SEDIMENTOLOGY OF THE RUSH SPRINGS SANDSTONE (PERMIAN/GUADALUPIAN), WESTERN OKLAHOMA: EVIDENCE OF AN ERG-ERG MARGIN DEPOSITIONAL SYSTEM

By

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Bachelor of Science in Geology

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Wichita, Kansas

2008

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
July, 2011

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ACKNOWLEDGMENTS

First of all, I wish to thank the faculty and staff of the Boone Pickens School of Geology at Oklahoma State University. I would especially like to thank Sandy Earls and Nancy Dryden for their help with day to day activities and Tim Sickbert for all his technical support. I am eternally grateful to my committee members, Dr. Anna Cruse and Dr. Darwin Boardman for their insight and their thoughtful discussions and Dr. Jim Puckette, for all his time and effort in this project. I am indebted to Dr. Alexander Simms for the idea of this project, his assistance in the field, the stimulating discussions and friendship. I would like to give a special thanks to the Oklahoma Geological Survey and Mr. George Standridge in particular, for providing access to previously unpublished maps that were extremely helpful. I would like to recognize the Caddo Nation of Oklahoma for granting me access to do field work on tribal lands. My gratitude goes out to Brent McCullough for his help with the equipment used in my research and Jessica Magers for her help throughout this project. I greatly appreciate Brian Varacchi for his help with sample preparation. I am grateful to Dr. Stan Paxton and the United States Geological Survey for discussion and access to core. I wish to thank Dr. Sal Mazzullo and Beau Morris at Wichita State University for access to, and assistance with, equipment used in this study. Many thanks are due to Gareth Seward at the University of California-Santa Barbara for his assistance with the Scanning Electron Microscope. I would also like to express my deep appreciation to the Geological Society of America for financial support of this project (GSA Research Grant # 9464-10), without it, this project would not have been able to be undertaken. Most of all, I would like to thank my parents, Brian and Tammy, and my wife Laura, for the constant support, encouragement, understanding and love they provided me during this challenge.

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CHAPTER I

INTRODUCTION

The Permian siliciclastic red beds of the southern midcontinent, including Oklahoma, have traditionally been interpreted to be shallow marine/fluvial-deltaic in origin (Al-Shaieb, 1988; Johnson et al., 1991; O'Brien, 1963). Recent work on Permian red beds in the southern midcontinent and elsewhere, have challenged some of these shallow marine interpretations (Benison and Goldstein, 2002; Benison et al., 1998; Templet and Soreghan, 2010; Treece, 2009), suggesting instead that they may represent terrestrial or lacustrine deposits. Accurate depositional models are important for this area as they provide a key piece of data needed to fit Oklahoma's Permian rocks into recent paleoclimatic models for the southern midcontinent of North America during the Permian (Peyser and Poulsen, 2008; Poulsen et al., 2007; Soreghan, 1992; Tabor and Montanez, 2004). Eolian depositional systems have not been identified in the southern midcontinent however; their identification would strengthen these new alternative depositional systems as well as paleoclimate models. Eolian depositional systems were extremely important over what is now the Colorado Plateau during the Late Paleozoic through the Middle Mesozoic (Blakey, 1988, 1996; Blakey et al., 1988; Walker and Middleton, 1983), yet there is little or no documentation of eolian systems over the southern midcontinent region during the same time period. Given the prevalence of eolian deposits elsewhere in North America during the Permian, why have they not been identified within the southern midcontinent if conditions there were similar to those further west? I contend that they do exist within the southern midcontinent, but have yet to be recognized due to the lack of detailed sedimentological studies on these units since the widespread recognition of the importance of eolian systems in the 1970's and 1980's. A review of past literature (lithologic descriptions) suggests that the Rush Spring Sandstone (Permian/Guadalupian) is the best candidate for an eolian unit within the Permian succession of Oklahoma.

For this study, the sedimentology of the Rush Springs Sandstone of western Oklahoma was analyzed in detail to document evidence for an eolian origin or influence on these deposits. Other questions that will be addressed by this study include 1) what is the spatial and temporal distribution of Rush Springs facies and depositional environments and 2) what are the nature of the upper and lower contacts of the Rush Springs Sandstone.

In addition to paleoclimatological implications, this study is also important for public health and mineral exploration. The Rush Springs Sandstone is one of the most important aquifers in western Oklahoma (Johnson et al., 1991). Many water wells within the aquifer have arsenic values that are over the safe drinking limit (Magers et al., 2010). Studies on the Garber-Wellington aquifer in central Oklahoma indicate that arsenic abundance varies with lithofacies, with the finer grained lithologies containing more solid-phase arsenic than the relatively coarser grained sandstones (Ground Water Protection Council, 2009). A detailed facies model for the Rush Springs Sandstone will aid in developing a strategy for predicting which units may produce unsafe levels of arsenic in water from this important aquifer.

Permian rocks are also of great economic importance to the state of Oklahoma in that they have produced extensive amounts of hydrocarbons, and other mineral resources, such as gypsum, coal, aggregates and uranium. Eolian deposits are texturally and depositionally complex, which upon diagenesis have proved to be very heterogeneous reservoirs that exhibit intricate porosity and permeability variations (Ahlbrandt and Fryberger, 1982). Better facies and depositional models for the Permian rocks of Oklahoma may lead to new and/or improved exploration and production strategies.

CHAPTER II

BACKGROUND

Geologic Setting

The Rush Springs Sandstone was deposited throughout the Anadarko Shelf and Basin covering a wide area of the North American midcontinent (Figure 1). The Anadarko Basin is a foreland basin, which underlies approximately 60,000 km^2 of west-central Oklahoma and the Texas panhandle (Johnson et al., 1991). In Oklahoma, the basin is bounded by the Nemaha Uplift to the east, the Arbuckle uplift to the southeast, and the Wichita-Criner uplifts on the south (Figure 1). The basin developed as an independent feature from the Southern Oklahoma Aulacogen during the Early Pennsylvanian (Carboniferous) as a result of a collision between North America and Gondwana (Perry, 1989).

By the Early Permian, uplift of the Wichita fault block had mostly ceased (Johnson et al., 1989). During post-Pennsylvanian times, the Anadarko Basin filled with Permian carbonates, evaporates and siliciclastic ‘red beds’ including the sands of the Rush Springs.

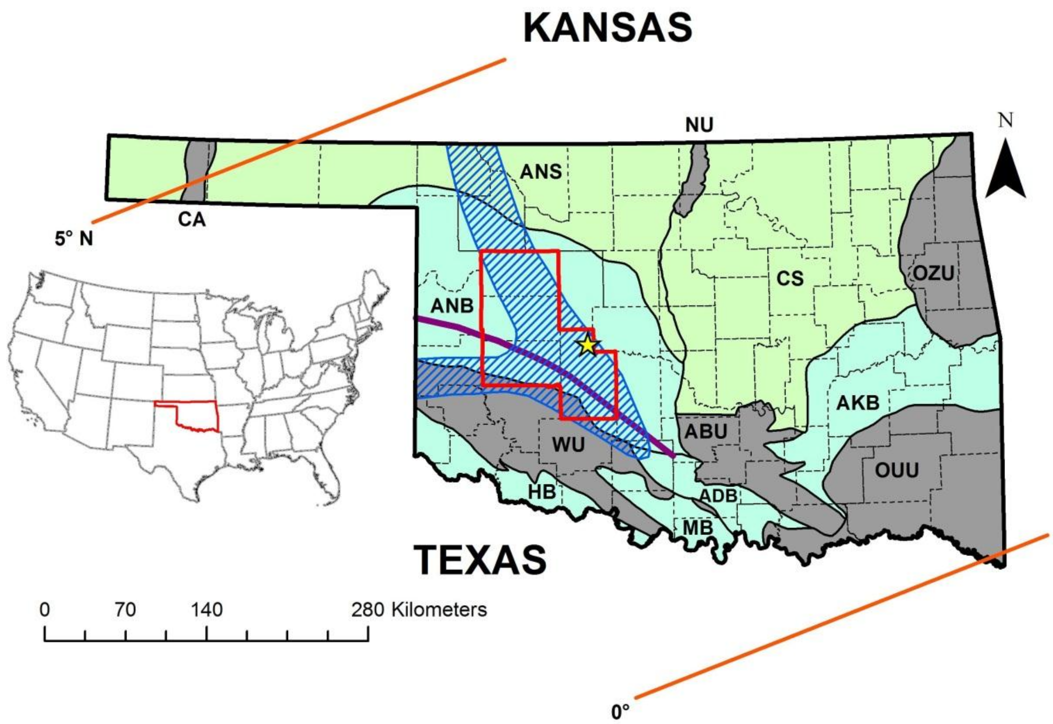

Figure 1. Major geological provinces of Oklahoma and study area location (red border). Hachured area is approximate location of the Rush Springs Sandstone outcrop belt, star is location of Red Rock Canyon State Park, and purple line is the approximate axis of the Anadarko Basin. Approximate Late Permian paleolatitudes from Kocurek and Kirkland (1998) shown in orange. ABU-Arbuckle Uplift, ADB-Ardmore Basin, AKB-Arkoma Basin, ANB-Anadarko Basin, ANS-Anadarko Shelf, CA-Cimarron Arch, CS-Cherokee Shelf, HB-Hollis Basin, MB-Marietta Basin, NU-Nemaha Uplift, OUU-Ouachita Uplift, OZU-Ozark Uplift and WU-Wichita Uplift. Shapefiles of geologic provinces of Oklahoma courtesy of the Oklahoma Geological Survey.

Study Area

With the exception of some Quaternary alluvium and a few Mesozoic remnants, the surface rocks of western Oklahoma are dominantly Permian age. The Rush Springs Sandstone outcrops in a narrow belt extending across the western part of Oklahoma from the Kansas border to the southern portion of the state and west towards the Texas panhandle (Figure 1). The study area for this project is located within this outcrop belt and concentrates on parts of a four county area (Figure 1). In addition, a few sites were visited just outside of the focused study area.

The study area was picked because of its potential to offer the best outcrops available for observation of the Rush Springs Sandstone within the generally low-relief topography of western Oklahoma. The study area includes Red Rock Canyon State Park (Figure 1), which offers the best Rush Springs exposures of anywhere known to the author with public access. The canyon is as much as 45 m deep and vertical canyon walls are generally 13-15 m high, and reach 18 m locally (Suneson and Johnson, 1996). Red Rock Canyon allows for the observation of a large portion, but not the complete interval of the Rush Springs Sandstone, as both the upper and lower contacts are not present at this site. However, other areas allow for the entire Rush Springs Sandstone to be observed.

Upper Permian Stratigraphy of Western Oklahoma

The Rush Springs Sandstone and the underlying Marlow Formation comprise the Permian (Guadalupian) Whitehorse Group (Figure 2). The Whitehorse Group is underlain by the Dog Creek Shale of the El Reno Group (Cisuralian/Guadalupian) and is overlain by the Cloud Chief Formation (Guadalupian/Lopingian).

Fossils are largely absent from the Guadalupian Series of Oklahoma. The only report of fossils within the entire Whitehorse Group has been restricted to the Doe Creek and Verden Lentils of the Marlow Formation (Fay, 1964; Newell, 1940; O'Brien, 1963). Fauna found in these lentils are similar to those found in the Capitan rocks of west Texas (Fay, 1964; Newell, 1940). These fossils include: *Dozierella gouldii* and *Pleurophorus albequus* pelecypods, worm tubes formed by *Spirorbis* sp., and a single species of bryozoan *Lioclema dozierense* (Newell, 1940). Newell (1940) and Fay (1964) both suggest that the fauna represent a lagoonal/brackish-marine environment. Because the strata of the Guadalupian Series in the Anadarko Basin are largely devoid of fossils, age assessments are based mostly on lithostratigraphic correlation to strata in other basins to the south (Johnson et al., 1989). Strontium isotopes from gypsum and anhydrite have been used to date some of the evaporite beds within adjoining units (Denison et al., 1998). Using fossils found in the Marlow below and strontium ages from the Moccasin Creek Gypsum Member of the Cloud Chief Formation above, the Rush Springs Sandstone is bracketed to a Wordian/Roadian age (Soreghan et al., 2008b).

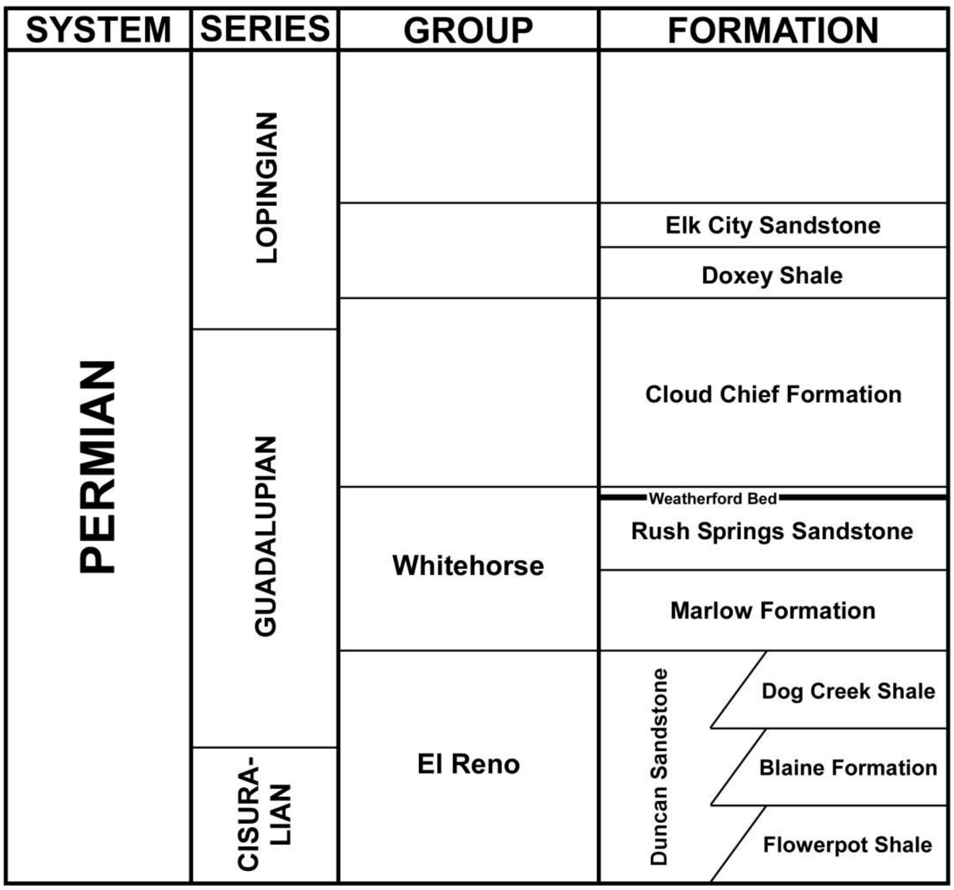

Figure 2. Stratigraphic column of the Upper Permian of western Oklahoma showing the Rush Springs Sandstone and adjacent strata.

