CHARACTERIZATION AND GEOCHEMISTRY OF CARBONATE CAPROCK ASSOCIATED WITH THE GYPSUM VALLEY SALT WALL, PARADOX BASIN, COLORADO: IMPLICATIONS FOR UNDERSTANDING LATERAL CAPROCK EMPLACEMENT

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Dedication

To Dr. Eric Hiatt, who unknowingly put me on the road to find my passion for science.

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by

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Abstract

On the northeastern side of Gypsum Valley salt wall in the Paradox Basin of Colorado, discontinuous exposures of layered gypsum and carbonate rocks were previously mapped as the contact between diapiric Paradox Formation and marine limestone of the Pennsylvanian Honaker Trail Formation. Utilizing new and existing mapping, petrographic and isotopic geochemical analyses, this study reinterprets this zone to represent lateral gypsum and carbonate caprock that formed in the Triassic during passive rise of the Gypsum Valley salt wall. Gypsum Valley lateral carbonate caprock can be distinguished from Pennsylvanian and Permian depositional carbonate strata exposed elsewhere on the salt wall by the recognition of caprock distinctive fabrics (i.e. massive, porphyritic, layered and brecciated), the lack of fossils or sedimentary structures, the lack of depositional interfingering with the adjacent outboard Triassic Chinle Formation stratigraphy, and its carbon isotopic signature (< –6 ‰) that reflects the contribution of isotopically light carbon from the oxidation of hydrocarbons during caprock formation. Additionally, the preliminary results from the lateral carbonate caprock produced a U-Pb age of 211 ±16Ma, which is consistent with the upper Triassic age suggested by the association with the Chinle Formation. The orientation of the lateral caprock layering parallels that of the adjacent halokinetically drape-folded Chinle strata, which contains fluvial channel conglomerate-bearing, caprock-derived clasts. This confirms that the carbonate caprock had already formed in the Triassic in a crestal position on top of the Gypsum Valley salt wall during Chinle deposition and was subsequently rotated by halokinetic drape folding to its flanking position during continued passive diapirism.

In addition to the reinterpretation of the studied gypsum and carbonate units as lateral caprock, the term “capstone” was introduced when discussing a particular caprock lithology, as a distinction from the term “caprock” that is generally used in reference to the entire rock body. A

capstone classification is proposed based on the recognition of four distinct megascopic fabric types: 1) massive: consisting of a homogeneous mineralogy and texture; 2) porphyritic: comprising two distinct crystal sizes; 3) layered: subdivisions based on layer size that includes: microlaminated (1-3mm), laminated (3-10mm), and banded (>10mm); and 4) brecciated: these units are subdivided based on the degree of separation between brecciated capstone fragments, which may be close, loose, or spatially independent and subdivided into crackle breccia, mosaic breccia, and disorganized breccia, respectively. Paragenetic relationships indicate micritic dolomite to be the original carbonate capstone fabric formed during the Triassic. Thus, the additional capstone fabrics and mineralogies exposed today signify the diagenetic alteration of the original dolomite capstone, likely by multiple fluid flow events. Therefore, it is possible to use the evolution of capstone fabrics as an archive of fluid flow at the salt-sediment interface.

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Chapter 1: Introduction

1.1. Caprock Formation

Caprocks associated with salt diapirs are mineral assemblages formed as salt dissolution-related insoluble residues (Murray, 1966; Kyle et al., 1987) that are typically found on the diapir crest, and occasionally in a flanking position, where they are referred to as lateral caprock (Jackson and Lewis, 2012). Caprock assemblages commonly consist of a vertically zoned layered sequence, containing in ascending order: anhydrite, gypsum, and carbonate lithologies such as limestone and dolostone (Kyle and Posey, 1991) (Figure 1). The formation of the anhydrite/gypsum caprock involves a cross-flow of halite-undersaturated phreatic water to the diapir, which causes the halite in the salt diapir to preferentially dissolve from the rising diapir. As the halite dissolves, the less soluble components of the diapir, such as $CaSO_4$ minerals (i.e. anhydrite and gypsum) accumulate as insoluble residues and accrete to the base of the developing caprock by underplating (Kyle et al., 1987; Kyle and Posey, 1991) (Figure 2.1). The formation of carbonate caprocks involves the alteration of $CaSO_4$ minerals by bacterially controlled diagenetic processes (Kyle et al., 1987). This occurs in a two-stage process: first, fluids dissolve $CaSO_4$ from the anhydrite caprock, releasing Ca^{2+} and SO_4^{2-} to solution; second, if in the presence of sulfate-reducing bacteria and organic matter, sulfate is reduced and hydrocarbons are oxidized, releasing bicarbonate and hydrogen sulfide as a result. The bicarbonate in solution bonds with calcium to precipitate calcite, and if magnesium is present, dolomite precipitates, producing a carbonate caprock (Figure 2.2) (Hallager et al., 1990; Kyle and Posey, 1991; Warren, 2006).

