a relationship between the evolution of Dry Creek and Paradox Valley salt structures. Note the highly rotated and oversteepened dips in the Jms tongue extending into the valley floor.

Figure 6.18: USGS geological map of the Naturita NW quadrangle, highlighting the NW termination fault connectivity between Dry Creek and Paradox Valley (modified from Cater, 1955).

Figure 6.19: Comparison of Klondike Ridge at the SW termination of Gypsum Valley and NW termination of Dry Creek anticline. (A) Klondike Ridge graben in the center of the Gypsum Valley termination. The offset on the N-S trending normal faults decreases to the south, away from the termination. (B) Faults at the NW termination of Dry Creek. The small fault block between NW_01 and NW_02 becomes a graben bounded by NW_03 to the northwest of the termination. The faults extend northwest to the southeastern termination of Paradox Valley.
# LIST OF TABLES

Table 3.1: Lithology percentages for each formation used in the restorations, with surface porosities and depth coefficients calculated in *Move 2016*. .................. 33

Table 3.2: Ages for each formation used in the restorations. Ages derived from Doelling (2001) and the International Chronostratigraphic Chart 2017 v2. *Note the ages for Cutler P05-P01 are inferred. ................................. 36

Table 4.1: Local stratigraphy of Dry Creek anticline from field study data. Thickness ranges are taken from Cater (1955). Bedding dip measurements are from the entire study area. Moenkopi does not outcrop, so no thickness or dip measurements are recorded. The unit is included in the study because a well top exists for the unit in the subsurface dataset. The anomalously high Salt Wash maximum dip was taken in a vertical to overturned exposure in the southeastern termination of Paradox Valley (Figure 4.2). *Indicates units in which the top portion has been eroded. ................................. 40

Table 5.1: Horizons interpreted across the Hamilton Creek 3D seismic survey. ............... 78
ACKNOWLEDGMENTS

This project would not have been possible without the support and guidance of my advisor, Bruce Trudgill. My committee members, Mary Carr and Thomas Hearon, were incredibly supportive and patient with me as I worked through this project. Your discussion, ideas, and input were invaluable and I could not have completed this project without it.

A big thank you to my field assistants, Cheryl Fountain and Jessie Jobe, for the all time and energy they spent with me in the field.

This research could not have been conducted without the seismic and well data provided by Encana Oil and Gas.

I am fortunate to have received scholarships and awards from Apache, RMAG, and AAPG; this project would not have been possible without them.

I would like to thank my friends, both the new and the old, for their friendship and encouragement.

Last but not least, I would like to thank my family, especially my parents, for their unfailing love and support. You have fostered a passion for learning and research, and I wouldn’t have gotten this far without you. This thesis is dedicated to you.
CHAPTER 1

INTRODUCTION

The Pennsylvanian-Permian Paradox Basin is an asymmetrical basin on the Colorado Plateau (Figure 1.1) that has been studied for decades due to its unique geologic history and economic quantities of potash, petroleum, and minerals such as uranium, vanadium, radium, and copper. The basin has a complex tectonic history, made more difficult to interpret due to the large volume of Pennsylvanian-aged salt deposited in the northern part of the basin, now forming a series of salt walls. The basin has been interpreted as a foreland basin by Barbeau (2003), formed in response to loading by the Uncompahgre Uplift, which delineates the northeastern boundary of the basin. There is no definitive evidence, to date, of the tectonic influence of later tectonic events, namely the Late Cretaceous Laramide orogeny. Understanding the evolution of the salt walls and intervening strata within the basin will help identify indicators of tectonic regimes and influences throughout the basin history.

The Paradox Basin contains the thickest contiguous salt deposit in continental North America (Hite, 1960), which makes it an important outcrop analog for subsurface salt systems around the world, including the Gulf of Mexico, North Sea, and south Atlantic Margin. Most of the work to date in the northern Paradox Basin has been conducted on the large-scale salt walls, such as Castle Valley, Salt Valley, and Moab Valley in Utah (Figure 1.1), but relatively little work has been done on the Colorado side of the basin to the southeast. Additionally, little work has been conducted on smaller-scale salt structure, such as Gibson dome, Lockhart anticline, and Rustler dome (Figure 1.1). Research must be conducted on these small-scale salt features to further academic and industrial understanding of the geology and evolution of this salt system because these features are more intact, less eroded, and, therefore, may contain better preserved evidence of the relationship between tectonic movement and reactivation, salt wall evolution, and halokinetic stratigraphy.
Figure 1.1: Regional map of the Paradox Basin and Uncompahgre Uplift, highlighting major salt walls, salt anticlines, and Laramide uplifts (modified after Doelling, 1983).
1.1 Research Objectives

The main objective of this project is to investigate the structural evolution of the Dry Creek-Hamilton Creek salt anticline in relation to the southeast termination of Paradox Valley salt wall in southwest Colorado. This project integrates subsurface well data (well log and top data), and 2D and 3D seismic datasets with field data taken at field exposures across the Dry Creek salt anticline near the Paradox Valley termination. Based on outcrop mapping, the Dry Creek salt anticline appears to be a very different structure from other salt walls in the Paradox Basin due to the folded geometry and faulting through all stratigraphic units at the structure’s northwest termination. The structure’s small size makes it a unique study subject because there is greater stratigraphic control across the structure axis. Analysis of these perceived differences could make the Dry Creek salt anticline an analog for shortened or pinched-off salt structures. A better understanding of the structural evolution of the salt walls will help assess the feasibility of future petroleum exploration in the Hamilton Creek field, and constrain the regional tectonics of the Uncompahgre Front and Laramide deformation of the Colorado Plateau.

This study will expand the dataset of salt walls in the Paradox Basin by adding structural field data and subsurface interpretations of salt features in the Colorado region of the basin. Analysis of smaller salt features will provide valuable insight into the regional evolution of the basin, in relation to both salt tectonics and external influences on the basin through time.

Specifically, this study has the following goals:

• Interpret, in detail, the mini-basin stratigraphy, basement faults, and crestal salt-related faults in the 3D seismic survey over the Hamilton Creek salt pillow, using well logs and well tops in the extensive Hamilton Creek gas field well dataset of over 50 wells in Petrel 2016.

• Use 2D regional profiles to place the Hamilton Creek structure in the regional context of the evolution of the Uncompahgre Front.
• Extend the subsurface interpretation to the northwest using regional data to tie to the outcrop exposures of the Dry Creek anticline, which sits along strike from the Hamilton Creek salt pillow (Figure 1.2).

• Reconstruct the evolution of the Hamilton Creek salt pillow and Dry Creek anticline through time using Midland Valley Move 2016.

• Determine the relationship between the Hamilton Creek – Dry Creek salt feature and the southeast termination of Paradox Valley using regional seismic lines, interpreted surfaces and reconstructions in Midland Valley Move 2016.

1.2 Study Area & Dataset

The study area is located in the Paradox Basin, in southwest Colorado, southwest of Naturita, Colorado (Figure 1.1 & 1.2). The outcrop geology of the basin is primarily of Jurassic and Cretaceous age, but older strata, as old as Pennsylvanian Paradox caprock, crop out in the valley floors.

This research is based on outcrop and subsurface data from the following sources:

• Field structure measurements

• Seismic data

• Well data (logs and tops)

1.2.1 Field Data

The field component of this thesis focuses on the Dry Creek structure, southeast of Paradox Valley (Figure 1.2). A USGS geologic map of the Dry Creek structure area was published by Fred Cater in 1955, and is the primary source for stratigraphic identification. Two sets of structural measurements taken across the structure were combined for this study: the first by previous graduate students (Lehmann, 2015 and Timbel, 2015), and the second in the fall of 2016 during this study.
Figure 1.2: Map of study area showing the location of the field study area, well dataset, and 2D and 3D seismic data.
1.2.2  Seismic

The study area contains two time migrated seismic datasets donated to Colorado School of Mines by Encana Oil and Gas. A 3D volume sits over the Hamilton Creek dry gas field, and covers 78 km$^2$ (30 mi$^2$) with inline and crossline spacings of 33 m (110 ft). A larger 2D survey contains a series of 36 lines covering a total length of 419 km (260.3 mi) over the Uncompahgre Front near Nucla, Colorado. The 3D dataset is used to interpret the structural evolution of the Dry Creek/Hamilton Creek salt feature in the subsurface and the 2D datasets are used for a regional constraint of the Hamilton Creek/Dry Creek system within the basin (Figure 1.2).

1.2.3  Wells

There are 120 wells in the study area with formation tops and log data. Well data was collected from the COGCC (logs and tops) and well tops were donated to CSM by Encana Oil and Gas. The formation top data are primarily used to constrain cross-sections over Dry Creek anticline, and to create correlative surfaces across the study area. The log data are used to create a time-depth conversion between the seismic interpretations in time, and the depth interpretations.

The following wells were used to create cross-sections across Dry Creek anticline and Paradox Valley (Figure 1.3A):

- Kirby Government Unit 1
- Martin Mesa 1 A 12
- Masterbrook 1
- Montrose Unit Government 2
- Montrose Unit Well 3
- Sawtooth 1-22

The following wells contain sonic and density logs and were used to create the time-depth conversion over the 3D seismic volume (Figure 1.3B):
**Figure 1.3:** Maps showing well control and section lines across the Dry Creek field study area and the Hamilton Creek 3D seismic volume. (A) Subsurface well control across Dry Creek salt anticline. Wells are located on the southwestern flank, Sawtooth Ridge, and Naturita Ridge. (B) Wells drilled on and around the Hamilton Creek dry gas field, with synthetic seismogram wells colored in the seismic.
1.2.4 Software

Structural measurements in the field were collected with the Midland Valley FieldMove Clino iPhone application. Digital mapping was performed in ESRI ArcMap 10.5. Seismic interpretation was completed in Schlumberger’s Petrel 2015. Structural restorations were constructed in Midland Valley Move 2016.
CHAPTER 2
GEOLOGIC BACKGROUND

2.1 Tectonics

The Paradox Basin is located on the Colorado Plateau in southeastern Utah and southwestern Colorado. It is bounded by the Uncompahgre Plateau to the northeast, the San Luis Uplift and San Juan mountain range to the southeast, the Monument Uplift to the southwest, and its western boundary is demarcated by the depositional extent of the Pennsylvanian Paradox salt (Figure 2.1). The basin formed in Pennsylvanian-Permian time as a response to the Uncompahgre Uplift of the Greater Ancestral Rocky Mountains (GARM). However, the tectonics of the GARM are poorly understood, especially in the Paradox Basin, due to tectonic overprint by later tectonic events, including the Laramide orogeny, and by the salt tectonics within the basin (Blakey, 2009).

Figure 2.1: Map of the Paradox Basin and Uncompahgre Uplift, highlighting major salt walls, salt anticlines, and Laramide uplifts, modified after Doelling, 1983. Orange section line reference for Figure 2.5.
The GARM were intracratonic uplifts and basins that spanned a large area of the American Southwest (Kluth and Coney, 1981; Blakey, 2009) (Figure 2.2). Prior to the GARM orogeny (Cambrian – Mississippian), the western US was covered in shallow, marine shelf environment (Blakey, 2009). Deposition of shallow marine sediment was interrupted by the broad, gentle uplift of the Transcontinental Arch trending NE-SW from northeastern Arizona up through Colorado (Blakey, 2009). Many of the GARM uplifts occur on the at right angles to the trend of the Transcontinental Arch (Figure 2.2) (Mallory, 1972; Blakey, 2009).

Studies of various GARM uplift-basin systems have caused much debate on the cause of the GARM orogeny. Kluth and Coney (1981), interpret the GARM uplift as the intraplate response to the Ouachita-Marathon orogeny, which formed a suture zone during the collision between North and South American continents. Ye et al (1996), however, argue that the orientation of the GARM resulted from the northeast-southwest intraplate shortening caused by the shallow subduction of the Mojave-Sonora megashear along the late Paleozoic Andean margin on the southwestern margin of North America (Figure 2.3).

Figure 2.2: Ancestral Rocky Mountains and interpreted transcontinental arch (modified from Blakey, 2009). PaB: Paradox Basin, UnU: Uncompahgre Uplift.
Baars and Stevenson (1981, 1982) described the Paradox Basin as a pull-apart basin that formed at the intersection of two conjugate Precambrian rift lineaments with opposing displacements (Figure 2.4). This interpretation, however, does not explain the uplift of other structures, such as the San Luis Uplift, Apishapa Uplift, and Front Range Uplift, associated with the GARM. The existence of basement architecture could help explain the orientation and placement of the valleys and salt features in the northern region of the basin.

The most recent hypothesis of the tectonic setting of the Paradox Basin is that of an immobile intracontinental foreland basin (Barbeau, 2003). Barbeau compared the shape, sediment load, and thrust fault offset of the Paradox Basin to other foreland basin studies and determined that it shared more characteristics with other foreland basins than with basins formed by distant subduction zones, mountain building, or wrench-faulting (Figure 2.5). However, the Barbeau (2003) model does not provide an explanation for the regional tectonic event that caused the Uncompahgre Uplift-Paradox Basin system, or other GARM systems, to form. Nor does it explain the structural differences in thrust character along the southwestern margin of the Uncompahgre Uplift, which will be discussed in the next section.

Figure 2.3: Uncompahgre Uplift-Paradox Basin location relative to the interpreted Mojave-Sonora megashear (Ye et al., 1996).
2.2 Structural Geology

The Paradox Basin formed in response to the uplift of the crystalline Uncompahgre block (Barbeau, 2003). Well data and seismic studies have revealed that the thrust style along the southwestern margin of the Uncompahgre Uplift changes from a single thrust fault plane at its northwestern end in Utah to a series of imbricate thrusts to the southeast in Colorado (Figure 2.6). Frahme and Vaughn (1983) used seismic data to study the Uncompahgre front zone west of the Green River in Utah. They were able to infer a dip of approximately 20°, relative to the dip of the underlying Mississippian and Cambrian strata, with a horizontal displacement of 10,000 meters and a vertical displacement of about 6,000 meters. Near Gateway, CO, the Uncompahgre fault style changes from a single bounding thrust fault to a series of thrust faults that protrude into the basin with progressively shallower dips and lesser vertical displacement (White and Jacobson, 1983).

In addition to the faulting on the northeastern boundary of the Paradox Basin, there has been much speculation as to the existence of Precambrian age basement faulting and
architecture underlying the basin fill, and are interpreted to control the locations of the salt walls in the northern part of the basin (Baars and Stevenson, 1981; Friedman et al., 1994). Baars and Stevenson (1981) hypothesized the existence of conjugate shear zones with northwest-southeast and northeast-southwest orientations using well-based isopach maps of Mississippian and Cambrian strata (Figure 2.4). More recently, gravity, magnetic, and Landsat imagery have been used to interpret lineation orientations and have also interpreted northwest-trending and northeast-trending Precambrian basement lineaments (Friedman et al., 1994).

The present-day Uncompahgre Plateau is a topographic high formed by broad, anticlinal folding during the Laramide orogeny, which rejuvenated the pre-existing faults of Pennsylvanian-Permian age that bounded the GARM Uncompahgre Uplift (White and Jacobson, 1983). Faults related to the GARM are those that do not cross the Triassic Unconformity, while GARM faults reactivated during the Laramide orogeny cross-cut Cretaceous age strata (White

---

**Figure 2.5:** Basin model profile results showing the similarities between the Paradox Basin and a flexural foreland basin. Paradox stratigraphy has been applied to the schematic foreland basin profile. Modified from Barbeau (2003).
Figure 2.6: Interpreted cross sections along the southwestern Uncompahgre Front from northwest to southeast, after White and Jacobson (1983). Cross sections reveal a change in structural style from a single, steeply dipping fault plane in the northwest to imbricate thrust faults on the southeastern end of the uplift.
Laramide deformation has not been clearly interpreted within the Paradox Basin, but evidence has been found on the Uncompahgre Plateau. The monoclinal Uncompahgre Plateau has been interpreted as a Laramide feature (White and Jacobson, 1983), as well as the Monument Uplift and San Rafael Swell. The Ridgway Fault, on the southern end of the Uncompahgre Plateau, has been interpreted as a fault in a series of Laramide-age normal faults that bound the Uncompahgre Plateau (Weimer, 1981). White and Jacobson (1983) studied well logs and outcrops near Ridgway, CO and determined that the bounding faults on the southern plunge end of the uplift are high-angle reverse faults. Alternatively, these bounding faults have also been interpreted as sinistral strike-slip faults of Pennsylvanian age (Thomas, 2007).

Although most maps draw the Uncompahgre Uplift primarily as a straight line from northwest to southeast, the topographic expression of the Uplift suggests a local change of the Uncompahgre front northeast of Naturita, CO (Rasmussen and Rasmussen, 2009).

### 2.3 Stratigraphic Framework

The Paradox Basin contains sediments of Cambrian to Cretaceous age (Figure 2.7). The sediments are thickest (~4,600 m) proximal to the Uncompahgre Uplift, and thin to the southwest (Cater, 1970). Stratigraphic studies on basin fill show that the basin margins were set by Atokan time (Baars and Stevenson, 1982), and that the basin continued to subside through Early Permian (Jordan and Mountney, 2012) The stratigraphic units of interest to this thesis are those that were controlled by salt tectonics basinwide, from the Upper Pennsylvanian Honaker Trail Formation to the Upper Triassic Chinle Formation, and units locally controlled by salt tectonics from the Lower Jurassic Wingate Sandstone to the Upper Jurassic Brushy Basin Member of the Morrison Formation (Figure 2.7).

The Pennsylvanian-Permian units make up the primary basin fill, and were deposited on Mississippian marine limestones and sandstones. These units are the Pennsylvanian Paradox Formation (carbonates, black shales, and evaporites) and Honaker Trail Formation (carbonates,
**Figure 2.7:** Regional stratigraphic chart modified after Doelling (2001) and Trudgill (2011). Formations found in the study area are colored, those missing are white. Note that salt may control deposition of younger Jurassic formations in the study area.
sandstones, and shale) of the Hermosa Group and Pennsylvanian-Permian Cutler Group (alluvial fan deposits). These strata document lateral facies variations and cyclical deposition patterns across the basin, interpreted as being related to changes in depositional environment from northeast to southwest across the basin, glacio-eustatic sea level changes, tectonic uplift, and basin morphology (Hite, 1960; Goldhammer et al., 1991; Grammer et al., 1996; Trudgill and Arbuckle, 2009; Fillmore, 2011; Jordan and Mountney, 2012).