Previous Lithologic Descriptions

The Rush Springs Sandstone is described as a very fine to medium grained, subangular to subrounded, friable, subarkosic sandstone that exhibits predominantly medium to large scale trough cross-bedding and less commonly plane bedding (Al-Shaieb, 1988). It has also been described as being a highly silty sandstone (Davis, 1955; Fay, 1962; Tanaka and Davis, 1963).

Analysis by Davis (1955) found the grain size to range from 0.061 to 0.991 mm, with an average grain size of 0.124 mm. Common cements found within the Rush Springs Sandstone include hematite, calcite, dolomite and gypsum (Suneson and Johnson, 1996). The most common cement in the subsurface is gypsum (Johnson et al., 1991). Several thin unnamed evaporite beds exist at various intervals throughout the Rush Springs Sandstone, and a massive gypsum/carbonate bed up to 3 m thick, is found in the upper portion of the unit (the Weatherford Gypsum Bed). Overlaying the Weatherford Bed is a dolomitic sandstone that exhibits less cross-bedding than the lower siliciclastic portions of the Rush Springs Sandstone (Figure 2).

The thickness of the Rush Springs Sandstone varies, with reports ranging from 54 m (Fay, 1962), to 100 m (Tanaka and Davis, 1963). The wide range in thickness has been attributed to erosion of the unit before deposition of the overlying Cloud Chief Formation (Green, 1936). In south-central Oklahoma, the thickness of the Rush Springs Sandstone is approximately 91 m, but the unit thins and becomes increasingly shaly to the north. Because of this northward thinning and fining trend, Fay (1962) proposed that the Rush Springs has a provenance to the south or southeast (probably the Wichita, Arbuckle and Ouachita uplifts). However, Davis (1955) stated that the direction of dip of the foreset beds show that the provenance of the sediments was from the northwest, and that the high degree of sorting and rounding of the grains show that the sediments traveled a great distance. Others favor a provenance to the east/southeast (Suneson and Johnson, 1996).

Nature of Rush Springs Contacts

The stratigraphic relationship of the Rush Springs Sandstone to the adjacent strata has been debated. Donovan (1974) considered the lower contact to be conformable with the Marlow Formation and the upper contact unconformable with the Cloud Chief Formation. Green (1936) considered both contacts to be unconformable. Others consider both contacts to be conformable (Al-Shaieb, 1988; Fay, 1962; Tanaka and Davis, 1963).

Whitehorse Group Depositional Environments

Interpreted depositional environments for the Rush Springs Sandstone also vary, although it has generally been interpreted as a fluvial-deltaic and/or shallow marine unit deposited within a restricted Permian sea. O'Brien (1963) and Davis (1955) considered it to be almost entirely of shallow marine origin. This interpretation was based on the presence of marine fossils within the Doe Creek and Verden Lentils of the underlying Marlow Formation. However, no fossils have been reported from the Rush Springs Sandstone. A deltaic and shallow marine origin for the Whitehorse Group has also been proposed (Nelson, 1983). In addition to the shallow marine environment, some have also suggested an eolian component for the Rush Springs Sandstone. This eolian component has had varying degrees of importance, ranging from none (Davis, 1955; Nelson, 1983; O'Brien, 1963), to very minor (Al-Shaieb, 1988; Tanaka and Davis, 1963), to a significant portion being of eolian character (Johnson et al., 1991; Kocurek and Kirkland, 1998; Myers et al., 1969). Suneson and Johnson (1996) interpret a fluvial origin for Rush Springs sediments that were later re-worked by eolian processes.

Permian Paleoclimate and Paleogeography

By the Permian, the supercontinent Pangaea was almost completely assembled (Parrish, 1995). During the Guadalupian, the North American midcontinent was located at low northern paleolatitudes in central Pangaea just north-northwest of the equatorial Appalachian/Ouachita mountain range (Figure 1). Arid belts bounded the central mountain system to the north and south (Zharkov and Chumakov, 2001).

The Carboniferous-Permian boundary was a time of climate transition (Poulsen et al., 2007). Glaciation in Gondwana during the Carboniferous was extensive, and records the greatest glaciation event of the Phanerozoic (Montanez et al., 2007; Soreghan et al., 2008a). Deglaciation occurred during the Late Carboniferous/Early Permian (Poulsen et al., 2007). This period of climate transition is not only recorded in the glaciation/deglaciation of southern Pangaea, but is also recorded in the tropical Pangean rock record. Paleosols indicate progressive continental drying during this time, from humid tropical during the Late Carboniferous to semi-arid/arid tropical climate during the Early Permian (Tabor and Montanez, 2002, 2004). Atmospheric circulation during the Pennsylvanian consisted of zonal easterly flow (Tabor and Montanez, 2002). However, strong monsoonal atmospheric circulation was established during the Permian (Parrish, 1995; Soreghan et al., 2002; Tabor and Montanez, 2002).

Continental drying and strong monsoonal circulation may help explain why eolian sedimentation dominates deposition in the Colorado Plateau during this time period (Blakey et al., 1988; Johnson, 1989b; Soreghan, 1992). The Pangean tropics during the Late Paleozoic may have seen episodes of freezing continental temperatures, in contrast to today's warm tropics (Soreghan et al., 2008a; Soreghan et al., 2008b). The importance of this new proposed climate for the Permian tropics to erg development is twofold. First, "icehouse" climate weathering processes have been documented to effectively produce large volumes of fine grained siliciclastic sediment for eolian transport and deposition (Smalley, 1966, 1995; Smalley and Vita-Finzi, 1968). Secondly, the aridity that accompanies glaciation would hinder stabilization of sediments by plants. The proposed colder Pangean tropics is in sharp contrast to the traditional lithologic indicators of paleoclimate such as red beds, which have commonly been held to form in hot, dry regions (Habricht, 1979).

Biological stabilization of modern eolian systems is due mostly to grass. Grasses evolved long after the time of dominance by eolian sedimentation in Western Equatorial Pangaea during the Permian through the Jurassic. Although other plants most likely helped stabilize eolian systems during that time, the absence of modern grasses coupled with the continental configuration of Pangaea created favorable conditions for erg development and preservation during that time. It has been proposed that eolian deposition was much more important during the Paleozoic, prior to the evolution of grasses and other land plants, than today (Dott et al., 1986).

CHAPTER III

METHODOLOGY

Measured Sections

23 outcrops were measured and described (Figure 3). Due to the relatively low relief of western Oklahoma, most of the measured sections were 2-3 meters in height. Transects of exposures representing the lower, middle and upper Rush Springs Sandstone were targeted. An outcrop in the western portion of the study area, where the Marlow Formation and the Rush Springs Sandstone are mapped together as the Whitehorse Group was also observed at location MS-11. In addition to measuring section, a long continuous core from the Cloud Chief Formation through the Marlow Formation taken from the western portion of the study area was measured and described (MC-01, Figure 3). Three separate locations were used to collect paleocurrent readings within the study area (MS-16, OL-01 and OL-04). Additional sections were not measured, but used to help determine the temporal and spatial distribution of facies within the Rush Springs Sandstone. Sample selection for grain-size, thin section and SEM analysis was based on lithofacies interpreted from field observations.

Grain-Size Analysis

The friability of the Rush Springs Sandstone allowed for grain-size analysis to be

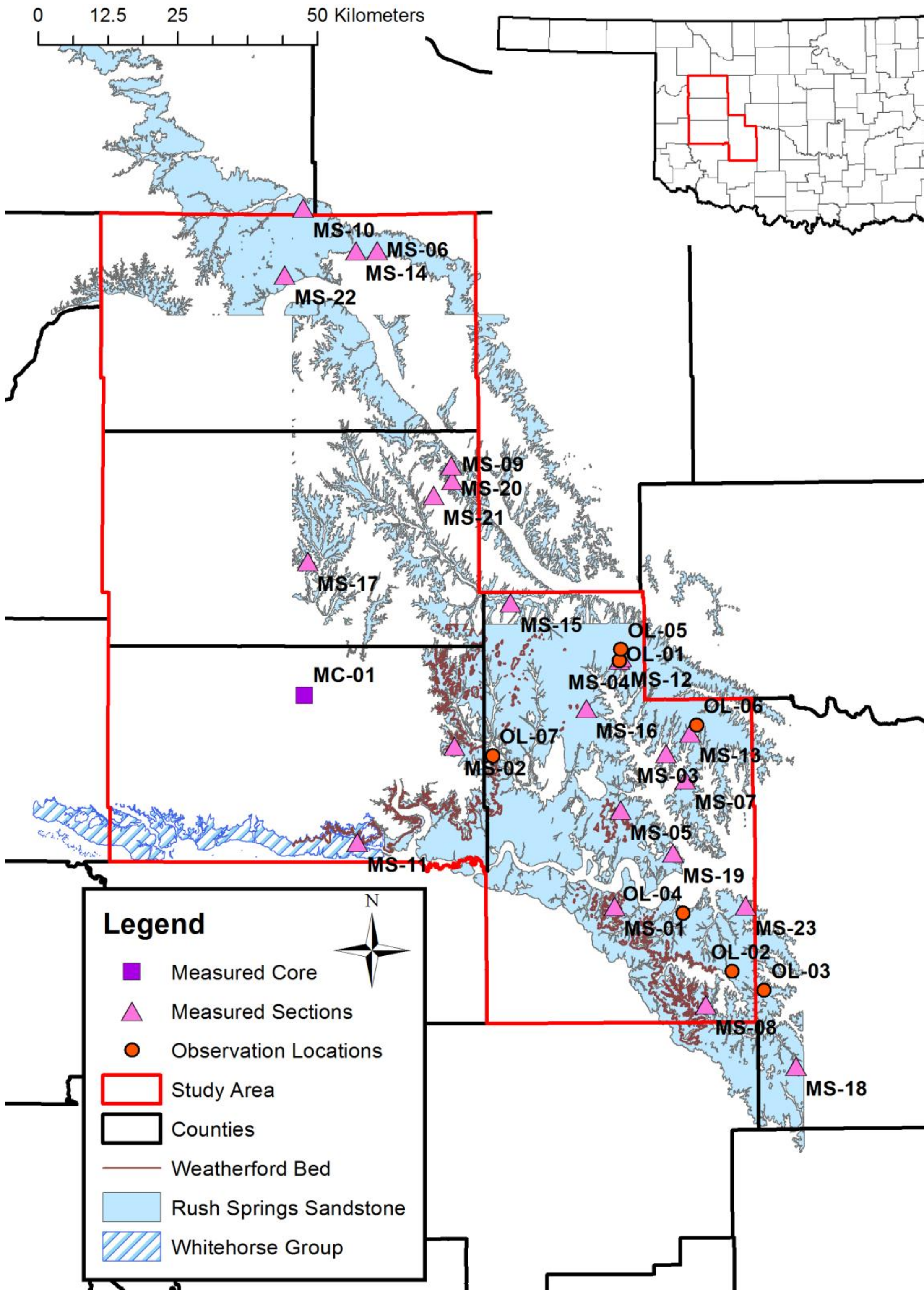

Figure 3. Study area with observation locations plotted over a geologic map showing the Rush Springs Sandstone outcrop belt. MC-measured core, MS-measured section and OL-observation locations. Outcrop belt modified from Johnson et al., 2003; Miller and Stanley, 2004; Oklahoma Geological Survey, Unpublished ; Stanley, 2002; Stanley and Miller, 2005; Stanley et al., 2002.

conducted on 26 different samples, which included all facies identified in the Rush Springs Sandstone, using a CILAS 1180 laser particle-size analyzer. Samples were placed in a hot water bath set at 60°C with 50 ml of 1 M HCl for approximately 8 hours to dissolve cements. After centrifuging and decanting, the samples were rinsed and centrifuged again. This process was repeated three times. Samples with a visible organic component were placed in a hot water bath set at 60°C with 50 ml of 30% hydrogen peroxide for 8 hours to dissolve the organic matter. Samples were centrifuged and rinsed. Once the sample was completely disaggregated, it was split into volumes of between 15-18 ml and soaked overnight in 100 to 125 ml of sodium metaphosphate solution (5.5 g/L), which was used as a dispersing agent. Upon stirring in a magnetic stirrer, a pipette was used to obtain a sub-sample and grain-size analysis was conducted using the method of Sperazza et al. (2004). Each sample was measured at least two times to check for precision. The results from the CILAS were used to calculate mean grain size, standard deviation (grain sorting) and skewness using the method of moments (Folk, 1974; Folk and Ward, 1957) for each sample.