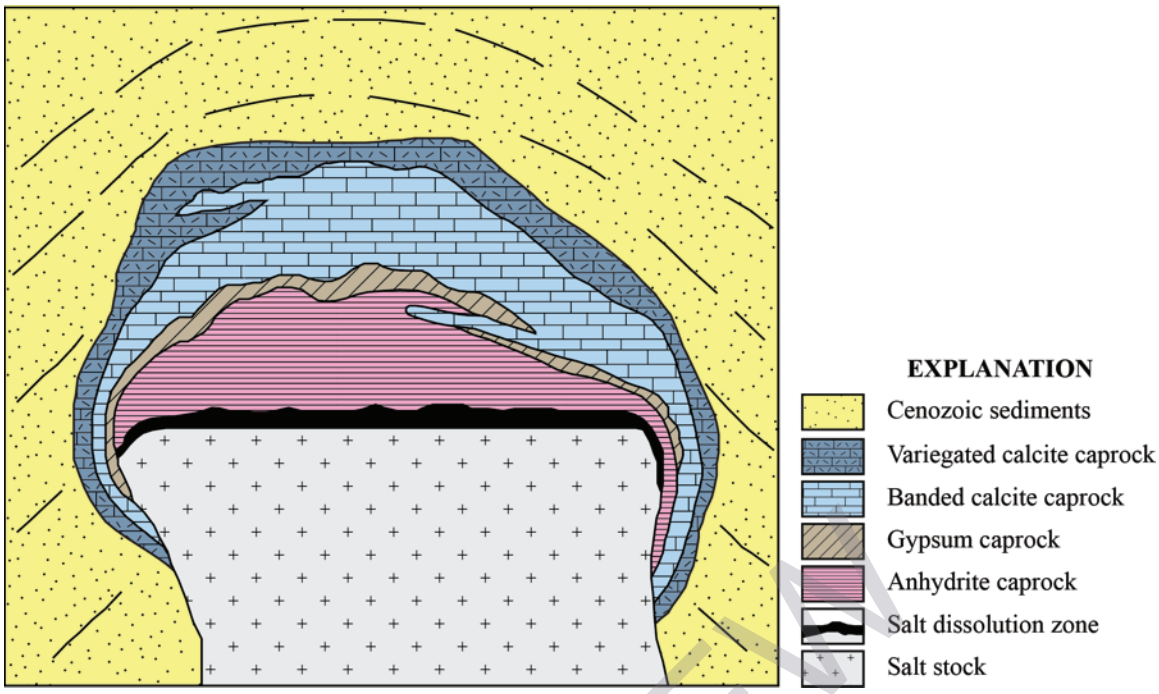

Figure 1. Cross sectional view of a Texas Gulf Coast salt dome showing generalized caprock lithologic zonation. Modified from Kyle and Posey, 1991.