**Paradox Formation (Atokan-Desmoinesian):** the Paradox Formation is a heterogeneous unit containing dolostone, dolomite, black shale, siltstone, anhydrite, halite and other salts (Figure 2.7) (Hite, 1960; Nuccio and Condon, 1996). The Paradox Formation was deposited cyclically in a minimum of 29 cycles interpreted as the result of cyclic marine inundation and desiccation of the basin due to glacio-eustatic changes (Hite and Buckner, 1981). In the basin center, the formation is dominated by the evaporite facies, which has been deformed by salt movement and has a present day thickness range of 0 m to 4,000 m in the salt walls. Peterson and Hite (1969) estimate the original depositional thickness of the evaporite sequences to be around 2,200 m. The evaporite sequences are confined to the deeper, northern region of the basin proximal to the Uncompahgre Uplift and the formation facies transition to shelf carbonates and biohermal carbonate mounds in the southwest, shallow margin of the basin (Trudgill, 2011).

Franczyk et al. (1995) concluded that the Cutler Formation must be syn-depositional with the Paradox Formation to preclude the deposition of salt in the deepest part of the basin, suggesting that the Uncompahgre Uplift had vertical displacement in the Late Pennsylvanian. More recently, Kluth and DuChene (2009) have interpreted the Uncompahgre Uplift to have no topography during the deposition of the Paradox salt, and for the evaporites deposited on top of the uplift to have been later displaced or removed as the block was uplifted.

**Honaker Trail Formation (Missourian-Virgilian):** the Honaker Trail Formation is a heterogeneous formation of interbedded limestone, sandstone, and shale that overlies the Paradox Formation in the basin center (Figure 2.7) (Barbeau, 2003). Based on well log correlations,
the formation was deposited in intertonguing carbonate shoals and coastal channels on a broad shelf off a terrestrial fan system (Peterson and Hite, 1969; White and Jacobson, 1983). Strong lateral thickness and facies variations, especially against salt walls indicates that the salt had already started moving due to differential loading by sediment was being shed off the rising Uncompahgre Uplift (Kluth and Duchene, 2009).

**Cutler Group (Desmoinesian-Wolfcampian):** The Cutler Group is a progradational, heterogeneous sequence of arkosic conglomerate with lesser arkosic sandstone, siltstone, and mudstone that was shed off the Uncompahgre Uplift in fan-glomerate and debris flow deposits (Figure 2.7) (Campbell, 1980; Mack and Rasmussen, 1984; Condon, 1997). It is typically dark red, purple, or maroon in color, with conglomeratic clast size range of sand to boulders 7.6 m in diameter (Condon, 1997).

These sediments record the filling of accommodation created by the upward movement and flexural loading of the Uncompahgre Uplift (Barbeau, 2003). The coarse alluvial sediments grade to finer grained sediments to the southwest and west, transitioning to marine deposits at the

*Figure 2.8: Wolfcampian paleogeography and depositional environment for the Cutler Group. Alluvia fan and fluvial environments in the NW transition to dune fields and marginal marine environments to the SW. From Condon (1997).*
basin’s westernmost margin (Condon, 1997). Salt tectonics played a major role in the deposition and thickness of the Cutler Group, trapping between 2,400 and 4,600 m of arkosic sediments between the salt walls in the northeastern part of the basin (Condon, 1997).

Proximal to the Uncompahgre Uplift, the Cutler contains only undifferentiated arkosic alluvial fan system deposits (the facies found in the study area), but to the northwest and southwest parts of the basin, the Cutler transitions to separate formations, deposited in marine, fluvial, and eolian environments (Figure 2.8): the Elephant Canyon Formation (marine limestones and sandstones; fluvial and eolian strata), the Cedar Mesa Sandstone (eolian dunes and playa siltstones), the Organ Rock Formation (sadkha sandstone and siltstone), and the White Rim Sandstone (eolian sandstone) (Nuccio and Condon, 1996).

Mack and Rasmussen (1984) identified three megasequences, each on the scale of hundreds of meters thick, within alluvial-fan sediments of the lower Cutler near Gateway, CO. Each megasequence is composed of a coarsening-upwards sequence of proximal alluvial fan facies, marking periods of renewed uplift of the Uncompahgre block, overlain by a fining-upwards sequence of more distal facies (Mack and Rasmussen, 1984). The youngest of these megasequences marks the end to the uplift of the Uncompahgre block, and the cessation of basin filling sediment deposition. Kluth and DuChene (2009) speculate that the Cutler sequences may be of vastly different ages across the basin.

**Moenkopi Formation (Lower Triassic):** The Moenkopi Formation is a widespread redbed unit that covers much of the Colorado Plateau (Figure 2.7). In the Paradox Basin, the formation is exposed in and around the salt walls, but is missing over the crests of some salt walls due to nondeposition or pre-Chinle erosion (Stewart and Wilson, 1960). Deposition was controlled by salt movement, creating erratic thickness variations in salt minibasins, ranging from 0 to over 750 m (Stewart and Wilson, 1960; Banham and Mountney, 2013). Sediment was sourced from the remnants of the Uncompahgre Uplift and deposited in a mixed marine/terrestrial conditions of near-shore tidal flats and river flood plains (Stewart et al., 1972).
**Chinle Formation (Upper Triassic):** The Chinle Formation consists of red to orange-red siltstone interbedded with red fine-grained sandstone, shale, and limestone-pebble and clay-pellet conglomerate that is unconformable with all underlying units (Figure 2.7) (Cater, 1955, 1970). These units were deposited in fluvial and fluvial-lacustrine setting controlled by salt diapirism (Hazel, 1994). Local intraformational unconformities also exist on the flanks of the salt walls, indicating that salt movement was a major control on deposition (Hazel, 1994). The formation thickness and facies varies greatly across the basin; in the southwestern Colorado region of the basin, the Chinle is 0 to 230 meters thick (Cater, 1970; Hazel, 1994).

**Glen Canyon Group (Lower Jurassic):** The Glen Canyon Group is made up of three formations (from base to top): the Wingate Sandstone, the Kayenta Formation, and the Navajo Sandstone (Figure 2.7). The group is book-ended by erg deposits, which were disrupted by fluvial sands shed off the ancestral Rocky Mountains (Peterson, 1994).

The Wingate Sandstone is a cliff-forming, massive bright red sandstone that lies unconformably over the Chinle Formation (Figure 2.7), a regional boundary called J-0 (Pipiringos and O’Sullivan, 1978; Fillmore, 2011). It is predominantly crossbedded eolian sandstone with minor irregularly bedded, silty sandstone, sabkha deposits (Peterson, 1994). Its thickness varies greatly across the northern part of the Paradox Basin, from 76-107 meters, due to the linear salt walls (Trudgill, 2011).

The Kayenta Formation is primarily red fluvial sandstones with minor red overbank mudstone and forms a series of thin, cliff-forming ledges in outcrop (Peterson, 1994; Fillmore, 2011). The Kayenta was deposited from southwestern Arizona to central Utah and southwestern Colorado, onlapping against the Uncompahgre Uplift (Fillmore, 2011). Riggs and Blakey (1993), however, interpret the silty sandstone beds of the Kayenta in the southwest Colorado Plateau to be mixed facies of the lower Navajo Sandstone.

The uppermost unit of the Glen Canyon Group, is the Navajo Sandstone, a large-scale crossbedded eolian sandstone with minor lenses of limestone and silty sandstones associated
with lakes and ponds scattered throughout the Navajo dune field (Peterson, 1994). Although, not present at outcrop in the field area or southern Paradox Valley (Cater, 1955), it is a significant cliff former of yellow-white color over much of the Colorado Plateau and records the largest erg in Earth history (Fillmore, 2011).

**San Rafael Group (Middle Jurassic):** The San Rafael Group is composed of, from base to top, the Lower and Upper Carmel Formation and the corresponding Dewey Bridge Member, and the Entrada Sandstone with its Slick Rock and Moab members, and the Summerville Formation (Figure 2.7). The only formations of the San Rafael Group mapped in the southwestern Colorado region of the Paradox Basin are the Entrada Sandstone and the Summerville Formation.

The Entrada Sandstone is a crossbedded eolian red-brown sandstone that weathers into vertical cliffs and steep, rounded bands of slickrock (Peterson, 1994; Fillmore, 2011). The Summerville Formation overlies the Slick Rock Member of the Entrada in western Colorado (Figure 2.7). It records the final stages of the narrow Middle Jurassic seaway in its thin, interbedded red and brown mudstone and sandstone intervals that were interpreted to be deposited on a tidal-influenced low-relief coastal plain (Fillmore, 2011).

**Morrison Formation (Upper Jurassic):** The Morrison Formation is separated from the underlying San Rafael Group by the regional J-5 Unconformity (Pipiringos and O’Sullivan, 1978). The formation contains three members, in ascending order: the Tidwell, Salt Wash, and Brushy Basin members, of which the younger two are found in southwestern Colorado (Figure 2.7). The Morrison Formation marks the end of the seaway that invaded the Colorado Plateau during the Middle Jurassic (Fillmore, 2011).

The Salt Wash Member is an interbedded coarse-grained sandstone and mudstone fluvial deposit that weathers into brown cliffs (Fillmore, 2011). The grain size decreases to the east and the amount of mudstone increases, indicative of renewed uplift to the west and southwest (Fillmore, 2011). The Brushy Basin Member conformably overlies the Salt Wash (Figure 2.7). It is dominated by mudstones that weather into slopes of yellows, greens, blues, and purples due
the uranium deposits within the formation and interbedded tuffs (Fillmore, 2011).

2.4 Salt Movement

The majority of salt movement occurred within the northern region of the Paradox Basin. The region was first described as the Paradox Basin Fold and Fault Belt (PFFB) in 1959 by Kelley; the northern part of the PFFB was later renamed the Northern Paradox Basin (NPB) by Trudgill (2011). The NPB sits in the deepest part of the basin against the Uncompahgre Uplift and contains four northwest-trending en echelon lines of salt-cored anticlines that run subparallel to the Uncompahgre Front (Jones, 1959; Cater, 1970b). The Salt, Fisher, Moab, and Lisbon valleys sit in Utah, and the Sinbad, Paradox, Gypsum, and Dolores valleys sit to the southeast in Colorado (Figure 2.1). The Utah and Colorado anticlines are separated by the Late Oligocene intrusion of the La Salt Mountains (Ross, 1998). Note that the term “salt anticline” implies a compressional structural evolution, but this is not an accurate portrayal of the salt structure evolution so salt anticlines, as defined by Kelley (1959), will be called salt walls in this study.

The salt walls in the NPB formed due to differential loading on the Paradox salt by the overlying Cutler Group as the arkosic sediment was shed off the Uncompahgre Uplift and prograded southwest into the basin, forcing the salt to flow in the same direction (Kluth and DuChene, 2009; Trudgill, 2011). Kluth and DuChene (2009) termed the process of salt wall growth as "downbuilding." Models conducted by Ge and others (1997) illustrate this process in cross sectional view (Figure 2.9). By this process, the overlying Cutler sediment is deposited in lows, creating minibasins that force salt evacuation away from the sediment depocenters until the salt is welded out. Once the salt has welded out and there is no more accommodation in the minibasin, sediment deposition shifts southwest creating a new salt structure and minibasin (Figure 2.9). This creates a younging direction of salt walls to the southwest (Kluth and Duchene, 2009). NW-trending faults at the top Mississippian level localized the development of salt walls, forming en echelon linear structures seen today (Trudgill, 2011). Salt wall evolution continued from Permian through Jurassic time.
Figure 2.9: Cross sections showing the evolution of a salt system above a stepped basement where salt evacuation is initiated by differential loading and overburden progradation (modified after Ge et al., 1997). Progradation forces salt to evacuate in the direction of sedimentation and salt diapirs rise where there are changes in basement elevation.
2.5 Salt Terminology

Salt tectonics concepts and terminology with which the reader may not be familiar are introduced in this section.

Salt withdrawal minibasins, simply referred to as minibasins in this paper, are defined by Jackson and Talbot (1991) as synkinematic basins that subside into relatively thick, allochthonous or autochthonous salt. They are much smaller than sedimentary basins, rarely larger than tens of kilometers in diameter (Hudec and Jackson, 2009). Minibasin-subsidence mechanisms are not fully understood, but basin subsidence and growth is accommodated by salt flow, or withdrawal, away from the depocenter (Hudec and Jackson, 2009).

Halokinetic sequences are defined as 'successions of growth strata genetically influenced by near-surface or extrusive salt movement' (Giles and Lawton, 2002), and form in minibasins adjacent to passive diapirs in response to changes in diapir-rise rate versus local sediment-accumulation rate (Giles and Rowan, 2012). Giles and Rowan (2012) define two end-member halokinetic sequences: (1) hook halokinetic sequences, and (2) wedge halokinetic sequences (Figure 2.10). Hook halokinetic sequences have narrow zones of deformation of drape folding

Halokinentic Sequences

- Drape folding 50-200m from diapir
- \( \leq 90^\circ \) angular unconformities
- Near-diapir abrupt facies change

- Drape folding 300-1000m from diapir
- \(< 30^\circ \) angular unconformities
- Broad zone of gradational facies changes

Figure 2.10: Diagrams of the halokinetic sequences end-members: (a) hook halikentic sequences, and (b) wedge halokinetic sequences (from Giles and Rowan, 2012).
no more than 200m from the diapir (Giles and Rowan, 2012). Wedge halokinetic sequences have broad zones of deformation of drape folding up to 1000m from the diapir (Giles and Rowan, 2012).

A megaflap is defined as a "panel of deep minibasin strata that extends far up the sides of a steep diapir or its equivalent weld (Rowan et al., 2016, p. 1725). The strata in the megaflap typically originates as the relatively thin roof over the original salt structure (Rowan et al., 2016). The drape folding width and vertical relief of the strata span multiple kilometers, and the folded strata can be subvertical to overturned (Rowan et al., 2016).
CHAPTER 3

METHODOLOGY

To better understand the salt system evolution and controls on the stratigraphic sequences of the Dry Creek anticline-Hamilton Creek anticline, a geologic model was constructed based on field and subsurface data. The following workflow was carried out based on the available dataset:

• Field work
• Seismic interpretation
• Cross section construction
• Restorations
• Result assessment and integration of regional data

3.1 Field Work

Field work was focused on the Dry Creek anticline. Structural measurements were taken in and around the Dry Creek anticline using the Midland Valley Fieldmove Clino iPhone application. Field data were collected in October and November 2016. These data points were added to an existing structural dataset (Lehmann, 2015 and Timbel, 2015). Bedding plane, fault, joint, deformation band, and slickenline measurements were taken across the Dry Creek structure (Figure 3.1). In addition, measurements from the Cater (1955) geological quadrangle map were digitized and added to the dataset.

The geologic units mapped in the Cater (1955) geologic quadrangle were used for formation identification and structural measurement assignment in the field (Figure 3.1). Upon completion of the field study portion of this project, the units were digitized and modified in ArcMap 10.5 based on stratigraphic interpretation of the field exposures. Aerial imagery was also used to aid in the reinterpretation of geologic units where the Cater map shows alluvial cover. These units were used to quality control the structural measurement locations across Dry Creek anticline, and in the cross-section construction process across Dry Creek.

3.2 Seismic Interpretation

Seismic interpretations were based on seismic stratigraphy, well log character of wells drilled within the 3D seismic volume, and synthetic seismograms generated for five wells used
Figure 3.1: Geologic map of Dry Creek salt anticline showing the location of structural measurements.
in the depth conversion (Figure 3.2). Well tops from two sources, Encana Oil and Gas and the Colorado Oil and Gas Conservation Commission (COGCC), were combined into a single well top database to easily compare tops and create a complete dataset. Well top depths were compared to log characteristics to quality check the well top locations.

All seismic interpretation was conducted using Schlumberger’s Petrel 2015 program in time across the 3D seismic volume and 2D seismic datasets (Figure 3.2). Eleven horizons were interpreted in the Hamilton Creek 3D volume for detailed study of the evolution of the Hamilton Creek salt pillow and associated minibasins. A regional interpretation consisting of eight horizons was conducted on the 2D seismic datasets for regional constraint on the character of the Uncompahgre thrust front proximal to the Hamilton Creek-Dry Creek system.

Figure 3.2: Map of study area showing the distribution of subsurface well control, 2D seismic, and 3D seismic.
The eleven horizons interpreted in Hamilton Creek were: Basement, Mississippian (base salt), Paradox (top salt), Ismay, six horizons within the Cutler showing minibasin evolution (P01-P06), and Chinle. The Chinle horizon was the youngest horizon interpreted due to the poor quality of the seismic data within the first second (TWT) of the seismic volume. The Cutler horizons were interpreted based on seismic stratigraphic relationships: bright, continuous reflectors, and onlapping and truncating reflectors to determine the development of the Cutler minibasins and timing of salt flow and evacuation below the minibasins. Challenges in the Cutler interpretation were encountered due to the discontinuous nature of the seismic reflections within the Cutler, faulting and expansion of sediment in the minibasins.

3.3 Cross Section Construction

Cross sections were created in Move 2016 across the Dry Creek and the Hamilton Creek structures. Each study area required different methods of cross section construction, as outlined in the following sections.

3.4 Dry Creek Cross Sections

Surface data and well tops from six wells were used to generate cross sections across the Dry Creek structure and the southeastern termination of Paradox Valley (Figure 3.3). A line orientation of 041 north was used for all Dry Creek cross sections. This value was calculated in Move by averaging the strikes of the bedding measurements (Figure 3.3). Three cross sections were drawn from the Dry Creek structure to Paradox Valley: across the center of Dry Creek (Section A), across the northwestern termination of Dry Creek (Section B), and across the southeastern termination of Dry Creek (Section C) (Figure 3.3).