Thin Sections

A total of 16 thin sections of the Rush Springs Sandstone were made for this study, with 3-5 thin sections from each facies assemblage within the Rush Springs Sandstone. Thin sections were analyzed to determine the mineralogical and textural maturity of the Rush Springs Sandstone. Four point counts of 100 points each were conducted on a grid for each thin section, with special attention devoted to the amount and type of framework grains, matrix, cements, and porosity.

SEM

Four Rush Springs Sandstone samples were analyzed using an FEI Quanta 400F environmental SEM in order to identify surface textures on quartz sand grains (Abd-Alla, 1991; Krinsley and Donahue, 1968; Krinsley et al., 1976; Krinsley and Takahashi, 1962b). Samples analyzed were restricted to the fluvial and eolian dune facies of the Rush Springs Sandstone. Sample preparation consisted of gently disaggregating samples by hand and sieving the samples to isolate the 63-150 μm grains. These grains were treated with ultasonics for less than 5 minutes to remove any possible clay coatings. After ultrasonic treatment the grains were decanted and allowed to dry. Once dry they were mounted on stubs using conductive double sided tape.

CHAPTER IV

RESULTS

Facies and Interpretations

Based on field and lab observations 4 facies assemblages are identified within the Rush Springs Sandstone. These facies assemblages are grouped together based upon sedimentary structures and textures and inferred depositional processes. These assemblages represent eolian dune, interdune, eolian sand sheet and extradune processes (Table 1).

Dune Facies Assemblage

The dune facies assemblage contains large (meter) scale cross-bedded facies, climbing translatent strata facies, grainfall laminae facies and grainflow cross strata facies (Table 1; Figure 4). The average grain size of the dune facies assemblage is very fine sand (3.29 ϕ). The sediments are poorly sorted, although part of its poorly sorted nature may be attributed to diagenesis (see discussion). The skewness of the grain-size distribution is nearly symmetrical, grain-size frequency curves (GSCF) of the dune facies assemblage are unimodal (Figure 5). Thin section analysis reveals that this facies assemblage is a submature subarkose (Figure 6). SEM images show grain surface textures indicative of eolian deposits (Figure 7) including: upturned plates (Krinsley and McCoy, 1978), graded arcs (Krinsley and Donahue, 1968) and elongate

Table 1. Facies assemblages of the Rush Springs Sandstone (Permian/Guadalupian), western Oklahoma.

System	Facies Assemblage	Facies	Fossils/Trace Fossils	Lithology	Interpreted Environment
Continental	Eolian Dune	Large cross-bedding (various types, a few meters thick), elongate depressions (ED), upturned plates (UP), graded arcs (GA)	Rare vertical/sub-vertical burrows	Sandstone (arenite), very fine grained, poorly sorted subarkose	Leeward slope of large migrating dunes or draas
		Large (meters) trough cross-beds, ED, UP, GA			Interpreted as cross-beds perpendicular to dune migration
		Climbing translatent strata (inverse grading), ED, UP, GA	NA		Migrating wind ripples
		Small to medium trough and tabular cross bedding w/ grainfall and grainflow cross strata, ED, UP, GA	NA		Leeward slope of small to medium sized migrating dunes
	Eolian Interdune/ Sand Sheet	Convolute bedding	NA	Sandstone (arenite), very fine grained, poorly sorted subarkose	Water saturated leeward slope of migrating dunes, interdune ponds
		Planar bedding	NA		Interdune
		Massive	NA		Interdune/eolian sand sheet
		Cut and fill, ripple lamination, mud drapes, structureless	NA	Siltstone, coarse silt	Eolian sand sheet
		Laminated, planar and ripple lamination (CRL)	NA	Sandstone (arenite), very fine grained, poorly sorted subarkose	Interdune ponds
		Massive, laminated (planar, ripple, algal)	Tapered root casts	Very calcareous sandstone, mud-shale, matrix supported mudstone conglomerate	Interdune ponds/playa lake
	Extradune	Massive (structureless), flaggy, blocky	NA	Siltstone, coarse silt	Playa, siliciclastic sabkha
				Mudstone conglomerate, gypsum, dolomite	Sheet floods on playa, sabkha
		Graded bedding, low angle cross-bedding, massive bedding, generally smooth surface texture	NA	Sandstone (arenite), very fine sand, very poorly sorted	Fluvial (braided streams)
		Normal graded bedding, small trough cross-bedding, smooth surface texture	NA	Pebble conglomerates to Sandstone (arenite)	Incising fluvial channels, seen in core, not found in outcrop
		Planar lamination	NA	Silt-shale, siltstone	Mudflat
		Ripples; CRL, algal	NA	Silt-shale, siltstone, gypsum, dolomite	Mudflat
Marine		Laminated (algal), crinkly, desiccation cracks, massive	NA	Sandy carbonate, gypsum	Restricted marine, playa lake (Weatherford Bed)

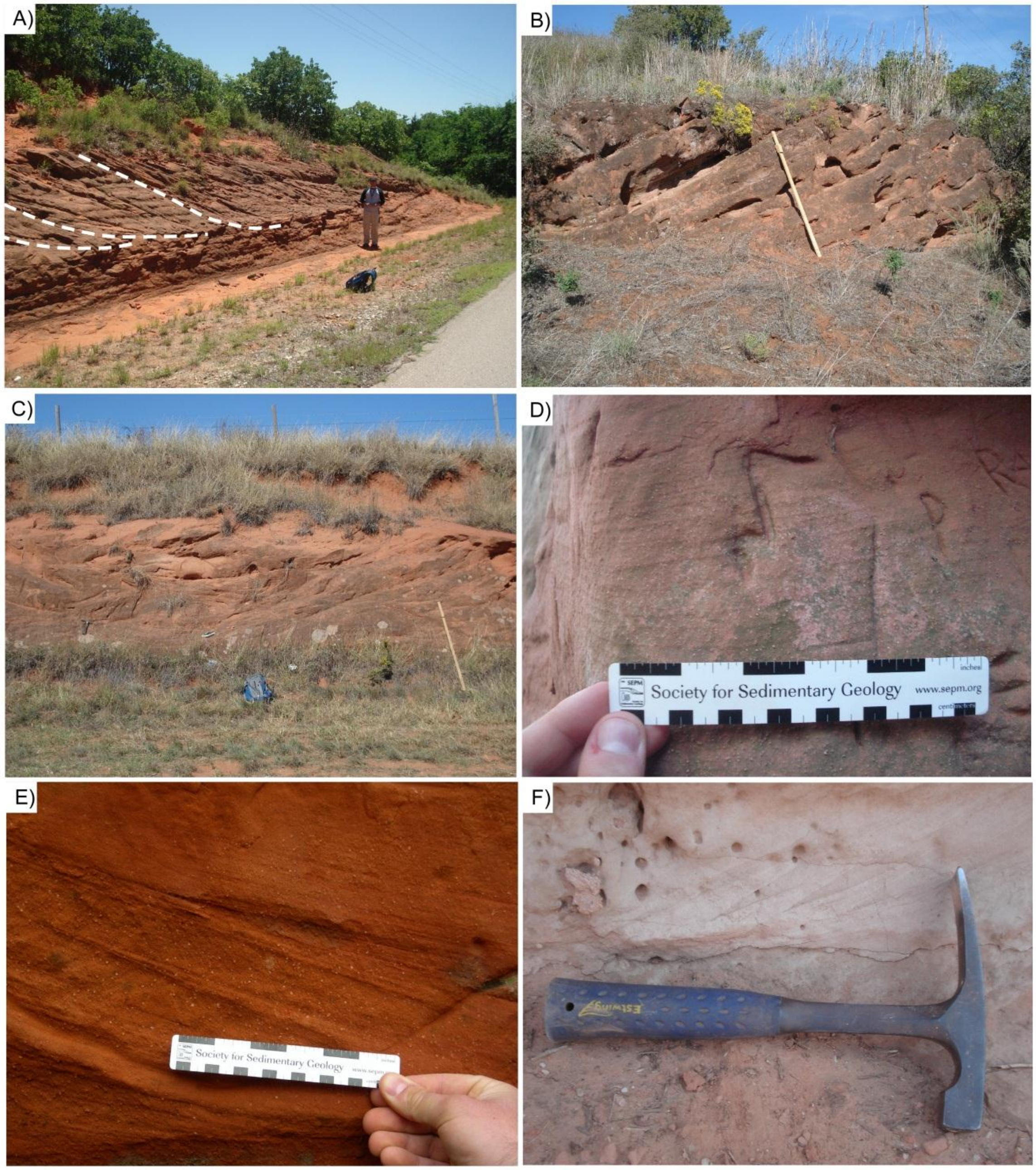

Figure 4. Eolian dune facies assemblages. A) Wedge-planar cross-bedded facies preserving foresets and toesets, note tangential bedding at base (dashed lines), MS-19, B) tabular-planar cross-bedded facies, OL-07, C) large trough cross-bedded facies of dunes along strike, MS-16, D) climbing translatent strata facies, MS-12, E) tabular cross-bedded facies with grainfall laminae and grainflow cross strata, MS-12, F) grainfall laminae and grainflow cross strata facies, MS-09.

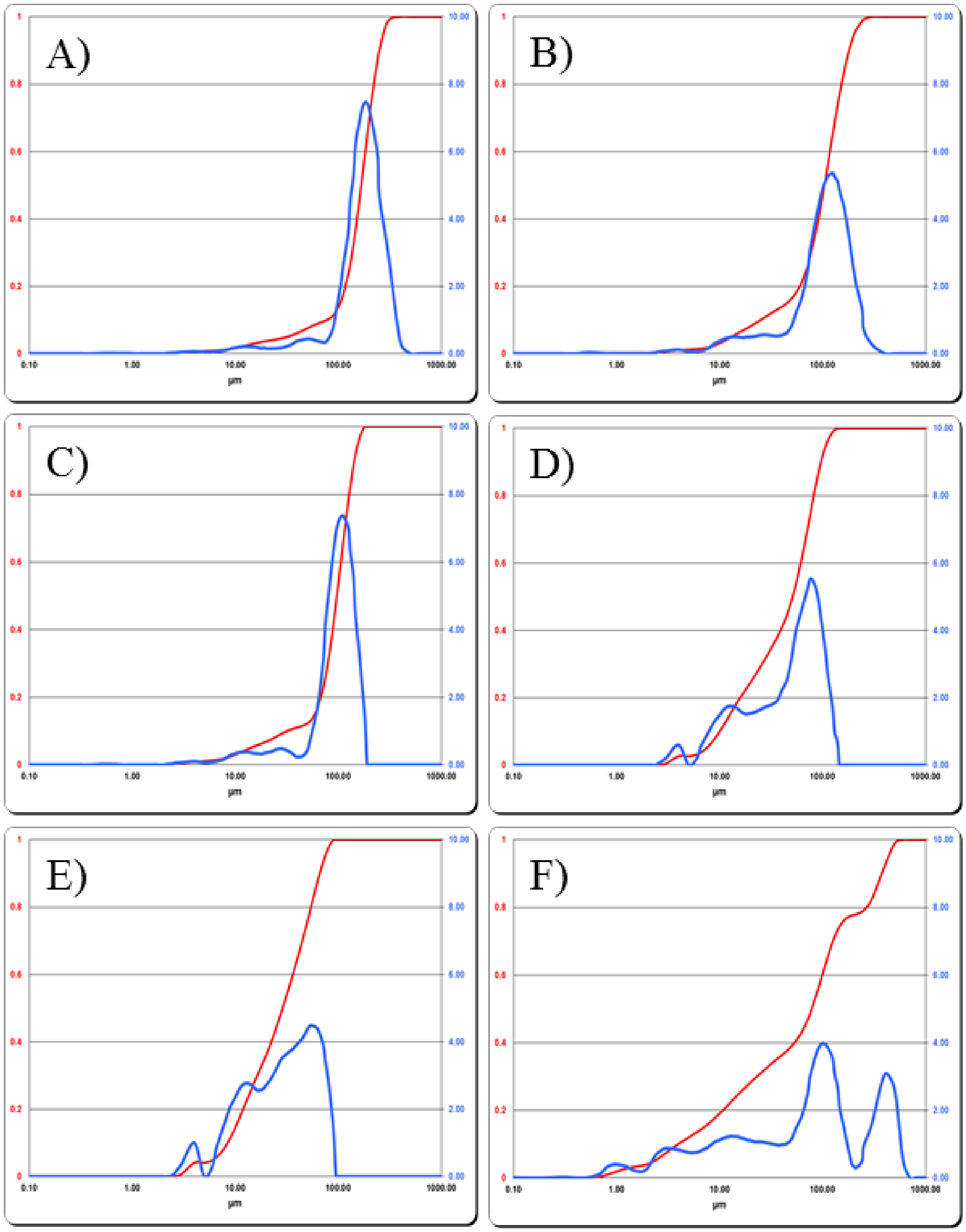

Figure 5. GSFC of Rush Springs Sandstone, blue curve is histogram percent; red curve is cumulative percent, x-axis is grain size in µm. A) Dune facies assemblage, MS-19, B) interdune facies assemblage, MS-19, C) deflationary sediments, MS-02, D) eolian sand sheet facies assemblage, MS-21, E) argillaceous sabkha facies of the extradune facies assemblage, MS-14, and F) fluvial facies of the extradune facies assemblage, MC-01.

