Detection Of Sedimentary Depositional Cycles In The Salado Formation, Southeastern New Mexico

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ABSTRACT

An abundance of evaporitic features is preserved throughout the approximately 2,000-foot-thick Salado Formation that is present across West Texas and southeastern New Mexico. The formation and preservation of evaporitic features are largely influenced by hydrology, and so those found in the Salado represent an uninterrupted record of hydrogeologic conditions in what is now the southwestern United States during the late Permian. Because it is home to the Waste Isolation Pilot Plant (WIPP) repository chamber, the Salado has been the subject of countless studies ranging from areas of sedimentology, to geochemistry, to geotechnical engineering, to hydrology. However, until now there have been no concerted efforts to perform a cyclostratigraphic analysis of the Salado and its constituents.

After examining the WIPP Air Intake Shaft Mapping Report (Holt and Powers 1988a, b), I extracted the quantitative data recorded by Holt and Powers and performed several techniques of geostatistical analysis with the goals of a.) confirming the findings of previous workers who had described depositional cycles present in the Formation, and b.) uncovering the previously hidden signature of climatic forcing (Milankovitch Cycles) during the late Permian. While we can confirm the presence of the “Ideal Halite Sequence” (as described by Holt and Powers, 1988a, b), as well as identify plausible evidence of an overall drying-out sequence throughout Salado deposition. The results of some of our analyses were uninformative and we recommend higher-end time series analysis techniques for future efforts in detecting the influence of climatic forcing on Salado deposition.
DEDICATION

Dedicated to the memory of my Mother, Kathy, who would tell me “Take everything one chunk at a time, and go do something fun.” I’m only getting started, Mom. I Love You.
LIST OF ABBREVIATIONS OR SYMBOLS

A.I.S. – Air Intake Shaft
C.W.T. – Continuous Wavelet Transform
D.M.R.H. – Dilated Mud-rich Halite
D.O.E. – Department of Energy
D.V.T. – Death Valley-type
F.F.T. – Fast Fourier Transform
H.M. – Halite Mudstone
M.T.M. – Multi Taper Method
P.M.H. – Podular Muddy Halite
P.S.D. – Power Spectral Density
S.M.P.H. – Stratified Mud-poor Halite
U.L.M. – Unnamed Lower Member
U.U.M. – Unnamed Upper Member
W.I.P.P. – Waste Isolation Pilot Plant
X² – Chi-squared
ACKNOWLEDGEMENTS

I would like to thank my adviser, Dr. Robert Holt, for his guidance and assistance throughout the completion of this thesis. I would also like to thank my committee members- Dr. Brian Platt, Dr. Louis Zachos, and Dr. Dennis Powers, as well as both Department Chairmen during my stay- Dr. Joel Kuszmaul and Dr. Greg Davidson.

I would also like to thank fellow graduate students Taylor Carnes, Kimberly Tanner, Christian Kunhardt, and Lee New; undergraduates David Webb and Michael Gratzer; and my professional associate, Eric Fair.

Lastly I would like to thank my family for their unwavering love and support throughout what I can most eloquently describe as “my grad school odyssey.”
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CHAPTER I. - INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) was conceived in the mid-1970s as a deep geological repository for the long-term isolation of nuclear waste that was created as a byproduct of Cold War-era weapons generation. WIPP is situated in the Delaware Basin, approximately 20 miles East of Carlsbad, New Mexico. This site was selected due to the presence of thick evaporite sequences in the area, which inhibit fluid migration. The Salado Formation was chosen as the repository horizon. Following partial excavation of the underground facility, the Air Intake Shaft (AIS) was excavated to maintain fresh air circulation in the repository. Mapping of the AIS was conducted by Holt and Powers (1990a, b) over the course of one and a half years with the goals of “1) providing confirmation and documentation of strata overlying the WIPP horizon; 2) providing detailed information of the geologic conditions in strata critical to repository sealing and operations; 3) providing technical basis for field adjustments and modification of key and aquifer seal design, based upon observed geology; 4) provide geology data for the selection of instrument borehole locations; 5) and characterize the geology at geomechanical instrument locations to assist in data interpretation.” To accomplish these goals, detailed mapping of the shaft was conducted through the Salado and its overlying units (the Permian Rustler and Dewey Lake Formations; the Triassic Santa Rosa Formation; and the Tertiary Gatuña Formation and Mescalero Caliche). Prior to mapping of the Salado, the shaft walls were pressure washed with fresh water. In addition to cleaning the surface, underlying halite was dissolved, revealing Salado sedimentary structures and features in unprecedented detail (Figure 1a and b). Using shaft data, Holt and Powers (1990a) constructed an idealized halite sequence consisting of four distinct
lithofacies and documented previously undescribed sulfate interbed textures and fabrics. In addition, they quantified vertical variations in clay content, sulfate content, halite crystal size, and a number of other sedimentary features and textures, including dissolution pits and pipes (e.g., Holt and Powers, 2011). The data collected by Holt and Powers (1990a) reflect cyclicity in the Salado depositional environment. These data were recorded at scales of 0.1 foot or less and are ideal for cyclostratigraphic analysis.

Our objective is to conduct a preliminary cyclostratigraphic study of the Salado Formation using the data collected by Holt and Powers (1990a). Until now, only low resolution, gray scale copies of the AIS report were available via online publication. These copies fail to convey the scale and detail of the observed features to the reader. Our work began with scanning an original hardcopy of the AIS report in color and at high resolution, which was then made available on the Internet. We then extracted the Lithologic Log section (Figure 2) from the scanned report and digitized several variables including the abundances of halite vs. nonhalite in the shaft; halite crystal size; textural variations; the presence of exposure/solution surfaces; and others. This data was interpolated to an even sample interval of 0.1 foot and regularly checked for error. Lastly, we used a number of geostatistical and spectral analysis techniques on the assembled data to estimate the occurrence and magnitude of sedimentary depositional cycles preserved in the Salado. Confidence intervals for our results were verified using chi-square and F-tests. Our ultimate hope was the detection of Milankovitch-scale (20,000 year to 100,000 year) climate cycles that result from orbitally driven insolation fluctuations.

Our efforts have resulted in a sedimentological dataset that is the first of its kind for the Salado numbering ~60,000 data points. The results of our preliminary analysis indicate that while the detection of preserved sedimentary cycles is possible, the precise delineation of climate
cycles using our data remains incomplete without the presence of reliable isochrons within the Salado.

In this thesis, we present 1) background theory of orbitally-driven climate cycles and different schools of thought regarding the analysis of these patterns using sedimentary rock deposits; 2) a summary of the geologic history of the Delaware Basin and detailed stratigraphy of the rocks in that area; 3) a more detailed sedimentological and stratigraphic summary of the Salado Formation, including lithofacies and idealized halite sequences; 4) the methodology and materials used during the creation and preliminary analyses of our dataset; 5) the results of digitization and preprocessing of our data as well as the results of preliminary analyses; and 6) a discussion of our results including possible future studies utilizing our dataset.
CHAPTER II. - CYCLOSTRATIGRAPHY & SEDIMENTARY DEPOSITIONAL CYCLES

Mathematician Milutin Milankovitch concluded that the course of Earth’s orbit around the sun is marked by periods of exaggerated eccentricity, precession, and obliquity that cycle on the order of tens to hundreds of thousands of years (Figure 3) (Milankovitch, 1930). His theories, as well as those of workers who came before him, were largely rejected by the scientific community until the findings of deep-sea sediment cores confirmed his suspicions (Hayes et al., 1976). In modern times, it is generally accepted that climate patterns on Earth respond to orbitally forced increases in insolation (the receipt of solar energy at the surface of the Earth per unit area), as Earth’s axial orientation and solar proximity vary. The eccentricity of Earth’s orbit is defined by the relationship between the semimajor and semiminor axes of the elliptical orbit path, and the position of the ellipse around the sun. During periods of high eccentricity, the ellipse is elongated on its semimajor axis, and the sun is positioned at one of the two elliptical foci. During this period, insolation levels contrast drastically between aphelion and perihelion. During low eccentricity, Earth’s orbit is more circular and insolation is more evenly distributed through time, but periods of close and far proximity to the sun impact the Earth’s glaciation cycle, thereby constricting sedimentary basin-input. Axial precession describes the change in Earth’s rotational axis and dictates the position of the hemispheres during perihelion and aphelion. If a hemisphere points towards the sun during perihelion, it will point away at aphelion (the reverse is true for the opposite hemisphere), causing changes in seasonal extremity. Axial tilt (obliquity) varies from 22.1° - 24.5° and dictates seasonal extremes. When the northern
hemisphere tilts towards the sun, solar radiation is unequally distributed between the equator and the poles, thus seasonal extremes become more exaggerated. Eccentricity, obliquity, and precession cycle once every ~400:100:40:20 kyr, respectively (Graham, 2000). The frequencies of orbitally induced climatic fluctuations (Milankovitch cycles) are preserved in a variety of sedimentary depositional environments across the stratigraphic record and form the basis for cyclostratigraphic study. Preservation of cycle magnitude and frequency is attributed to variations in insolation that affect climate, oceanography, and sedimentary systems (de Boer and Smith, 1994).

Xiao and Chen (2013) show depositional cyclicity to be detectable in mudstone cores with autocorrelation functions; they find that sharp decreases in autocorrelation (in correlograms) indicate cycle boundaries. Fourier and spectral analyses are also a proven tool of measure in calculating the magnitude and temporal distribution of depositional cycles (e.g., Rampino et. al., 2000, Mawson and Tucker, 2009, Franco et. al., 2011, Wu et. al., 2014, and Yao, et al. 2015). These studies constrain 400-412:100 kyr cycles for eccentricity, 32-40 kyr cycles for axial obliquity and ~40 kyr cycles for precession and attribute findings to insolation-derived fluctuations in aridity-humidity relationships and/or temperature. Rampino et al., (2000) performed wavelet transforms on $^{13}$C values across the Permian-Triassic (P-Tr) boundary and found similar timelines for Milankovitch cycles. Matched with sedimentary U-Pb age dates, Wu et al., (2014) constrained 405:100:43:19-21 kyr cycles for eccentricity, obliquity, and precession during the late Permian using spectral analysis.