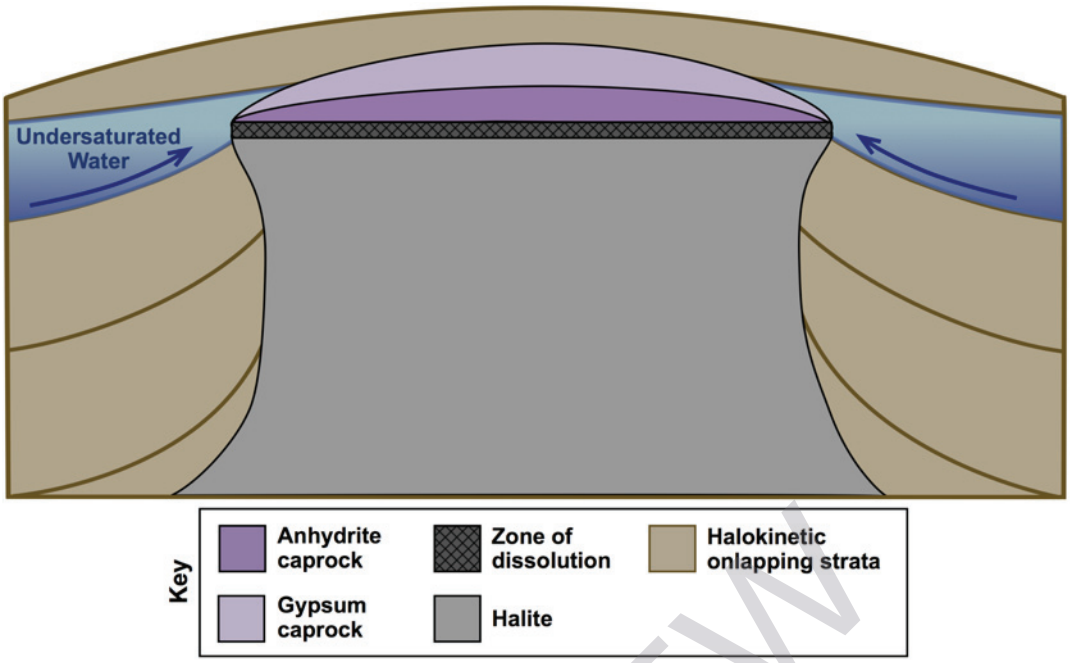

Figure 2.1. Schematic diagram of anhydrite/gypsum caprock formation. No scale implied.

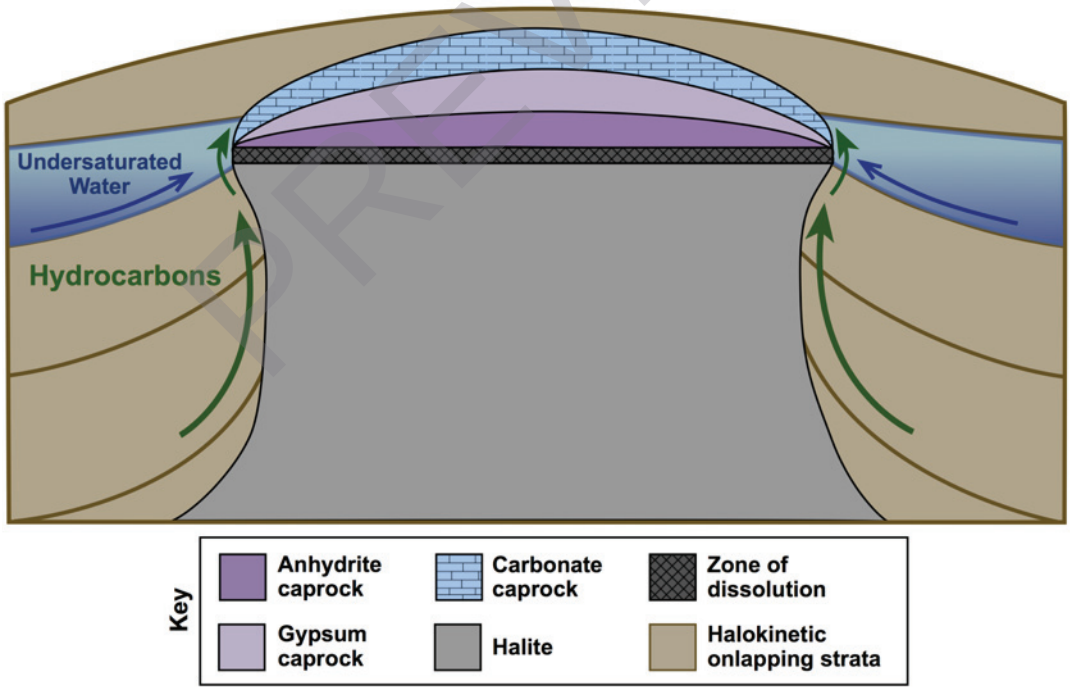

Figure 2.2. Schematic diagram of carbonate caprock formation. No scale implied.