In each cross section, elevation data, geologic unit field exposures, and well tops were used to constrain the cross-section interpretations. The elevation profile was extracted using the purchased Nextmap DEMs over Dry Creek and Moab one degree contours converted to DEM. Stratigraphic units were digitized in ArcMap from the Cater (1955) geologic quadrangle of NW Naturita and the Moab one degree map (Williams, 1964). The digitized units were brought into
Move and projected to the DEMs for accurate elevation intersections along each section line.

Six wells and their corresponding well tops were imported into Move from Petrel for subsurface constraint (Figure 3.3).

Horizons were created by connecting stratigraphic tops at outcrop to those picked as well tops, using structural measurements to constrain dip. All data were plotted normal to the section lines. Dip measurements were projected from an area 150 meters from the section line on both sides, and up to 500 meters if no data fell within the 150-meter radius. The data points furthest from the section line were given lowest priority when building horizons.

Faults were incorporated into the section lines at the northwest and southeast terminations of the Dry Creek salt anticline. Digitized fault locations were taken from the Cater (1955) quadrangle, but only those with actual offset visible in the field during the study were used in the
cross sections. Fault offset was estimated from stratigraphic unit offset mapped by Cater (1955) in the Naturita NW quadrangle.

3.5 Hamilton Creek Cross Sections

A time-depth conversion was constructed in Petrel using interval velocities from synthetic seismograms created for five wells within the 3D survey. A laterally variable interval velocity grid was built based on five wells within the 3D volume and five time surfaces (Chinle, P06 (top Cutler), Ismay, and Mississippian, and Basement). Combining well interval velocities with time surfaces ensured that the lateral interval velocity variability followed the dip of each surface. Modifications were made on the depth-converted surfaces and faults based on well top picks in wells within the Hamilton Creek 3D seismic volume.

The depth-converted Hamilton Creek horizon and fault surfaces were imported to Move from Petrel. 2D section lines were built for the restoration process from the 3D interpretation.

**Figure 3.4:** Map of Hamilton Creek 3D seismic volume showing the location of the wells used for depth conversion and restoration section lines overlain on the Top Salt time structure map.
because there are no constraints on salt flow in and out of the area within the 3D volume. Two different section line orientations were used for the Hamilton Creek cross sections because the basements faults have a different orientation from the minibasin and supra-salt faults (Figure 3.4). The cross-section lines were chosen in Petrel, and imported into Move as 2D seismic lines from the 3D seismic survey. Once the data had been imported into Move, the cross sections were built by projecting all surface and fault data to the section lines for the restoration process.

3.6 Restorations

Four procedures were used in the restoration process in Move: (1) decompaction, (2) isostatic adjustment, (3) restoration to paleo-depositional datum, and (4) structural restoration. These methods were modified after Rowan (1993), Rowan et al. (2004 and 2016) and the 2016 Midland Valley Move Tutorials. In each restoration, the youngest unit was removed, decompaction and an isostatic adjustment were applied to all underlying units, then the underlying unit was unfolded and restored to a regional datum. When faults were present, structural restoration was performed to remove fault offset prior to unfolding and decompaction. Each procedure is described in detail in the following paragraphs.

(1) Decompaction

The 2D Decompaction module in Move strips off the youngest unit and adjusts the underlying units according to compaction and porosity loss with burial. The module decompaction curve assumes an exponential porosity decrease with increasing depth, using the following function:

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

Where:

- \( f \) = the present-day porosity at depth
- \( f_0 \) = the initial porosity at surface
- \( c \) = the porosity-depth coefficient (\( \text{km}^{-1} \))
- \( y \) = depth (m)
The porosity values were based on input lithology percentages of sandstone, shale, and carbonate assigned to each formation in Move. These percentages were extrapolated from the Moab and Lisbon localities of Nuccio and Condon (1996) and the Delicate Arch area from Solum et al (2016). The lithology percentages were used to calculate surface porosity and depth coefficients using average compaction values for North Sea sediments from Sclater and Christie (1980). Salt, however, does not change density with depth, so it can be assumed that its porosity does not change with depth (Midland Valley, 2016). Move assigns salt zero values for both surface porosity $f_0$ and porosity-depth coefficient $c$ (km$^{-1}$). Table 3.1 shows the calculated

**Table 3.1:** Lithology percentages for each formation used in the restorations, with surface porosities and depth coefficients calculated in Move 2016.

<table>
<thead>
<tr>
<th>Formation</th>
<th>% Sandstone</th>
<th>% Shale</th>
<th>% Carbonate</th>
<th>Surface Porosity ($f_0$)</th>
<th>Depth Coefficient (km$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tertiary (eroded)</td>
<td>50</td>
<td>50</td>
<td>0</td>
<td>0.56</td>
<td>0.39</td>
</tr>
<tr>
<td>Mancos</td>
<td>17.1</td>
<td>82.9</td>
<td>0</td>
<td>0.6061</td>
<td>0.47</td>
</tr>
<tr>
<td>Dakota</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0.49</td>
<td>0.27</td>
</tr>
<tr>
<td>Burro Canyon</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.49</td>
<td>0.27</td>
</tr>
<tr>
<td>Brushy Basin</td>
<td>29.8</td>
<td>70.2</td>
<td>0</td>
<td>0.5883</td>
<td>0.44</td>
</tr>
<tr>
<td>Salt Wash</td>
<td>73.8</td>
<td>26.2</td>
<td>0</td>
<td>0.5267</td>
<td>0.33</td>
</tr>
<tr>
<td>Summerville</td>
<td>25.3</td>
<td>74.7</td>
<td>0</td>
<td>0.5946</td>
<td>0.45</td>
</tr>
<tr>
<td>Entrada</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0.49</td>
<td>0.27</td>
</tr>
<tr>
<td>Kayenta</td>
<td>49.4</td>
<td>50.6</td>
<td>0</td>
<td>0.5608</td>
<td>0.39</td>
</tr>
<tr>
<td>Wingate</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0.49</td>
<td>0.27</td>
</tr>
<tr>
<td>Chinle</td>
<td>50</td>
<td>50</td>
<td>0</td>
<td>0.56</td>
<td>0.39</td>
</tr>
<tr>
<td>Moenkopi</td>
<td>50</td>
<td>50</td>
<td>0</td>
<td>0.56</td>
<td>0.39</td>
</tr>
<tr>
<td>Cutler</td>
<td>42</td>
<td>58.1</td>
<td>0</td>
<td>0.5134</td>
<td>0.31</td>
</tr>
<tr>
<td>Honaker Trail</td>
<td>11.1</td>
<td>41.05</td>
<td>47.85</td>
<td>0.5092</td>
<td>0.43</td>
</tr>
<tr>
<td>Ismay</td>
<td>39.5</td>
<td>26.3</td>
<td>34.2</td>
<td>0.4995</td>
<td>0.38</td>
</tr>
<tr>
<td>Paradox</td>
<td>(Salt)</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mississippian</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0.41</td>
<td>0.4</td>
</tr>
</tbody>
</table>
values for each stratigraphic unit for the Dry Creek-Hamilton Creek area.

(2) Isostatic adjustment

It is possible to calculate isostatic response in the 2D Decompaction module in Move. Due to the small scale of the cross sections, airy isostacy was used to calculate the mean isostatic response to the decompaction of unit formation. Although there is a flexural isostatic response from sediment loading and laterally variable stratigraphic loads, it can only be seen on regional restorations with lengths of at least 35 km. The airy isostatic response was calculated using sub aerial loads on all stratigraphic units except the Mancos shale and Mississippian units and by calculating the bulk density of the underlying units based on lithology parameters and area occupied by each unit (Midland Valley, 2016). Move calculates the isostatic response at points along each horizon. The point-based isostatic response was used to depth shift the supra-salt units, and the mean airy isostatic response was used to depth shift the Mississippian and Basement horizons. The mean isostatic response was used for the pre-salt horizons to prevent the Paradox salt thickness from growing unbalanced throughout the restoration process, and to account for some rebound as the overlying sediment load was removed since the flexural response calculation was not possible.

3) Restoration to a regional datum

Each horizon was unfolded to a regional datum using the 2D Unfold module. The units were unfolded to remove the effects of differential compaction and any potential compression or extension applied to the units. Three algorithms were tested to determine the impact on salt body shape and to look for indications of a compressional regime on either structure. The Line Length (LL) algorithm was used to test the compressional restoration over Dry Creek anticline, and the Flexural Slip (FS) and Simple Shear (SS) algorithms were tested on all other restorations to determine the impact of each algorithm on salt shape. Little difference was noted in the shape of the salt between FS and SS at the scale of the Dry Creek restorations. FS was used to unfold the strata faulted by the basement thrusts in the Hamilton Creek restorations.
4) Structural restoration

Fault offsets were removed (where present) by applying the Simple Shear (SS) and Tri-Shear (TS) algorithms in the 2D Move-on-Fault module. SS algorithm was used on the faults in the northwestern termination of Dry Creek shown in Section A, and to restored the growth fault in the post-salt sediment in Hamilton Creek. The TS algorithm was used to restore the basement thrusts in Hamilton Creek.

3.7 Result Assessment

The complete restorations were then viewed chronologically, using formation ages shown in Table 3.2. Restoration results on each structure were compared for similarities and differences to determine evidence of Laramide shortening, timing of salt movement, and the relationship between Dry Creek anticline and Hamilton Creek anticline, the relationship of the Dry Creek-Hamilton Creek system to the Paradox Valley salt wall and the regional setting of the Paradox Basin.
Table 3.2: Ages for each formation used in the restorations. Ages derived from Doelling (2001) and the International Chronostratigraphic Chart 2017 v2. *Note the ages for Cutler P05-P01 are inferred.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Age at top (my)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tertiary (eroded)</td>
<td>2.58</td>
</tr>
<tr>
<td>Mancos</td>
<td>87</td>
</tr>
<tr>
<td>Dakota</td>
<td>105</td>
</tr>
<tr>
<td>Burro Canyon</td>
<td>125</td>
</tr>
<tr>
<td>Brushy Basin</td>
<td>145</td>
</tr>
<tr>
<td>Salt Wash</td>
<td>150</td>
</tr>
<tr>
<td>Summerville</td>
<td>163</td>
</tr>
<tr>
<td>Entrada</td>
<td>166</td>
</tr>
<tr>
<td>Kayenta</td>
<td>192</td>
</tr>
<tr>
<td>Wingate</td>
<td>199.3</td>
</tr>
<tr>
<td>Chinle</td>
<td>201.3</td>
</tr>
<tr>
<td>Moenkopi</td>
<td>247</td>
</tr>
<tr>
<td>Cutler (P06)</td>
<td>251</td>
</tr>
<tr>
<td>P05*</td>
<td>259</td>
</tr>
<tr>
<td>P04*</td>
<td>267</td>
</tr>
<tr>
<td>P03*</td>
<td>275</td>
</tr>
<tr>
<td>P02*</td>
<td>283</td>
</tr>
<tr>
<td>P01*</td>
<td>291</td>
</tr>
<tr>
<td>Honaker Trail</td>
<td>299</td>
</tr>
<tr>
<td>Ismay</td>
<td>303</td>
</tr>
<tr>
<td>Paradox</td>
<td>306</td>
</tr>
<tr>
<td>Mississippian</td>
<td>323</td>
</tr>
</tbody>
</table>
4.1 Introduction

The Dry Creek salt anticline is located 1.5 km southwest of the southeast termination of Paradox Valley salt wall (Figure 4.1). The feature is 4 km long by 3.5 km wide with a northwest-southeast trending axis and contains rocks of Pennsylvanian to Cretaceous in age (Figure 4.2). It is transected at its center by Dry Creek, which flows northeast, similar to the large salt valleys in the Paradox Basin. Although the large structures in the Paradox Basin are called “salt valleys” in this thesis, the Dry Creek salt structure is called an anticline, because it may contain evidence of compression.

The geometry of the northwestern termination of Dry Creek salt anticline resembles the three-dimensional models of pinched-off salt walls created and studied by Guglielmo et al. (2000). The structure’s small size provides a unique opportunity to study the potential influences of Jurassic-age and younger deformation events in the Paradox Basin, because rocks of this age...
Figure 4.2: Geologic map of Dry Creek with wells and representative structural measurements. Four of the six subsurface control wells are seen at this scale (Sawtooth 1-22 and Martin Mesa 1 A 12 are not shown.)
are still present close to the center of the structure. Alternatively, the anticline’s proximity to the Paradox Valley salt wall could make the structure an analog for the relationship between large salt diapirs and small salt features located at their margins.

This chapter focuses on the structural evolution of Dry Creek salt anticline through collection of structural measurements and observed stratigraphic thickness changes in the field and subsurface. Structural measurements were collected across the anticline. The location of existing and new measurements can be seen in Figure 4.2. No new work has been published on the structure since Cater published a USGS quadrangle map in 1955. For ease of discussion, the anticline has been divided into quadrants along the anticline axis and the intersection of Dry Creek: northwest, northeast, southeast, and southwest (Figure 4.3).

The structural measurements and outcrop stratigraphy are combined with well top data from six wells drilled on and around the anticline to build cross sections for the structural restorations (Figure 4.2).

The wells drilled on the structure defined a failed oil and gas field known as the Montrose Dome Field (Krivanek, 1978). Gas-bearing sandstones in the Lower Cutler and Honaker Trail

![Map showing the naming conventions for Dry Creek anticline. (Google Maps, 2017)](image)

**Figure 4.3:** Map showing the naming conventions for Dry Creek anticline. (Google Maps, 2017)
were tested by the discovery well, Kirby Petroleum No. 1 Government well (Figure 4.2). These and similar intervals were also drilled in the Union Oil Company Montrose wells 2 and 3 (Figure 4.2), but production rates and location off the salt structure made the wells uneconomic (Krivanek, 1978). The restorations are used to determine the structural history of Dry Creek salt anticline and the feasibility of a compressional or tightening event(s) on the structure.

4.2 Stratigraphy

The local outcrop stratigraphy of Dry Creek salt anticline ranges from Pennsylvanian to Cretaceous, spanning the entire range of post salt deposition in the basin, pre-Colorado Plateau uplift. The local stratigraphy in Table 4.1, includes structural dip and thickness ranges for each unit, based on field mapping. In this study, the primary focus was placed on the older units; less emphasis on latest Jurassic and Cretaceous units. Each unit is briefly described below from oldest to youngest.

Table 4.1: Local stratigraphy of Dry Creek anticline from field study data. Thickness ranges are taken from Cater (1955). Bedding dip measurements are from the entire study area. Moenkopi does not outcrop, so no thickness or dip measurements are recorded. The unit is included in the study because a well top exists for the unit in the subsurface dataset. The anomalously high Salt Wash maximum dip was taken in a vertical to overturned exposure in the southeastern termination of Paradox Valley (Figure 4.2). *Indicates units in which the top portion has been eroded.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Age (ma)</th>
<th>Thickness Range (m)</th>
<th>Minimum Dip</th>
<th>Maximum Dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mancos</td>
<td>87</td>
<td>15*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dakota</td>
<td>105</td>
<td>195*</td>
<td>7°</td>
<td>18°</td>
</tr>
<tr>
<td>Burro Canyon</td>
<td>125</td>
<td>48-76</td>
<td>2°</td>
<td>37°</td>
</tr>
<tr>
<td>Brushy Basin</td>
<td>145</td>
<td>97-146</td>
<td>7°</td>
<td>44°</td>
</tr>
<tr>
<td>Salt Wash</td>
<td>150</td>
<td>85-103</td>
<td>4°</td>
<td>89°</td>
</tr>
<tr>
<td>Summerville</td>
<td>163</td>
<td>30-33</td>
<td>20°</td>
<td>31°</td>
</tr>
<tr>
<td>Entrada</td>
<td>166</td>
<td>27-30</td>
<td>3°</td>
<td>79°</td>
</tr>
<tr>
<td>Kayenta</td>
<td>192</td>
<td>0-67</td>
<td>18°</td>
<td>67°</td>
</tr>
<tr>
<td>Wingate</td>
<td>199.3</td>
<td>0-73</td>
<td>6°</td>
<td>49°</td>
</tr>
<tr>
<td>Chinle</td>
<td>201.3</td>
<td>0-160</td>
<td>0°</td>
<td>90°</td>
</tr>
<tr>
<td>Moenkopi</td>
<td>247</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cutler</td>
<td>251</td>
<td>0-60</td>
<td>14°</td>
<td>86°</td>
</tr>
<tr>
<td>Paradox</td>
<td>306</td>
<td>0-4000</td>
<td>23°</td>
<td>89°</td>
</tr>
</tbody>
</table>
The Paradox Formation caprock crops out along the anticline axis. Layered black shale was found at the base of the NE flank outcrop, suggesting that the core of the caprock exposure is of Paradox-age. Alternatively, the black shales suggest that the Paradox was at, or near the surface at some point during the evolution of the salt structure (Figure 4.4).

**Figure 4.4:** Photos of Paradox caprock (Phpc) on the NE flank of Dry Creek anticline. (A) Paradox caprock at the base of the NE flank, approximately 40 m thick. Thin layers of Cutler and Chinle crop out above the caprock. (B) Fairly continuous layer of black shale at the base of the caprock unit. (C) Bedding planes visible in the shale layer, indicating that at least the base of the caprock is Paradox age.

### 4.2.1 Paradox Formation (Pennsylvanian)

The Paradox Formation caprock crops out along the anticline axis. Layered black shale was found at the base of the NE flank outcrop, suggesting that the core of the caprock exposure is of Paradox-age. Alternatively, the black shales suggest that the Paradox was at, or near the surface at some point during the evolution of the salt structure (Figure 4.4).
4.2.2 Cutler Group (Penn-Permian)

The Cutler Formation is found in the lower half of the anticline flanking slopes, and is characterized by its deep red-purple color. The formation is primarily composed of arkosic conglomerate units at the base of the slope, seen in ravines where the overlying alluvium is eroded (Figure 4.5). Further upslope, the formation is broken up into several benches of arkosic conglomerate divided by slopes of finer-grained material obscured by alluvial cover. The conglomeratic benches are continuous enough to be outlined on aerial imagery (Figure 4.6).