Of cyclostratigraphic studies, there are two types. The first type focuses on linking activity within the study area to global timescales. Common goals of these studies include the establishment of depositional rates in a basin, the influence of global climate on sediment
deposition, and the identification of global-scale climatic events. These types of studies require utilizing at least two reliable isochrons within a rock group such as isochrons determined from U-Pb age dates (e.g., Wu et al., 2014). The second type of study does not require isochrons and aims more to isolate the occurrence of depositional cycles within a basin. Because we lack reliable isochrons in the Salado, our study falls under the category of the second type of cyclostratigraphic study.
CHAPTER III. - DELAWARE BASIN GEOLOGY

III.I. DELAWARE BASIN STRATIGRAPHY

The Delaware Basin (Figure 4) is one of two major subdivisions of the greater Permian Basin present across West Texas and southeastern New Mexico. It is separated from the Midland Basin by the Central Basin Platform to the East, and bound by the Diablo Platform and Northwestern Shelf to the West and North. It is a vaguely kidney-shaped depression measuring 12,000 feet in total depth and 10,000 square miles in area (Harris et al., 1997). Keller et al., (1980) recounts the history of the tectonic and stratigraphic history of the Delaware basin. The Permian Basin began as one end of the ancestral Tabosa Basin. During the early-mid Paleozoic, it stood as a passive margin shelf that accumulated carbonate and clastic sediment. Beginning in the mid-Carboniferous, the Ouchita orogeny uplifted the Central Basin Platform, bisecting the Tabosa Basin into the Delaware and Midland Basins. By the late Permian, carbonate accumulation on the margin and northwestern edge of the basin formed the Capitan Reef Complex causing near-total basin isolation. With the exception of two transgression events in the late Ochoan, ocean levels continued to recede through the Triassic, allowing terrestrial deposition to dominate. Cretaceous deposits resulting from advance of the Epicontinental Sea are scarce in the basin. Mesozoic deposits are unconformably overlain by Tertiary sedimentary rocks and calcretes.
There are three main stratigraphic subdivisions of geologic units in the vicinity of the AIS- 1) Paleozoic, 2) Mesozoic, 3) and Cenozoic units (Figure 5). During the mid-late Permian (Guadalupian) the clastic Delaware Mountain Group was deposited in the central part of the basin. The Artesia Formation (including the Goat Seep Dolomite and Capitan Limestone) concurrently accumulated along the basin flanks. Ochoan evaporites (Castile and Salado Formations) were initially contained within the basin, while later evaporites (Salado and Rustler Formations) spilled over the basin margin, atop which the Dewey Lake Formation marks the transition from marginal-marine to terrestrial paleoenvironments in the Delaware Basin. The overlying Triassic Dockum Group reflects a continuation of continental deposition. The youngest units present in the basin are the Gatuña Formation and the Mescalero Caliche, a calcrete paleosols.

III.I. I. GUADALUPIAN SERIES

Reef deposits

Reef deposits along the basin’s southwestern flank include the Goat Seep Dolomite and the overlying Capitan Limestone (King, 1948, Newell et al., 1953, and Hayes, 1964). This is the ancestral Capitan barrier reef complex; arguably, the dominant feature of importance in the Guadalupian series, particularly as it applies to the accumulation of the Ochoan series. Reef units provide the framework for basin-filling deposits that accumulated during the latest Guadalupian and early Ochoan. Powers et al., (1978) assert that the thickness of the reef complex may have been as high as ~1,000 feet in some areas. Holt and Powers (1993) show that near-total basin isolation by the reef complex allowed for continuous accumulation in an evaporating lagoon that received limited input from marine or terrestrial sources, resulting in one of the thickest, uninterrupted records of evaporite deposition in the world.
Back-reef/shelf deposits

Hayes (1964) reports that the back-reef and shelf deposits present in the south of the basin along the Central Basin Platform and in the adjacent Midland Basin - the upper San Andres Formation and the Artesia Group- are correlatable to the basin-fill and reef deposits present elsewhere in region. The San Andres is mostly dolomite and limestone with some sands and reddish muds. The Artesia Group includes the basal Grayburg Formation, the Queen Formation, the Seven Rivers, Yates, and Tansill Formations. Significant accumulations of evaporites occurred in back reef depositional environments.

Basin-fill deposits

Guadalupian basin-fill units comprise the Delaware Mountain Group. Members of the group include the Brushy Canyon, Cherry Canyon, and Bell Canyon Formations; ~3,944 feet (2 miles northeast of the WIPP site) of clastic and occasional thin, dark shale and lime units that indicate frequent sea level variations (Powers et al, 1978).

III.I. II. OCHOAN SERIES

The Castile Formation

Richardson (1904) performed reconnaissance mapping in Culberson County, Texas and named the massive, white gypsum that he observed in the area “Castile” after the Castile Spring that is present approximately 12 miles south of the Texas-New Mexico state line. The Castile Formation is described as a ~ 1476-foot thick, varved evaporite sequence consisting of a basal limestone member and interlaminated halite and anhydrite units by Anderson et al., (1972). Based on the presence of laterally continuous, uninterrupted laminae through eight Castile subunits and an upward-increasing abundance of halite, they conclude that Castile evaporites were deposited in a deep-water environment that experienced progressive shallowing over time.
Based on the appearance of pseudomorphs on top of chevron and displacive halite textures at the
top of sub-cycles within the Castile and evidence of simultaneous turbidite deposition along the
basin’s flanks, Leslie et al., (1996) constrain the depth of the Castile lagoon to several hundred
feet.

The Salado Formation

Lang (1935, 1937, and 1939) delineated the upper, halite-rich portions of Richardson’s
(1904) Castile under the name “Salado” and subdivided its total ~2,000 feet into three sub
members (1942). The Salado is predominantly halite with regionally traceable clay and sulfate
marker beds and, of the three evaporite-bearing units in the Delaware Basin, perhaps the most
extensively characterized. The sedimentological and hydrologic properties of the Salado have
been heavily scrutinized in order to ensure the isolation of waste held in the WIPP repository
(e.g. Holt and Powers, 1984, 1986, 1988, 1990a, b; Bachman, 1985, 1987; and others). We
present the detailed sedimentology, stratigraphy and depositional history of the Salado in a
separate section of this report.

The Rustler Formation

Richardson (1904) also named the third evaporite unit in the Delaware Basin for springs
in Culberson County, Texas, dubbing the clastic, carbonate and sulfates in that area “Rustler.”
Holt and Powers (1988) state that the Rustler has a maximum thickness of ~560 feet, which thins
to ~309 feet near the AIS and that, of the Ochoan evaporite-bearing units in the area, the it is
unique in that its variable lithology represents a time of drastic environmental change in the
Delaware Basin. Vine (1963) introduced the five-member subdivision of the Rustler: an
unnamed clastic basal unit that sharply overlies the Salado (later formally named the Los
Medaños by Powers and Holt [1999]); the highly-fractured Culebra Dolomite Member; the
Tamarisk Member; the Magenta Dolomite Member; and the Forty-niner Member, which is sharply overlain by the Dewey Lake Redbeds. The Rustler is the first water-bearing unit above the WIPP horizon. Holt and Powers (1988) indicate that it is a product of marine transgressions into a low relief, desiccating saltpan and mud flat environment. These transgressions were significant enough to promote the subaqueous deposition of carbonate and sulfate atop an unstable mud substrate (Holt, 1997). Synsedimentary fracturing, and bioturbated intervals found in the Los Medanos and Culebra indicate that transgressions were significant enough to lower salinity levels to life sustaining levels for a time (Holt and Powers; 1988). Data collected during AIS mapping has been instrumental in the refinement of depositional models for the Rustler (Powers et al., 2006) and the isolation of variables contributing to the transmissivity of the Culebra Dolomite (Holt et al., 2005; Powers et al., 2003). The findings of these studies confirm Holt and Powers’ (1988) original paleoenvironment interpretation.

The Dewey Lake Formation

The term “Dewey Lake” originates from Lang (1935) and was applied to the red beds present in Nash Draw by Vine (1963). Although unsupported by radiometric dating or fossil evidence (Lucas and Anderson 1993), the Dewey Lake Redbeds are considered the youngest Ochoan unit in the Delaware Basin (Holt and Powers, 1993). In the vicinity of the AIS, the Dewey Lake conformably overlies the Rustler with minor erosional relief and consists of ~476 feet of interbedded, fine-grain, reddish-brown sandstone, siltstone, mudstone, and claystone. The Dewey Lake is distinguished from other redbeds in the area by greenish-gray reduction spots and locally abundant, horizontal to sub-horizontal, fibrous gypsum-filled fractures (Holt and Powers 1990b) The Dewey Lake can be subdivided into 1) an upper sequence consisting of fine-grain clastics deposited by an ephemeral fluvial system (Schiel, 1988), and 2) a lower saline mudflat
sequence that reflects marine-influenced Rustler style deposition (Holt and Powers, 1988). Holt and Powers (1990a, b) assert that marine-derived floodwaters were persistent through Rustler time but not through Dewey Lake time and that the Dewey Lake represents the Delaware Basin’s transition from an isolated marginal lagoon to a broad, low relief fluvial plain. The contact between the Dewey Lake and the overlying Dockum Group is sharp and erosional with ~2 feet of relief (Holt and Powers 1990a).

III. III. MESOZOIC SERIES

The Dockum Group

In the past, study of Triassic red beds in the Delaware Basin has been marred by debate over the use of proper nomenclature. We use the simplified stratigraphy as proposed by Gould (1907) and advocated by Lehman (1994a & b). The name “Dockum” was first applied to red beds exposed by the Dockum Creek in the Southern High Plains beneath the Caprock Escarpment by Cummins (1890). The Group’s four sub units comprise two mud-to-sand sequences: the Santa Rosa Formation > the Tecovas Formation and the Trujillo Formation > the Cooper Canyon Formation. Holt et al., (2010) described two sedimentary facies in the Dockum. Channel sediments appear as areally limited zones of silty-sand are consistent with deposition on a flat, ephemeral fluvial plain. Shearing at the base of sand zones exhibits strong bed load movement, indicating that flood events were chaotic, both in timing and intensity. Broader sections of reddish, bioturbated mudrocks are consistent with overbank and floodplain deposits and heavy pedogenic overprinting and desiccation suggest prolonged arid conditions in between flood events. In the vicinity of the AIS, only the bottommost ~25 feet of the conglomeritic Santa Rosa Sandstone is present, which presents alternating sequences of channel deposits with fluvial bar sequences and, less commonly, mudstone or claystone. The contact between the Dockum and the
overlying Formation Gatuña is sharp and erosional (Holt and Powers, 1990a).

III.I. IV. CENOZOIC SERIES

The Gatuña Formation

The Gatuña Formation occurs across the across the WIPP site area as a thin veneer of sandstone. At the AIS, the Gatuña is 13 feet thick and consist of light red, calcareous, friable, sandstone that is gradationally overlain by calcretes. The Gatuña exhibits stringers, concretions, and probably rhizolithic structures indicative of the early stages of calcrete pedogenesis (Bachman, 1985; Holt and Powers, 1990a, b).

The Mescalero Caliche

The Quaternary, pedogenic calcrete found up to 10 feet below the surface of the WIPP site is informally referred to as the Mescalero Caliche and is thought to have begun developing ~510,000 years ago as a pedogenic caliche on an aggrading Aeolian surface (Bachman, 1985). The upper portion of the Mescalero caliche displays well-developed laminar texture, while the lower portion is marked by the appearance of poorly sorted, carbonate cemented sandstones.

III.II. REGIONAL GEOLOGIC HISTORY

Initial WIPP site characterization reported in Powers et al., (1978) summarize the geologic history of the Delaware Basin in three main stages: 1) ~500 million years of unobserved, but assumed, uplift and erosion of Precambrian rock; 2) ~225 million years of marine submergence resulting in prolonged carbonate deposition; 3) and finally, further uplift and subaerial exposure that has persisted for the last ~225 million years with the exception of brief marine transgressions during the late Permian and late Cretaceous. The rocks occupying the Delaware Basin are exceptional in that together, they represent an extensive record of events spanning the late Permian into the early Cenozoic. This includes the End Permian Extinction—
the most severe of such known events— in which nearly 96% of all marine species and approximately 70% terrestrial vertebrates disappeared from the fossil record (Retallack, 2013). The opportunity to characterize a continuous series of such events is rarely afforded. Conceptually, climate changes through this time are discernable based solely on the stratigraphic order of the lithologies present in the area. The transition of fossil rich carbonates > varved evaporites > thick, relatively pure halite > desiccated, terrestrial muds suggests an overall sea level regression and climatological shift from subtropical to arid.