1.2. Lateral Caprock

Lateral caprock has been identified at the Epsilon Diapir in the North Sea Egersund Basin (Jackson, et al., 2013) and at the Hockley, Boling, and Moss Bluff salt domes in the Texas Gulf Coast (Kyle and Posey, 1991) in diapir-flanking positions hundreds of meters in the subsurface (Figure 3). Currently, three general models have been proposed for the formation of lateral caprock: 1) *in-situ* model, 2) rotated layered evaporite sequence model, and 3) halokinetic drape fold ("event") model. The *in-situ* model, proposed by Evans et al. (1991), suggests that emplacement of lateral caprock is the result of unusual undersaturated deeply circulating basinal waters that flow upward along the flanks of the diapir. The outward dipping geometries of the surrounding strata assist the buoyancy-driven flow that then preferentially dissolves halite and accretes $CaSO_4$ minerals resulting in lateral caprock development (Figure 4) (Evans, 1991; Jackson, et al., 2013). The rotated layered evaporite sequence (LES) model, proposed by Schwerdther et al. (1978), suggests that a depositional/early post-depositional anhydrite-dominated evaporite sequence associated with the autochthonous depositional salt strata has been rotated upward to a position against the flank of the diapir during diapiric rise (Figure 5). Giles et al. (2012), suggest that lateral caprock initially forms in a roughly horizontal position on the crest of a diapir and is subsequently rotated to the lateral position by halokinetic drape-folding of the coupled caprock and roof strata during continued passive diapiric rise. The lateral caprock is associated with a discrete package of roof strata. Thus, the formation age of the caprock should be roughly equivalent to that of the adjacent halokinetically deformed strata. Giles et al. (2012) refers to this process as a "caprock event" (Figure 6), and a single passive diapir may have multiple caprock events. In contrast, existing models of crestal caprock formation envision caprock