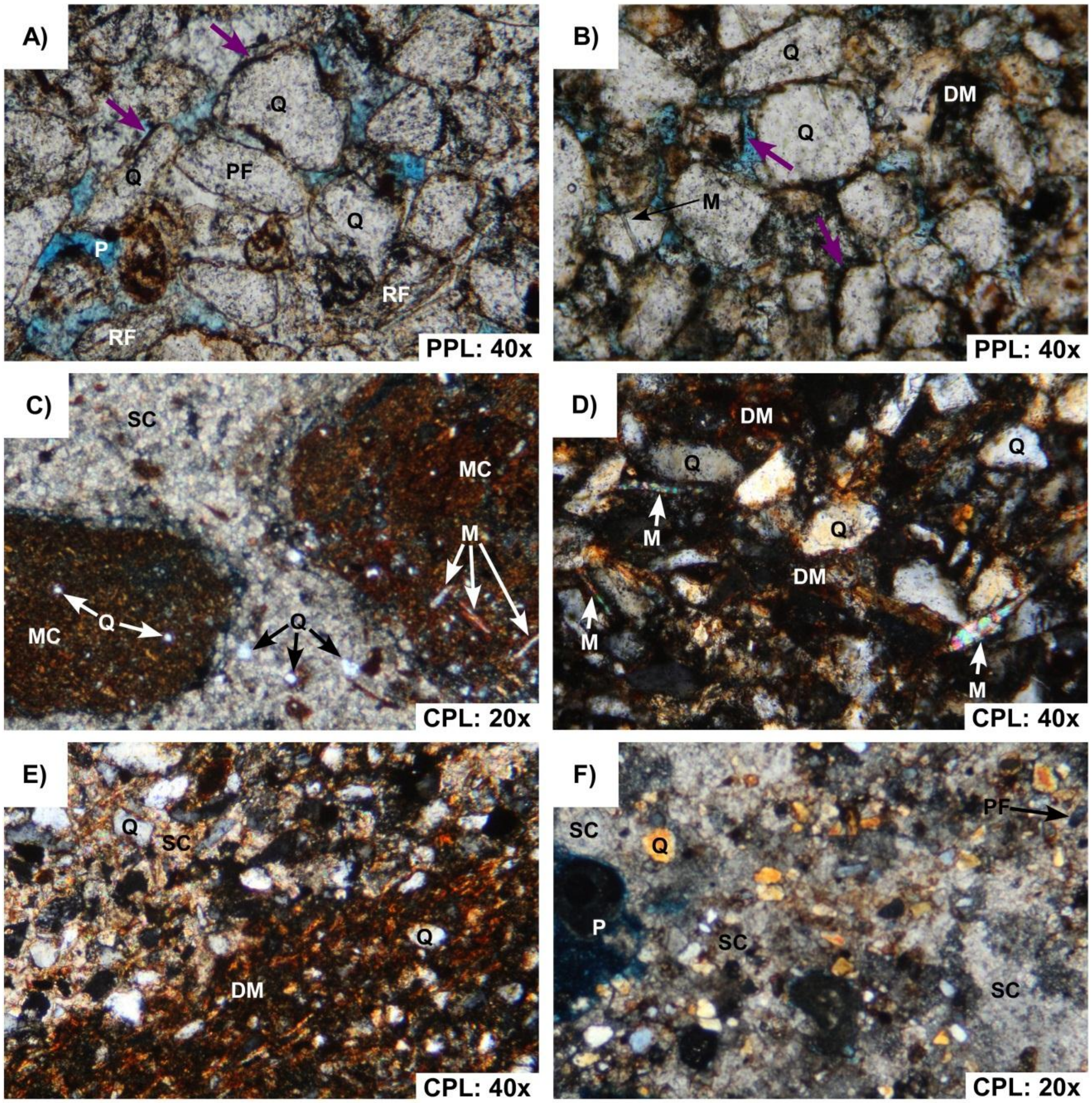

Figure 6. Thin section photomicrographs of the Rush Springs Sandstone. A) Dune facies assemblage, OL-07, showing grain roundness and clay coatings (purple arrows), Q = quartz, PF = plagioclase feldspar, P = porosity, RF = rock fragment, B) Interdune facies assemblage, MS-12, showing grain roundness and clay coatings (purple arrows), DM = detrital matrix, M = muscovite, C) mudstone conglomerate of the lacustrine facies of the eolian sand sheet facies assemblage, MS-06, showing mudstone clasts (MC) in a calcareous sandstone matrix of siliciclastic grains in sparry calcite cement (SC), D) Cut and fill facies of the eolian sand sheet facies assemblage, MS-21, showing increase in amount of muscovite (M) and detrital matrix (DM), E) argillaceous sabkha facies of the extradune facies assemblage, MS-14, showing laminations of fine grained siliciclastics with much detrital matrix (DM) and laminations of relatively larger grains with extensive sparry calcite cement (SC), and F) calcareous Weatherford facies of the extradune facies assemblage, MS-02, showing poikilotopic texture of siliciclastic grains floating in sparry calcite cement (SC). PPL = plane polarized light, CPL = cross polarized light, stratigraphic top is towards top of page in all cases.

depressions (Krinsley et al, 1976). Although individual facies within the dune facies association share the same basic petrographic characteristics as discussed above, they differ in their sedimentary structures.

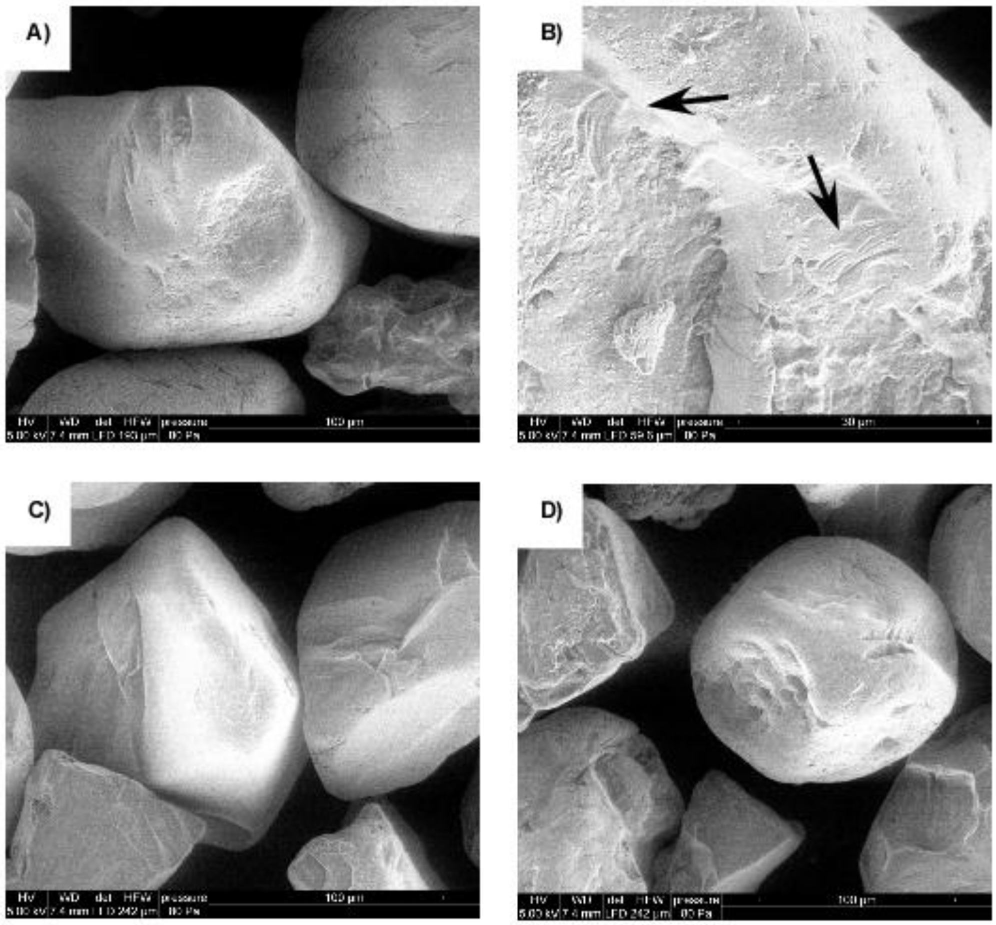

Figure 7. SEM photomicrographs of the Rush Springs eolian dune facies assemblage, OL-05. Showing A) interpreted uptuned plates within the depression (Krinsley and McCoy, 1978), B) graded arcs (arrows) (Krinsley and Donahue, 1968), C) elongate depressions (Krinsley et al., 1976) and D) excellent grain rounding.

<u>Large-scale cross bedded facies</u>

The first facies is marked by the most common characteristic used to describe the Rush Springs Sandstone, large scale trough cross-bedding (Al-Shaieb, 1988; Johnson et al., 1991; O'Brien, 1963). In outcrops along strike, classic festoon trough cross-beds on the order of one to two meters thick and seven to ten meters wide seem to prevail (Figure 4C).

However, parallel to dip, the same beds within the Rush Springs Sandstone take on a wedge-planar or a tabular-planar shape (Figure 4A & 4B). Fryberger (1979) attributes the appearance of differing cross-bedding types to the angles of exposure. Instead of having curved basal surfaces of erosion, bounding surfaces of the cross-bedded facies often converge to become tangential at the base, forming a shallow crescent-like shape (Figure 4A). McKee and Weir (1953) suggest that tangential bounding surfaces implies deposition by wind. Deposition on the lee side of dunes (high dip angle) forms cross-bedding with decreasing dip angle that gradually grades into low angle to horizontal stratification formed in dune aprons on the upwind portion of the adjoining downwind interdune (Kocurek and Havholm, 1993). This large scale cross-bedded facies represents the deposits of large bedforms (dunes and draas).

Climbing translatent strata facies

The second facies found in the dune facies assemblage of the Rush Springs Sandstone contains the climbing translatent strata of Hunter (1974) (Figure 4D). They consist of thin inversely graded strata that exhibit uniform thickness (Hunter, 1980). Climbing translatent strata are one of the most diagnostic eolian signatures (Hunter, 1977; Hunter, 1980; Hunter, 1981; Kocurek and Dott, 1981; Loope, 1984b). They are formed by the migration of wind ripples on the topsets, bottomsets and gently dipping lee sides of dunes and on dune aprons (Hunter, 1980; Irmen and Vondra, 2000; Loope, 1984a). Inverse grading within translatent strata is due to the concentration of coarser grains in the ripple crest.

Grainfall laminae and grainflow cross strata facies

Other sedimentary facies found in the eolian dune facies assemblage of the Rush Springs Sandstone include discrete intervals, usually less than a meter thick, of tabular-planar cross-beds that exhibit grainflow cross strata intertonguing with grainfall laminae (Figure 4E & 4F). Grainflow cross strata are formed from the avalanching of sand down the lee side of dunes when the angle of repose has been exceeded. Grainfall laminae form when saltating grains are no longer able to be carried by the flow because of flow separation on the leeward sides of dunes (Hunter, 1977). Grainflow cross strata have a tendency to rework grainfall laminae upon avalanching. As a result, grainfall laminae and grainflow cross strata are often found together. Grainfall laminae are more likely to be preserved within eolian systems, and thus have been argued to be representative for eolian systems (Hunter and Kocurek, 1986). These relatively thin intervals exhibiting grainfall laminae and grainflow cross strata are bounded on the top and bottom by sharp, roughly planar contacts. This facies is thought to be formed by the migration of small eolian dunes on sand flats. In Red Rock Canyon State Park, this facies exhibits a range of paleocurrent directions. Because smaller bedforms are more responsive to periodic changes in wind directions than larger bedforms, a variety of paleocurrent directions suggest that the small bedforms were not arranged in regular trains but were responding rapidly to seasonal shifts in paleowind direction (Loope and Simpson, 1992; Mountney, 2006).

Interdune/Eolian Sand Sheet Facies Assemblages

The interdune/eolian sand sheet facies assemblage of the Rush Springs Sandstone includes convolute bedded facies, planar bedded facies, massive bedded facies, cut and fill facies, laminated facies, and lacustrine facies (Table 1; Figure 8). As eolian sand sheets are a transitional zone between dune/interdune and extradune depositional environments (Fryberger et al., 1979), they share many similarities with these neighboring environments. We grouped interdune and eolian sand sheet facies assemblages together due to the similarity of the facies within the assemblages, and because they are both characterized by low angle/horizontal stratification.