Pre-Paleozoic

Very little of the Delaware Basin’s history prior to the Paleozoic can be known for sure. No rock older than the late Cambrian has ever been observed in the area (Hayes, 1964). Early radiometric dating of the granitic basement complex in the region yielded ages around 1 billion years (Kelley, 1971).

Mid-Paleozoic

From at least the late Cambrian until about the close of the Mississippian, the Delaware Basin existed as part of the greater Tabosa Basin; a broad, low-lying region of tectonic stability submerged by an ancient sea, first described by Galley (1958). Over the next ~180 million years, a nearly continuous period of shelf-type carbonate deposition took place. Deposition was interrupted on at least three occasions by brief, episodic shale sedimentation originating from the ancestral Central Basin Platform, which was, at that time, a chain of exposed islands or granitic highlands (Powers et al., 1978). While no evidence of major tectonic events in the area during the mid-Paleozoic has been in found, subsidence of the Marathon-Ouchita geosyncline began in the Ordovician and continued through the Devonian, gently dragging the Tabosa Basin with it. Subsidence continued into the Mississippian, when regional tectonic activity began folding the
Central Basin Platform along Precambrian faults (Hills, 1972). The emerging Tabosa sub lobes to the West and East—the Delaware and the Midland Basins—were deepened and carbonate deposition continued along their margins. Around this time, orogenic forces responsible for the uplift of the Ancestral Rocky Mountains tilted the basin southward (Bachman, 1975).

Late-Paleozoic – Mesozoic

Erosion of clastic materials that were uplifted during the Mississippian provided sediment input during the early Pennsylvanian, but by Desmoinesian time, limestone deposition once again dominated the Permian Basin (Powers et al., 1978). Throughout the late Pennsylvanian, weathered clastics from the Central Basin Platform mixed with marine sediments and accumulated in the lowest parts of the basin, while strong reef and back reef (lagoon) deposits continued to develop along its flanks.

Hills (1972) notes that the ocean regression that had begun during the Pennsylvanian had come full swing by the early Permian and sedimentation was continuous in most of the basin. Following the activation of normal fault zones during the late Wolfcampian, tectonic activity in the area ceased until around the Jurassic. Regional tectonic stability, coupled with restricted marine circulation caused by sea level drop, promoted the development of the Capitan Limestone; considered by most to be a true Barrier Reef. Further restriction of the Delaware Basin lagoon from marine waters drastically increased the salinity of its waters, halting reef growth. Beginning at the start of late Permian time (Ochoan) the Delaware Basin filled with hundreds of feet of Castile evaporites. Deposition of Salado and Rustler units spilled over the Central Basin Platform and into the adjacent Midland Basin (Holt and Powers, 1993).

Prior to total isolation from marine waters and a transition to terrestrially dominated sedimentation during the latest Permian and early Triassic, the Basin was transgressed at least
three times, resulting in Los Medaños, Culebra, and Magenta deposition (Holt and Powers, 1988). Following transgression and basin drainage, erosion dominated the Delaware Basin throughout the Triassic. Uplift during the Jurassic was probably accompanied by some dissolution of Permian salts. Transgression of the Epicontinental Sea during the Cretaceous resulted in the deposition of a thin, fossiliferous limestone and conglomeritic sand layer across the interior of the Western United States. There is little evidence of these deposits left in the Delaware Basin.

**Cenozoic**

Deposition of the youngest deposits in the Delaware Basin occurred following the end of the Laramide uplift and drainage of the Epicontinental Sea, during which time Cretaceous and Triassic sediments underwent intense erosion. Bachman (1985) asserts that the climate of the Permian Basin has grown more humid since deposition, resulting in the dissolution of evaporites present at the surface.
CHAPTER IV. THE SALADO FORMATION

IV.I. GENERAL DESCRIPTION

The Salado is the second of three Ochoan evaporite-bearing units present in the Delaware Basin. It is a major source of potash for fertilizer in the United States. Since the 1980s, it has been home to the DOE’s only active repository for the long-term isolation of transuranic waste. As a part of WPP site characterization, the sedimentological and hydrologic properties of Salado halite have been heavily scrutinized since the late 1970s (e.g. Holt and Powers, 1984, 1986, 1988, 1990a, b; Powers et al., 1978 and others). Findings indicate that the Salado is thick deposits of bedded halite interbedded by sulfate deposits (anhydrite or polyhalite) and clay. Initial estimates conclude that the entirety of the Salado is 85-90% pure halite (Jones et al., 1973), but that individual beds are rarely pure (Holt and Powers 1990a, b). Halite crystal size and condition vary greatly and a number of syndepositional alteration structures are common throughout the entirety of the Formation.

Analyses of the Salado’s hydrologic properties show that it is an ideal home for the WIPP repository. The formation owes its ultra-low permeability to its depth of burial and cementation in the depositional environment. Holt and Powers (2010) show how these conditions create an isotropic stress field at depth in which the fluid pressure within the evaporites is greater than in the adjacent water-bearing units. Holt and Powers (2011) also show that these hydrophobic properties are able to affect the total isolation of fluid inclusions from which preserved
specimens of ~250 million-year-old halotolerant bacteria (Vreeland et al., 2000) and cellulose (Griffith et al., 2008) have been recovered.

**IV.II. STRATIGRAPHY**

Jones (1972) concludes that abundances of halite, anhydrite, and polyhalite are similar across all members, but that distinctions between the three made primarily on the abundance of potassium-minerals. Based on this and data from Holt and Powers (1990a, b), we use the following informal stratigraphic subdivisions (Figure 6). The middle unit-dubbed the McNutt Potash Zone- separates the upper and lower unnamed members, here designated UUM and ULM, respectively. The Union Anhydrite and Vace Trista marker beds in turn bound the McNutt. The Vace Trista, McNutt, and Union occupy a depth range of 1340 – 1536 feet at the AIS. The unnamed upper and lower members occupy depths of ~900-1340 feet and 1536-2135 feet (the upper brow of the WIPP horizon, totaling 1235 feet in thickness.

**IV.III. SEDIMENTOLOGY**

**IV.III. I. HALITE LITHOFACIES**

Mapping of Ochoan evaporites in the Delaware Basin began in the mid 1980s as part of WIPP site characterization. Among others (Lowenstein 1988, and others) Holt and Powers (1990a, b) compiled the results of 1,290 feet of shaft mapping reports including an interpretation of paleoenvironment, based on the presence of repeated evaporite lithofacies patterns. Using a sedimentological approach to study ancient halitic rocks (which was relatively unheard of at the time of mapping), they established four distinct halite lithofacies and a number of sulfate interbeds in the Salado. We report the details of their findings by presenting 1) the sedimentological details (including paleoenvironment interpretations) of each halite lithofacies and 2) marker bed lithology, 3) hydrologic conditions governing phreatic and vadose alteration.
textures and fabrics, 4) and interpretation of “ideal” halite deposition sequences based on the repetition of these features, as interpreted by Holt and Powers (1990a, b).

**Stratified Mud-poor Halite (SMPH) Lithofacies**

SMPH lithofacies (Figure 7) can be subdivided into three zones (Holt and Powers 1990a, b). The lower zone exhibits abundances of bottom-growth halite, indicating continuous subaqueous deposition resulting from a long-standing body of shallow water. The middle zone contains relatively equal abundances of subaqueously deposited halite and dissolution pits, pipes, and macropores that formed during periods of point dissolution in the vadose zone. Upper zones of SMPH are dominated by displacive cements and point dissolution fabrics, indicative of a deep water table. Interpretation of the SMPH lithofacies changes depending on the scale at which it is viewed. Nearly-horizontal stratification suggests subaqueous deposition. However, upward-increasing vadose and phreatic alteration suggests that freshening events invaded a mud-poor salt pan environment and were followed by longer periods of desiccation leading to pronounced small and large water table fluctuations.

**“Podular” Muddy Halite (PMH) Lithofacies**

PMH lithofacies (Figure 8) display pods and lenses of finely crystalline halite bound by planar and point solution zones that are dominated by displacive cement fabrics, as well as abundant dissolution pits and pipes (Holt and Powers, 1990a, b). Pipes, pits, pods and lenses developed in the vadose zone during long and repeated periods of subaerial exposure. As vadose alteration continued, these features were exaggerated and insoluble material lags appeared on the exposed surfaces, resulting in a hummocky deposition surface. As spires, hummocks, and pinnacles developed, the eventually tipped over and collapsed, adding to the “podular” appearance of the halite in PMH lithofacies. The entire podular sequence records numerous
episodes of prolonged subaqueous deposition followed by extensive vadose alteration above a deep water table. These features and their formative processes are ancient, preserved examples of those found at currently-developing salt pans like the Devil’s Golf Course in Death Valley, California, and are thusly dubbed ‘Death Valley-type’ or ‘DVT’ features.

Dilated Mud-rich Halite (DMRH) Lithofacies

The lithology of DMRH lithofacies (Figure 9) indicates that freshening events were significant enough to transport large volumes of mud into the basin, but a lack of well-defined horizontal stratification, podular textures, and dissolution features suggest that subsequent water table fluctuations were small and frequent. Significant water tables drops and rises were uncommon. Small-scale water table variability caused planar dissolution of subaqueously deposited halite in the vadose zone, mechanically weakening the substrate, and allowing largely uninhibited growth of displacive cements under phreatic conditions. The textural expansion of the facies by displacive cements gives the halite its “dilated” appearance. Holt and Powers (1990a, b) concluded that DMRH lithofacies were deposited in a mud-rich salt pan with lower relief than the environment in which PMH accumulated. Prolonged subaerial exposure was punctuated by unpronounced, small fluctuations in water table depth that promoted the development of displacive cements.

Halitic Mudstone (HM) Lithofacies

Displacive halite crystals encased in a mud matrix (Figure 10) characterize the upper portions of Salado sequences (Holt and Powers, 1990a, b). Crystals are isolated, fine-coarse grain aggregates, or halite cement fabrics. Some laminations occur but are often disrupted by expansive halite growth. Distorted laminae and smeared intraclast textures suggest subaqueous deposition and repeated episodes of vadose alteration. Some portions of HM lithofacies exhibit
laminae distortion without displacive fabrics. This is likely the result of synsedimentary halite
dissolution. Some halite may have formed as solution lag following water table drop, and
prismatic cracks and disk shaped strata indicate periods of subaerial exposure. HM lithofacies
commonly drape the underlying topography and sharply contact overlying lithofacies with some
undulation, consistent with saline mud flat sediments that are deposited subaqueously and
repeatedly reworked by episodes of phreatic and vadose alteration.