The conglomerate intervals are less than one meter thick, ranging from 30-70 cm. The conglomerate clasts are matrix-supported, and no sedimentary structures can be identified. The conglomeratic clasts range from angular-sub-angular small pebbles to rounded, elongate small cobbles. The cobbles are igneous and metamorphic in origin, most likely derived from the Uncompahgre Uplift to the northeast.

Figure 4.5: (A) Deep red, purple Cutler outcrop in a ravine at near the base of the NW flank. The formation is bleached proximal to fractures seen in clusters along the outcrop. (B) Close up of matrix-supported conglomeratic texture. Grain size ranges from small pebbles to small cobbles.
The fine-grained units are composed of large sand to silt-sized grains. The individual beds contain cross-lamination and typically coarsen upwards. Towards the top of the Cutler sequence, these units are closely interbedded with the arkosic conglomerates.

### 4.2.3 Triassic Formations

There is no clear boundary between the Cutler Formation and the overlying Triassic sediment on the anticline flanking slopes, but it is most likely the top of the highest arkosic conglomerate bed. It is also unclear if the Triassic Moenkopi Formation is present across the structure. In this study, all Triassic aged sediment is called Chinle, however, it is possible that an internal angular unconformity seen in the slope could actually be the contact between the Moenkopi and overlying Chinle Formation (Figure 4.7). This confusion is exacerbated by the published USGS quadrangle which miss-maps the Cutler Formation as Moenkopi in some areas, even though it is along strike with other areas mapped as Cutler. Modifications have been made to the geologic map of the area to reflect the correction of the basal slope unit as Cutler (Figure

---

**Figure 4.6:** Google Earth satellite imagery of the NW flank showing continuous conglomeratic benches near the top of the Cutler Group. Red box shows the location of the images in Figure 4.5.
Figure 4.7: Angular unconformity seen on the NW flank in the Chinle that could define the contact between Triassic Moenkopi and the overlying Triassic Chinle. There is no lithological difference in the rock across the unconformity, but the units below the unconformity have undulating beds.
The Triassic interval is identified by its bright red color and interbedded fine-grained sand and silty units (Figure 4.8a). The lower portions of the formation are obscured by alluvium, but small outcrops have fine-grained clay to silty units with fine sand lenses. The formation coarsens upwards to fine-grained sand intervals with thin cross-strata at the base of the overlying Wingate cliffs (Figure 4.8b).

![Figure 4.8: Chinle outcrop images. (A) Close up of characteristic bright-red color of the Chinle with fine-grained sand to silt laminations. (B) Contact between the top of the Chinle and base Wingate. The Chinle coarsens upward, but remains more thinly bedded than the Wingate.](image)

### 4.2.4 Jurassic Formations

The Jurassic units found in Dry Creek salt anticline are: the Wingate Sandstone and Kayenta Formation of the Glen Canyon Group, the Entrada Sandstone and Summerville Formation of the San Rafael Group, and the Salt Wash and Brushy Basin members of the Morrison Formation (Table 4.1). The red to dark brown Wingate sandstone is the prominent cliff former on the inner flanks of the anticline. It is a well-sorted, thickly bedded, fine-grained quartz sandstone with meters thick cross-strata (Figure 4.9). The Kayenta Formation conformably
Figure 4.9: Wingate outcrop images. (A) Wingate forms cliffs on the anticline flanks approximately 30 meters thick. (B) Close up of the stratigraphic architecture of Wingate. Thick sandstone beds with up to 3 meter thick cross-strata.
Figure 4.10: Kayenta outcrop of red interbedded sand and silt units on the NW flank. The beds steeply dip at approximately 55° to the southwest. The southeastern termination and southern flanks are annotated in the background. The high dips can be seen on the annotated SW flank, locally defining a halokinetic hook sequence adjacent to the core of the structure.
overlies the Wingate, and has a similar red color. It is a heterogenous unit of thinly bedded siltstones and sandstones, with some shales (Figure 4.10). Importantly, the formation is missing at the northwestern termination of Dry Creek Anticline.

The Entrada Sandstone unconformably overlies the Kayenta Formation and generally forms a rounded cliff except in areas close to the anticline center (Figure 4.11). It has a pinkish-red color in the basal two thirds of outcrop with a tan-white cap (Figure 4.12). It is a well-sorted, fine-grained quartz sandstone with cross strata a maximum of one meter thick. The Summerville Formation forms a steep slope set back from the top of the Entrada. The formation is composed of thinly bedded, interbedded sandstone, siltstone, and sandy shale intervals with varying colors.

**Figure 4.11:** Satellite imagery of the contact between the Kayenta (Jk) and Entrada (Jec) on the NW flank. Jk is the bright red slope former and Jec forms a pink bench above the slope. The contact is demarcated by a change in color and end of vegetation. Note the bleaching in the Upper Jec and close to the axis.
Figure 4.12: Entrada Sandstone outcrops on the NW flank. (A) Close up of Jec showing the basal pink "member" capped by the bleached upper "member" of the formation. (B) Google Earth satellite imagery photo of bleaching through the entire Jec thickness near the axis of the anticline. Note the high dips in the Jk and Jec, locally defining a halokinetic hook sequence adjacent to the core of the structure.
of red, gray, tan, and white, and variable grain size. The sandy intervals are more predominant at
the base of the unit, fining upwards to shaley intervals at the top.

Two members of the Morrison Formation are present in the field area: the Salt Wash and
the Brushy Basin members. The Salt Wash member crops out above the Summerville in a series
of sandstone ledges and benches with interbedded silty to shale intervals (Figure 4.11 & 4.12).
The sandstone ledges are white to gray and composed of amalgamated sandstone lenses. The
lenses contain cross stratification, ripple marks, and cut and fill structures. The interbedded fine-
grain units are thinner and typically redder in color. The Brushy Basin member consists of
varicolored bentonitic shale and mudstones, forming debris covered slopes. The typical colors
around Dry Creek salt anticline are grays with local green to blue to purples. The shales and
mudstones contain sandstone conglomerate lenses with some chert.

4.2.5 Cretaceous Formations

The Cretaceous-aged formations that crop out near Dry Creek salt anticline are the Burro
Canyon Formation and the Dakota Sandstone. These units sit too far back from the center of the
anticline, and thus, do not provide useful constraint to the structural restorations.

4.3 Field Observations and Mapping Results

Field observations and mapping are the primary methods for evaluating the structural
history of Dry Creek Anticline. The stratigraphic and structural data are used, in conjunction with
aerial imagery, to create an updated geologic map (Figure 4.13), modified from Cater (1955).
Stratigraphic and structural observations are discussed in the following sections.

4.3.1 Stratigraphic Observations

The Cutler Formation is miss-mapped in areas on the published geologic quadrangle
(Cater, 1955). On the published map, Cutler and Moenkopi crops out along strike with each
other on the western flanks of the anticline. Closer study in the field, shows that the area mapped
as Moenkopi on the northwestern flank contains beds of arkosic conglomerate, which are more
typical of the Cutler Formation.
Figure 4.13: Updated geologic map of Dry Creek anticline
Moenkopi is not present in the updated geologic map because contacts could not be differentiated on debris-covered slopes. However, there is an angular unconformity within the interval mapped as Chinle on the northwestern flank that could mark the top of the Moenkopi formation (Figure 4.7). The outcrop on this section of the slope contains interbedded siltstones and sandstone with a darker red color than the fine-grained sandstones in the upper Chinle.

Mapping efforts revealed stratigraphic thickness trends for each unit across the structure. The Cutler and Triassic units are significantly thicker on the western flank than the eastern flanks. The Wingate has a uniform thickness across the anticline axis. The Kayenta Formation wedges out at the northwestern termination. The Entrada and Summerville formations have uniform thickness across the structure. The Morrison members appear to have variable thickness across the structure, but that could be related to the distance of the outcrop from the inner flank cliffs.

The Paradox caprock crops out on the northeastern flank of the anticline – not along the anticline axis. This could suggest several things: (1) the present-day anticline geomorphology is not centered on the underlying salt diapir, (2) the underlying salt has an irregular shape, or (3) a structural event occurred that altered the shape of the Paradox salt below the anticline and its relationship with the overlying sediment, or (4) it has been dissolved out of the center in the low and preserved in the flanks.

4.3.2 Structural Observations

Analysis of the bedding plane and fault dip measurements taken across Dry Creek salt anticline reveal structural patterns that help understand the structural evolution of the anticline. Structural bedding plane dip measurements range from 90° to 0° across the anticline (Appendix A). The maximum dip values are observed in the Paradox caprock and Cutler exposures adjacent to the anticline axis (Figure 4.17), and the structural dips shallow with distance from the anticline axis. The dips are greater on the western flanks than the eastern flanks. Both terminations are faulted, with fault dip measurements ranging from 86° to 58°. The northwestern termination plunges approximately 20° to the northwest, while the southeastern termination plunges
**Figure 4.14:** Close up map of the NE flank of Dry Creek. Dips range from 75° to 7°. The dips generally decrease away from the axis, quickly shallowing from 75° in the Paradox to <40° dips in the Chinle and younger units.
approximately 15° to the southeast. Detailed observations of each flank and termination are described in the following sections.

### 4.3.3 Northeast Flank

The highest dips were measured in the Paradox caprock and Cutler formations on the flank slope near the anticline floor (Figure 4.14). The dips rapidly decrease in magnitude through the Chinle Formation into the Jurassic units, with maximum dip values in the lower 30s.

![Figure 4.15](image_url)

**Figure 4.15:** Sketch of dip changes along NE flank showing gradual dip changes from SW to NE. Dips consistently above 20° until the Jmb.

However, along the Dry Creek exposure, variable dips between 37° and 45° are observed in the Entrada, Summerville, Salt Wash, and Brushy Basins. The dip values decrease once again, below 15°, in the Cretaceous units approximately 2,300 meters from the anticline axis (Figure 4.18).

### 4.3.4 Southeast Flank

Few measurements were taken on this flank near the Dry Creek intersection of the anticline, but the measurements are congruent with those taken on the northeast flank (Figure 4.19). Due to the proximity of the outcrops on either side of Dry Creek, it can be assumed that the same dip patterns are observed on each flank. Measurements taken proximal to the
**Figure 4.16:** Close up map of the SE flank of Dry Creek. Dips range from 75° to 7°. Measurements on this flank are highest closest to the fault in the southeastern termination, and quickly decrease to <30° values less than 100 meters from the axis.
southeastern termination of the anticline are not greater than 20° in magnitude. However, dip measurements in the Salt Wash adjacent to the main fault running down the southeastern termination approach 75° (Figure 4.19).

4.3.5 **Northwest Flank**

Structural dips on the flank slope in the anticline axis show dips up to 88° in the Cutler at the base of the slope. A wide range of dip measurements are seen on this flank (Figure 4.17). Dip values remain high (above 50°) through the Jurassic units closer to the northwestern termination and appear to shallow to the southeast along the flank (Figure 4.17 & 4.18). At the southern end of the northwest flank, near the creek, the dips in the Permian and Triassic sediment range from 18° to 60°, but the average dip is around 35° in the southern end of the flank slope (Figure 4.17, Figure 4.18B). Approximately 250 meters along the Dry Creek “canyon,” the dips in the Triassic units shallow to values less than 20° (Figure 4.17 & 4.18).

Halfway up the northwest flank where the Entrada Sandstone crops out, the dips in the Jurassic Kayenta and Entrada units are consistently greater than 50°, which suggests that dips in the underlying Triassic and Permian rocks are of equal or greater magnitude. Although the dips on the edge of the flank are high, measurements along the Entrada outcrop show that the dip magnitude rapidly decreases away from the cliff edge – measurements of 13° are seen in the Entrada only 110 meters back from the edge (Figure 4.17 & 4.18). The structural dip values are 10° shallower in the overlying Summerville and Salt Wash formations above the Entrada, but the Entrada dip measurements stay above 50° up to the northwestern termination (Figure 4.17). Significant fracturing and jointing was documented in the Wingate, Entrada, and Summerville on this flank, but too few measurements were collected to determine a trend. Slickenslides were also common along bedding surfaces, indicative of flexural slip along bedding planes.

4.3.6 **Southwest Flank**

Structural measurements on the southwest flank are concentrated near Dry Creek and in the fault zone at the southeastern termination (Figure 4.19). The dips suggest that dips
Figure 4.17: Close up map of the NW flank of Dry Creek. Dips range from 88° to 3°. Measurements on this flank are high through Js on the flank near the axis. The dips rapidly steepen towards the anticline axis, increasing from 13° to >50° in under 100 meters in the Jec.
Figure 4.18: (A) Rapid steepening of dips seen in the halokinetic hook sequence in the Jec and Jk on the NW flank in measurements and bed rotation on the flank close to the axis. Jurassic units wrap around the flank to the NW termination. Although perspective in the photo does not show this, the Jec, Js, Jms, and Jmb units continue to the NW towards the NW termination, and do not rise in elevation towards the structure axis, which is why the sketch in 4.18B shows the flank profile. (B) Sketch showing dips across the outcrop from the base of the flank along Dry Creek, to the rotated units in the axis at the Jec-Jk cliff. The dips are < 20° across the flank and abruptly increase to >50° close to the axis. The sketch combines data from the top of the NW flank, along the Jec outcrop, with data taken at the base of the flank along the creek bed to show the orientation of beds across the western flank of the structure.
Figure 4.19: Map of the SW flank showing steep dips in the axis center near the Pc outcrop. The dips quickly shallow in the Trc on the flank. No measurements were taken in the Jk and Jec to compare to the NW flank.
continue to shallow with proximity to the southeastern termination. The greatest dip measured in the anticline axis is $62^\circ$. On the northern end of the flank slope, dips range from $32^\circ$ to $66^\circ$. Published dips on the geologic quadrangle show dips up to $90^\circ$ (Cater, 1955), which do not align with any measurements collected in this study. About halfway down the flank, published dip values shallow to $35^\circ$ in the Wingate cliff, which does fit with the findings of this study. Only two measurements were taken on this flank: (1) $30^\circ$ in the Wingate, and (2) $18^\circ$ in the Entrada, showing a continual shallowing of the dips on the western flanks towards the end of the anticline.

### 4.3.7 Southeastern Termination

The southeastern termination of the anticline comes to a narrow point where a steep normal fault, SE_01, marks the boundary between the southeast and southwest flanks (Figure 4.20). Three smaller normal faults, SE_02, SE_03, and SE_04, cut through the southeast flank, probably intersecting the main fault, SE_01, below the alluvial cover (Figure 4.21). All faults have rapid lateral variation along their fault planes, making it difficult to determine the sense of slip along each fault. The units on either side of the termination have relatively shallow dips with a maximum dip of $30^\circ$ measured in the Entrada on the southwest flank and $34^\circ$ in the Salt Wash on the southeast flank (Figure 4.20). Measurements were collected on fault SE_01, but not on the faults in the southeast flank.

SE_01 has a brecciated fault zone no more than a meter wide (Figure 4.21). The rock in the zone is highly fractured with pervasive calcite veins. No evaporitic veins were found, but the authors did not make it below the base Wingate-Salt Wash contact on the fault, so evaporitic material may be found lower along the fault zone if the fault detaches on the Paradox salt at depth. At the base Wingate-Salt Wash contact, the fault dip ranges from $76^\circ$ to $58^\circ$. Slickenside measurements in this region of the fault have plunges ranging from $65^\circ$ to $54^\circ$ on both the hanging wall and footwall.
Figure 4.20: Map of the SE termination. Dips are very shallow near the termination <20°, except for measurements proximal to Fault SE_01 which are >70°. The sense of fault slip is difficult to determine on SE_02, SE_03, and SE_04. Fault SE_01 is a steep, down-to-the-northeast normal fault.
Figure 4.21: Annotated photo of the SE termination. Fault SE_01 divides the SW and SE flanks, down dropping the SE flank. 3 faults in the SE flank (SE_02, SE_03, and SE_04) cross-cut the SE flank, connecting to fault SE_01 in the anticline axis. Note the rapid steepening of beds, like the NW flank (Figure 4.18), is seen in the Jk and Jec on the SW flank.
Figure 4.22: Map of the NW termination. The folded Phpc, PC, and Trc units in the termination have highly variable dip ranges and strike directions. Measurements in the Jec and Js shallow from the NW flank. Strike values do not change much, but are controlled by fault movement.
4.3.8 Northwestern Termination

The northwestern termination has a very different morphology than the southeastern termination: it is broad, folded, and faulted, and elevated above the NE and NW flanks. From the northwest flank, the units ramp up to the elevated termination, and the ramping is clearly visible in the Entrada (Figure 4.22). The termination is cut by several normal faults with variable offset, which were mapped by Cater (1955) and included in the geologic map of Dry Creek (Figure 4.12 & 4.23). Four of the faults were identified in the field and on Google Earth (Figure 4.24). The easternmost faults, NW_01 and NW_02, have the most offset, and the westernmost faults, NW_03 and NW_04, were not identified in the field but could be seen on Google Earth.

Fault measurements taken along the eastern faults have dips between 74° and 86°, with the shallower measurements taken near the top of the fault in the Wingate. Faults NW_01 and NW_02 connect in the Triassic units on the termination and trap a graben between them (Figure 4.23 & 4.24). Fault NW_01 is a down-to-the-northeast normal fault, and fault NW_02 is mapped as a down-to-the-west reverse fault. However, it is only a reverse fault because the units

Figure 4.23: Ramp and fold from the NW flank to the NW termination. The ramp is clearly visible in the Jec.
in the footwall are down dropped, not because the hanging wall block was forced upward by compression.

Within the anticline, only Paradox caprock and Triassic Chinle formation are identified in the structural measurements, however, some of the deeper measurements are most likely taken on Cutler misidentified as Chinle. The Jk pinch out is visible on the NW flank against Fault NW_03.

4.4 Restorations

Three cross sections were built across Dry Creek salt anticline (Figure 4.25 & 4.26), two of which were turned into restorations. As discussed in Chapter 3, the cross sections were built from the modified geologic map, structural measurements, and subsurface well top data. Due to the limited data, the cross sections represent simplified salt geometries and salt-sediment
interactions. The cross sections chosen for structural reconstruction were selected by data availability and importance to this project, and can be seen in Figure 4.27 and Figure 4.28.