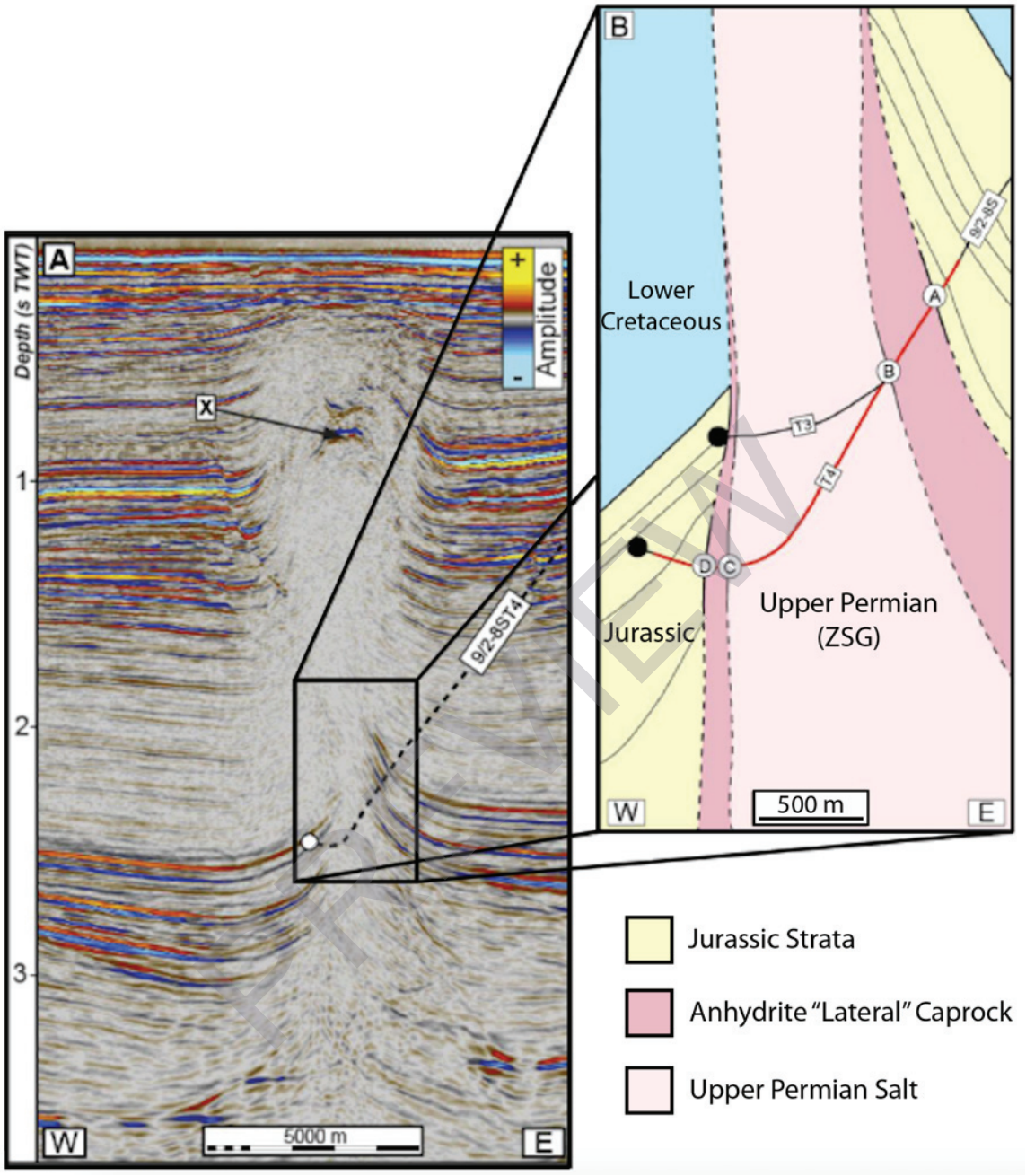

Figure 3. A. Seismic reflection, B. Seismic interpretation of the Epsilon Diapir in the Egarsund Basin, North Sea. Well 9/2-8S penetrated anhydrite caprock along the flanks of the Epsilon Diapir while drilling a Jurassic prospect (Jackson, C. A., et al, 2013).

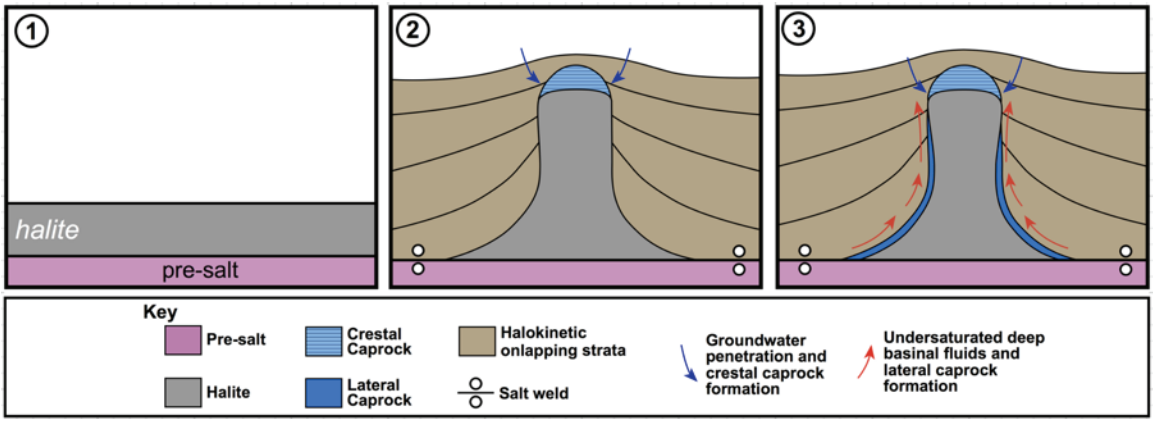

Figure 4. Conceptual model representing the *in-situ* model of lateral caprock as a mode of lateral caprock emplacement, proposed by Jackson and Lewis (2012). The model proposes that lateral caprock forms as a result of migration of undersaturated basinal fluid migration along the diapir flank. Modified from Jackson and Lewis, 2012.