IV.III. II. SULFATE INTERBEDS

Laterally extensive sulfate interbeds have long been recognized as regional marker beds
across the greater Permian Basin (Jones, 1954 and Jones et al., 1960). Descriptions of these
interbeds were originally limited to observations made from core and mine-working horizons
until excavation and mapping of the AIS. As part of AIS mapping, Holt and Powers (1990a)
expanded on the findings of earlier comparative sedimentological analyses by describing
previously unreported textures, features, and lithologic associations from Salado sulfate
interbeds. In the vicinity of WIPP, interbeds are mostly anhydrite, polyhalite, and magnesite,
with minor halite and other potash minerals indicated periods of basin submergence. Interbeds
display a number of fabrics and textures associated with depositional and diagenetic phreatic and
vadose alteration. The majority of interbeds are between 0.1 and 1 foot thick, but reach 16.5 feet
thick in some areas and cumulatively total ~124 feet throughout the Salado at the AIS. The
development of each type of interbed reflects variable hydrologic conditions of the freshening
event responsible for its deposition.

Thin Sulfate Interbeds

Thin sulfate interbeds (Figure 11) are less than 2 feet thick and are separated from other
interbeds by thick halite deposits (Holt and Powers, 1990a). They generally exhibit evidence of
underlying salt dissolution, but lack collapse structures observed in multiple and thick interbeds. The lateral extent, bed thickness, and lithology of thin marker beds suggest that freshening events were basin-wide, shallow, and quickly evaporated. Large-scale freshening events were likely marine-derived and may reflect local responses to eustatic seal level change. As lagoon waters reached the point of halite saturation, sulfate deposition ceased and halite deposition resumed. Long periods of subaerial exposure punctuated by minor flooding events persisted between these freshening events.

**Multiple Sulfate Interbeds**

In the Salado, the appearance of two or more closely spaced thin sulfate interbeds that are separated by subaqueously deposited halite, and show no signs of vadose alteration, constitute Multiple Sulfate Interbeds (Holt and Powers, 1990a). They are similar to thin sulfate beds in thickness and texture, but show more planar lower contact. Clay is common beneath the lowest interbed but not the second. Like thin interbeds, multiple interbeds were deposited as the result of shallow, basin-wide freshening, but the presence of multiple interbeds suggests multiple, closely-spaced freshening events. Connection to meteoric or marine waters was repeatedly established and broken over short periods of time, as indicated by the halite in between multiple interbeds.

**Thick Sulfate Interbeds**

Thick interbeds (Figure 12) typically consist of 1 inch to 2 feet-thick basal sections of magnesitic muds overlain by anhydrite (Holt and Powers, 1990a). Thick beds also have planar lower contacts and undulatory upper contacts. Upper contacts show significant relief caused by prismatic gypsum crystals, teepee structures, stromatolites, and soft sediment deformation. Thicker beds suggest that causal freshening events were large-volume, basin wide, and probably
large-scale eustatic responses. Changes in salinity did not occur rapidly or frequently with evaporation due to extended connection to marine waters and the dissolution of underlying salts.

IV.III. III. HALITE TEXTURES AND FABRICS

Subaqueous Textures

Repeated patterns of textures indicating cycles of subaqueous deposition are present throughout the Salado (Holt and Powers, 1990a, b). Chevron-style halite showing fluid inclusions and bound by cumulate halite crystal fabrics composed of sunken rafts and hoppers was simultaneously deposited with clay or sulfate that line crystal face boundaries. This suggests shallow, standing brines were diluted and chemically mixed by runoff during minor freshening events. No evidence of vadose zone alteration is shown in these sequences.

Vadose Zone Alteration Fabrics

A number of synsedimentary alteration fabrics and textures are apparent throughout the Salado (Holt and Powers, 1990a, b). Chief amongst these are the appearance of pipes and pits that occur as percolation through the vadose zone promotes point dissolution to the water table. The depth and girth of dissolution pipes are reflective of the time for which vadose conditions persisted. Insoluble material that would have been introduced during later flood events often fills the dissolution pits and pipes.

Phreatic Zone Alteration Fabrics

Water originating in the phreatic zone often encourages the growth of displacive and pore-filling halite cements (Holt and Powers, 1990a, b). Hypersaline ground waters are more saturated with halite relative to salt-pan evaporites and so pores are filled with expansive cements, effectively reducing porosity to zero. There is a rough correlation between the extent of phreatic alteration and the amount of overlying vadose dissolution. Under highly porous vadose
conditions, phreatic cements can completely overprint depositional textures including sulfate marker beds.

**IV.III. IV. DEPOSITIONAL CYCLES AND THE IDEAL HALITE SEQUENCE**

Workers have observed cyclicity in the Salado since the 1930s. Lowenstein (1988) identified two types of depositional cycles based on... Type I consisting of 1) a basal clastic-carbonate mudstone > massive, laminated anhydrite-polyhalite > halite > halite with mud; and Type II- an incomplete Type I cycle of halite grading into halitic mudstone. He interpreted Type I cycles to record perennial basin shallowing and brine concentration in a lagoonal > salt pan setting, and Type II cycles to record terrestrially driven flooding in the basin. He distinguished the two by the presence of anhydrite/polyhalite or clastic units at the base of the observed cycles.

Exposures at the AIS allowed Holt and Powers (1990a, b) to observe Salado halite lithofacies at a level of detail unavailable to previous workers. Based on their four identified lithofacies, Holt and Powers constructed an “ideal” halite sequence consisting of SMPH > PMH > DMRH > HM lithofacies. They concluded that the onset of each cycle was dominated by subaqueous deposition of mud poor halite. Muddy halite showing significant vadose alteration developed on the ensuing “hummocky” surface, similar to the Devil’s Golf Course in Death Valley, California. Deposition of muddy halite showing an abundance of displacive halite cements followed, and finally the halitic mudstone lithofacies formed on a saline mudflat. The cycles show 1) an upward-decreasing amount of halite and increasing clastic content; 2) increasing desiccation through time; and 3) extensive phreatic and vadose alterations. Each sequence was produced by a first-order flood event of significant magnitude that was ensued by second-order flood events of progressively decreasing intensity. The cessation of halite sedimentation by punctuating sulfate marker beds denotes the beginning of each new sequence.
CHAPTER V. - METHODS AND MATERIALS

In the following section, we detail the methods used in this study. We first review the mapping of the AIS. Then, we discuss the conversion of AIS data to a digital form. Finally, we discuss various data analysis techniques employed during this study.

V.I. CONSTRUCTION AND MAPPING OF THE AIR INTAKE SHAFT (AIS)

Holt and Powers (1990a) summarize construction efforts of the AIS. The pilot hole for a raise-bore was begun on December 4th, 1987 and completed on February 7th, 1989. Raise-boring began on April 30th, 1988 and was completed on August 25th, 1988 to the specification of 20 feet, 3 inches wide and 2,135 feet deep. Geologic mapping of the shaft was conducted in two phases between September 14th, 1988 and completed on November 14th, 1989. Reconnaissance mapping (phase 1) was conducted by cataloging a single strip of the south face of the entire shaft from the surface to the repository chamber. 5 to 20 foot sections of the strip were cleaned prior to each mapping exercise and allowed to dry in order to distinguish cleaning waters from marker bed discharges. Evaporite textures and features were made vividly clear due to brief dissolution of the shaft surface caused by washing. Vertical control was established using a survey chain from a known reference point in the shaft and horizontal lines were spray painted on the strip at 5-foot intervals. Features were described, graphically recorded to scale, photographed, and sampled (if appropriate) through the entire shaft. Observations were limited to the delineated strip with the exception of notable features. Detailed geologic mapping (phase 2) was conducted by similar methods, except that the entire circumference of the shaft was mapped and
photographed after painting a 5-foot by 5-foot grid on the wall and that features were drawn on a mylar sheet at a horizontal and vertical scale of 1 inch to 5 feet. The findings of all mapping efforts in the AIS were then published in Holt and Powers (1990a).

V.II. DATA PREPARATION

Our data preparation procedures are detailed in Figure 13. We first dissected a hardcopy of the AIS report. Using a digital scanner, pages of the report containing text were scanned at 600 dots per inch and pages with photographs were scanned at 1200 dots per inch to preserve their resolution. Unlike previous online publications of the report, ours is a full color, high-resolution .pdf that better convey the details of small-scale features observed in the AIS. The core log section of the report was scanned separately as a.tif image and imported into GetData graph digitization software. Each of the 32 pages of the Salado graphic core log was individually digitized by setting the planes of maximum and minimum depth per page on the y-scale and values of 0-100% on the x-scale. The x-scale was set as 0-100% to measure the relative abundances of halite, sulfate, clay, and halite crystal size in the shaft. The sampling interval for this portion of our data was unequal, but averaged ~0.1 foot. A grid denoting 6 inches on the graphic log scale was created in Adobe illustrator and overlain on each graphic log page (Figure 14). The abundances of alteration fabrics and textures (chevron halite, podular halite, and displacive halite) were measured using this half-foot interval grid using a system of 0 = none, 1 = trace, 2 = moderate, 3 = abundant. The appearance of smeared intraclasts was also measured in this manner. Death Valley Type surfaces were measured every 6 inches using a binary-type system, 0 = not present, 1 = present. All data was exported to and compiled in Microsoft Excel 2010.

Following compilation, the exported data was interpolated on equal intervals of 0.8, 0.5,
and 0.1 feet using the ‘FORECAST’ function in Excel 2010. The 0.1 interpolation was chosen for further processing in order to minimize error due to biasing that may occur during interpolation. For this reason, interpolated sample intervals that most closely resemble the original sampling interval are the best suited for cyclostratigraphic analysis (Weedon, 2003). The accuracy of the interpolated data was then assessed using the ‘LOOKUP’ function in Excel 2010, which matched the interpolated values with their originally exported counterparts at the original depth scale. The data was frequently spot-checked throughout preprocessing.

Minor discrepancies in the recorded values of halite vs. nonhalite became apparent during preprocessing. For example, at a depth of ~905 feet, our digitization yields a halite abundance of ~87% and ~13% nonhalite. Of that 13% nonhalite, ~93% of it is clay, and ~7% of it is sulfate. In this case, we made corrections so that the analyzed data reflects a reading of ~87% halite, 12% clay, and 1% sulfate at a depth of ~905 feet. Furthermore, some sulfate marker beds (which are in reality 100% sulfate) may have marked within ~1-2% of 100% due to human error. Their depths were denoted by hand in the AIS report using an engineer’s scale. The dataset was manually amended to reflect the proper abundances of 0% halite and 100% sulfate at the depths at which marker beds appear.

Our measured values for halite crystal size are not entirely reflective of those found in Holt and Powers (1990a). In their original work, Holt and Powers record halite crystal size on a continuous scale with uneven intervals (1, 3, 5, 10, and 20 mm in diameter). We were unable to replicate this scale in the GetData Graph Digitizer software, and so crystal size (like halite vs. nonhalite abundances, e.g.) was recorded on a scale of 0-100 during the data acquisition process. For this reason, halite crystal sizes are listed as “relative.” The results of analytical techniques
performed on our measured values of crystal size are meant only to convey the general trends of crystal size through the Salado and less so to characterize minute variations at precise depths.