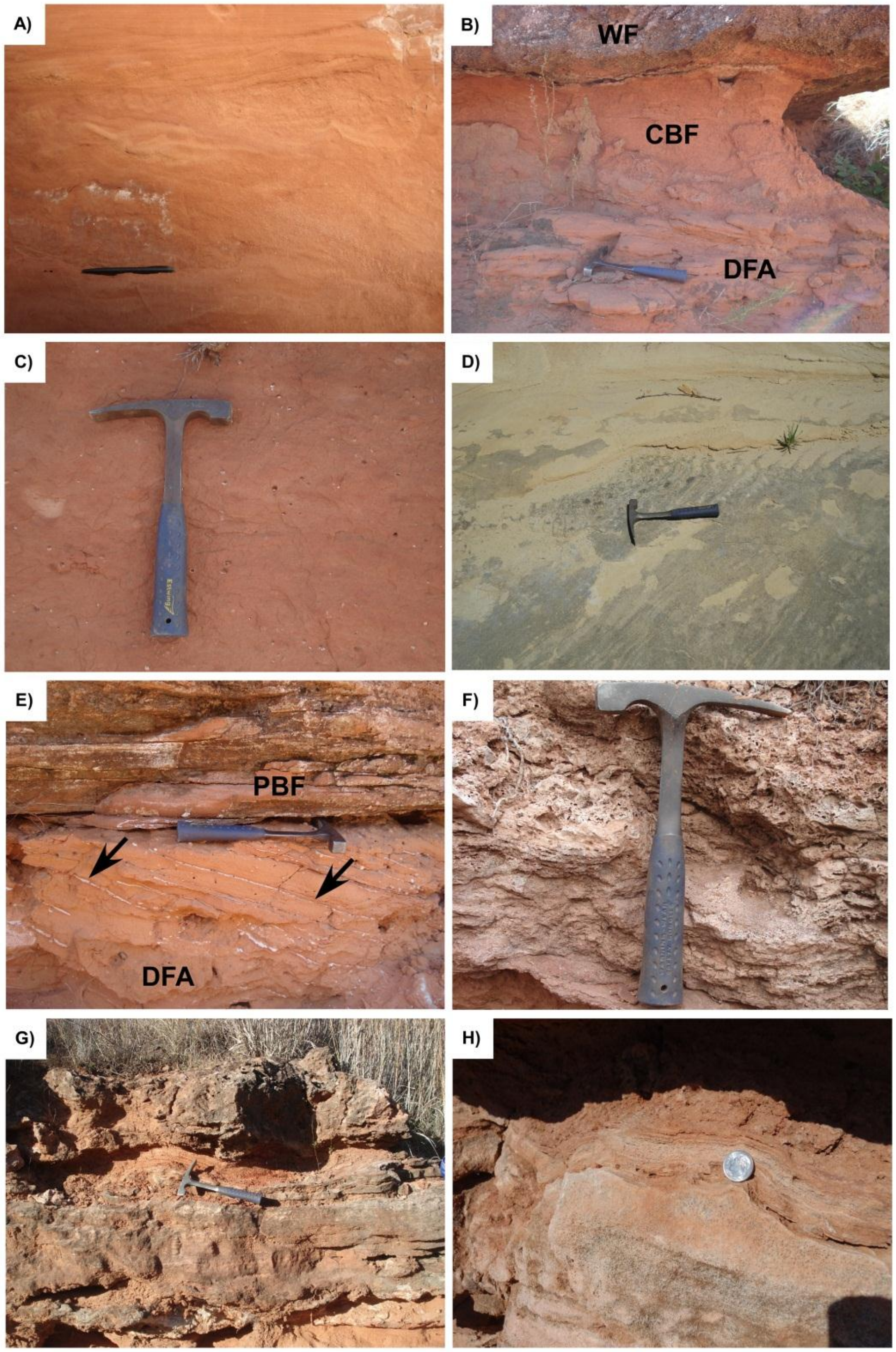

Figure 8. Interdune and eolian sand sheet facies assemblages. A) Convolute bedded facies of the interdune facies association, MS-12, B) convolute bedded facies (CBF) associated with the Weatherford Bed (WF), note cross-bedding of the dune facies assemblage (DFA) below, MS-02, C) cut and fill facies of the eolian sand sheet facies assemblage with a small scour and fill structure, MS-21, D) low index (~14) ripple laminated facies in interdune facies assemblage, OL-03, E) plane bedded facies (PBF) of the interdune facies assemblage erosionally truncating high angle cross-bedding of the dune facies assemblage (DFA), MS-13, note white calcareous nodules (arrows) along bedding planes below the truncating surface, F) & G) lacustrine facies, MS-06 and MS-18 respectively and H) algal laminations of sandy carbonate and mudstone of the lacustrine facies, MS-18.

The average grain size of the interdune facies assemblage is very fine sand (3.94 ϕ). The sediments of the interdune facies assemblage are poorly sorted, with a skewness that is nearly symmetrical. Like the dune facies assemblage, the poor sorting of the interdune facies assemblage is attributed to diagenesis. GSFC of the interdune facies assemblage are unimodal (Figure 5). The interdune facies assemblage, like the dune assemblage, is a submature subarkose (Figure 6). The eolian sand sheet facies assemblage has a mean grain size of coarse silt (4.67 ϕ). Sediments of this facies assemblage are poorly sorted and the grain-size distributions are fine skewed. GSFC of the eolian sand sheet facies assemblage are generally bimodal (Figure 5). The eolian sand sheet facies assemblage contains more muscovite and detrital matrix than the interdune facies assemblage (Figure 6). The eolian sand sheet facies assemblage is immature to submature.

In general, interdune deposits of the Rush Springs Sandstone are less than two meters thick. No evidence of deflation lags have been found in the interdune facies assemblage of the Rush Springs Sandstone, therefore they are considered depositional. Several facies comprise the interdune and eolian sand sheet facies assemblage and are distinguished by their sedimentary structures.

Convolute bedded facies

The convolute bedded facies is common in the interdune facies assemblage of the Rush Springs Sandstone (Figures 8A & 8B). The convoluted beds are on the order of 5-15 cm thick with wavelengths of several tens of centimeters. The convolute bedded facies of the Rush Springs Sandstone is most commonly found directly below the Weatherford Bed (Figure 8B, Figure 9). However, in some cases, such as at Red Rock Canyon State Park (MS-12, Figure 8A) convolute bedding is found independent of evaporites. Convolute bedding is found in many eolian sandstones of the western United States, and their modern analogs (Ahlbrandt and

Fryberger, 1982; Fryberger, 1979; Fryberger et al., 1983; Kiersch, 1950; McKee, 1966; Walker and Middleton, 1983). Convolute beds immediately below the evaporites within the Rush

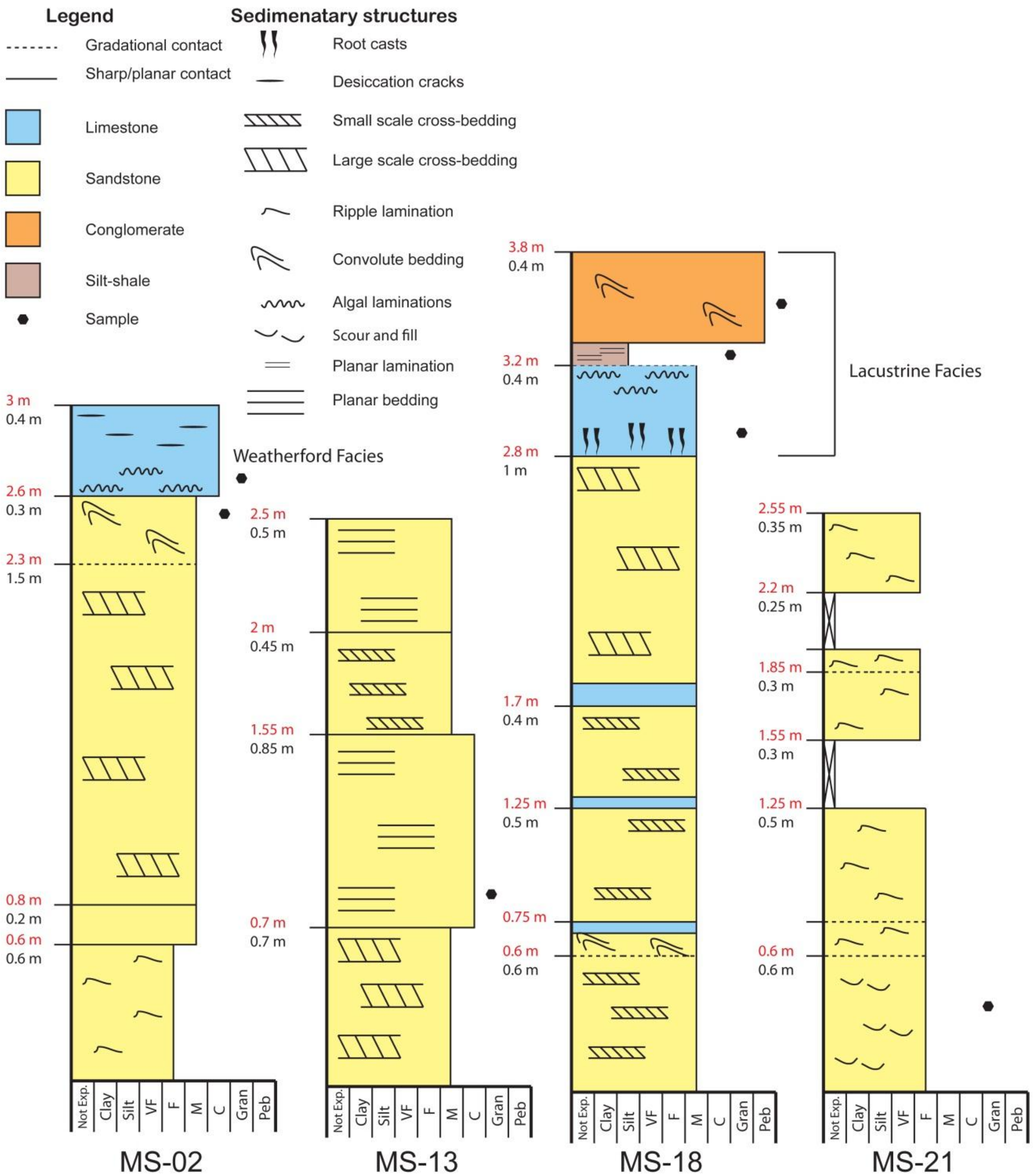

Figure 9. Select measured sections from the interdune and eolian sand sheet facies assemblages. These sections show the convolute bedding below the Weatherford Bed (MS-02), the sharp contacts between interdune and dune facies assemblages as the result of downwind migration of bedforms (MS-13), the lacustrine facies of the interdune facies assemblage (MS-18), and the cut and fill facies of the eolian sand sheet facies assemblage (MS-21).

Springs Sandstone probably formed due to saturation of the sand upon marine or lacustrine encroachment into the dune field prior to desiccation and evaporite deposition. In the cases where they are not found below evaporite beds, they may have formed from saturation of interdune sand due to a high water table or seasonal rainfall.

Planar bedded facies

A planar bedded facies is also a common component of the interdune facies assemblage of the Rush Springs Sandstone. In the Rush Springs Sandstone, the planar bedded facies commonly truncates underlying large, high angle (~25°) cross-bedded facies of the dune facies assemblage (Figure 8E, Figure 9). The sharp, horizontal boundaries between the high angle cross-beds (dune) and the planar beds (interdune) form from the climbing of successive bedforms, resulting in the truncation of the previous dune's cross-bedding as the trailing bedform migrates downwind. Occasionally, nodules appear just below this truncation surface (Figure 8E). Rubin and Hunter (1984) attribute similar evaporite precipitation along bedding planes to be the result of evaporite precipitation on an interdune flat or dune-free surface.

Massive facies

The structureless facies is common to both the interdune and eolian sand sheet facies assemblages of the Rush Springs Sandstone. The massive beds are usually <70 cm thick. True massive bedding is very rare and often attributed to destruction of primary bedding by bioturbation. However, burrows or root casts are rare within the Rush Springs Sandstone. The scarcity of evidence for bioturbation in the Rush Springs Sandstone suggests the massive bedding represents deposition without bedforms rather than non-preservation of sedimentary structures.

Cut and fill facies

The cut and fill facies consists of cut and fill structures, ripple lamination, mud drapes, massive bedding and silt sized grains. Cut and fill structures in the Rush Springs Sandstone are less than a decimeter wide and are a few centimeters deep and filled with massive fine grained sandstone and siltstone. Cut and fill structures have been widely reported in interdune and sand sheet deposits in the literature (Ahlbrandt and Fryberger, 1981; Ahlbrandt and Fryberger, 1982; Fryberger et al., 1979; Fryberger et al., 1983; McKee, 1966). Locally cut and fill structures are present in the Rush Springs Sandstone (Figure 8C, Figure 9) where they are found cutting into the massive and laminated facies. Ripple laminations with mud drapes are also found within this relatively finer grained facies. This facies is interpreted to be eolian sand sheet deposits that occasionally experienced fine grained sheet floods. Similar environments have been described in modern eolian sand sheets in western North America (Kocurek and Nielson, 1986).

Laminated facies

Another facies common to both the interdune and eolian sand sheet facies assemblages is the laminated facies. The laminated facies is a fine grained sandstone to sandy siltstone. This facies contains ripple marks and climbing ripple lamination (Figure 8D). Both planar and climbing ripple lamination forms are present. Ripple index (the ratio of ripple wavelength/height) is a reliable indicator of the transporting fluid (McKee, 1934). The average ripple index of ripples in the interdune facies assemblage of the Rush Springs Sandstone at OL-03 is 14.07. Ripple indices >15 are considered to be of wind origin (Ahlbrandt and Fryberger, 1982; McKee, 1934; Walker and Middleton, 1983). When ripple indices <15, subaqueous deposition is indicated. Ahlbrandt and Fryberger (1982) state that subaqueous deposits are compatible with eolian depositional systems. These low index ripples probably formed in interdune ponds, possibly after a rainstorm, or during times of a high water table, consistent with their occurrence in the interdune facies assemblage.

Lacustrine facies

The interdune and eolian sand sheet facies assemblages of the Rush Springs Sandstone also contain a repeated succession generally <60 cm thick of bed sets comprised of four lithologies (Figure 9). They are (in ascending order): 1) massive, very calcareous sandstone and or sandy carbonate (Figure 8G), 2) laminated sandy limestone, that exhibits evidence of desiccation in the form of sheet cracks (Figure 8H), 3) laminated (of various types) mud-shale or silt-shale (Figure 8H), and 4) massive, calcareous, matrix (sand) supported, mudstone conglomerate (Figure 6, Figure 8F). The mudstone clasts of the mudstone conglomerates are round, less than 1.5 cm in diameter (pebble sized), and appear to be sourced from the mud-shale/silt-shale below (Figure 8). The mudstone conglomerates weather vuggy in outcrop due to differential weathering between the mudstone clasts and the calcareous sandstone matrix. The boundaries between the differing lithologies in the sequence are often gradational, and locally, some of the lithologies are missing from the succession.