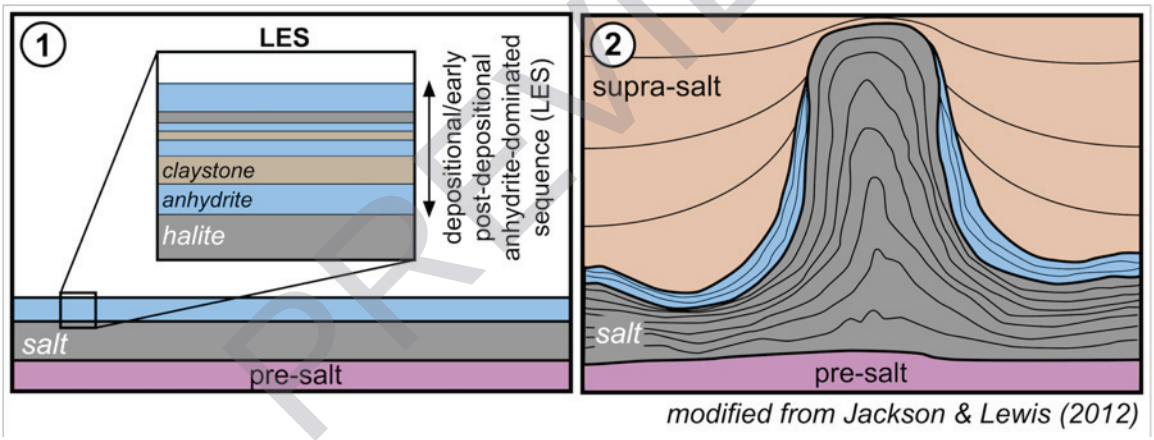

Figure 5. Simplified diagram illustrating the layered evaporite sequence (LES**)** model, proposed by Schwerdther et al. (1978) suggests that lateral caprock could essentially be a LES associated with the mother salt that has been plastered against the flank of the diapir during the rise of less dense halite. No scale is implied. Modified from Jackson and Lewis, 2012.