To remove the effects of data biasing that results from the presence of the sulfate marker beds, a subset of data was created by compiling the data taken from halite deposits present between the 47 marker beds. Some of these marker beds were originally recorded in Holt and Powers (1990a) and some were noted for the first time during our data preparation. New marker beds were distinguished by noting areas of the data where the nonhalite abundance of the data was greater than 99% (usually in close proximity to the already-established marker beds, e.g. 1-2 feet above or below) and where the sulfate portion of the data was greater than 99%. The top and bottom depths of each unit were noted, which allowed us to calculate each unit’s thickness, as well as the median depth. The median depth of each unit was used to plot summary statistics (e.g.- means, standard deviations, correlation coefficients, and unit thicknesses).

V.III. ANALYSIS TECHNIQUES

The digitized AIS data are similar to time-series data and can be analyzed using geostatistical and other time-series-based approaches to reveal non-stationary behaviors, spatial correlation, and cyclicity within the Salado. Standard statistical methods were used to characterize the distributions of each of the continuous variables (percentage of halite, sulfate, and clay and relative crystal size). Each data set was examined for second-order stationarity and detrended, where necessary. Variograms were developed for each of the data types. Power-spectral analyses were performed to identify the frequencies of periodic signals within the data. Attempts were made to use variograms and power spectra to determine spectral exponents for each of the data sets. Wavelet analysis was conducted to detect regions of similar cyclicity and identify chaotic and periodic variations in the data. Finally, all results were interpreted in the context of the Salado depositional system and used to infer changes in Salado depositional
processes. In the following, we describe some of the analysis techniques that were used in this study.

V.III. 1. VARIOGRAM ANALYSIS

Variograms were determined for each data set. Variogram analysis, like autocorrelation analyses (e.g. Xiao et al., 2013), reveals the scale of depositional cycles by allowing us to identify the correlation length of our data. Experimental variograms are calculated using [e.g., Deutsch and Journel, 1998]

\[
\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [U(x_i + h) - U(x_i)]^2
\]

where \(N(h)\) is the number of samples in lag interval \(h\) and \(U(x)\) is the random field. Cross-variograms will be generated using

\[
\gamma_{UV}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [U(x_i + h) - V(x_i)]^2
\]

where \(V(x)\) is a second random field. Experimental variograms and cross-variograms will be fitted with a variogram model. Preliminary variograms of the data are well fit by an exponential variogram model

\[
\hat{\gamma}^m(h) = \sigma_m^2 \left[ 1 - \exp \left( -\frac{3h}{\hat{\lambda}_c} \right) \right] + \sigma_n^2
\]

where \(\hat{\lambda}_c\) is the estimated “correlation length”, \(\sigma_m^2\) is the “model variance”, and \(\sigma_n^2\) is the nugget variance. The model variance differs from the variance in that it is a fitting parameter while the variance is a directly calculated statistic. The variance of the fitted data is the sum of model and nugget variances. By breaking the dataset into the inter-marker bed subsections and performing variogram analysis, some correlation lengths calculated in GS+ per continuous
variable appear too large relative to other variables (e.g. the section of halite in between MB 130-131 shows correlation distances of 5.16, 2.28, and 4.32 feet for halite, clay, and crystal size, but a correlation distance of 45.1 feet for sulfate). In these instances, in order to calculate more coherent correlation distances, variance values were fitted to other models, such as a spherical model

\[
\hat{r}^m(h) = \begin{cases} 
\sigma_m^2 \left[ \frac{3}{2} \frac{|h|}{\hat{\lambda}_c} - \frac{1}{2} \left( \frac{|h|}{\hat{\lambda}_c} \right)^3 \right] + \sigma_n^2 & |h| \leq \hat{\lambda}_c \\
\sigma_m^2 + \sigma_n^2 & |h| > \hat{\lambda}_c
\end{cases}
\] (4)

a Gaussian model,

\[
\hat{r}^m(h) = \sigma_m^2 \left[ 1 - \exp \left( -3 \frac{|h|^2}{\hat{\lambda}_c^2} \right) \right] + \sigma_n^2
\] (5)

V.III. II. MARKOV ANALYSIS

Markov transition analysis were conducted by categorizing our dataset into seven bins: pure halite (>90% halite), sulfatic halite (<90% halite and >50% sulfate-nonhalite component), argillaceous halite (<90% halite and >50% clay-nonhalite component), pure mud (>90% clay), halitic mud (>90% mud and an abundance of halite that is greater than sulfate), sulfatic mud (>90% mud and an abundance of sulfate that is greater than sulfate), and pure sulfate (90-100% sulfate). Our “pure sulfate” bins were marked during the pre-proposal phase of this project as marker beds. Ternary plots (Figure 15a, b, c, d) were created in Microsoft Excel to determine the cutoffs for each bin. Once this was completed, as per Davis (2009) a 7 x 7 matrix of each bin was created in Matlab R2016 to calculate the number of state-to-state transitions.

Testing for the presence of the Markov property (the hypothesis that sequential states occur independently) in our dataset was performed in Matlab R2016 using the formula
\[ X^2 = \sum_{i=1}^{m} \sum_{j=1}^{m} \frac{(O_{ij} - E_{ij})^2}{E_{ij}} \]  

(6)

where \( O_{ij} \) is the observed number of transitions from \( i \) to \( j \) and \( E_{ij} \) is the expected number from transitions (expected frequencies) from \( i \) to \( j \) under the assumption of independence. The score of the Chi-square \((X^2)\) test has

\[ v = (m - 1)^2 - m \]  

(7)

degrees of freedom \((v)\) where \( m \) is the number of states in the transition matrix. \( v, X^2 \) and confidence values \((\alpha)\) values were looked up and compared via Davis (2009) in order to confirm the presence of the of the Markov property at the .05 significance level. Testing for the presence of the Markov property was performed two ways in this study: spatially and by attempting to detect embedded Markov chain. Spatial Markov analysis was performed by calculating the number of state transitions between the seven facies bins, including the transition of one facies type to itself. Detection of embedded Markov chain properties was performed by removing transitions from the diagonal of our transition matrix (e.i. setting the number of times pure halite transitions to pure halite to zero), and then dividing the number of state-state transitions per row by the total number of transitions in a row. Transition probabilities were recalculated based on the results and the results of both methods are evaluated using the \( X^2 \) test in Matlab R2016.

V.III. III. POWER SPECTRAL DENSITY ANALYSIS

A variety of techniques were employed to examine the power spectrum of each data set. The power spectrum, or autospectral density function, is determined directly using Fourier transforms of a data set. The Fourier transform of a second order stationary function of space \( f(x) \) is given by
\[ F(\omega) = \int_{-\infty}^{\infty} f(x)e^{-2\pi i x \omega} \, dx \quad (8) \]

where \( i \) is the imaginary number and \( \omega \) is a complex variable. The power spectrum of \( f(x) \) is given by the multiplying the Fourier transform by its complex conjugate

\[ S(\omega) = |F(\omega)|^2 \quad (9) \]

The autocorrelation function of \( f(x) \) can be related to the power spectrum by taking the inverse Fourier transform of the spectrum

\[ R(h) = \int_{-\infty}^{\infty} S(\omega)e^{2\pi i h \omega} \, d\omega \quad (10) \]

where \( h \) is the separation distance. The power spectrum of \( f(x) \) can be derived from the autocorrelation function using

\[ S(\omega) = \int_{-\infty}^{\infty} R(h)e^{-2\pi i h \omega} \, dh \quad (11) \]

We directly calculated the power spectrum of our data sets using Fast Fourier Transforms (FFTs). FFTs require that data sets have a length that is equal to a power of 2 (e.g., 64, 128, 256, etc.). Because the length of our data sets is not equal to a power of 2, we zero padded the data sets prior to taking the FFT using the Wavelet Design toolbox in Matlab R2016a. Following determination of the FFT, we used equation 5 to determine the power spectrum. Two types of low pass frequency filters from the signal analysis toolbox in Matlab R2016a were applied to the signal to reduce any white noise present.

The Multi-Taper Method (MTM) of Power Spectral Density (PSD) estimation was utilized in this study. When employing the Multi-Taper Method (MTM), the dataset was fed through a series of four to eight windows that tapered the time series, suppressing periodogram leakage (e.g., Weedon, 2003). After each taper was applied, the resulting orthogonal
periodograms were averaged together to produce a periodogram with small bias, good
smoothing, and high frequency resolution. The main drawback of MTM was the production of
flat-topped spectral peaks. Naturally, MTM is ill suited for a time series with long spectral peaks.

V.III. IV. WAVELET ANALYSIS

We explored the use of wavelet transforms with our data sets. Wavelet analysis (Cooper
and Lyngsie, 2006) holds an advantage over traditional Fourier analysis in that it matches
frequency components with scaled resolution. This is useful in our analysis as our data is
characterized by somewhat chaotic, abrupt changes in values typical of punctuated aggradation
cycles.

Data pretreatment for Wavelet Analysis included padding with zeros (to the next \(2^N\))
using the Wavelet Design Toolbox in MATLAB R2016a and transformation into the frequency
spectrum using by the same application. Wavelet transformation of the Fourier signal was
performed by the introduction and stretching/compressing of the Mother Wavelet to the data:

\[
\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi \left( \frac{t - b}{a} \right) \quad (12)
\]

where \(\psi\) is the mother wavelet, \(a\) is the scaling factor, and \(b\) is the translation factor. Time
localization was achieved by repeatedly translating the wavelet function (8) through the dataset
at different scales, which lead to the Continuous Wavelet Transform (CWT) of our data
illustrated by

\[
Wf(a,b) = \frac{1}{\sqrt{a}} \left[ f(x) \psi \left( \frac{x - b}{a} \right) \right] dx \quad (13)
\]

We initially utilized MATLAB 2016a’s Wavelet Analysis Toolbox to perform
Continuous Wavelet Transforms (CWT) for the total halite, clay, sulfate, and halite crystal size
in the Salado. However the inability of the toolbox to represent the calculated wavelet
coefficients in terms of depth prevented meaningful interpretation of our results. For that reason, Matlab code based around the ‘morl’ function (e.i. the Morlet family of wavelets) was developed to calculate wavelet coefficients. Morlet wavelets were chosen over other wavelet types because of their frequency output due to constant wavelength of the Morlet mother wavelet. The raw signal of each variable was plotted in conjunction with the coefficients generated by passing the wavelet through the signals. Coefficients and raw signals were plotted against depth for each variable in the total Salado dataset.
CHAPTER VI. - RESULTS

Our compiled dataset consists of depth measurements, four measured lithologic variables and four estimated textures/features. Depth and variable measurements yielded ~60,000 data points. Measured textures and features yielded another ~7,500 data points.