Cross section A passes through Sawtooth Ridge, Coke Oven Syncline, and the northwestern termination of Dry Creek salt anticline (Figure 4.26). Cross section B goes from Coke Oven Syncline in the northeast through the northeast and northwest flanks of the anticline (Figure 4.26). Cross section C cuts through the southeastern termination (Figure 4.26). The surface outcrops of Paradox caprock along with the subsurface well data define a narrow salt wall, plunging to the southeast, sourced from an autochthonous salt layer at least 4,000 m below the flanking minibasins.

Figure 4.25: Map of section line locations and subsurface well control across Dry Creek anticline.
Figure 4.26: Mapping data and subsurface well control constrain the shape of the salt wall. The Dry Creek salt diapir is a narrow salt wall connected to autochthonous salt 4,000 meters below the surface. Salt may or may not be welded out under Coke Oven Syncline to the NE, and there is no control over salt depth and thickness to the SW of Dry Creek anticline.
4.4.1 Assumptions and Potential Sources of Error

There are several assumptions and sources for error in these restorations. There is no available seismic data covering the Dry Creek salt anticline so all subsurface data are derived from well tops provided by the COGCC and Encana. Individual unit thicknesses may vary in the subsurface, which could influence the decompaction and structural reconstruction algorithms used in the restoration process. It is assumed that all salt is pure halite. Structural measurements are projected to the section lines from up to 150 meters away. There is no control over the anticline axis, across the center of the structure, due to erosion.

4.4.2 Cross Section A

Figure 4.27 shows the structural restorations for this section.

299 Ma restoration – Honaker Trail: it is assumed that the Paradox salt was uniformly deposited over the section line; the line length is too short to show thickening and thinning related to the basin floor response to the flexure of the Uncompahgre Uplift. The Honaker Trail Formation is thicker on the northeast end of the line, thinning towards the center of the line above a small salt pillow, and has a uniform thickness to the southwest of the mobilized salt. There is no evidence of a reactive phase of diapirism, so the Honaker Trail roof must have been sufficiently thin, less than several hundred meters thick, to allow the salt subsequently to break through (Hudec and Jackson, 2007).

251 Ma restoration – Cutler Formation: deposition of Cutler Group in thick minibasins on either side of a narrowing salt wall, which formed during downbuilding of Cutler sediment into the underlying salt. The salt thickness on either side of the salt wall narrows with continued deposition, suggesting that the early salt wall formed via passive growth as sediment continued to be deposited along the margins, forcing salt to flow. The Cutler is thicker to the northeast of the salt wall, which suggests a progradational character of the unit. The Cutler units have a steeper dip on the southwest flank of the salt wall, resembling a megaflap, due to the subvertically rotated beds (Rowan et al., 2016). Alternatively, the bed rotation could be caused
by the continued vertical rotation of the Honaker Trail roof as salt rise continues in the salt wall.

201 Ma restoration – Triassic units: the Chinle and Moenkopi formations have asymmetrical deposition across the narrow salt wall. Unlike the Cutler time, the sediment depocenter has changed to the southwest flank of the salt wall. A small trough has developed adjacent to the salt wall on the southwest flank, and although it restores to the present-day interpretation, it could be an artifact of restoration algorithms.

199 Ma restoration – Wingate: the Wingate Sandstone is deposited in the same southwestern depocenter as the underlying Triassic units. The Wingate thins against the sides of the salt wall, which is interpreted to be at or close to the surface. The salt thickness away from the salt wall continues to thin, and the salt wall continues to narrow; the available salt budget could have decreased as sediment was deposited into minibasins on the flanks of the salt wall, or the narrowing of the salt wall could have slowed the upward flow of salt. The salt wall remains at the surface through Wingate time, suggesting that passive salt rise rate kept pace with sedimentation (Hudec and Jackson, 2007).

166 Ma restoration – Kayenta and San Rafael Group: the Kayenta, Entrada, and Summerville formations have uniform thicknesses across the section. However, a halokinetic hook sequence develops on the southwest flank of the salt wall (Figure 4.17 & 4.21). The development of a hook sequence on the northwest flank in concert with uniform unit thicknesses across the salt wall indicate that sedimentation rate decreased, relative to diapir-rise rate, causing an increase in salt flow as the diapir continued to rise. Alternatively, the diapir could have been exposed at the center of the structure during this time.

145 Ma restoration – Morrison: the Salt Wash and Brushy Basin members are the first units to be deposited across the salt wall since Honaker Trail time, indicating the end of major upward salt flow. The units have variable thickness across the section line, thinning onto the salt wall, suggesting that sedimentation has begun to outpace salt flow during this time. The salt budget was depleted from the NE side of the salt wall as sediment in Coke Oven Syncline
Figure 4.27: Dry Creek restoration of Section A. See text for detailed description of each restoration.
Figure 4.27, continued
continued to sink onto the underlying salt.

105 Ma – Cretaceous: during the deposition of the Burro Canyon and Dakota formations, there is a decrease in salt flow in the salt wall. The units on either flank continue to drape over salt wall and differential compaction increases dip magnitudes. The Coke Oven Syncline begins to form during this time to the northeast of the salt wall. The units to the northeast of the salt wall have a lower elevation than those to the southwest.

Sediment in the anticline axis has been removed from the structure via erosion so the cause of the elevation difference is unknown. The change in elevation could be caused by a combination of the following: continued downbuilding and salt evacuation on the northeast flank, development of a growth fault along the edge of the salt wall enabling the units to the northeast to move downward, or a compressional event could have elevated the units southwest of the salt wall relative to those to the northeast. The resolution of the restorations does not allow for a more detailed analysis of the structure axis.

4.4.3 Cross Section B

There will not be a detailed description of each time slice for this restoration. The faulted termination cliff will be the focus of this restoration discussion because the faults are the primary difference from section A. Faults NW_01 and NW_02 were the only faults incorporated into the restorations because they have measurable offset. The faults crosscut Permian through Jurassic units, so fault movement must have occurred after deposition of these units, or the faults are long lived. Figure 4.28 shows the comparison of fault restoration orders.

The present-day interpretation of the units across the northwest termination shows the two faults, NW_01 and NW_02, with a small block pinned between them. The small block is elevated above the units on the northeast flank, making NW_02 a reverse fault. However, NW_02 is most likely an apparent reverse fault, resulting from rotation of fault blocks in relation to the underlying salt flow and salt dissolution.
Figure 4.28: Dry Creek restoration of Section B showing the difference in line length and salt wall shape created by fault restoration orders. Restoration Version 1 (A-C) restores Fault NW_01 (B) before fault NW_02 (A). The restoration results in folded units on the NE flank and a rotated salt wall in Mancos time (C). There is also a 2-1% loss in length of all units after the fault restoration. Restoration Version 2 (D-F) restores Fault NW_02 (E) before NW_01 (D). The restoration results in folded bed orientations that are similar to the restorations in Figure 4.27.
The order in which the two faults are restored result in very different salt shapes (Figure 4.28). It is important to note that although some of these differences may be real, some may be related to the orientation of the section line, which is not perpendicular to the fault plane strikes or all bedding plane strikes at this location on the structure. If Fault NW_01 moved before NW_02, the restoration shows a fold in the Jurassic through Triassic units on the northeast flank of the diapir (Figure 4.28 A-C). Additionally, there is a line length change of 1-2% in the units between Figure 4.28 A and Figure 4.28 C, which could suggest shortening, but that amount of shortening is well within the error bar for these restorations. The shape of the salt also changes from a narrow, vertical wall to a wider wall with a northeastern tilt. If Fault NW_02 moves before NW_01 (Figure 4.28 D-F), the result shows relatively flat-lying units with a narrow minibasin to the southwest of a vertical, narrow salt wall.

The restoration created by the movement of Fault NW_02 prior to NW_01 looks similar to the restoration of Cross Section A. However, a detailed study should be conducted on the units and faults in the northwestern termination for a more accurate restoration of this part of the salt structure. The work done here does not prove or disprove the hypothesis of a Laramide-age or younger compressional event on Dry Creek salt anticline.
CHAPTER 5

HAMILTON CREEK SALT PILLOW

5.1 Overview

The Hamilton Creek salt pillow is on trend with Paradox Valley and Dry Creek anticline on the southeast end of Naturita Ridge, 14 km from the southeastern termination of Dry Creek salt anticline (Figure 5.1). The salt pillow sits beneath the Hamilton Creek dry gas field, discovered in 1983 by the Hamilton State #1-36H (API 05-113-06047) (Figure 5.1). 54 wells have been drilled over the Hamilton Creek salt pillow since 1980 (Davis, 2015). The production comes from arkosic fluvial sandstones in the Pennsylvanian Paradox, the Pennsylvanian Honaker Trail, and Permo-Pennsylvanian Cutler Group.

Field exposures of Cretaceous Dakota Sandstone and Burro Canyon Formation (Kbd) (Figure 5.2) above the structure do not reflect the complex geology recorded in the 3D seismic survey that was shot over Hamilton Creek dry gas field in 2004 by Encana. Unlike Paradox

Figure 5.1: Map showing the location of the Hamilton Creek salt pillow in relation to Dry Creek anticline and Paradox Valley.
Valley salt wall and Dry Creek salt anticline, the Hamilton Creek salt pillow is a subtle, dome-shaped structure with a NNE-SSW trend (Figure 5.3). Two primary Cutler minibasin depocenters are interpreted flanking the salt pillow: (1) a turtle/rollover minibasin sits north of the pillow, and (2) a faulted minibasin sits east of the pillow (Figure 5.3). The post-salt sediment also thickens to the west and south of the salt pillow, but those areas are not analyzed in this study.

This chapter focuses on the structural evolution of the Hamilton Creek salt pillow through interpretation of seismic horizons and faulting across the structure. The seismic horizons are interpreted from well top data and seismic stratigraphy. Faults are interpreted from offset seismic reflections. The stratigraphic and structural components are combined to create structure and isopach maps to study the evolution of salt movement and sediment depocenters. 2D cross sections are built from the 3D interpretations for structural restorations of the salt pillow through time to better constrain the timing of fault movement and development of the salt pillow.

Figure 5.2: Surface geology above Hamilton Creek 3D seismic volume shows no structural topography.
5.2 Stratigraphy

Within the Hamilton Creek dry gas field, the stratigraphic units range from Precambrian basement to Cretaceous Dakota Sandstone. Well tops from the COGCC and Encana provide a detailed calibration for the dry gas field source, reservoir, and seal intervals (Davis, 2015), however, many of these horizons were not used in this study because they could not be projected to the Dry Creek salt anticline. Additionally, the top second (TWT) of the seismic volume was noisy and few wells were logged through the Jurassic and Cretaceous section, so the Chinle is the youngest horizon interpreted across the 3D volume. The minibasins are primarily filled with Cutler-age sediment. Six minibasin packages were interpreted using seismic stratigraphy and the age of each interval was estimated by dividing the entire Cutler interval into six intervals of equal time.

Figure 5.3: Time structure map of Top Paradox Salt across the Hamilton Creek salt pillow, revealing a low relief structure with a NNE-SSW strike. Salt minibasins are interpreted N and E of the salt pillow.
Table 5.1: Horizons interpreted across the Hamilton Creek 3D seismic survey.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Age at top (my)</th>
<th>Thickness (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entrada</td>
<td>166</td>
<td>-</td>
</tr>
<tr>
<td>Wingate</td>
<td>199.3</td>
<td>-</td>
</tr>
<tr>
<td>Chinle</td>
<td>201.3</td>
<td>-</td>
</tr>
<tr>
<td>Cutler (P06)</td>
<td>251</td>
<td>18-270</td>
</tr>
<tr>
<td>P05*</td>
<td>259</td>
<td>0-161</td>
</tr>
<tr>
<td>P04*</td>
<td>267</td>
<td>0-239</td>
</tr>
<tr>
<td>P03*</td>
<td>275</td>
<td>0-238</td>
</tr>
<tr>
<td>P02*</td>
<td>283</td>
<td>0-159</td>
</tr>
<tr>
<td>P01*</td>
<td>291</td>
<td>0-219</td>
</tr>
<tr>
<td>Ismay</td>
<td>303</td>
<td>0-334</td>
</tr>
<tr>
<td>Paradox (Top Salt)</td>
<td>306</td>
<td>0-636</td>
</tr>
<tr>
<td>Mississippian (Base Salt)</td>
<td>323</td>
<td>0-552</td>
</tr>
<tr>
<td>Basement</td>
<td>541</td>
<td>-</td>
</tr>
</tbody>
</table>

The synthetic seismograms used in the seismic depth conversion were also used as guides for seismic horizon interpretation. Each well used to generate synthetics has different log and well top coverage, so all synthetics were compared to determine which horizons could easily be picked for a regional study. Two synthetics are included to show the relationship between the seismic reflectors and well tops that are used for seismic horizon interpretation (Figure 5.4, Figure 5.5). The synthetic generated from well HC Federal 5-21 (API 05-113-06078) shows the deeper logged section from intra-Cutler to Mississippian, and was used to constrain interpretation of the Ismay, Top Salt, Base Salt, and Basement picks. It is important to note that HC Federal 5-21 is drilled through the front edge of a basement thrust (Figure 5.4), which obscures some of the well top detail in the synthetic seismogram. However, when the well is viewed in the seismic volume, it is easier to understand the relationship between the well tops and the seismic horizons (Figure 5.4).

The pre-Paradox units, while present in well logs, are not broken out by individual horizons. A Base Salt horizon was interpreted as the first high amplitude reflector at the base
Figure 5.4: (A) Synthetic seismogram of HC Federal 5-21 showing the correlation between the synthetic seismic and well top picks. (B) Well location (time projected) on the SE edge of seismic volume. (C) Well location on seismic drilled through the upper fault tip of B_01, showing the correlation of the synthetic seismogram to the seismic character of the Paradox Salt.
Figure 5.5: (A) Synthetic seismogram of Hamilton Creek State 36-23 showing the correlation between the synthetic seismic and well top picks. (B) Well location on the W edge of the salt pillow. (C) Well location on seismic. The well is not drilled through the salt (time projection), but shows the correlation between the synthetic seismogram and seismic character.
of the mobile salt interval to constrain the thickness of the mobile Paradox salt. The Basement horizon reflects the last continuous, high amplitude seismic reflector, and may represent Pre-Cambrian basement rock or younger Cambrian and Mississippian units. However, at least one well within the seismic volume contains a Pre-Cambrian basement well top.

The Paradox Formation is broken out into two units: the Ismay and Top Salt to differentiate mobile salt (Top Salt) from the brittle, interbedded carbonates and fine-grained material that was also deposited in the formation (Ismay). The Top Salt horizon coincides with the majority of Paradox well top picks. On seismic, the mobile Paradox salt is characterized by low continuity, low amplitude reflectors. This contrasts with the overlying and underlying high continuity, high amplitude reflectors, and is the only constraint on the accuracy of the synthetic seismograms. There are discrepancies between the Encana and COGCC picks for the Ismay, but it is picked as the first high amplitude positive reflector above the Top Salt horizon.

Honaker Trail and Hermosa Group tops were picked many of the wells across the seismic volume, but were not included in the seismic interpretation. The well top picks varied greatly between wells, and the seismic character of these horizons in the synthetic seismograms were not consistent or distinctive, so the formations were grouped with the Cutler intervals.

The synthetic generated from Hamilton Creek State 36-23 (API 05-113-06134) was used to constrain the six Cutler Group horizons and the Chinle seismic horizon interpretation (Figure 5.5). However, the six Cutler Group horizons were broken out by seismic reflector onlap and truncation patterns and were not derived from the synthetic seismograms. There was no consistent top Cutler well pick in the COGCC-Encana well pick database, and the seismic character in the top two seconds (TWT) make it difficult to extract a consistent seismic character for that horizon. The P06 (top Cutler Group) horizon was picked based on downlapping seismic reflector characteristics. Based on the Hamilton Creek State 36-23 synthetic seismogram, this could be too deep, but it is the only mappable seismic characteristic in the upper portion of the seismic volume. The Chinle horizon is the shallowest horizon that can be interpreted across the
seismic volume. It is the last high continuity, low amplitude horizon around 500 ms (TWT) with downlapping reflectors above.

5.3 Seismic interpretation

TWT seismic interpretation of the Hamilton Creek 3D volume reveals a complex relationship between basement thrust faults, the salt pillow, and the overlying minibasin stratigraphic and structural architecture. Interpretation was based on seismic reflection characteristics. Faults were interpreted based on seismic reflection offset, and horizons were interpreted on continuous reflectors, stark contrast in reflection amplitudes, and onlap patterns of seismic reflections. Based on the existing well top database, it is assumed that most of the post-Paradox section in the seismic volume was composed of Cutler sediments, and that the Triassic and younger sections were constrained to the poorly imaged section within the first two seconds of TWT. Cretaceous Dakota Sandstone and Burro Canyon Formation, and Jurassic Brushy Basin member crop out at the surface, and published dips no greater than 2.5° are mapped on the geologic quadrangle (Figure 5.2) (Williams, 1964).

5.3.1 Basement Architecture Interpretation

Six basement-involved thrust faults were interpreted in the pre-salt strata. These thrust faults dip to the southwest, thrusting towards the Uncompahgre. Basement Faults 01-05 are interpreted in the central area of the volume, and the top tip of Basement Fault 06 is interpreted on the southwestern edge of the seismic (Figure 5.6). B_01 has the longest length, extending across the volume from northwest to southeast. B_02 has the greatest offset between hanging wall and footwall across the seismic. B_04 and B_05 are splays below and off B_02. B_03 has the least amount of offset and is interpreted between B_01 and B_02.

The thrust faults have the steepest dip at the upper fault tips, and the strata in the footwall of the faults appear folded (Figure 5.7). Based on seismic reflectors, the basement faults tip out at the base of the Paradox salt and do not continue through the mobile Paradox salt to the top of the salt (Figure 5.7). Structure maps of the Basement and Top Mississippian surfaces show the
Figure 5.6: Map and 3D view of six basement thrust faults (B_01-B_06) interpreted across the seismic volume. B_01 and B_02 are the largest faults with the greatest throw. B_03 is a minor thrust between B_01 and B_02. B_04 and B_05 are imbricates off B_02. B_06 is on the SW edge of the seismic and is omitted from the restorations. Note: Hamtilon Creek salt pillow sits above B_01 and B_03, and the northern minibasin sits in the basement low created by the offset of B_02.
basement dropping down to the northeast (Figure 5.6), suggesting that the thrust faults could control basement level and original salt depocenters.