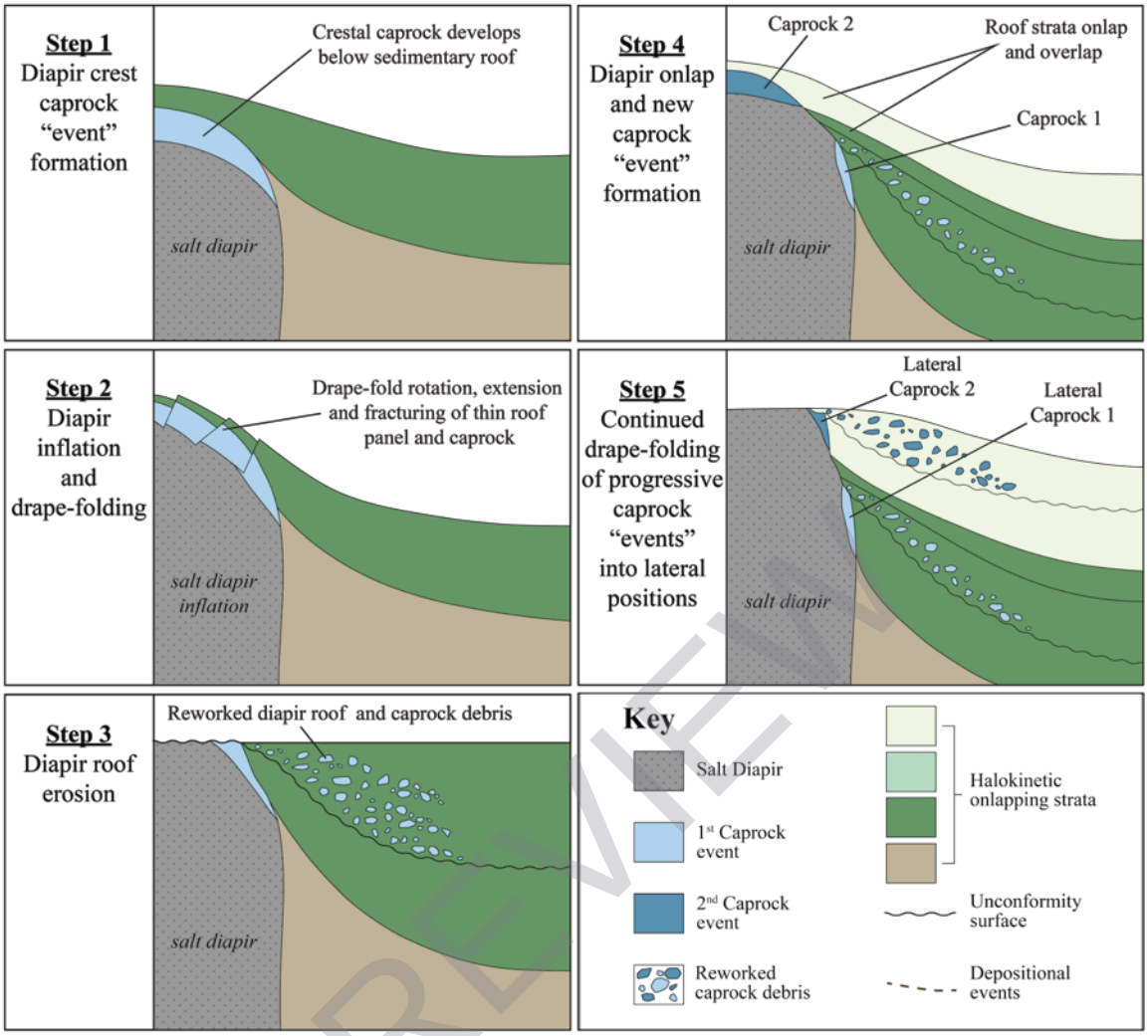

Figure 6. Conceptual diagram illustrating the halokinetic drape-fold model proposed by Giles et al. (2012) for a mode of lateral caprock emplacement, which suggests caprock forms in a crestal position during distinct periods of time and are then rotated into a lateral position as a result of halokinetic drape folding. No scale is implied. Modified from Giles et al., 2012.

generation by long-lived, crestal dissolution of halite with the caprock rising continuously along with salt during ongoing diapirism (Murray, 1966; Kyle and Posey, 1991).

The halokinetic drape-fold event model consists of four steps: 1) caprock develops in a crestal position by cross-flow of undersaturated waters; 2) continued diapiric rise and minibasin subsidence causes drape-folding of roof strata and competent caprock, which detaches from the underlying halite-dominated diapir and rotates off the crest into a lateral position; 3) topography generated by diapir inflation as diapir-rise rates exceed sedimentation rates results in erosional thinning of the roof to create an angular unconformity that truncates the underlying lateral caprock and potential incorporation of caprock clasts into the surrounding sediments; 4) increasing rates of sedimentation relative to diapiric rise lead to onlap and formation of the overlying halokinetic sequence, which may or may not develop a new crestal caprock assemblage (Giles et al., 2012).

Shock (2012) established the applicability of the halokinetic drape fold model as the mode of emplacement for the Permian Cutler Formation-age equivalent lateral caprock found at the margin of Castle Valley salt wall, Paradox Basin, Utah (Figure 7). Here, vertical layers of dolomitic and calcitic caprock separate the massive gypsum exposures of the Castle Valley salt wall from vertical to overturned strata of the Permian Cutler Formation. Fluvial channel conglomeratic facies in this Cutler strata contain caprock-derived clasts (Shock, 2012). Recently, lateral gypsum and carbonate caprock has also been documented at the Gypsum Valley salt wall in the Paradox Basin, CO, (Figure 7) (McFarland, 2016; Brunner et al., 2016; Lerer, 2017), where it is associated with 25 degree NE dipping strata of the Triassic Chinle Formation (Figure 8). McFarland (2016) and Heness *et al.* (2017) interpret carbonate clasts in the fluvial conglomerate facies to be derived from the caprock. Carbonate caprock clasts found in the halokinetic sequence of the overlying Triassic Chinle Formation are essential pieces of evidence supporting the drape