VI.I. RAW PLOTS AND SUMMARY STATISTICS

Raw plots of each variable are shown in Figures 16, 17, 18, and 19. The mean and standard deviation values for the measured variables in the Salado and its members are presented in Tables 1 and 2 Mean halite values decrease upward (ULM- 75.2%, McNutt- 72.3%, UUM- 70.4%), while the standard deviation for halite content increases upward, from 27.72% in the ULM to 33.38% in the McNutt and UUM. The mean clay content (Table 1) and mean sulfate content increases upward (ULM- 7.7%, McNutt- 7.1%, UUM- 9.1% for clay and ULM-17.1%, McNutt- 21%, UUM- 21% for sulfate). The standard deviation of sulfate and clay content increases upward (Table 2) while the standard deviation of crystal size decreases upward. These trends are consistent with increasing vadose zone exposure and alteration and greater input of terrestrial clays during freshening events. Halite contents are reduced by dissolution processes within the vadose zone, while the concentrations of insoluble materials (clay and sulfate) increase. Increased variability in halite, sulfate, and clay content is the result of increased vadose zone exposure and phreatic zone alteration. The decrease in the standard deviation in crystal size likely reflects homogenization of halite cycles by displacively-grown, phreatic zone cements.
Correlation coefficients were also calculated between variables in the entire Salado and its constituent data sets (Tables 3, 4, 5, and 6). The strongest correlations lie between halite and sulfate (-0.89 and -0.92) in all three Salado members. All other variables show very weak correlations (between -0.01 and -0.24). The strong, negative correlation between sulfate and halite is likely due to the lithology presence of sulfate markerbeds, which transition from ~100% sulfate and 0% halite to much lower sulfate and higher halite values over very short distances.

Mean values for halite, sulfate, and clay abundances sampled from units between sulfate marker beds are shown in Figure 20. Overall, mean halite abundance increases slightly upward, mean sulfate decreases upward, and mean clay increases upward. There are, however, many zones where the mean halite content decreases upward (e.g., from ~1,050 to 900 feet, ~1,150 to ~1,050 feet, etc.). These zones cross both the halite cycles identified in Holt and Powers (1990) and several sulfate marker beds. Zones showing upward decreasing mean halite content tend to be thicker in the UUM and thinner and less variable in the McNutt and ULM. Lower halite concentrations generally coincide with evidence of increased subaerial exposure and vadose zone alteration. The persistence of these zones across multiple sulfate interbeds (which formed as the result of basin-wide freshening events) suggests that long drying cycles were not reset by the extreme events that lead to basin-wide flooding and the accumulation of sulfate interbeds. The standard deviations of halite, sulfate, and clay are shown in Figure 21. Halite standard deviation generally decreases upward, while the average standard deviation of sulfate increases slightly upward and the average standard deviation of clay decreases slightly upward. Sections where the standard deviation of halite and sulfate and/or clay content increase together (e.g., ~1,100 feet and ~1,200 feet) reflect moderate amounts vadose zone alteration, as both subaqueous accumulation of halite and extreme vadose zone alteration leads to lower variation in
halite content. Mean crystal size increases slightly upward (Figure 22) and crystal size standard deviation decreases dramatically upward (Figure 23). The thickness of inter-marker bed halite units decreases upward (Figure 24) from 33.5 feet in the ULM to 21 feet in the McNutt to 15.5 feet in the UUM., suggesting that flood events were less common earlier on and became more frequent as time went on. Time periods between flooding events may have been longer during ULM accumulation.

Correlation coefficients were evaluated for each variable for intervals between sulfate markerbeds (Figures 25, 26, 27, 28, 29, and 30). The correlation coefficients between halite and sulfate contents are negative (Figure 25). Halite-sulfate correlation coefficients increase upward in zones that span multiple sulfate interbeds (e.g., above ~1,050 feet, between 1,200 and 1,050 feet, etc.). The thickest zones are in the UUM. When halite accumulates in subaqueous conditions, we would generally expect that as the sulfate content increases, the halite content would decrease, reflecting increasing presence of sulfate laminae. Vadose zone alteration processes, however, will remove halite and redistribute sulfate vertically through the section due to physical translocation in solution pits and pipes, leading to weaker negative correlation. Here again, we see upward trends, associated with increasing vadose zone alteration, that are unaffected by extreme events causing basin-wide flooding.

Halite – clay correlation coefficients for intervals between sulfate markerbeds are also negative, with one exception (Figure 26). In general, zones defined by vertical trends are not as well defined as those showing trends in the halite – sulfate correlation coefficient; however, where the correlation between halite and sulfate is strong, the correlation between halite and clay tends to be weak.
Halite and halite crystal size are strongly-positively correlated at greater depths and show no coherent patterns (Figure 27). The halite and halite crystal size correlation coefficient generally decreases upward, while still retaining a positive correlation. Sulfate-crystal size, sulfate-clay, and clay-crystal size correlation coefficients reveal no distinct pattern (Figures 28, 29, and 30).

VI.II. VARIOGRAM ANALYSIS

Variograms for the Salado halite, sulfate, and clay and crystal size are presented in Figures- 31, 32, 33, and 34. The variograms were fit to evaluate vertical correlation lengths (Table 7). Correlation lengths for halite are longest in the ULM (21.0 ft), shortest in the McNutt (6.0 ft), and of intermediate length in the UUM (9.9 ft). By comparison, the mean unit thickness between marker beds is 33.5 feet in the ULM, 21 feet in the McNutt, and 15.5 feet in the UUM, implying that the halite content of the inter marker bed units is most consistent in the ULM and the UUM, and less so in the McNutt. This is consistent with the findings of the summary statistics, which show that sulfate deposition was more frequent in later stages of deposition. The halite variogram for the McNutt shows evidence of some cyclicity beyond the correlation length, with a scale of ~ 4 ft (Figure 31). The vertical correlation length for sulfate decreases upward from 25.5 ft in the ULM to 7.5 ft in the UUM (Table 7), and sulfate variograms (Figure 32) display weak cyclicity beyond the correlation length. These correlation lengths mainly reflect decreasing thickness of intervals between sulfate interbeds upward. Shorter halite correlation lengths in the McNutt are likely due to consolidation by repeated vadose zone alteration.

The vertical correlation length for clay is greatest in the UUM (5.6 ft) and lowest in the McNutt (3.3 ft) (Table 7) and clay variograms for the McNutt and UUM (Figure 33) show
regular cyclicity beyond the correlation length, with scales ranging from 8 feet (McNutt) to 14 feet (UUM). The shorter correlation length in the McNutt also reflects compressed halite cycles. Variograms of relative crystal size for the ULM and the McNutt show increasing values and cyclicity beyond the correlation length (Figure 34). The correlation length is largest within the McNutt (11.7 ft) (Table 7), which is about twice the correlation lengths in the ULM and UUM (5.0 and 4.5 ft, respectively). The larger correlation length in the McNutt likely reflects homogenization of crystal sizes due to the growth of coarser void-filling and displacive halite cements.

Cross-correlation between halite and sulfate persists for distances of 23.5 feet in the ULM, 9.0 feet in the McNutt, and 11.1 ft in the UUM (Table 7). These cross-variogram correlation lengths mimic the correlation lengths of halite in each of the three members. The cross-covariograms from the McNutt and UUM show some cyclic behavior beyond the correlation length (Figure 35).

Correlation lengths for each variable were also established from the 48 subsections of the data set (Figure 36). The average correlation length for halite (Figure 37) is 5.2 feet. Sulfate (Figure 38) shows an average correlation length of 4.73 feet. Clay correlation lengths (Figure 39) average 5.1 feet. Halite crystal size correlation length (Figure 40) averages 5.3 feet. Correlation lengths in the UUM repeatedly decrease and increase in length. Correlation lengths in the McNutt are generally larger across all four variables at the base, than at the top. Correlation lengths in the ULM decrease overall with depth. Overall, correlation lengths taken from inter-marker bed units appear to change together as a group, but overall lack discernable patterns. Each variable’s correlation length decreased upward except for clay.
VI.III. MARKOV ANALYSIS

The results of Markov analysis to determine the presence of independently-ordered strata succession for the total Salado and its members are shown in Table 8a, b, 9a, b, 10a, b, and 11a, b. Self-state transitions total 12,265 in the total Salado (4,367 in the UUM, 1961 in the McNutt, and 5,937 in the ULM). Non-self-state transitions total 596 in the entire Salado (213 in the UUM, 89 in the McNutt, and 294 in the ULM). Only the results of the non-self-state transitions are recorded and discussed.

In all Salado members, there is a statistically significant likelihood of halite transitioning into sulfatic halite over argillaceous halite, but the probability of halite transitioning into argillaceous halite does increase upward as the likelihood of a pure halite to sulfatic halite transition decreases. Sulfatic halite typically transitions back into pure halite over argillaceous halite, but only by ~1% (averaged across all three members) and decreasingly upward. There is also an increasing likelihood of sulfatic halite transitioning into a sulfate marker bed upward. However, from the ULM to the UUM, the probability of a sulfate marker bed transitioning back into sulfatic halite drops, and the probability of a marker bed > pure/argillaceous halite transition increases. There is only a low possibility of transitioning into pure mud (in the ULM).

Comparison with the Chi-square ($\chi^2$) tests yields critical values of ~60,098.71 and 539.8 in the total dataset for transition and embedded transition probabilities, respectively. The ULM $\chi^2$ tests yielded critical values of ~20,213.26 and 555.8 for transition and embedded transition probabilities. Davis (2009) lists the $\chi^2$ critical value for 29 degrees of freedom and a 5% significance level of 42.56, which our critical values far exceed. Thus we can confirm that there is a statistically significant tendency for certain lithologies to be preferentially ordered throughout the Salado.
By determining which of the state-state transition probabilities are greatest in the Salado, we can determine an approximate order of strata succession. In upward order, pure halite is most commonly followed by sulfatic halite, which is most commonly followed by pure halite or argillaceous halite, which then transitions back into pure halite or sulfatic halite. The case of the sulfatic halite > pure halite > argillaceous halite sequence is analogous to the ideal halite sequence as identified by Holt and Powers (1990a, b) where stratified mud-poor halite (sulfatic halite) is succeeded by podular muddy halite (pure halite) and then by mud-rich halite (argillaceous halite). As is also reported by Holt and Powers (1990a, b), our Markov analysis revealed very little likelihood of any pure mud or clay units in the Salado.