At MS-18, excellent examples of root casts are found in the calcareous sandstone at the base of the succession described above (Figure 10). Root casts found in the Rush Springs Sandstone are vertical to sub-vertical and less than 4 cm in diameter. These root casts differ from the micritic rhizoliths Loope (1988) described from Paleozoic/Mesozoic eolianites in the western United States, because they are molds of roots that have been filled with sand from above, then preferentially cemented, in the same manner as Glennie and Evamy (1968) described. Root casts are quite common in both modern (Ahlbrandt et al., 1978; Fryberger et al., 1983; Lancaster and Teller, 1988) and ancient (Driese, 1985; Loope, 1988) eolian deposits, and are excellent indicators of a subaerial environment (Esteban and Klappa, 1983). Root casts in the Rush Springs Sandstone can be differentiated from burrows because they exhibit tapering (Figure 10). The distribution of vegetation is closely linked to water availability in the eolian environment (Riese et al., 2011).

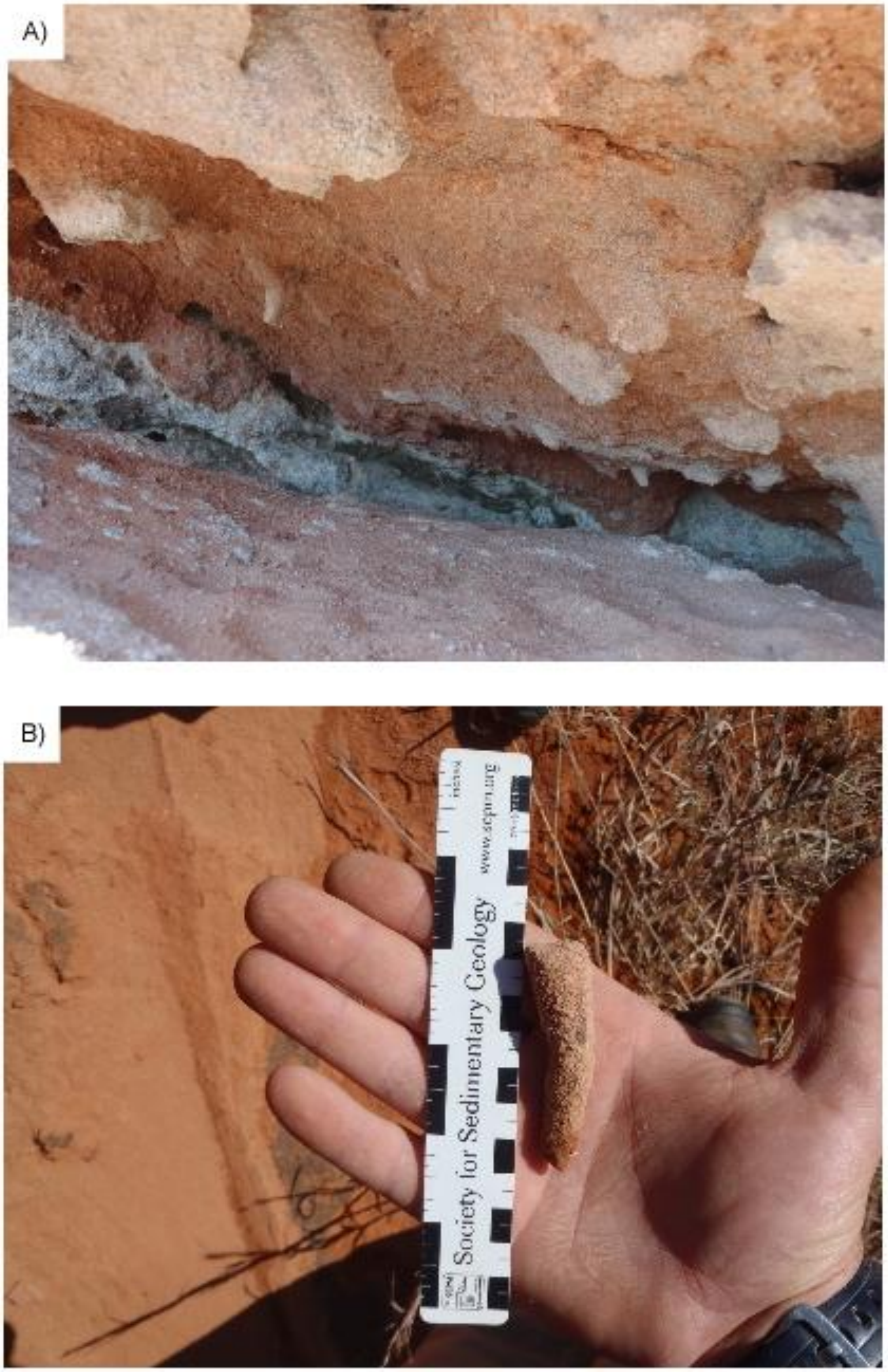

Figure 10. Root casts from Rush Springs Sandstone, MS-18. A) root casts form positive features within the calcareous sandstone bed due to differential weathering (sole feature), B) root cast showing well defined tapering.

The sandy carbonate and mudstone conglomerates found in the lacustrine facies of the interdune and eolian sand sheet facies assemblages are interpreted to be interdune pond and playa lake deposits respectively. This interpretation is based on 1) the occurrence of these deposits vertically adjacent to high angle cross stratified sandstone of eolian dune origin, 2) the gradational nature of the contacts of the deposits with dune deposits, 3) evidence of desiccation due to subaerial exposure in the form of sheet cracks, 4) the absence of marine fauna within the carbonates, 5) the presence of tapered root casts, and 6) the similarity between the sand grains of this facies and those of the eolian dune facies assemblage.

Freshwater carbonates deposited in interdune ponds, similar to those found in the Rush Springs Sandstone have been observed in a number of Paleozoic and Mesozoic eolian sandstones of the western United States. These include the Cedar Mesa Sandstone of southeastern Utah (Loope, 1985), the Casper Formation of Wyoming and Colorado (Hanley and Steidtmann, 1973), the Navajo Sandstone of southeastern Utah (Gilland, 1979; Pipiringos and O'Sullivan, 1975; Winkler et al., 1991), and the Weber Sandstone of northern Colorado and Utah (Driese, 1985; Fryberger, 1979). Freshwater carbonates are also common in the modern Namib Erg in southwestern Africa (Lancaster and Teller, 1988). The laminated mud-shale/silt-shale in the middle of the association was probably the result of trapping of fines in suspension by standing water or damp surfaces. The laminations in the shales and sandy carbonates commonly exhibit an algal form (Figure 8H).

Some freshwater carbonates in eolian sandstones described in the literature, like those of the Rush Springs Sandstone, are found below conglomerates (Driese, 1985; Hanley and Steidtmann, 1973). Driese (1985) and Hanley and Steidtmann (1973) believe that these conglomerates arise from desiccation of pond sediments due to subaerial exposure and subsequent reworking of the clasts either by wind (Driese, 1985) or water (Hanley and Steidtmann, 1973). Similarity between the mudstone clasts found in the conglomerates to the underlying mud-shale/silt-shale suggests that the same process could have operated in the Rush Springs Sandstone, producing intraformational conglomerates. A lack of cross-bedding within the conglomerates supports an intraformational origin. In the Rush Springs Sandstone, a subaqueous reworking for the mudstone clasts is favored because of the extent of calcite cementation and the convolute bedding of the conglomerates. Mudstone clasts within the conglomerates are not evenly spaced as is generally the case for eolian deflation lags (Ahlbrandt and Fryberger, 1981; Rodriguez-Lopez et al., 2010; Walker and Middleton, 1983; Walker and Harms, 1972).

Extradune Facies Assemblage

The Rush Springs Sandstone thins and fines in the northern portion of the study area, where it also exhibits a different character than it does to the south and southeast. This lithologic change was also noted by Fay (1962) and Johnson et al. (1991). In the north part of the study area, large scale cross-bedding is rare and a different facies assemblage consisting of sabkha facies, fluvial facies and the Weatherford facies are found (Table 1, Figure 11). Chaotic or structureless deposits of siltstone and sandstone are also observed. It is unclear whether these structureless deposits are depositional or formed by secondary processes. Sinkholes formed by the dissolution of evaporites in the subsurface are common in the area (Stanley et al., 2002), and these chaotic deposits could have formed from collapse and fill of subsurface caverns. Evidence of this process is observed at MS-10, where structureless Rush Springs deposits are in contact with a cave collapse breccia containing clasts of Rush Springs Sandstone and younger deposits (Figure 12). Two additional gypsum beds appear with the Weatherford Bed in the upper Rush Springs Sandstone in the north part of the study area.

Figure 11. Extradune facies assemblage. A) Argillaceous sabkha facies, MS-14, B) arenaceous sabkha facies, in core MC-01, showing convolute bedding, C) arenaceous sabkha facies in outcrop, MS-22, showing ripple laminations, D) fluvial facies, MC-01, showing normal graded bedding, E) block of gypsum facies of Weatherford Bed, MS-17 and D) carbonate facies of the Weatherford Bed, MS-02.

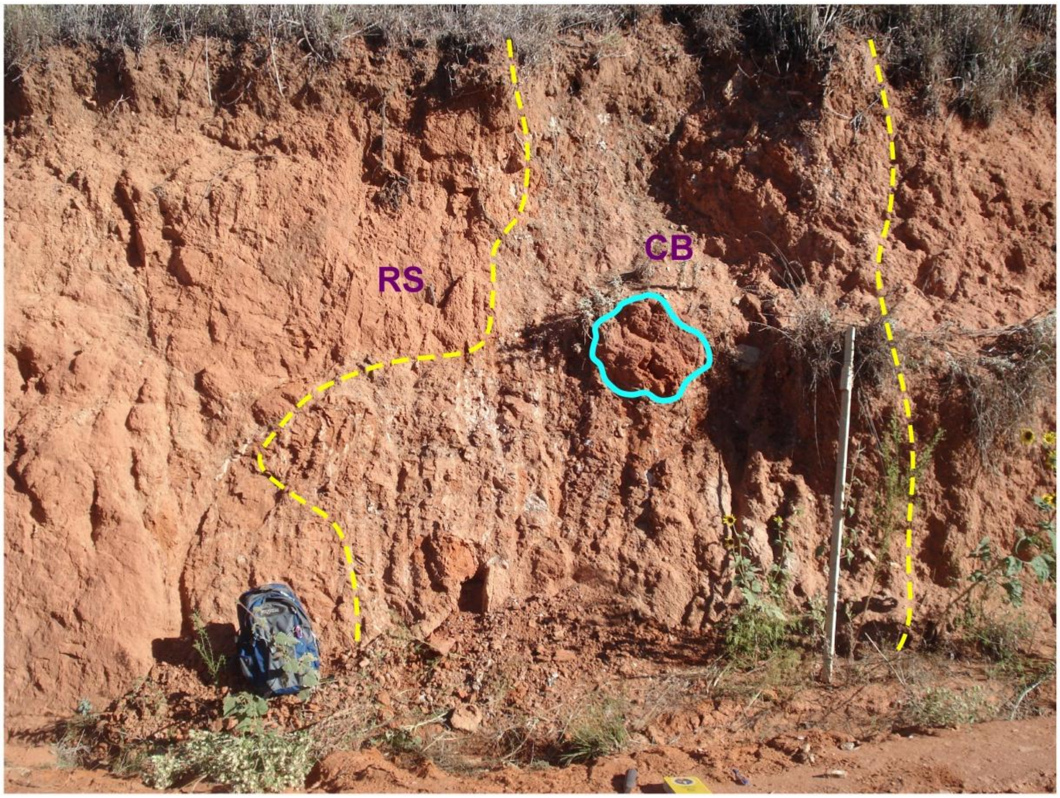

Figure 12. Cave collapse fill at MS-10. Structureless Rush Springs Sandstone (RS) in contact with cave collapse breccia (CB). Note large boulder (blue outline) of Rush Springs Sandstone in middle of breccia.

Grain-size analysis of the extradune facies assemblage shows a mean grain size of coarse silt (4.05 ϕ), the sediments are poorly sorted and grain-size distributions are fine skewed. GSFC of the extradune facies assemblage are bimodal to polymodal (Figure 5). Thin sections show that rocks from the extradune facies assemblage contain more detrital matrix, muscovite and cements (Figure 6). Sediments of the extradune facies assemblage are texturally immature.

The sabkha facies of the extradune facies assemblage is characterized by planar or ripple laminations, planar bedding and convolute bedding. Evaporite nodules are common to the sabkha facies. Two basic types of sabkhas have been identified in both the modern and ancient. They have been termed arenaceous (siliciclastic) and argillaceous sabkha (Holm, 1960). Both types are found in the extradune facies assemblage of the Rush Springs Sandstone. Grain size is the main difference between the two sabkha subfacies. The argillaceous sabkha subfacies of the Rush

Springs Sandstone has a mean grain size of medium silt (5.21 ϕ). The mean grain size of the arenaceous sabkha subfacies is coarse silt (4.29 ϕ).