5.3.2 Salt Interpretation

Within the 3D area, the Paradox salt creates two salt pillows, only one of which is fully imaged in the seismic volume. The fully imaged salt pillow sits in the center of the volume and has a very low, broad relief as shown in the top salt structure map (Figure 5.3). The second, potentially larger salt pillow, extends beyond the eastern edge of the seismic volume. The salt is welded out where thrust B_02 breaks through the base salt horizon, in the northern portion of the volume where the basement block is deepest, and in the southern region of the volume (Figure 5.7 & 5.8). The image quality on the edge of the dataset is poor, so there may be more salt than interpreted in the northern region.

5.3.3 Minibasin Interpretation

The main minibasin sits in the northern portion of the seismic volume (Figure 5.3). It is divided into six growth packages based on onlap and truncation patterns of the seismic reflectors (Figure 5.8A). These packages were difficult to pick across the whole seismic volume, especially close to faults, due to the discontinuous character of the seismic reflectors in the minibasins. The minibasin shows typical roll over and growth/expansion packages north of the Hamilton Creek salt pillow that rolls into supra-salt fault S_02. There are numerous minor growth faults in this part of the minibasin but none with offset significant enough to affect the interpretation (Figure 5.8A).

The minibasin intervals become harder to interpret to the south, near the crest of Hamilton Creek salt pillow due to two normal supra-salt faults, S_01 and S_02, that detach on the salt and form a graben relay zone in their hanging walls (Figure 5.8B). These faults sit on the eastern side of the seismic volume and trend approximately northeast-southwest (Figure 5.9). The westernmost fault, S_01, has a strong linear trend NNE-SSW, southeast dip, and is down-to-the-southeast. Fault S_02, on the eastern edge of the seismic volume, is down-to-the-
Figure 5.7: Seismic interpretation of basement faults B_01-B_05, Hamilton Creek salt pillow, and minibasin intervals. Axial surfaces in the Mississippian interval define the folds in the strata near the upper fault tips. The line also illustrates the low, broad relief of the salt pillow.
Figure 5.8: Seismic lines showing the interpretation of the Cutler minibasins above the Hamilton Creek salt pillow. (A) Northern rollover minibasin off the northern edge of the salt pillow. The minibasin welds out the salt north of the salt pillow, and is bounded by supra-salt fault S_02 to the east. (B) Faulted minibasin on the eastern edge of the salt pillow. The minibasin is bounded by supra-salt faults S_01 and S_02 and welds out the salt east of Hamilton Creek salt pillow.
west and has a curved shape, following the salt pillow on the easternmost edge of the seismic volume, with a north-south trend at its northern end that rotates to a northeast-southwest trend as it approaches the northern end of S_01 (Figure 5.9). The dip on S_02 appears shallower than that on S_01, but the fault extends to the south beyond the seismic volume, so the complete shape and orientation is unknown.

Fault S_01 controls the offset of the mapped minibasin packages. Along the center of the fault, the offset is as much as one second (TWT) (Figure 5.8B). Mapping the minibasin packages across the faults was accomplished by interpreting the horizons on a composite line
that circumvented the faults and then interpreting across S_01 using the horizon intersections in
the hanging wall and footwall as guides. S_02 bounds the minibasin units on the eastern edge of
the seismic data; no strata were interpreted in the footwall of S_02, so offset and relationship of
S_02 to the minibasin is undeterminable.

5.4 Seismic Horizon Structure and Isochron Mapping Results

Eleven time structure maps were constructed on each interpreted horizon in the 3D
seismic volume, including all Cutler intervals. Ten isochron maps were constructed from the
horizons to show salt thickness, total Cutler thickness, and between each Cutler interval to show
thickness changes between each interval across the seismic volume. Only time maps are used
because of potential error with the seismic depth conversion. All significant thickness changes
occur in the northern minibasin and east of Fault S_01. The main minibasin thickening events
occur between P01 and P03, with some thickening occurring between P04 and P05. Thickening
occurs between P03 and P05 over the minibasin on the eastern edge of the volume.

5.4.1 Major Horizon Maps

Basement (Figure 5.10 F): the basement structure map shows the deepest time elevation
at the northern end of the seismic volume, which is to be expected from the imbricate back thrust
faults dipping to the southwest. The thrust faults create a down-stepping geometry from S to N.

Base Salt (Figure 5.10 E): the Base Salt structure map mimics the basement horizon
structure map. The highest region in the southeastern end of the hanging wall of B_01 and the
deepest area is in the footwall of B_02.

Top Salt (Figure 5.10 D): the fault pattern seen in the basement and base salt horizon
structure maps is not carried through to the top salt horizon, because the faults stop at the base
salt level or fault movement has been accommodated in salt flow. The Hamilton Creek salt pillow
is located in the hanging wall of B_02 (Figure 5.7), suggesting that movement of the basement
thrust trapped the salt in place, compartmentalizing the autochthonous salt and preventing
significant salt flow on and off the hanging wall. The deepest elevation of salt deposition, and
Figure 5.10: Time structure maps of the major horizons: Basement, Base Salt, Top Salt, Ismay, P06 (top Cutler), and Chinle. The basement thrusts are imprinted in the Basement and Salt_Base maps. Salt_Top, Ismay, and P06 are influenced by the shape of the underlying salt and the post-salt faults. The Chinle map does not reflect any of the underlying faults or salt structures.
where salt is close to welded (Figure 5.13).

Ismay (Figure 5.10 C): the Ismay structure map mirrors the top salt horizon map, except for a slight change in shape of Hamilton Creek salt pillow.

P06 – Top Cutler (Figure 5.10 B): the Top Cutler map is similar to the Ismay and Top Salt maps, but another low develops on the SW edge of the seismic and there are two structural highs, in the hanging wall and footwall of S_01. The Cutler isochron (Figure 5.11) reveals that Cutler deposition was thickest on the flanks of the salt pillow, and thinnest on top of the salt pillow. The thickest deposition occurs north and south of the Hamilton Creek salt pillow, with a lesser concentration in the minibasin east of the salt pillow (Figure 5.11).

Chinle (Figure 5.10 A): the top Chinle structure map does not exhibit any similarities with the underlying Cutler horizons. The structural highs have moved off the salt structures, suggesting the cessation of downbuilding and sediment loading into salt minibasins around

Figure 5.11: Time thickness maps of the Paradox salt (A) and total Cutler (P06-P01) (B). Thicks are purpler and thins are red. (A) The Hamilton Creek salt pillow and pillow on the eastern edge of the seismic volume are the thickest regions. There are two thins, on basement faults, in the northern area of the seismic volume. (B) Total Cutler isochron highlights post-salt depocenters across the seismic, flanking the salt pillow. The two minibasins analyzed in this study are outlined by what dashed lines.
Hamilton Creek salt pillow.

5.4.2 Minibasin Horizon Maps

P01 (Figure 5.12 A & B): this interval shows the deepest level of deposition at the north end of the seismic volume, and the shallowest level of deposition in the south-central region of the volume on the Hamilton Creek salt pillow. The isochron map results match the structure map, with the thickest accumulation at the north end of the seismic and depositional thins onto the Hamilton Creek salt pillow and on the edge of the salt pillow interpreted on the eastern edge of the seismic. Fault S_01 is visible in a linear NE-SW trending steepening of contours on the southeastern edge of the salt pillow. A similar pattern is found in the isochron map.

P02 (Figure 5.12 C & D): during deposition of P02, there is a slight rotation in the location of the deepest accumulation from north to northeast. The shallowest level of deposition remains on top of Hamilton Creek salt pillow, and S_01 remains visible on the edge of the salt pillow. There is less variability in the P02 thickness than P01. The thickest deposition occurs on the northern and southern edges of the seismic. The interval is thinnest on the eastern end of the map between the two salt pillows and has fairly uniform thickness west of Hamilton Creek salt pillow. The limited seismic coverage on the second salt pillow prevents analysis of the relationship between it and the Hamilton Creek salt pillow, however, the two could have been one salt pillow prior to the development of the supra-salt growth faults S_01 and S_02 and the minibasin bounded by the faults.

P03 (Figure 5.12 E & F): there is no change in the structurally deepest area between P02 and P03 and the unit has a structural high on top of Hamilton Creek salt pillow. Fault S_01 remains delimited on the eastern edge of Hamilton Creek. P03 is the thickest unit in the northern minibasin, which is demonstrated in the isochron map. Two smaller depocenters can be seen east of S_01. The interval is thinnest between the two salt pillows and at the southern end of the map.

P04 (Figure 5.13 A & B): the structurally deepest point during P04 deposition has shifted slightly to the east, still on the northeastern edge of the map. The structurally highest point
Figure 5.12: Time structure and isochron maps for Cutler seismic horizons P01-P03. On the structure maps, red is high and purple is low. On the isochron maps, red is thin and purple is thick. See text for detailed description of each map.
Figure 5.13: Time structure and isochron maps for Cutler seismic horizons P04-P06. On the structure maps, red is high and purple is low. On the isochron maps, red is thin and purple is thick. See text for detailed description of each map.
has not changed, but a local high has formed to the southeast of Hamilton Creek salt pillow. The thickest minibasin deposition accumulation occurs on the eastern edge of the map, on the northeastern edge of Hamilton Creek salt pillow.

*P05 (Figure 5.13 C & D):* there is little difference between the P04 and P05 structure maps. The width of the oval-shaped low to the east of fault S_01 has increased, but the other structural trends remain the same. The isochron map shows two changes in sediment accumulation: (1) east-west trending area of maximum sediment deposition to the north of the Hamilton Creek salt pillow (darker blue band across isochron map), and (2) the depocenter to the east of fault S_01 the has shifted to the southern end of the fault.

*P06 (Figure 5.13 E & F):* the P06 structure map reveals a stark change from P04 and P05. The offset on the hanging wall of fault S_01 has narrowed dramatically, almost disappearing. And the deepest regions of sediment deposition are seen to the west, north, and northeast of the Hamilton Creek salt pillow. The isochron shows the thickest sediment accumulation on the downthrown side of fault S_01 and on the northeastern edge of the seismic volume, on the downthrown side of fault S_02. Sediment thickness appears uniform on the western and southern edge of the volume.

### 5.5 Structural Restorations

The structural restorations over the Hamilton Creek salt pillow are restored to pre-salt Mississippian level. The restorations demonstrate the relationship between the mobile salt, the basement thrusts, the post-salt faults, and the minibasin stratigraphy. Two cross sections were made from the depth-converted 3D seismic interpretation (Figure 5.14). One cross section runs parallel to the dip of the basement thrust faults, and the second runs roughly perpendicular to the faulted minibasin.

#### 5.5.1 Assumptions and Potential Sources of Error

There are several assumptions and potential error sources in the structural restorations. The primary assumptions are the following: (1) all salt is pure halite which is mobile and does
Figure 5.14: Section lines used for the Hamilton Creek salt pillow restorations. Line locations can be seen on the Top Salt time structure map. The section lines were based on time seismic interpretations of the three lines shown in figures 5.7 & 5.8. Section 1 transects the basement back thrusts and salt pillow. Section lines 2 and 3 are roughly perpendicular to the two minibasins focused on in this study.
not compact, and (2) flexural slip is the only method by which rock layers slide across each other, movement along a fault can be via the simple shear algorithm. The age of the Cutler Group intervals cannot be known, and were given approximate ages by dividing the total time of deposition evenly. The Triassic and younger rock units were grouped by age proxies, tops with sufficient coverage over the dataset, and could therefore be grouped incorrectly.

The timing of movement along the imbricate thrust faults cannot be constrained because of the overlying Paradox salt. It is assumed that the salt absorbed all thrust movement because no evidence of reverse faulting or inversion is seen in the overlying sediment. The thrust faults could have been in place prior to slat deposition, but no pre-foreland basin interpretations document compressional systems prior to the Ancestral Rock Mountains (Baars and Stevenson, 1981; Blakey, 2009).

The depth conversion is the biggest potential source of error. No checkshot data are available for the wells drilled within the seismic volume, so wells with sonic and density logs were used to create a time-depth relationship. Only five wells have both logs, but the well log coverage varies between wells. The interval velocities calculated by Petrel are anomalously high, especially in the upper well section where the sonic and density logs were run through casing. The high values projected the depth converted horizons too deep so they were corrected to align with well tops.

5.5.2 Section 1

Figure 5.15 shows the structural restorations for this section, and it’s location can be seen in Figure 5.14.

306 Ma restoration – Paradox: it is assumed that the Paradox was deposited on an unbroken Mississippian horizon, dipping NE towards the Uncompahgre Uplift. The Mississippian unit would dip to the NE towards the Uncompahgre Uplift in a flexural foreland basin setting, but the dip may not be as exaggerated as it is on this section line.

303 Ma restoration – Ismay: the Ismay has uniform thickness across the section, with
slight thickening to the northeast. The undulation and apparent thickening at the NE end of the line could be caused by the restoration algorithm or depth conversion.

291(?) Ma restoration – P01 (Cutler): movement has occurred along the imbricate back thrusts by the deposition of the earliest Cutler interval. P01 thickens to the northeast in response to the accommodation created in that direction by the thrust blocks to the southwest. Movement has occurred along the southwest-dipping thrust faults during early Cutler deposition. There is no definitive time-control on the fault movement, but the basement faults isolate the Hamilton Creek salt pillow, and create accommodation for the northern minibasin so movement must occur early. However, the thickness change could be due to downbuilding into the salt, and not related to movement along the thrust faults.

283(?) Ma restoration – P02 (Cutler): the P02 Cutler interval has less thickness change across the section line, with minimal thickening to the northeast, indicating the early stages on downbuilding into the salt.

275(?) Ma restoration – P03 (Cutler): the P03 Cutler interval shows thickening on the edges of the section lines and thinning in the center of the line above the nascent salt pillow. P03 thickness is greatest to the northeast where the primary minibasin is starting to form.

267(?) Ma restoration – P04 (Cutler): the P04 Cutler interval has subtle thickness changes from the top of the salt structure at the line center out to the southwest and northeast, following the preexisting pattern of greatest thickness increase to the northeast.

251 Ma restoration – P06 (Cutler): the top Cutler interval shows thickening to the northeast and constant thickness in the southwest.

201 Ma restoration – Triassic: the Triassic units (Chinle proxy) are missing over the top of the salt pillow, most likely due to nondeposition, thickening to the northeast and southwest, with the primary depocenter (area of greatest thickness) to the northeast.

105 Ma restoration – Cretaceous: the Cretaceous units (Dakota proxy) show uniform
Figure 5.15: Hamilton Creek Section 1 restoration. See text for detailed description of each restoration level.
Figure 5.15, continued
thickness across the structure, suggesting that salt movement has stopped by Cretaceous time.

No evidence of Laramide shortening was interpreted across the Hamilton Creek 3D seismic volume; no growth faults or associated growth strata appear inverted in the Cutler minibasin. If Laramide shortening did occur across the Hamilton Creek salt pillow, it was most likely accommodated in the reactivation of the basement back thrusts and movement of the mobile Paradox salt. Movement on the back thrusts would have been minimal to prevent the faults from influencing the Cutler minibasin strata, or the thrust reactivation was accommodated by evacuation of the Paradox salt which could have caused late, Cretaceous-age salt tectonics in an area beyond the 3D volume where we have no data.

5.5.3 Section 2

Figure 5.16 shows the structural restorations for this section, and its location can be seen in Figure 5.3.

303 Ma restoration – Ismay: the Ismay is the oldest unit faulted by S_01. The formation appears to thin to the east across the fault, but that is most likely due to the low resolution of seismic data on the edge of the line. S_01 detaches on the top of the Paradox salt.

291(?) Ma restoration – P01 (Cutler): the P01 Cutler interval shows thinning in the hanging wall, but thickens towards the fault. This suggests that the salt had begun moving on the eastern edge of the salt wall, most likely due to movement on the basement back thrusts.

283(?) Ma restoration – P02 (Cutler): the P02 Cutler interval shows constant thickness across the section.

275(?) Ma restoration – P03 (Cutler): the P03 Cutler interval thins towards the footwall from west to east, and thickens from east to west into the hanging wall.

267(?) Ma restoration – P04 (Cutler): the P04 Cutler interval has constant thickness in the footwall of S_01, and a greater constant thickness in the hanging wall.

251(?) Ma restoration – P05 (Cutler): the P05 Cutler interval also shows constant
Figure 5.16: Hamilton Creek Section 2 restoration. See text for detailed description of each restoration level.
thickness in the footwall of S_01, and a subtle increase in thickness across the fault, maintaining a constant, greater thickness in the hanging wall. This suggests that fault movement during deposition of P05 was minimal, sediment accumulation was lower during that time.

251 Ma restoration – P06 (Cutler): the P06 Cutler interval shows the greatest thickness change across S_01, suggesting the time of greatest fault movement and/or sediment accumulation. The unit has uniform thickness of 320 meters in the footwall of the growth fault, and almost 1,000 meters of sediment against the fault in the hanging wall. The sediment in the hanging wall thins quickly to the east, leveling off at around 500 meters.

201 Ma restoration – Triassic: the Triassic unit shows thickening in the footwall to the west, away from S_01. In the hanging wall, the Triassic thickens against the fault, thins on top of the faulted minibasin section, and thickens again towards the east.

166 Ma restoration – Jurassic: fault movement stopped during the deposition of Jurassic sediment; the fault extends into Jurassic sediment but there is no offset. The Jurassic units uniformly cover the faulted minibasin, and thicken to the west off the main salt pillow.

105 Ma restoration – Cretaceous: the Cretaceous sediment shows uniform thickness across the section line, suggesting that all movement has stopped, except that caused by differential compaction.