VI.IV. POWER SPECTRAL ANALYSIS

The results of Multitaper PSD estimation (Figures 41, 42, 43, and 44) shows higher power (~10-20 dB/Hz) associated with lower frequencies (0-50 Hz) in the total halite, sulfate, and clay signals with a significant overall decrease in power at higher frequencies (~50-350 Hz). In the halite and clay signals, this overall decrease ceases at ~350 Hz and power varies between ~20-30 dB/Hz to a frequency of ~500 Hz. In the sulfate signal, the trend of decreasing power with increasing frequency continues until ~400 Hz before stabilizing between ~20 and 30 Hz. Halite, sulfate, and clay all show spectral peaks approximately every 10 Hz with an associated power of ~10-20 Hz. The relative halite crystal size signal (Figure 44) shows a similar trend in decreasing power with increasing higher frequencies until ~400 Hz, where power average begins to increase until 500 Hz. All four variables show spectral peaks approximately every 100 Hz. Each signal was fed through lowpass and pole zero filters and viewed again. These measures failed to produce any more meaningful results.
VI.V. WAVELET ANALYSIS

Morlet wavelet analysis shows, in the halite signal (Figure 45) (characterized by brighter displays of light), significant results at depths of ~950, and between 1300-1350 feet and 1450-1500 feet, with slightly weaker (but still significant) displays at 1240, 1620, and 1760 feet, indicating abrupt discontinuities at those depths. However, the higher proportion of halite to all other lithologies in the total Salado is evident in the CWT plots, as the distinction of discontinuity zones in the halite CWT is not as apparent as with other variables. The presence of halite is continuous throughout the entirety of the Salado, as one would expect. The sulfate CWT (Figure 46) shows many sharp discontinuities in the UUM and a few continuous intervals (darker areas) in the McNutt and ULM. The zone of continuity around the 1550-1600 depth markers are likely the Union Anhydrite. Similarly, the continuous zone in the clay CWT (Figure 47) at ~1340 feet is likely the Vace Trista. Aside these, there are several zones of interest in the clay and sulfate wavelet plots. Clay shows several discontinuous zones throughout the entirety of the Salado, and several continuous zones at 1150, 1200, 1600, and another below 2000 feet. Sulfate also shows several discontinuities throughout the Salado, but far more distinguishable continuous zones than that of clay at ~1550-1600 feet, 1600-1700 feet, 1800-1850 feet, two others below 2000 feet, and others. Halite crystal size CWT (Figure 48) shows only two areas of distinct discontinuity- in the ULM at depths of ~1950 feet and (to a lesser extent) around 1850 feet.
CHAPTER VII. - DISCUSSION

Several our analyses failed to yield meaningful results. The summary statistics for relative crystal size variable reveal little uninformative results, as does the cross-variogram between halite and sulfate. Also, while correlation lengths taken from inter-marker bed intervals tend to vary together, overall patterns are lacking. The Power Spectra contains too much noise to precisely delineate cycle boundaries, but it appears that greater amounts of power are associated with lower and higher frequencies. Finally, because the power spectrum can be related to the auto-correlation function, it contains essentially the same data as our variograms, so those results were minimally informative.

That aside, our method of applying elementary summary statistics proved extremely informative and we could identify the traces of preserved depositional patterns and trends in most of the Salado at the outset of our study. From the bottom to top of the Salado, mean halite content decreases (especially in zones with many sulfate marker beds where the negative relationship between halite and sulfate also weakens), while mean sulfate and clay abundances increase. Per the standard deviation calculations, it also appears that increasingly variable amount of material were introduced to the basin during later times. Concurrently, the inter marker bed unit thickness decreases upward. This is possibly related to increasing-upward amount of Vadose Zone alteration where low water tables allow more downward transport of material, effectively consolidating sediment in the upper portions of the Salado. Combining the results of our analysis with an analysis of the unexamined textural data may support this.

Evaporite deposition is controlled by the supply of source brines, their composition, and
brine-table position. In Salado, the preserved rock type was dependent on the intensity, composition, and length of freshening events that introduced new water into the basin. In the case of the earliest Salado (ULM time), increased thickness of sulfate markerbeds, increased mean sulfate abundance, less negative correlations of halite with sulfate, and higher probabilities of sulfatic to/from halite transitions over argillaceous to/from halite may imply that freshening events were more prolonged, to allow time for the accumulation of sulfate before surface waters became concentrated enough to begin halite precipitation. This was perhaps a connection of the basin with marine water that became more intermittent as time went on, leading to shorter depositional cycles. By comparison, in the UUM, sulfate beds are of greater number (but lower average thickness), clay abundances are greater, correlation distances for clay are longer, and clay becomes more positively correlated with halite, which also appears in thinner beds (implying that shortly after freshening events introduced clay to the basin, waters rapidly reached salinity levels necessary to begin halite precipitation). The increase of halite-clay correlation could be taken to mean the onset of a flood event. If so, then the rise in halite-sulfate correlation could be taken to delineate only flood events of greater magnitude or sustenance. The ultimate rise in halite-clay correlation suggests the Delaware Basin’s transition from a lagoonal-salt pan to saline mudflat as the Permian ended, with the pattern in correlation coefficient trends reflecting climatic forcing of this transition.

The results of our Markov analysis indicate a statistically significant tendency for certain lithologies to be preferentially followed by certain other states. These transitions occur in an order that approximately matches the ideal halite sequence identified by Holt and Powers (1990a, b). We show common transitions of sulfatic halite (which is analogous to the stratified mud-poor halite lithofacies) into pure halite (i.e. podular muddy halite lithofacies) into argillaceous halite
(dilated mud-rich halite) with the appearance of pure mud a statistical unlikelihood. While our Markov results are insufficient to precisely define the boundaries of depositional cycles, these results are strong verifiers of previous researchers’ work.

The Wavelet transform plots for clay and sulfate show a great number of abrupt transitions in the upper portions of the UUM and less disruption in the ULM, reflecting shorter-lived lagoons and more vadose zone alternation in the UUM and longer subaqueous deposition from longer-lived saline lagoons in the ULM. Freshening events in the later days of Delaware Basin filling may have been more frequent or intense at their onset, but also evaporated more rapidly. This makes sense, as later Salado deposition spilled over the top of the Capitan reef that had once restricted all circulation in times before. The greater thickness of sulfate beds in the ULM may not be the result of larger flooding events, but rather, may be indicative of more prolonged subaqueous deposition by means of cumulative freshening.

There is a slight inconsistency in the summary statistics between our original analysis and those performed after removing data pertaining to the marker beds. In our original analysis, mean halite content decreases upwards. In our second phase of analysis, mean halite content increases upward slightly (by ~1%). This is because where marker beds appear, the halite abundance equals 0. While the thickness of marker beds decreases in the upper portions of the Salado, the number of marker beds is greater here than in the lower portions (there are 24 marker beds in the UUM, 10 in the McNutt, and 14 in the ULM). So this discrepancy in results can be explained by that when the marker bed data is removed and summary statistics are calculated, the mean abundance of halite in each Salado member appears higher than it actually is. Note that the mean abundance of halite (in order from highest to lowest) per recalculated summary statistics is highest in the UUM, then the ULM, and then the McNutt.
CHAPTER VIII. – CONCLUSION

We examined approximately 2135 feet of graphic core log data and converted it to digital to further illustrate depositional cyclicity in the Permian Salado Formation. Analysis of the data prepared by Holt and Powers (1990a, b) has successfully created and characterized a data set for a full cyclostratigraphic analysis to be conducted in the future. The results of our preliminary analysis show that these sedimentary depositional cycles are preserved in the Salado.

Various methods of statistical analysis were utilized in our efforts. Markov analysis, variogram analysis, wavelet analysis, and power spectral analysis each yielded considerable results. Most telling of all are the summary statistics of inter-marker bed halite units, variograms of the individual Salado members, and the Markov transition matrices that indicate ordered sequences of sediment deposition in the Salado paleo environment. The depositional record appears to preserve differing sedimentation styles resulting from freshening events into the basin of varying intensity and persistence at depths that are approximately analogous with those found by previous workers. There are, perhaps, slight alterations to the accepted stratigraphic boundaries between Salado Members that would be considered plausible based on refinement of our findings.

At the outset of this study, the precise delineation of these cycles eludes our efforts. Considering this conclusion, it is our position that any one of the analysis methods presented here may be further expanded upon to reveal more informative results. Specifically, other PSD estimation methods may be explored to detect the precise boundaries of sedimentary depositional
cycles. Furthermore, to properly ascertain the timing of events in the Delaware Basin during the Ochoan, reliance on steadfast isochrons will be required, of which we are aware of none that so suit our purposes.

In the future, it may also be possible to differentiate between marine and terrestrially-driven flooding events by separating marker beds into zones of sulfate vs. polyhalite/langbeinite. Permian seawater is shown to have a similar chemical composition to modern seawater, but that by the latest Permian, $\text{Mg}^{2+}/\text{Ca}^{2+}$ ratios had increased from 3.5 to 3.7 due to a decrease in $\text{Ca}^{2+}$ abundances (Horita et al., 1991 and Lowenstein et al., 2005). Keeping these studies in parallel with our own, it would seem that the trend of decreasing $\text{Ca}^{2+}$ in seawater may be reflectant in the gypsum/sulfate of the Salado and perhaps also in the Rustler. If the reduction of calcium abundances in the marker beds can be tracked with some certainty, as well as the increase of $\text{Mg}^{2+}$ or $\text{K}^{+}$, these findings could be juxtaposed with the results of our study here, and reveal more about the nature of marker bed deposition from a geochemical standpoint. A study of the appearance and properties of dissolution pipes may be necessary in order to more accurately characterize water table movement during the early stages of Salado deposition. Also, the appearance of displacive halite textures and fabrics ought to be examined more thoroughly, to see if their greater abundance coincides at all with appearance of thinner bedding found in the UUM.


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LIST OF APPENDICES
APPENDIX A - TABLES
### Table 1. Mean Values for All Variables in the Salado.

<table>
<thead>
<tr>
<th></th>
<th>Halite</th>
<th>Sulfate</th>
<th>Clay</th>
<th>Rel. Crystal Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (total)</td>
<td>73.05</td>
<td>18.87</td>
<td>8.08</td>
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<td>Mean (UUM)</td>
<td>70.4</td>
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<td>Mean (McNutt)</td>
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<td>Mean (ULM)</td>
<td>75.24</td>
<td>17.06</td>
<td>7.70</td>
<td>54.06</td>
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### Table 2. Standard Deviation Values for All Variables in the Salado.

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<thead>
<tr>
<th></th>
<th>Halite</th>
<th>Sulfate</th>
<th>Clay</th>
<th>Rel. Crystal Size</th>
</tr>
</thead>
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<tr>
<td>Std. Dev. (Total)</td>
<td>31.90</td>
<td>30.93</td>
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<td>Std. Dev. (UUM)</td>
<td>33.49</td>
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<td>Std. Dev. (McNutt)</td>
<td>33.38</td>
<td>33.41</td>
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<tr>
<td>Std. Dev. (ULM)</td>
<td>27.72</td>
<td>27.90</td>
<td>11.61</td>
<td>5.73</td>
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</table>

### Table 3. Total Salado Correlation Coefficients.

<table>
<thead>
<tr>
<th></th>
<th>Halite</th>
<th>Sulfate</th>
<th>Clay</th>
<th>Rel. Crystal Size</th>
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</thead>
<tbody>
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<td>Halite</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Sulfate</td>
<td>-0.90</td>
<td>1</td>
<td></td>
<td></td>
</tr>
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<td>Clay</td>
<td>-0.22</td>
<td>-0.22</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Rel. Crystal Size</td>
<td>0.12</td>
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<td>-0.22</td>
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</tr>
<tr>
<td></td>
<td>Halite</td>
<td>Sulfate</td>
<td>Clay</td>
<td>Rel. Crystal Size</td>
</tr>
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<td>--------</td>
<td>---------</td>
<td>-------</td>
<td>-------------------</td>
</tr>
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<td><strong>Halite</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sulfate</strong></td>
<td>-0.91</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Clay</strong></td>
<td>-0.19</td>
<td>-0.22</td>
<td>1</td>
<td></td>
</tr>
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<td><strong>Rel. Crystal Size</strong></td>
<td>0.19</td>
<td>-0.05</td>
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</tr>
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</table>

Table 4. Unnamed Lower Member Correlation Coefficients.

<table>
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<tr>
<th></th>
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<th>Sulfate</th>
<th>Clay</th>
<th>Rel. Crystal Size</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Halite</strong></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sulfate</strong></td>
<td>-0.92</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Clay</strong></td>
<td>-0.2</td>
<td>-0.21</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Rel. Crystal Size</strong></td>
<td>0.19</td>
<td>-0.1</td>
<td>-0.2</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5. McNutt Potash Member Correlation Coefficients.