Weatherford Facies

The Weatherford Bed is composed of two facies. Throughout most of the study area, the Weatherford Bed is a 30-60 cm thick reddish-pink sandy limestone, commonly containing gray-green to green-black mottling. However, in a few spots, the Weatherford Bed exhibits a second facies of a massive or crinkly bedded gypsum up to 3 m thick (MS-08). Sand grains of both facies are similar to those found in adjacent sandstones in both size and mineralogy (Figure 6). Bedding in the calcareous Weatherford is laminated to crinkly. Some of the laminations appear to be the result of the presence of sediment trapping algae (Figure 13). The Weatherford Bed also contains sub-horizontal and sub-vertical cracks (Figure 13). Observed contacts between the sandstone and the Weatherford Bed are sharp, with the underlying sandstone exhibiting convolute bedding (Figure 8B).

Figure 13. Carbonate facies of the Weatherford Bed. Hand sample taken at MS-02. Note laminated bedding and large sheet cracks (arrow).

Although no grain-size analysis was carried out on the Weatherford Bed, thin sections show that the carbonate phase of the Weatherford contains nearly 40% siliciclastic grains, mostly coarse silt to very fine sand sized quartz. The Weatherford is composed of as much as 40% carbonate. Detrital matrix and other minor constituents account for the other 20% of the Weatherford Bed. Almost all of the carbonate is sparry calcite. In thin section, the Weatherford Bed has a poikilotopic texture of siliciclastic grains floating within extensive sparry calcite cement (Figure 6).

The Weatherford Bed and other evaporites in the upper Rush Springs Sandstone probably represent a restricted marine or saline lake deposit. This is based on the regional nature of the Weatherford Bed, and its stratigraphic relationship with the sandstones of the Rush Springs. Cracks found in the carbonate facies of the Weatherford Bed originated from desiccation (Figure 13). No skeletal grains of any kind were observed in point counts, supporting an evaporative origin for the calcite. Eolian facies are again found above the Weatherford Bed, but their character changed to that formed from small dune bedforms, interdunes and eolian sand sheets.

Core MC-01

In the 1990s, the Oklahoma Water Science branch of the United States Geological Survey took a core nearly 244 meters long in the western part of the study area (MC-01). For this study, 177 m of the core was described, from its base in the El Reno Group, to the Moccasin Creek Gypsum Member of the Cloud Chief Formation. Core recovery was moderate to poor with a total recovery factor of 53%. Core recoveries in MC-01 appear to be related to cementation, which is controlled by lithofacies. Better cemented rocks at the top of the observed interval (72.5-110 m depth) yielded an average recovery of almost 95%. The lower more friable rocks from 110-262 m depth had an average core recovery of approximately 43%.

In MC-01, the Rush Springs Sandstone is thicker than most reported sections, at 127 m. This is probably due to the location of the core near the axis of the Anadarko Basin (Figure 1). Three gypsum beds occur within the upper Rush Springs interval of MC-01, as opposed to the usual one, the Weatherford Bed, seen in outcrop over the southeastern portions of the study area. A similar increase in the number of gypsum beds in the upper portion of the Rush Springs Sandstone is found to the north and northwestern portion of the study area within the extradune facies assemblage. Gypsum beds in MC-01 range in thickness from 0.5-1.5 m and have sharp contacts with vertically adjacent sandstones that commonly contain gypsum nodules.

In addition to the four facies assemblages found in Rush Springs Sandstone outcrops, MC-01 also contains a fluvial facies (Figure 14). This fluvial facies was not observed in outcrop within the Rush Springs Sandstone. The prevalence of facies within the core varies with stratigraphic position, with sabkha and restricted marine/lake facies dominating the upper part of the Rush Springs Sandstone, and fluvial and eolian facies assemblages dominating the middle and lower part of the unit.

Sedimentary structures of the sabkha facies in MC-01 are similar to sabkha facies observed in outcrop and described above. These include planar bedding, planar and ripple lamination and convolute bedding.

The fluvial facies of the extradune facies assemblage are confined to the lower-middle Rush Springs Sandstone in MC-01. In these deposits, channel lags are common above erosive lower boundaries. Sedimentary structures in the fluvial facies include: normal graded bedding/fining upward sequences (FUS, Figure 14), low angle cross-bedding and massive bedding. Channel lags contain pebble sized mudstone and shale clasts. Coarse, well rounded and frosted quartz sand is common within these lags.

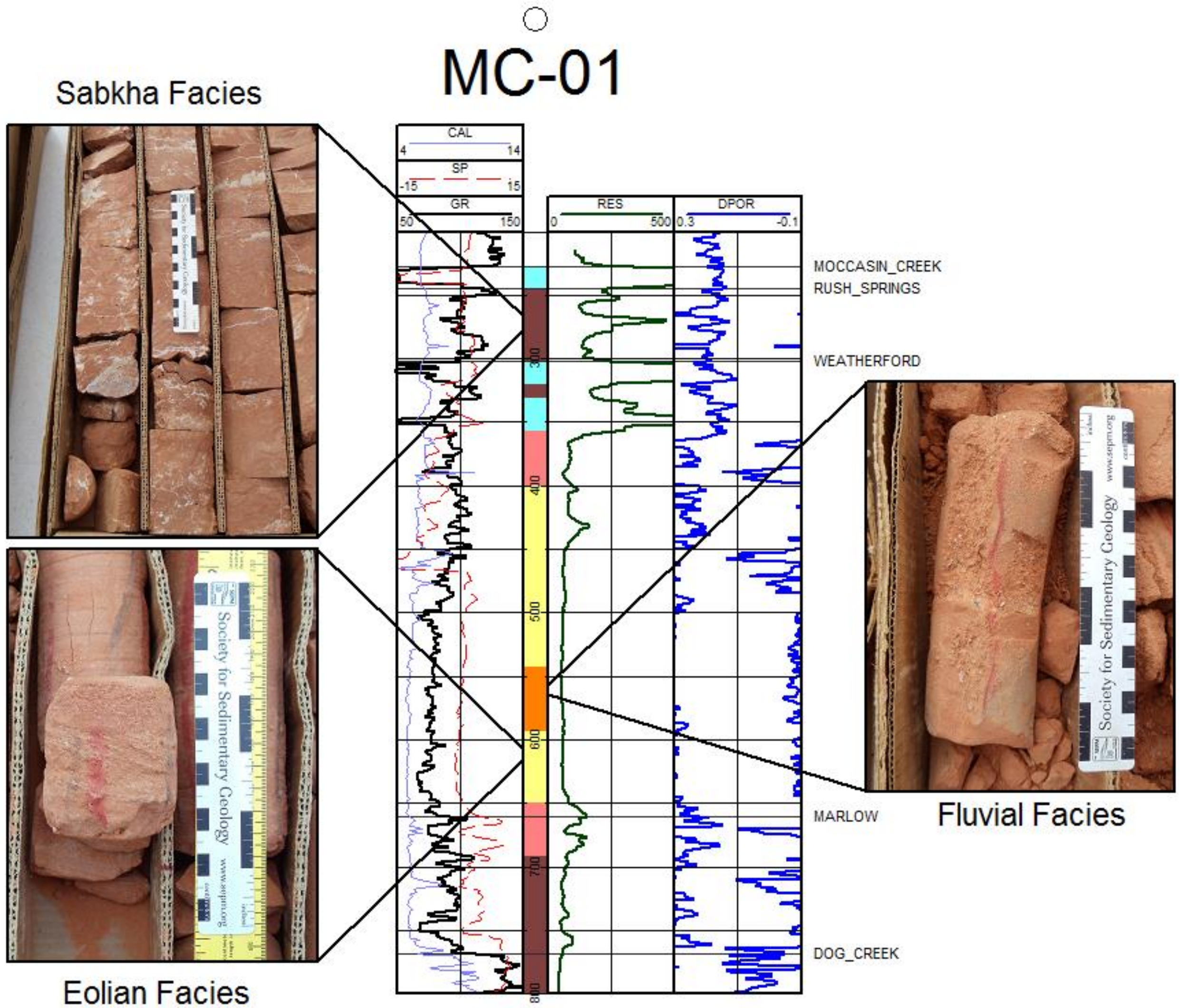

Figure 14. Geophysical well logs from MC-01 with stratigraphy (on right) and interpreted facies from core (in depth track). Sabkha facies shown in deep purple, eolian sand sheet facies assemblage shown in pink, eolian dune/interdune assemblages shown in yellow, fluvial facies shown in orange and restricted marine/playa lake facies shown in light blue.

The mean grain size of the fluvial facies is very fine sand (3.67 ϕ). Fluvial sediments are very poorly sorted, and their grain-size distributions are strongly fine skewed. SEM analysis was conducted on the fluvial facies (Figure 15) in order to compare surface textures of quartz grains from the fluvial facies with those from the eolian dune facies assemblage. Quartz grains of the submature fluvial facies exhibit smooth surfaces (Figure 15) and lack the characteristic textures of eolian transport.

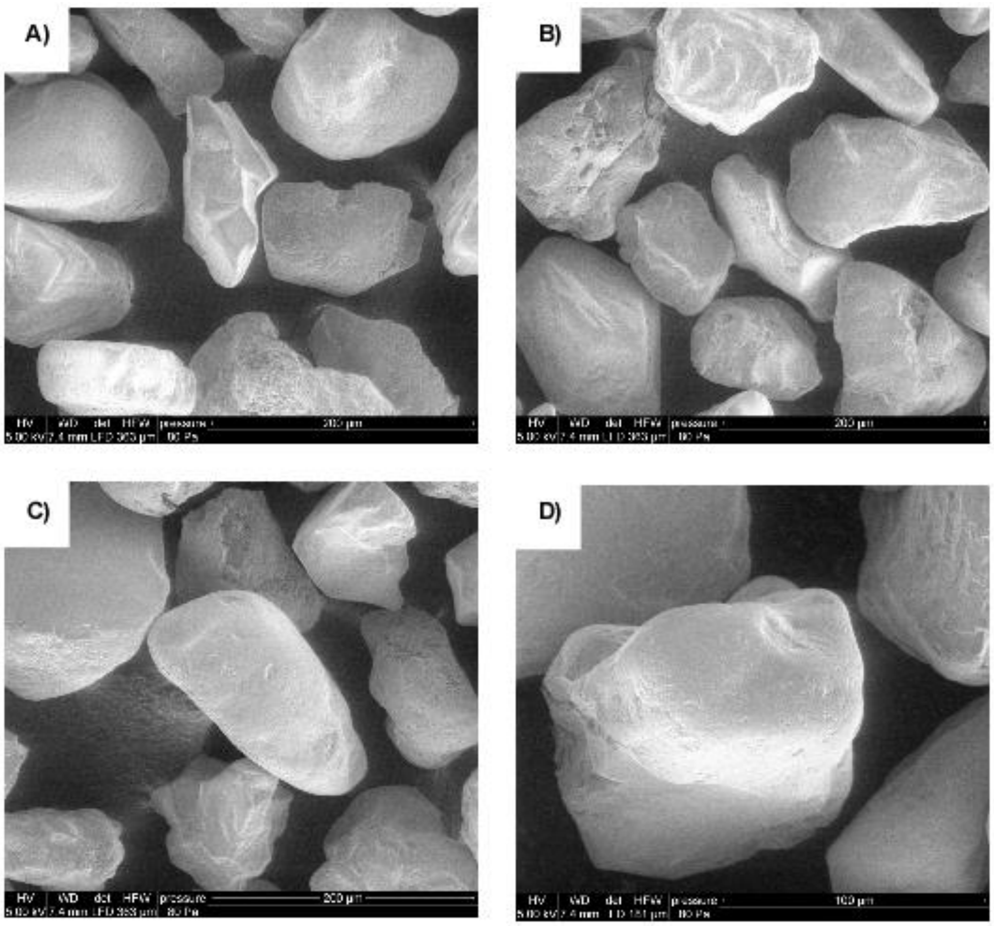

Figure 15. SEM photomicrographs of the fluvial facies from MC-01, showing grain angularity (A & B) and the generally smooth surface texture (C & D).

Fluvial facies in MC-01 are interpreted as braided stream deposits due to: 1) the erosive nature of the lower contact, 2) the presence of clear channel lags and FUS, 3) the thin nature of the individual FUS (generally less than 50 cm), 4) an absence of shale in hand sample or as discrete beds that would be expected in meandering stream deposits, and 5) the presence of low angle cross-bedding.

Deposits from the dune and interdune facies assemblages are also found in MC-01. Similar to the fluvial facies described above, they are restricted to the middle and lower Rush Springs interval. The eolian dune facies assemblage is characterized by the large, high angle (~20-25°) cross-bedded facies. Dip angles of cross-bedding increase vertically. This cross-bedding is truncated by the planar bedded facies of the interdune facies assemblage (Figure 14). The convolute bedded facies of the interdune facies assemblage is also found in MC-01. The interdune and dune facies assemblages found in the Rush Springs section of MC-01 exhibit a similar nature to those observed in outcrop and described above.

Rush Springs Paleocurrent

Three different locations within the southeastern portion of the study area provided outcrops where conditions were ideal for collecting paleocurrent information, these were: MS-16, OL-01 and OL-04 (Figure 16).