This section crosses the primary supra-salt fault, S_01, and highlights the relationship between the basement back thrusts, S_01, and the Cutler minibasin strata. There is no definitive evidence of Laramide shortening on the section. The uniform thickness of the Cretaceous units does not suggest significant movement during the time of the Laramide orogeny. It is important to note that the Cretaceous horizon was derived from well tops, so it does not have the same level of detail as the deeper horizons which are based on seismic interpretation.
CHAPTER 6

DISCUSSION

In order to better understand the geologic evolution of the Dry Creek and Hamilton Creek salt structures, it is important to combine the results from chapters 4 and 5 and analyze the results in a regional setting. The restorations in Chapters 4 and 5 reveal different evolutions for the Dry Creek and Hamilton Creek salt structures. The Dry Creek salt anticline grew through the latest Jurassic, possibly into the Cretaceous, while the Hamilton Creek salt pillow was fully developed by the end of the Permian. The possible reasons for such significant differences in evolution timing are discussed in the following sections.

6.1 Regional Structural Framework

Incorporating a regional interpretation and context for the Paradox Basin in southwest Colorado around Dry Creek and Hamilton Creek salt structures creates a better understanding of the external forces that influenced their structural evolution. Interpretation of a 2D seismic dataset, conducted during this study, over the Uncompahgre Front northeast of the study areas provides regional context for the study. The 2D seismic dataset was used by Timbel (2015), but the interpretation in this study is not based on his work. The seismic coverage and incipient interpretation can be seen in Figure 6.1.

6.1.1 Basement Architecture

A basement interpretation was only possible across the subsurface seismic datasets. The map in Figure 6.1 shows that the only type of basement fault interpreted across the study area are thrust faults. Seismic interpretation revealed imbricate thrust faults in the Uncompahgre Front dipping to the northeast (Figure 6.2, 6.3, & 6.4). This interpretation agrees with the imbricate thrust of White and Jacobson (1983), Huffman and Taylor (2004), and Kluth and DuChene (2009) along the southeastern Uncompahgre Uplift. Timbel (2015), interpreted the faults across the 2D dataset as part of the Sneffels Horst Fault System, wrench faulting related to the Colorado Lineament, and multi-phased Uncompahgre Uplift thrust faulting.
Figure 6.1: Map over the study area showing seismic coverage and location of 2D composite seismic lines. Basement thrust faults, dipping northeast and southwest are interpreted across the Uncompahgre Front to the southwest of the Uncompahgre salient. The northeast dipping faults are closest to the Uncompahgre Uplift, and the southwest dipping faults sit further in the basin. Diapiric salt (>0.25 secs TWT thick) was interpreted at the northwestern edge of the salient and in the basin on trend with the four major salt wall lineations. Remnant salt (<0.25 secs TWT thick) was interpreted on the eastern half of the study area. In general, the amount of salt and thickness of salt decreases to the southeast. Isochron map of the Cutler Group reveals the location of the primary depocenter in the study area between the salt against the Uncompahgre thrusts and the Paradox Valley salt trend.
Figure 6.2: Interpretation across Sawtooth Ridge composite line. Imbricate thrust faults extend from the Uncompahgre Uplift into the Paradox Basin. A relict salt pillow is trapped against the deepest thrusts, and salt is welded out on the SW end of the line. Expulsion rollover geometry is seen within the Cutler SW of the relict salt pillow and the edge of the main Cutler minibasin (Figure 6.1) is on the SW edge of the line. The Mississippian and Basement horizons were difficult to interpret in the northeastern most thrust blocks, but seismic reflection character suggests that the Mississippian horizon extends across the composite line. Refer to Figure 6.1 for line location.
Figure 6.3: Interpretation across Naturita Ridge composite zigzag line. Changes in direction along the zigzag line are noted above the seismic. The line starts in the thrust salient at the NE end, cut by two shallowly dipping thrust faults. Back thrusts are interpreted basinward of the Uncompahgre thrust front where folding of the Mississippian unit and minor basin uplifts are seen. Salt is trapped in the lows around the basement uplifts. A welded Cutler minibasin is interpreted at the SE end of the line on the NE flank of the Naturita Ridge salt ridge, barely imaged on the edge of the composite line. Refer to Figure 6.1 for line location.
Figure 6.4: Interpretation across Hamilton Creek composite line. Imbricate thrust faults, with steeper dips than those in Figures 6.2 and 6.2, extend from the Uncompahgre Uplift into the Paradox Basin. Thrust faults obliquely cut by the composite line are shown at the base of the Uncompahgre Front. Paradox salt is welded or not deposited against the Uncompahgre Uplift. A Cutler minibasin sits basinward of the uplift on the northern end of Hamilton Creek salt pillow. The salt is locally welded on the upper tips of back thrusts underneath the salt pillow. Refer to Figure 6.1 for line location.
The southwestward extent of the imbricate thrust faults into the basin seen in map view (Figure 6.1), indicates that the Uncompahgre Uplift steps forward in this region as a thrust salient, in advance of the main thrust front. The thrust salient can also be seen at the NE end of the Naturita Ridge composite line (Figure 6.3). This is the first interpretation to include a thrust salient NE of Naturita, CO along the Uncompahgre Uplift. Most authors draw a straight NW-SE trend for the Uncompahgre Uplift at its southeastern end (Doelling, 1983; Barbeau, 2003; Timbel, 2015), or as a thrust recess in the Uncompahgre Uplift NE of Naturita, CO (Rasmussen and Rasmussen, 2009).

The salt appears to be compartmentalized and trapped against the thrust faults (Figure 6.2, 6.3, & 6.4). There is no evidence that salt was deposited on the uplifted basement blocks in the salient. The salt could have been eroded off the hanging walls by deposition of the Cutler Group sediments, but total erosion across the entire thrust salient front is unlikely. The Paradox salt could have acted as a weak and mobile detachment for salient thrust propagation and emplacement into the basin, which suggests that the faults moved early (late Pennsylvanian-early Permian) before salt deposition could extend over the Uncompahgre Uplift in this area. This hypothesis agrees with Timbel (2015), who determined that compression began in early Pennsylvanian in this area, and continued through the Permian.

Normal faults were expected to be interpreted in the basement, since the basin is interpreted as a flexural basin with normal faults down dropping to the northeast towards the Uncompahgre Uplift in the Utah portion of the basin (Barbeau, 2003; Trudgill, 2011). However, thrust faults dipping to the southwest were interpreted across the Hamilton Creek 3D seismic volume and the 2D seismic dataset basinward of the Uncompahgre Front (Figure 6.3 & 6.1). The seismic character of these southwestward dipping faults is less obvious in the 2D seismic than those under Hamilton Creek salt pillow, but a local basement high coincides with the location of the upper fault tip (Figure 6.3).

Interpretation of thrust faults where normal faults were expected brings up the following
questions: Is this a localized change from normal faulting to thrust faulting? If so, is it controlled by the emplacement of a basement salient into the basin near Naturita? These questions cannot be answered definitively without subsurface control of the basement near the southeastern termination of Paradox Valley and Dry Creek salt anticline. A change in structural style could help explain why the Dry Creek salt anticline and the Naturita Ridge salt structure are offset from the Paradox Valley-Hamilton Creek trend. The most likely explanation is that the southwest dipping faults are a local backthrusting response to the emplacement of the thrust salient into the basin.

6.1.2 Timing the movement along southwest dipping basement thrusts

The results of the Hamilton Creek salt pillow restorations reveal that it is not possible to date the movement along the southwest dipping thrust faults. Work conducted by Timbel (2015) on the faults across the 2D seismic dataset suggest an early phase of northwesterly compression in the earliest Pennsylvanian NE of Naturita, CO. However, those models indicate that the earliest compression resulted in folding, and that faulting occurred later during the Pennsylvanian-Permian phase of continued compression (Timbel, 2015).

The unpredictability of salt flow in and out of the section plane makes it difficult to constrain the interaction between the pre-salt and post-salt units and structures (Rowan, 1993). In addition, the predicted salt thickness from the restoration for Permian through Cretaceous is thick enough to absorb any upward movement and compression along the basement thrusts. The faults are either: (1) back thrusts related to the emplacement of the salient into the basin, (2) thrusts related to Laramide or younger compression, or (3) back thrusts with reactivation during a Laramide or younger shortening event.

6.1.3 Influence of Basement Architecture on Salt Diapir Locations

Many authors have hypothesized that the normal faults in the basement (pre-salt) control the location and growth of the major salt walls across the basin (Baars, 1966; Baars & Stevenson, 1981; Ge et al., 1997; Trudgill, 2011). The results of these studies show northeast and northwest
trending lineaments that line up with the major salt walls in the northern part of the basin (Figure 6.5). Gravity data over the study area does not provide as much detail as that published by Trudgill (2011), but the northwest trend interpreted at the northern end of Paradox Valley can be extended to the valley termination (Figure 6.6).

Interpretation across the Hamilton Creek 3D seismic volume reveals that this salt pillow is controlled by southwest dipping thrust faults (Figure 5.7). Although there is no control on original salt thickness at Hamilton Creek or backthrust movement timing, the location of the salt pillow indicates that the thrusts compartmentalized the salt, trapping it in the hanging wall of fault B_02, during the early stages of salt flow and evacuation. The earliest Cutler horizons (P01-P03) show thickening northwest of B_02 fault tip (Figure 5.12), welding out the salt about the B_02 fault tip.

Figure 6.5: Interpreted controlling basement fault zone based on gravity gradient map from Trudgill (2011). Salt wall locations interpreted to be controlled by the location of the NW and NE trending faults at the top Mississippian level, inherited from PreCambrian basement architecture.
Figure 6.6: Observed gravity from Banbury (2005) (on the left) and the University of Texas El Paso PACES Gravity Database (on the right) show basement trends. The gravity boundary of the Uncompahgre Uplift extends further SW into the basin than the seismic fault interpretation. The gravity response south of Hamilton Creek suggests that the basement is shallower SE of the salt system, and that the system is close to the basin margin. Note that the maps have different scales so the color gradients do not match.
There is no subsurface control on the basement under Dry Creek salt anticline or the southeastern termination of Paradox Valley. The Mississippian horizon built on regional well tops shows a relatively steep drop on the horizon towards the northeast below the salt anticline (Figure 6.7). If this drop in the Mississippian horizon is real, it could be a southwest dipping thrust fault related to the faults mapped around the Uncompahgre salient (Figure 6.1), or it could be a normal fault, like those interpreted by Baars (1966), Baars and Stevenson (1981), and Barbeau (2003).

Examination of the map view trend lines of Dry Creek salt anticline and Hamilton Creek salt pillow reveals that Hamilton Creek is on strike with Paradox Valley, while Dry Creek and Naturita Ridge are en echelon but offset to the southwest (Figure 6.8). This southwestern offset of Dry Creek and Naturita Ridge was caused by the Uncompahgre salient encroachment into the basin, which in turn forced sedimentation further into the basin and forced salt evacuation on the
basement steps offset from the main Paradox Valley trend (Figure 6.1 & 6.3). Without subsurface control on the basement, it is impossible to know the style of the basement architecture, but the Dry Creek-Naturita Ridge anticline either sits on normal faults en echelon to those controlling the location of Paradox Valley or on backthrusts related to the Uncompahgre salient.

6.2 Salt System Evolution

The regional seismic interpretation shows diapiric and remnant salt up against the Uncompahgre Front extending out in the basin on trend with Paradox Valley (Figure 6.1), suggesting that Paradox Valley, Dry Creek, and Hamilton creek are all part of the same original salt system. Diapiric salt is interpreted as any region of salt with a time thickness greater than

Figure 6.8: Map highlighting the locations and trends of the salt structures in the study area. Hamilton Creek salt pillow is on strike with Paradox Valley salt wall. Naturita Ridge salt ridge and Dry Creek salt anticline have the same strike but offset to the southeast. The offset of Dry Creek and Naturita Ridge lines up with the location of the Uncompahgre thrust salient. (Google Maps, 2017).
Figure 6.9: Interpretation across NR-HC 2D seismic line. Refer to Figure 6.1 for line location. A strike-view of the Dry Creek-Hamilton Creek salt system reveals two salt pillows, Hamilton Creek salt pillow and SE Hamilton Creek salt pillow, separated by a welded, fault-bounded minibasin. The salt also thickens to the NW of Hamilton Creek salt pillow creating a salt ridge under Naturita Ridge. This is the same salt body interpreted at the SE edge of Naturita Ridge composite line (Figure 6.3). The plan view of the salt ridge can be seen on Figure 6.1.
0.25 seconds (TWT), and remnant salt is interpreted as any salt with a time thickness less than 0.25 seconds (TWT). The composite lines show relict salt pillows against the basement faults (Figure 6.2), followed by downbuilding of the Cutler Group onto the underlying salt, creating welds in places. The southwestern ends of the lines show grounded minibasins lying on Mississippian units. The edge of a salt diapir is interpreted at the southwestern end of the Naturita Ridge composite line (Figure 6.3). This diapir sits underneath Naturita Ridge and is also interpreted on a northwest oriented 2D line that cuts through the 3D survey (Figure 6.9). This suggests that Naturita Ridge is a salt-cored feature, possibly a salt ridge, that forms the broad topographic high (Figure 6.10).

The existence of salt under Naturita Ridge provides further evidence of the connectivity of Paradox Valley, Dry Creek, and Hamilton Creek salt structures. This is also supported by the northwestern structural trends of the four features (Figure 6.8). Paradox Valley and Hamilton

---

**Figure 6.10:** Comparison of Ge and others (1997) progradational models (A) to seismic interpretation (B) from Kluth and DuChene (2009). The seismic interpretation shows trapped salt and welds against the thrust front, followed by expulsion rollover and the creation of passive salt walls and salt anticlines.
Creek follow the same structural trend, while Dry Creek and Naturita Ridge have the same northwestern strike but are offset to the southwest. The trend and offset are due to the halt of salt movement against preexisting structures (compressional or extensional) and the differential loading of overlying sediment onto the mobile salt causing it to evacuate the deepest part of the basin, against the Uncompahgre Front.

6.2.1 Salt Flow Mechanism

Basement faults are interpreted as the determining factors for the location of salt diapirism, but the salt migration can only occur if there is a salt flow mechanism, which in the Paradox Basin is primarily the result of sedimentation of the Cutler Group off the rising Uncompahgre Uplift during the Permian (Doelling, 2001; Barbeau, 2003). The southwest
Figure 6.12: Restoration levels for Dry Creek and Hamilton Creek for the time of latest salt diapirism. (A) Development of the halokinetic hook sequence on the southwestern margin of the salt wall was complete by Summerville time (166 Ma). (B) Hamilton Creek salt pillow was fully developed by the end of the Triassic (201 Ma). The minibasin is fully developed, but the weld on fault B_02 has not developed.
progradation of the Cutler Group sediment of the Uncompahgre Uplift and subsequent differential loading onto the mobile Paradox salt created the mechanism for salt flow in the basin (Figure 6.10) (Ge et al., 1997; Kluth and Duchene, 2009). Seismic interpretations across the 2D seismic survey in this study and across Sinbad Valley (Kluth and DuChene, 2009) show prograding wedges of Cutler Group sediment behaving similarly to the kinematic models created by Ge and others (1997) (Figures 6.2, 6.3, & 6.4).

The prograding sediment wedges create relict salt pillows trapped against the Uncompahgre thrust front (Figure 6.2, 6.4, & 6.10), salt welds below the wedge (Figure 6.2, 6.3, & 6.10), and remnant salt is trapped in subtle basement lows in the southeastern region of the study area (Figure 6.4 & 6.1). A change from relict salt pillows and salt welds to remnant salt occurs from northwest to southeast across the study area. The study area sits towards the easternmost extent of salt deposition in the Paradox Basin (Figure 6.11), and it is interpreted here that the salt budget decreases towards the basin margins, which in turn decreases the amount of salt available to be displaced by the progradational wedge.

### 6.2.2 Halokinetic Sequences and Timing of Diapirism

The restorations created for Dry Creek and Hamilton Creek reveal that the salt structures developed over different periods of time. The Hamilton Creek salt pillow was fully developed by the end of the Permian, but the Dry Creek salt anticline continued to develop through the mid Jurassic (Fig 6.12). Although seismic interpretation of the Jurassic and Cretaceous units above the Hamilton Creek salt pillow was not possible due to seismic quality, well top horizons and surface geology do not suggest that any late salt movement occurred over Hamilton Creek, beyond continued subsidence of the surrounding minibasins (Figure 5.2). Interpretation of a halokinetic hook sequence in the Kayenta, Entrada, and Summerville units on the western flanks of Dry Creek salt anticline (Figures 4.21, 4.22, & 4.24) indicates that the salt anticline continued to develop until approximately ~182 Ma, during the deposition of the Summerville Formation (Fig 6.12). Continued deposition and differential compaction of Jurassic and Cretaceous units enhanced the dip of the Jurassic hook sequence and increased the dips of the overlying units.
The Dry Creek restorations reveal long-lived salt rise that ended in Summerville time with the development of a halokinetic hook sequence on the southwestern margin of the salt wall (166 Ma) (Figure 6.12 & 4.27). According to work conducted by Giles and Rowan (2012), halokinetic hook sequences form as a result of a low ratio of sediment-accumulation rate to diapir-rise rate. Diapir-rise rate must have outpaced or equaled sediment-accumulation rate in the early to middle Jurassic to create the hook sequence. The salt diapir must have remained close to, or at, the surface. Halokinetic sequences can also form by compressional forces acting on a diapir, however, the lack of subsurface control across Dry Creek makes it difficult to determine if shortening is present on the salt structure (Giles and Rowan, 2012).

The Honaker Trail roof on the southwest margin of the salt wall indicates that salt rise began early, and that the Honaker Trail and Cutler formations were syndepositional because the Honaker Trail roof had to be thin enough for the Paradox salt to break through the roof (Figure 6.12 & 4.27). Salt evacuation and diapirism in the Paradox Basin was triggered by differential loading, allowing the salt to break through the overlying units, so the Honaker Trail roof must be thinner over the location of the salt wall (Vendeville and Jackson, 1992).

6.3 The Argument for Laramide-aged Compressional Tectonics in the Paradox Basin

Definitive evidence of Laramide shortening has not be documented in the Paradox Basin salt walls, but the existence of Laramide shortening has been debated for decades. Laramide shortening is interpreted in several uplifts surrounding the Paradox Basin, including the San Rafeal Swell, Circle Cliffs, Monument Uplift, and Uncompahgre Uplift (Bump, 2004) (Figure 6.13). Laramide shortening seems to have bypassed the Paradox Basin, or, at least, is not preserved in the NPB.