<table>
<thead>
<tr>
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<th>Clay</th>
<th>Rel. Crystal Size</th>
</tr>
</thead>
<tbody>
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<td></td>
</tr>
<tr>
<td><strong>Sulfate</strong></td>
<td>-0.89</td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>Clay</strong></td>
<td>-0.24</td>
<td>-0.24</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Rel. Crystal Size</strong></td>
<td>-0.01</td>
<td>0.06</td>
<td>-0.09</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 6. Unnamed Upper Member Correlation Coefficients.
<table>
<thead>
<tr>
<th></th>
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<th>Sulfate</th>
<th>Clay</th>
<th>Crystal Size</th>
<th>Halite-Sulfate</th>
</tr>
</thead>
<tbody>
<tr>
<td>UUM</td>
<td>9.9 ft</td>
<td>7.5 ft</td>
<td>5.6 ft</td>
<td>4.5 ft</td>
<td>11.1 ft</td>
</tr>
<tr>
<td>McNutt</td>
<td>6.0 ft</td>
<td>9.0 ft</td>
<td>3.3 ft</td>
<td>11.7 ft</td>
<td>9.0 ft</td>
</tr>
<tr>
<td>ULM</td>
<td>21.0 ft</td>
<td>25.5 ft</td>
<td>4.2 ft</td>
<td>5.0 ft</td>
<td>23.5 ft</td>
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</table>

Table 7. Vertical Mean Correlation Distances from Variogram Analysis of all Variables and cross-covariance values from Halite-Sulfate.

<table>
<thead>
<tr>
<th></th>
<th>Halite</th>
<th>Sulf. Halite</th>
<th>Arg. Halite</th>
<th>Mud</th>
<th>Hal. Mud</th>
<th>Sulf. Mud</th>
<th>Sulfate MB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halite</td>
<td>95.94%</td>
<td>2.82%</td>
<td>0.82%</td>
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<td>0.00%</td>
<td>0.00%</td>
<td>0.41%</td>
</tr>
<tr>
<td>Sulf. Halite</td>
<td>4.62%</td>
<td>90.24%</td>
<td>3.30%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>1.85%</td>
</tr>
<tr>
<td>Arg. Halite</td>
<td>1.98%</td>
<td>1.35%</td>
<td>96.36%</td>
<td>0.00%</td>
<td>0.08%</td>
<td>0.08%</td>
<td>0.16%</td>
</tr>
<tr>
<td>Mud</td>
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<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Hal. Mud</td>
<td>0.00%</td>
<td>0.00%</td>
<td>20.00%</td>
<td>0.00%</td>
<td>80.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Sulf. Mud</td>
<td>0.00%</td>
<td>0.00%</td>
<td>2.13%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>97.87%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Sulfate MB</td>
<td>1.35%</td>
<td>1.52%</td>
<td>0.84%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>96.30%</td>
</tr>
</tbody>
</table>

Table 8a. Transition Probabilities from Markov Analysis of Salado Unnamed Upper Member.
<table>
<thead>
<tr>
<th></th>
<th>Halite</th>
<th>Sulf. Halite</th>
<th>Arg. Halite</th>
<th>Mud</th>
<th>Hal. Mud</th>
<th>Sulf. Mud</th>
<th>Sulfate MB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halite</td>
<td>0.00%</td>
<td>69.57%</td>
<td>20.29%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>10.14%</td>
</tr>
<tr>
<td>Sulf. Halite</td>
<td>47.30%</td>
<td>0.00%</td>
<td>33.78%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>18.92%</td>
</tr>
<tr>
<td>Arg. Halite</td>
<td>54.35%</td>
<td>36.96%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>2.17%</td>
<td>2.17%</td>
<td>4.35%</td>
</tr>
<tr>
<td>Mud</td>
<td>0.00%</td>
<td>0.00%</td>
<td>100.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Hal. Mud</td>
<td>0.00%</td>
<td>0.00%</td>
<td>100.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Sulf. Mud</td>
<td>0.00%</td>
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<td>100.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Sulfate MB</td>
<td>36.36%</td>
<td>40.91%</td>
<td>22.73%</td>
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</table>

Table 8b. Embedded Transition Probabilities from Markov Analysis of Salado Unnamed Upper Member.

<table>
<thead>
<tr>
<th></th>
<th>Halite</th>
<th>Sulf. Halite</th>
<th>Arg. Halite</th>
<th>Mud</th>
<th>Hal. Mud</th>
<th>Sulf. Mud</th>
<th>Sulfate MB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halite</td>
<td>97.32%</td>
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<td>0.21%</td>
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<td>0.31%</td>
</tr>
<tr>
<td>Sulf. Halite</td>
<td>5.80%</td>
<td>87.37%</td>
<td>4.78%</td>
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<td>0.00%</td>
<td>0.00%</td>
<td>2.05%</td>
</tr>
<tr>
<td>Arg. Halite</td>
<td>1.42%</td>
<td>2.61%</td>
<td>95.97%</td>
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<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Mud</td>
<td>0.00%</td>
<td>0.00%</td>
<td>1.25%</td>
<td>98.75%</td>
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<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Hal. Mud</td>
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<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Sulf. Mud</td>
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<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>95.74%</td>
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</table>

Table 9a. Transition Probabilities from Markov Analysis of Salado McNutt Potash Member.
Table 9b. Embedded Transition Probabilities from Markov Analysis of Salado McNutt Potash Member.

<table>
<thead>
<tr>
<th></th>
<th>Halite</th>
<th>Sulf. Halite</th>
<th>Arg. Halite</th>
<th>Mud</th>
<th>Hal. Mud</th>
<th>Sulf. Mud</th>
<th>Sulfate MB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halite</td>
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<td>11.54%</td>
</tr>
<tr>
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<td>0.00%</td>
<td>37.84%</td>
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<td>0.00%</td>
<td>16.22%</td>
</tr>
<tr>
<td>Arg. Halite</td>
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<td>64.71%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Mud</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
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<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Hal. Mud</td>
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<td>0.00%</td>
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<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Sulf. Mud</td>
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<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Sulfate MB</td>
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<td>62.50%</td>
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</table>

Table 10a. Transition Probabilities from Markov Analysis of Salado Unnamed Lower Member.

<table>
<thead>
<tr>
<th></th>
<th>Halite</th>
<th>Sulf. Halite</th>
<th>Arg. Halite</th>
<th>Mud</th>
<th>Hal. Mud</th>
<th>Sulf. Mud</th>
<th>Sulfate MB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halite</td>
<td>95.80%</td>
<td>3.52%</td>
<td>0.58%</td>
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<td>0.00%</td>
<td>0.11%</td>
</tr>
<tr>
<td>Sulf. Halite</td>
<td>3.15%</td>
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<td>3.77%</td>
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<td>0.00%</td>
<td>0.00%</td>
<td>0.74%</td>
</tr>
<tr>
<td>Arg. Halite</td>
<td>1.46%</td>
<td>2.48%</td>
<td>96.01%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.05%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Mud</td>
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<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
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</tr>
<tr>
<td>Hal. Mud</td>
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<td>0.00%</td>
<td>60.00%</td>
<td>0.00%</td>
<td>40.00%</td>
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<td>0.00%</td>
</tr>
<tr>
<td>Sulf. Mud</td>
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<td>0.00%</td>
<td>1.06%</td>
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<td>0.00%</td>
<td>0.00%</td>
<td>97.46%</td>
</tr>
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<td></td>
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<td>Sulf. Halite</td>
<td>Arg. Halite</td>
<td>Mud</td>
<td>Hal. Mud</td>
<td>Sulf. Mud</td>
<td>Sulfate MB</td>
</tr>
<tr>
<td>-------------</td>
<td>--------</td>
<td>--------------</td>
<td>-------------</td>
<td>-----</td>
<td>----------</td>
<td>-----------</td>
<td>------------</td>
</tr>
<tr>
<td>Halite</td>
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<td>13.75%</td>
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<td>0.00%</td>
<td>2.50%</td>
</tr>
<tr>
<td>Sulf. Halite</td>
<td>41.13%</td>
<td>0.00%</td>
<td>49.19%</td>
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<td>0.00%</td>
<td>0.00%</td>
<td>9.68%</td>
</tr>
<tr>
<td>Arg. Halite</td>
<td>36.49%</td>
<td>62.16%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>1.35%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Mud</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Hal. Mud</td>
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<td>0.00%</td>
<td>100.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Sulf. Mud</td>
<td>0.00%</td>
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<td>0.00%</td>
<td>100.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Sulfate MB</td>
<td>14.29%</td>
<td>64.29%</td>
<td>0.00%</td>
<td>21.43%</td>
<td>0.00%</td>
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</tr>
</tbody>
</table>

Table 10b. Embedded Transition Probabilities from Markov Analysis of Salado Unnamed Lower Member.

<table>
<thead>
<tr>
<th></th>
<th>Halite</th>
<th>Sulf. Halite</th>
<th>Arg. Halite</th>
<th>Mud</th>
<th>Hal. Mud</th>
<th>Sulf. Mud</th>
<th>Sulfate MB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halite</td>
<td>96.17%</td>
<td>2.97%</td>
<td>0.59%</td>
<td>0.03%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.24%</td>
</tr>
<tr>
<td>Sulf. Halite</td>
<td>3.85%</td>
<td>91.21%</td>
<td>3.74%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>1.20%</td>
</tr>
<tr>
<td>Arg. Halite</td>
<td>1.64%</td>
<td>2.09%</td>
<td>96.13%</td>
<td>0.00%</td>
<td>0.02%</td>
<td>0.06%</td>
<td>0.06%</td>
</tr>
<tr>
<td>Mud</td>
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<td>1.10%</td>
<td>2.20%</td>
<td>95.60%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
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<td>0.00%</td>
<td>66.67%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Sulf. Mud</td>
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<td>0.00%</td>
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<td>0.00%</td>
<td>2.08%</td>
<td>95.83%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Sulfate MB</td>
<td>0.97%</td>
<td>1.80%</td>
<td>0.37%</td>
<td>0.22%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>96.63%</td>
</tr>
</tbody>
</table>

Table 11a. Transition Probabilities from Markov Analysis of Total Salado.
Table 11b. Transition Probabilities from Markov Analysis of Total Salado.

<table>
<thead>
<tr>
<th></th>
<th>Halite</th>
<th>Sulf. Halite</th>
<th>Arg. Halite</th>
<th>Mud</th>
<th>Hal. Mud</th>
<th>Sulf. Mud</th>
<th>Sulfate MB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halite</td>
<td>0.00%</td>
<td>77.71%</td>
<td>15.43%</td>
<td>0.57%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>6.29%</td>
</tr>
<tr>
<td>Sulf. Halite</td>
<td>43.83%</td>
<td>0.00%</td>
<td>42.55%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>13.62%</td>
</tr>
<tr>
<td>Arg. Halite</td>
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APPENDIX C – ORIGINAL DATA
Appendix C for this paper is not attached. It includes a copy of the original digitized data taken from Holt and Powers (1988a) before any abundance or marker bed adjustments were made.
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