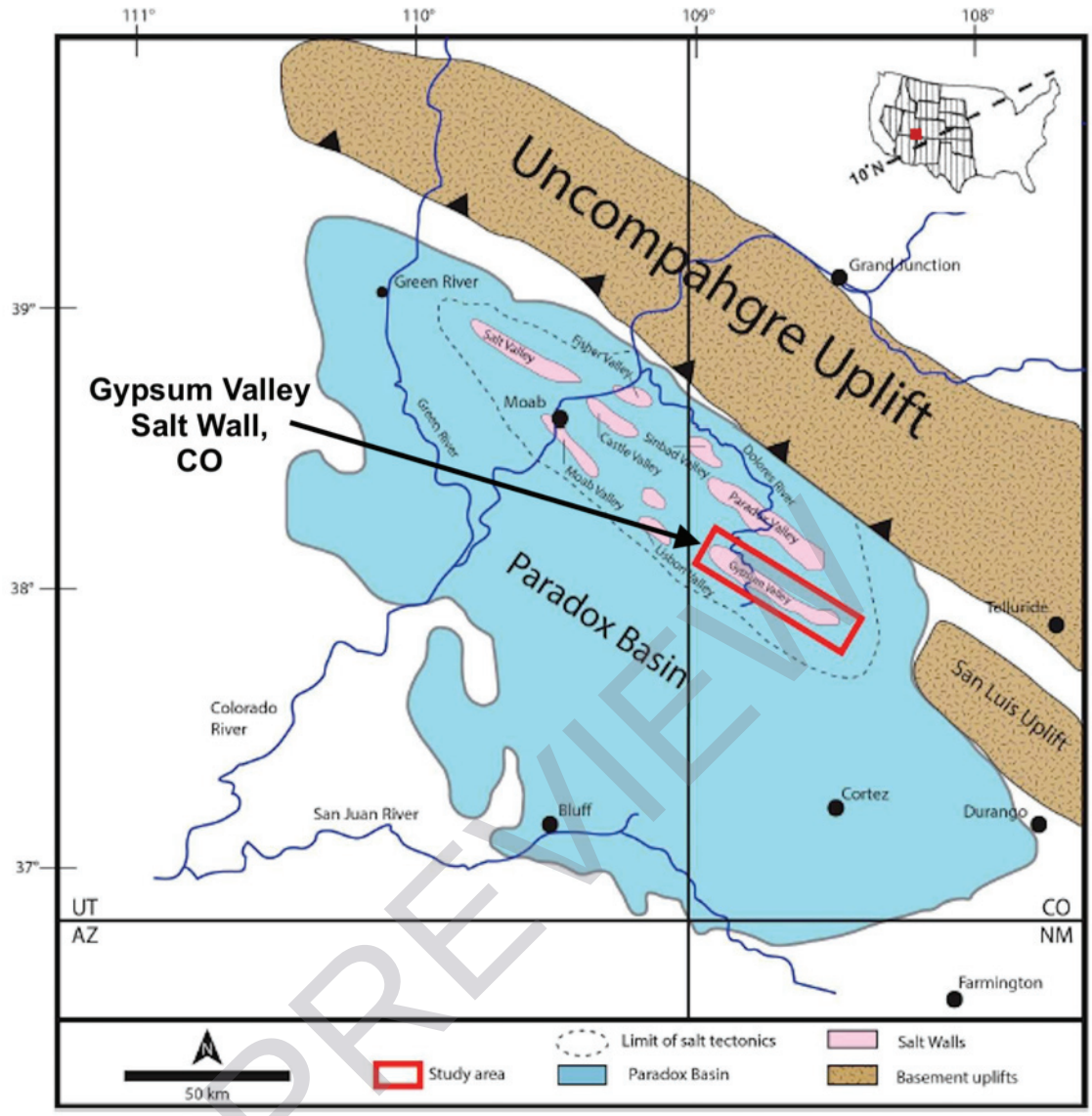

Figure 7. Location map of Paradox Basin and salt anticline province showing major uplifts and salt anticlines. Gypsum Valley salt wall study area is outlined in red. (modified from Barbeau, 2003; and Kues and Giles, 2004).