However, Kluth and DuChene (2009) suggest that the tilting of Mesozoic rocks on the flanks of salt walls could be related to Laramide shortening, but only if the minibasins on either side of the salt walls welded out in the Late Paleozoic. The northwestern termination of Dry Creek salt anticline resembles a pinched-off salt wall, like those modeled by Guglielmo et al.
Figure 6.13: Regional Laramide compressional tectonics that acted on the Paradox Basin. (A) Modified after Bump (2004). Location of Laramide uplifts on the Colorado Plateau (solid arrows indicate shortening direction). The inset map highlights the location of the Seveir thrust front on the northwestern margin of the Colorado Plateau. (B) Modified after Bird (2002) and Yonkee and Weils (2015). Maps of the Late Cretaceous and Paleogene deformation related to the Sevier and Laramide orogenies overlain by maximum stress azimuths from Bird (2002). (A) Sevier orogeny underway, development of flat-slab subduction in the S and beginnnig of Laramide orogeny. (B) End of the Sevier and Laramide orogenies. Study area outlined in red on each map.
The anticlinal shape of the Dry Creek termination resembles compressional folds modelled in the Guglielmo study (Figure 6.14), however, the fold limb dips are the reverse of the modeling results – the steeper dips at Dry Creek are in the backlimb and not the forelimb of the pinched-off salt wall.

**Figure 6.14:** Guglielmo model for pinched-off salt wall and present day cross section through northwestern termination of Dry Creek. The direction of compression is from left to right on both figures. (A) The Guglielmo model shows steeper dips in the forelimb and an asymmetrical salt anticline at the center. (B) The Dry Creek termination shows steeper dips in the backlimb and a symmetrical salt anticline in the structure’s core.

(2000) (Figure 6.14). The anticlinal shape of the Dry Creek termination resembles compressional folds modelled in the Guglielmo study (Figure 6.14), however, the fold limb dips are the reverse of the modeling results – the steeper dips at Dry Creek are in the backlimb and not the forelimb of the pinched-off salt wall.
6.3.1 Laramide Shortening in the Western United States

Evidence for Laramide shortening is interpreted on the northeast and southeast orientated basement-cored uplifts on the Colorado Plateau surrounding the Paradox Basin (Figure 6.13). Although the uplifts have roughly orthogonal shortening directions, they all moved between ~72-50 Ma (Bump, 2004), during the Laramide orogeny (~75-50 Ma) and the end of the Sevier orogeny (125-50 Ma) (Lawton, 2008; Yonkee and Weil, 2015). Bump (2004) hypothesized that the orthogonal shortening directions of the uplifts on the Colorado Plateau results from the interaction of the flat slab subduction of the Farallon plate under then North American plate, and the resultant tectonics of the two orogenies.

Measurements taken across the western United States reveal that the entire region has experienced multiple stress orientations during the Sevier and Laramide orogenies. During the early stages of the Farallon plate subduction, 85-50 Ma, the stress direction was fairly constant, but between 50-35 Ma, the stress azimuth experienced a major counterclockwise azimuth change (Bird, 2002), during the development of the Laramide uplifts on the Colorado Plateau (Figure 6.13). Yonkee and Weil (2015) attribute the azimuth change to rotation of the direction of westward motion of the North American plate. The plate dynamics of the subducting Farallon plate influenced the structural styles and shortening directions of the Sevier and Laramide orogenies (Figure 6.13). The subduction was orthogonal to the plate margin during the Sevier orogeny, which allowed decoupling of the upper crust and thin-skinned thrust belts to form (Yonkee and Weil, 2015). However, rotation of the subduction margin later in the Cretaceous resulted in shortening subparallel to plate motion and the thick-skinned Laramide orogeny and the varied orientations of Laramide uplifts (Yonkee and Weil, 2015).

6.3.2 Compressional Salt Diapir Analogs

The evidence for Laramide-aged compression on the large salt walls in the Paradox Basin may be eroded away, hidden by erosion, or masked by structure collapse or faulting due to salt dissolution. Comparison of the Dry Creek northwestern termination style to compressional salt diapirs in other basins with early salt diapirism and late shortening may provide insight into the
structure’s evolution to determine if compressional salt tectonics are present.

Many salt diapirs in the Central North Sea are interpreted to have undergone late-stage compression. A study conducted by Davison and others (2000) compared the effects of downbuilding and compressional diapir growth processes, which are summarized in Figure 6.15. Seismic interpretation across the South Pierce salt diapir reveals folded strata on the crest of South Pierce diapir, similar to the fold on the northwestern termination of Dry Creek salt anticline (Figure 6.16). However, it is difficult to assess the similarities beyond the overburden geometries because much of the Dry Creek overburden has been removed by erosion so there is no way to assess the salt structure for high angle onlap pattern of the late Cretaceous and Tertiary sediments. The dissimilar shapes of the salt diapirs also makes it difficult to compare the overburden folds. The North Sea compressional salt features are primarily detached from the autochthonous salt and have bulbous heads, while the Dry Creek salt anticline here is interpreted as a narrow, elongate salt wall (Figure 6.15 & 6.16). The Dry Creek salt anticline is not restricted from having a bulbous head, but the well control on the western flanks and elongate, narrow geometry of the exposed anticline prevents the structure from having a bulbous head like the

Figure 6.15: Schematic salt diapir showing the geometric characteristics of late-stage compression from Davison and others (2000).
Figure 6.16: Comparison of folded strata above South Pierce salt diapir, Central North Sea (modified from Davison and others (2000) the Quilitage salt anticlines from Li et a. (2012), and Dry Creek salt anticline. (A) Interpretation of a fold in the Eocene-Oligocene strata above the South Pierce diapir. The direction of compression is unknown. (B) Subsurface interpretation of the Quilitage salt anticlines of the Kuqa Basin projected above ground level. The anticlines are asymmetrical with steeper dips in the forelimbs than backlimbs. (C) Folded strata above Dry Creek anticline showing folded strata in the faulted units. Note there is no control in folding in the latest Cretaceous and younger strata.
North Sea salt diapirs.

The second analog is the salt-cored anticlines in the Kuqa basin, which formed when preexisting salt diapirs became sites for localized shortening during the Cenozoic reactivation of the Tian Shan mountain belt (Li et al., 2012). The southern and northern Qiulitage salt anticlines are overturned folds with tight salt cores (Figure 6.16). The forelimbs are overturned and broken by north-dipping thrust faults. The Qiulitage salt anticlines dip to the north, opposite to the direction of maximum compression. Unlike the Paradox Basin, it is proven that the salt-core anticlines formed by the shortening. The shape of the salt in the Qiulitage anticlines is more similar to the Dry Creek anticline than the Central North Sea diapirs, but the fault styles are different. The faults at the northwestern termination of Dry Creek are normal faults that splay from the anticline axis and may be connected at depth, while the Qiulitage anticline limbs are broken by thrust faults (Figure 6.16).

The two analogs provide endmembers for compressional salt tectonics: from slight folds in overburden strata on diapir crests to salt-cored anticlines with overturned fold limbs in the direction of compression. The folded northwestern termination of Dry Creek salt anticline most resembles the folded strata on the South Pierce diapir crest. However, it is important to note that the fold orientation of the Dry Creek northwestern termination is opposite from the orientations of the pinched-off salt wall in the Guglielmo (2002) model and the overturned anticlines in the Li study (2012). Both the model and field study show folds where the forelimb has steeper dips than the back limb, but the Dry Creek fold has steeper dips on what would be the back limb, relative to the direction of Laramide shortening (Figure 6.13 & 6.17).

Although the folded termination resembles anticlines in other compressional salt tectonic systems, there is no definitive evidence of compression on salt structures proximal to Dry Creek and the fold orientation on Dry Creek is the opposite of what is expected. Laramide compression could have been absorbed by the Paradox salt in the major salt walls and all evidence has been removed by erosion and salt dissolution. If the folded northwestern termination did not form as
Figure 6.17: Rotation in strike along the NE flank, part of Coke Oven Syncline, to the south-eastern termination fo Paradox Valley, marked by the white dashed lines. The change in strike suggests a relationship between the evolution of Dry Creek and Paradox Valley salt structures. Note the highly rotated and oversteepened dips in the Jms tongue extending into the valley floor.
a result of Laramide shortening, the fold could have formed by one of the following: (1) gravity gliding of the Paradox salt system further into the basin to the southwest, possibly in response to the rise of the Uncompahgre Plateau during Laramide shortening (Rowan et al., 2004), or, most likely (2) differential compaction, subsidence, and salt dissolution of both the Dry Creek and Paradox Valley salt diapirs.

6.4 Salt Structure Termination Geometries

Many authors describe the salt walls in Paradox Basin as long, linear features following a northwestern trend. However, close examination of the salt walls and other salt structures in the basin reveals that the structures are less similar than expected, especially when it comes to the salt wall termination geometry. Termination geometries provide insight into the structural evolution of the salt walls because they show the relationship of units across the salt wall and the relationship between the overburden and the underlying salt. Dry Creek anticline has two very

Figure 6.18: USGS geological map of the Naturita NW quadrangle, highlighting the NW termination fault connectivity between Dry Creek and Paradox Valley (modified from Cater, 1955).
Figure 6.19: Comparison of Klondike Ridge at the SW termination of Gypsum Valley and NW termination of Dry Creek anticline. 
(A) Klondike Ridge graben in the center of the Gypsum Valley termination. The offset on the N-S trending normal faults decreases to the south, away from the termination. (B) Faults at the NW termination of Dry Creek. The small fault block between NW_01 and NW_02 becomes a graben bounded by NW_03 to the northwest of the termination. The faults extend northwest to the southeastern termination of Paradox Valley,
different termination styles. The northwestern termination is elevated about the salt anticline flanks, folded, and faulted, while the southeastern termination comes to a narrow point that is transected by a single fault (Figure 4.21, 4.24).

6.4.1 Termination Geometry Observations from the Paradox Basin

The narrow, pointed geometry and gentle 15° plunge of the southeastern termination do not suggest influence of shortening at this end of the structure. The geometry was most likely created by crestal faulting and differential compaction above the underlying Paradox salt. Fault SE_01, running down the center of the termination, most likely detaches on the salt at depth. The fault formed as the flanks subsided and compacted into the underlying salt; the southeast flank subsiding more than the southwest. Faults SE_02, SE_03, and SE_04 formed splays off SE_01 as the southeast flank subsided.

The northwestern termination of Dry Creek is complexly faulted and folded (Figure 6.17). The fold could be related to a shortening event, but there is no definitive proof. The change in line length in the Section B restorations is well within the range of error during the fault restorations, and cannot be definitively interpreted as shortening. The movement along the faults is not well understood, and the line length difference could be related to fault block movement in and out of the section line plane. Also, it would not make sense for shortening to influence one end of a 4 km long salt structure and for there to be no evidence of shortening at the other. Compression could only create different termination geometries if salt moved along strike from southeast to northwest, forcing the overburden to fold at the northwestern termination of the structure.

6.4.2 Possible Scenarios for Development of Termination Geometries

It is more likely, that the geometry of the northwestern termination is related to interactions between Dry Creek salt anticline, Paradox Valley salt wall, and the overburden between the two salt structures. The northwestern termination of Dry Creek is only 1.8 km away from the southeastern termination of Paradox Valley, so the two salt structures could intrinsically
be very closely related. The Coke Oven Syncline, to the northeast of Dry Creek (Figure 6.8),
could have formed as a minibasin southeast of Paradox Valley, forcing salt evacuation further
south to the present-day location of Dry Creek and Naturita Ridge. This is supported by the
change in strike along the western side of Coke Oven Syncline from the northeast flank of Dry
Creek to the southeastern termination of Paradox Valley (Figure 6.17).

The faults in the northwestern termination of the Dry Creek anticline are mapped by
Cater (1955) to extend to the southeastern termination of Paradox Valley (Figure 6.22), providing
further evidence of the spatial connection between the two salt structures. Strike measurements
taken in the fault blocks reveal strikes that follow the trend of the faults, and do not plunge
away from Dry Creek or Paradox Valley. This suggests that fault movement accommodated salt
dissolution, and that subsidence or differential compaction of the overburden was not a major
factor.

The reverse fault on the termination, NW_02, is only a reverse fault because the graben
block between NW_01 and NW_02 was pinned up between the two larger blocks, so the footwall
block of NW_02 was the only side that could slide down fault into the underlying salt (Figure
6.20). Alternatively, the folded termination could be an attempt to accommodate rising salt, or an
influx of salt from the southeast end of Paradox Valley, similar to the pivoting hanging wall block
found in Klondike Ridge in the southeastern termination of Gypsum Valley (Figure 6.23), which
is interpreted to be a zone of failure where the rocks were unable to mimic the morphology of
termination (Lehmann, 2015).
CHAPTER 7

CONCLUSION

Structural restorations of 2D cross sections across two small salt structures in the Paradox Basin provide insight into the structural development of these salt structures and can be used to further understand the evolution of other analogous salt features. Integration of field data and seismic interpretation allows for the analysis of the studied salt structures on a regional scale gaining insight into the tectonostratigraphic relationships between shortening events, sedimentation, and salt tectonics in the southwestern Colorado region of the Paradox Basin. The main conclusions from this study are:

1) The structural restorations of Dry Creek and Hamilton Creek reveal different time periods for the structural evolution of the salt structures. Hamilton Creek salt pillow was fully developed by the end of the Triassic, while Dry Creek salt anticline continued to rise through the Jurassic Entrada/Sumerville time.

2) The regional seismic interpretation reveals that the Dry Creek and Hamilton Creek salt structures are part of the southeastern-most extent of the Paradox Valley salt system, and that Naturita Ridge is a salt-cored topographic high.

3) The seismic interpretation also shows a thrust salient in the Uncompahgre Uplift, northeast of Naturita, CO. This thrust salient is interpreted to cause the back thrusts interpreted basinward of the uplift, including the southwest dipping thrust faults under the Hamilton Creek salt pillow. There is no evidence that these thrust faults are related to Laramide shortening in the Paradox Basin. The Paradox salt decouples the back thrusts from the overlying strata, and no evidence of reactivation is seen across the seismic dataset.

4) Although the northwestern termination of Dry Creek anticline is folded, there is no definitive evidence of shortening preserved in the structure. The scale of the fold relative to the total structure length means any shortening measurements are well within the range of error in the restorations. This study interprets the folded termination as the result of the proximity of Dry
Creek to the southeastern termination of Paradox Valley. Dry Creek anticline is a narrow salt ridge on the margins of a large salt wall, which suggests that the structural evolution of the two salt structures is related, and that subsidence, differential compaction, and late salt evacuation and dissolution on both Dry Creek and Paradox Valley are the causes of the termination geometry.

5) There is no concrete evidence of Laramide-age shortening in the study area. If Laramide compression did influence the study area, it would follow pre-existing structural weaknesses, using the salt as a detachment surface. The salt would also absorb much of the compression, making it difficult to find proof of shortening.

6) Analysis of the Dry Creek terminations and the southeastern termination of Paradox Valley indicate that the structural evolution of the Paradox Basin salt diapirs and walls are more complex than originally believed. However, the evolutions are difficult to study due to the nature of the field exposures. Analysis of smaller salt structures may provide insight into the structural evolution of the larger salt walls because they have not been as altered by erosion or the effects of salt dissolution.

7.1 Recommendations for Future Work

1) Not enough detailed measurements were taken along the faults at both terminations of Dry Creek anticline, due to access issues. It would be interesting to conduct a detailed study on both terminations to see how that would influence the structural restorations across the salt diapir, and how it affects this study’s findings on the evidence of Laramide-aged shortening on the salt structure.

2) A basin-wide study of salt wall termination geometries would provide insight into the structural evolution of salt walls to understand their differences and similarities. It would also create new analogs to the existing termination geometries from other salt basins around the world.
3) Well log data were only used to support the seismic interpretation in the study area. A detailed well log study would provide insight and allow units not easily interpreted across the seismic dataset to be incorporated into a regional framework for a better understanding of the evolution of salt structures in the southwestern Colorado area of the basin.
REFERENCES


Society - 1983 Field Trip, p. 81-90.

Doelling, H.H., 2001, Geologic map of the Moab and eastern part of the San Rafael Desert 30’ x 60’ Quadrangles, Utah Geological Survey Map 180, scale 1:100.000.


Frahme, C.W. and Vaughan, E.B., 1983, Paleozoic geology and seismic stratigraphy of the northern Uncompahgre Front, Grant County, Utah, in J.D. Lowell, and R. Gries, eds., Rocky Mountain Foreland Basins and Uplifts: Rocky Mountain Association of Geologists, p. 201-211.


Hite, R.J., 1960, Stratigraphy of the saline facies of the Paradox Member of the Hermosa Formation of southeastern Utah and southwestern Colorado: Geology of the Paradox Basin fold and fault belt: Four Corners Geol. Soc. 3rd Annual Field Conference, p. 86-90.


Peterson, F., 1994, Sand dunes, sabkhas, streams, and shallow seas: Jurassic paleogeography in the southern part of the western interior basin: Mesozoic Systems of the Rocky Mountain Region,


Trudgill, B. D., 2011, Evolution of salt structures in the northern Paradox Basin: Controls on evaporite
deposition, salt wall growth and supra-salt stratigraphic architecture: Basin Research, p. 208–238.


Figure A.1: Map showing all measurements taken across the Dry Creek anticline.
Figure A.2: Map showing all measurements taken across the NE flank of Dry Creek anticline.
Figure A.3: Map showing all measurements taken across the SE flank of Dry Creek anticline.
Figure A.4: Map showing all measurements taken across the NW flank of Dry Creek anticline.
Figure A.5: Map showing all measurements taken across the SW flank of Dry Creek anticline.
Figure A.6: Map showing all measurements taken across the SE termination of Dry Creek anticline.
Figure A.7: Map showing all measurements taken across the NW termination of Dry Creek anticline.
Figure A.8: Map showing all measurements taken between the NW termination of Dry Creek anticline and the SE termination of Paradox Valley.