All three paleocurrent measurements were taken from rib and furrow structures developed on horizontal surfaces. All localities are located in the middle of the stratigraphic unit. Measurements on superposition surfaces are considered to be the best places for local wind patterns (Rubin and Hunter, 1983). However, because these surfaces were not identified at localities with well-developed rib and furrow structures, paleocurrent measurements were taken within cross-bedded sets. The method used is still appropriate and has been used in paleocurrent studies within other eolian successions (Peterson, 1988). At all locations at least forty dip vectors

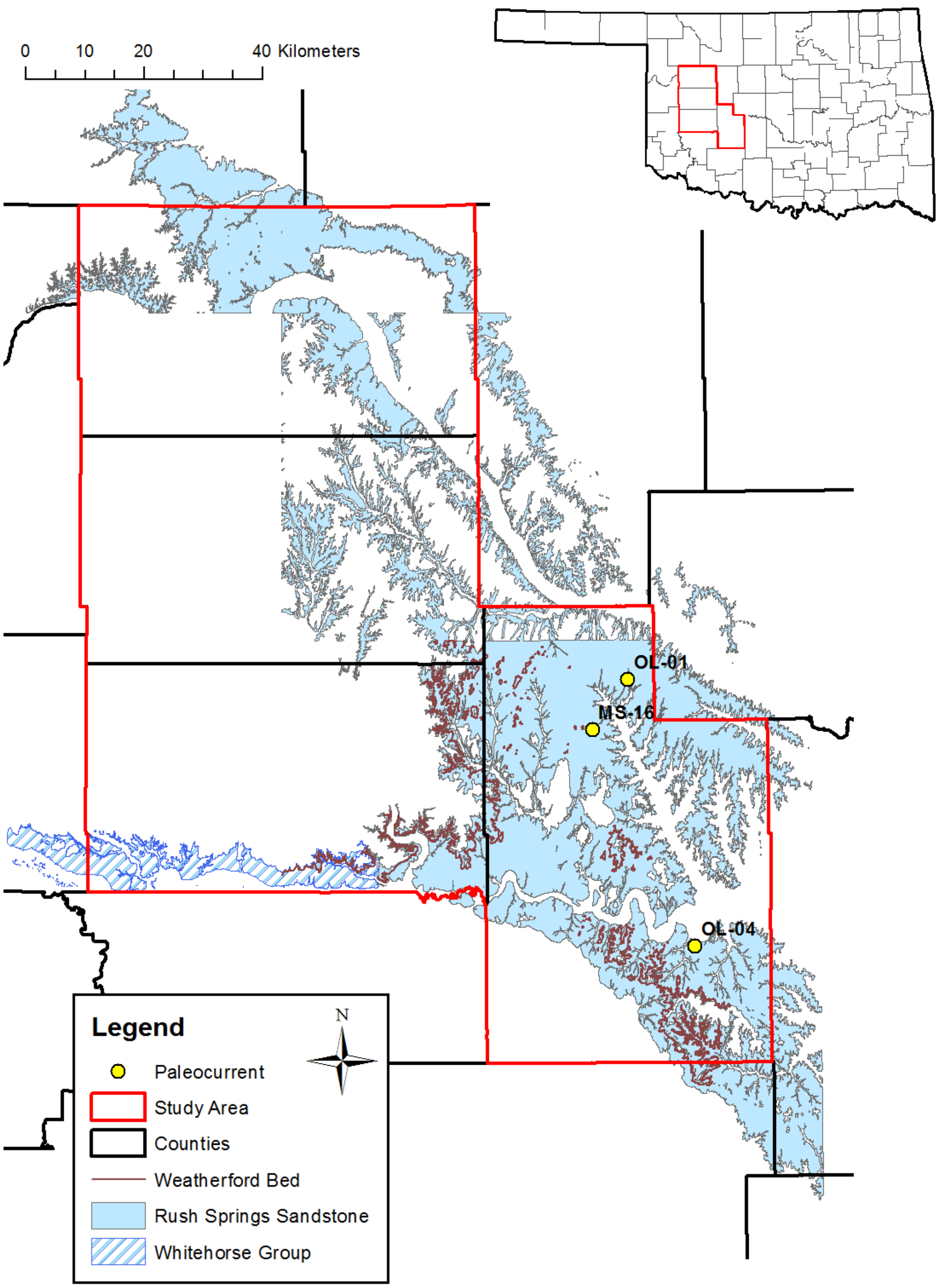

Figure 16. Map showing locations of Rush Springs paleocurrent observation sites within the southeastern portion of the study area. Outcrop belt modified from Johnson et al., 2003; Miller and Stanley, 2004; Oklahoma Geological Survey, Unpublished ; Stanley, 2002; Stanley and Miller, 2005; Stanley et al., 2002.

were taken in order to assure that a statistically significant number of data points were used to determine a mean dip direction.

Rush Springs paleocurrent data shows that the mean sediment transport direction is 206°. Vector mean strengths for the three locations are: 0.63 toward 186° for MS-16, 0.78 towards 242° for OL-01, and 0.75 towards 187° for OL-04. MS-16 and the OL-04 exhibit strong bimodality, whereas paleocurrent at OL-01 is much more unimodal (Figure 17). The difference is probably related to the bedforms that created the deposits. Bimodal dips indicate sinuous crested bedforms, while unimodal dips indicate more straight crested bedforms.

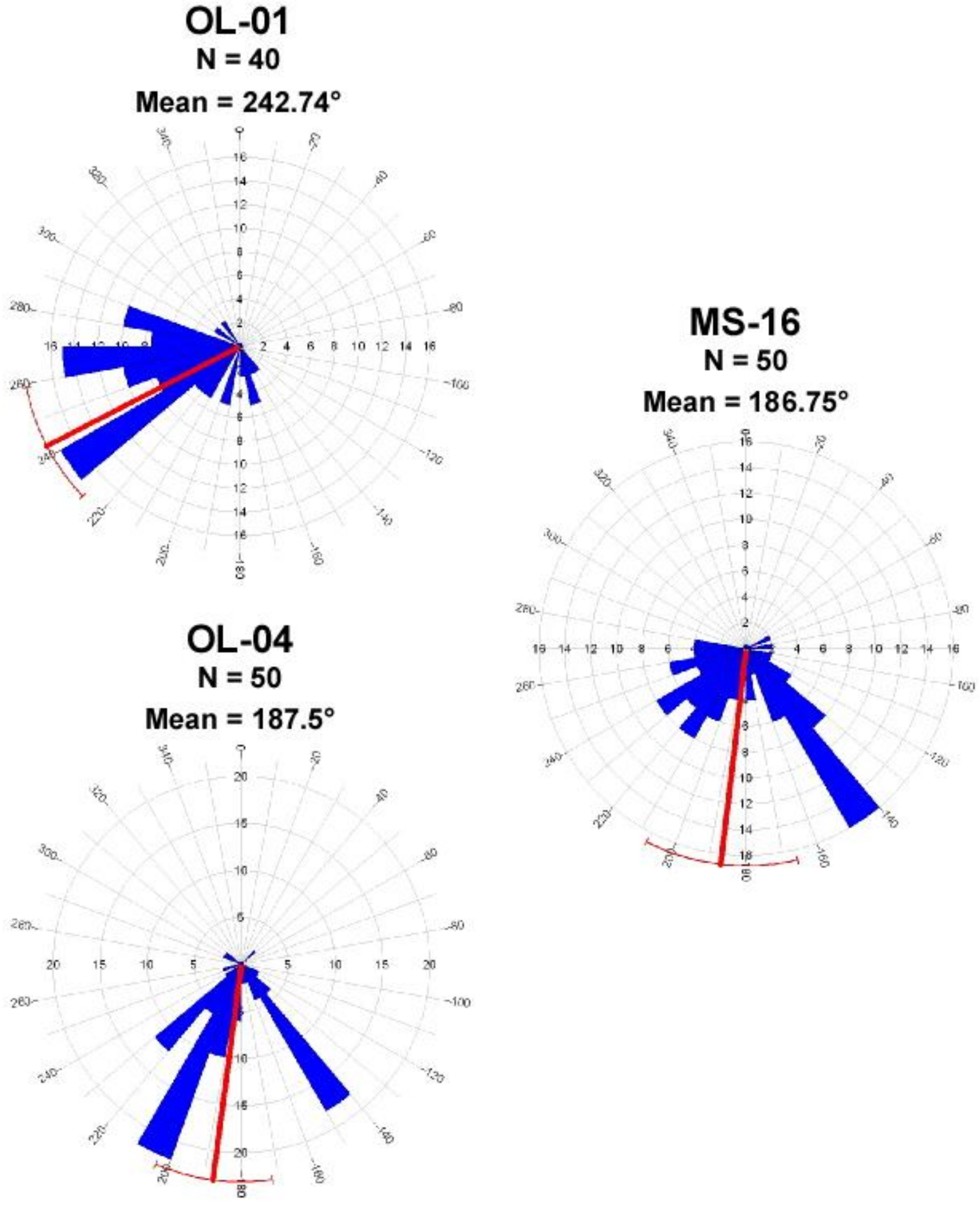

Figure 17. Rose diagrams of Rush Springs Sandstone paleocurrent data. Calculated mean current direction shown with the red ray. 95% confidence interval shown with thin red arch.

CHAPTER V

DISCUSSION

Eolian vs. Shallow Marine/Fluvial-Deltaic Interpretation

The reinterpretation of widely held eolian sandstones in the early 1970s (Baars and Seager, 1970; Freeman and Visher, 1975; Stanley et al., 1971; Visher, 1971), led Hunter (1974a) to seek to establish basic types of eolian stratification. The basic types of eolian stratification recognized by Hunter (1974a) in modern coastal dunes of Oregon and Texas have also been found in the 'classical' Paleozoic and Mesozoic eolian sandstones of the western United States (Hunter, 1981; Kocurek and Dott, 1981; Loope, 1984a), and are commonly used to identify eolian units in the rock record (Irmen and Vondra, 2000; Rodriguez-Lopez et al., 2010). The structures formed by eolian and subaqueous deposition exhibit some similar characteristics, but they can often be deciphered from each other (Hunter, 1981). Of those sedimentary structures identified by Hunter (1977a) within modern eolian dunes, climbing translatent strata, grainfall laminae and grainflow cross strata have been identified in the Rush Springs Sandstone (Table 1, Figure 4D-4F).

Climbing translatent strata can be differentiated from strata formed by subaqueous ripples in that ripple foresets are usually preserved in subaqueous deposits (Loope, 1984b).

Ripple foresets rarely occur in the climbing translatent strata of the Rush Springs Sandstone and other eolian sandstones that Hunter (1981) analyzed. Climbing translatent strata can be recognized because they appear structureless due to a lack of ripple foreset laminae, have low dip angles, contain inverse grading, and contain thin but uniform strata (Hunter, 1981). Grainfall laminae and grainflow cross strata occur in both eolian and subaqueous deposits. While they may show similar thicknesses, dips, porosities, and grain-size distributions (Hunter, 1976), some unique properties aid in differentiating the two. Subaqueous grainfall deposits are almost always incorporated into later grainflow cross strata (Hunter and Kocurek, 1986); therefore, it is extremely rare for them to be preserved. Grainflow cross strata resulting from eolian deposition are commonly separated by grainfall laminae (Hunter, 1976). Sand avalanching is nearly continuous in the subaqueous environment, whereas eolian sand flow is a much more periodic process (Hunter, 1976). Grainflow cross strata are clearly separated by layers of grainfall laminae within the dune facies assemblage of the Rush Springs Sandstone (Figure 4E & 4F). These structures formed from grainfall and grainflow deposition on the leeward side of ancient eolian dunes. The suite of sedimentary structures found in the Rush Springs Sandstone strongly supports an eolian, rather than subaqueous, origin for a majority of the unit.

The moderate to poor sorting and the near symmetrical grain-size distributions of the eolian dune and interdune facies assemblages of the Rush Springs Sandstone seems to contradict most models of eolian sediments (i.e. well sorted and fine skewed). However, the dune and interdune facies assemblages of the Rush Springs Sandstone are near moderately sorted at 1.01 ϕ and 1.09 ϕ respectively and some authors have cautioned against these generalizations (Ahlbrandt, 1975; Ahlbrandt and Fryberger, 1982). Skewness is dependent on mean grain size, and therefore has little relevance to eolian deposits, assuming that the mean grain size falls within the size range capable of saltation transport by wind (Ahlbrandt, 1975), as the grains of the Rush Springs Sandstone do. The mean grain size of the Rush Springs Sandstone never exceeds fine sand in the 60 measurements conducted in this study, and the modes for both the eolian dune and interdune facies assemblages are greater than 80 μm, the minimum size of Holocene windblown sands (Bagnold, 1941), and are generally in the 100-200 μm range (Figure 5). Diagenesis is known to have an effect on textural parameters. Some have proposed that the red coloration of dune sand is caused by clay coatings (Folk, 1969, 1976; Walker, 1979). These clays may have infiltrated dune sediments in the manner that Folk (1969) described in which dust settles on eolian sediments during calm periods and is transported into the sediments by rain or dew. Thin section analysis and SEM imaging of the Rush Springs Sandstone before treatment clearly shows the presence of clay coatings on grains (Figure 18, Figure 6). Treatment prior to grain-size analysis may have freed these clay coatings and allowed them to be measured in the GSFC, thus the GSFC may not fully reflect the 'original' grain-size distributions. This may explain some of the finer low amplitude modes in the GSFC that causes the standard deviation calculations to suggest moderate to poorly sorted values within the dune and interdune facies assemblages. Nonetheless, the textural differences between fluvial and eolian facies of the Rush Springs Sandstone are clear (Figure 5). Although the GSFC of the fluvial facies and the dune/interdune facies assemblages of the Rush Springs Sandstone are very different (Figure 5), they also show an important similarity, all three facies have a robust size population at approximately 100 μm. This shared grain-size population suggests reworking and recycling of sediments between these environments along the erg margin.

SEM analysis of grain surface textures from the Rush Springs dune facies assemblage reveals surface textures characteristic of eolian transport and deposition (Figure 7) including upturned plates (Krinsley and McCoy, 1978), elongate depressions (Krinsley et al., 1976), and graded arcs (Krinsley and Donahue, 1968). Analysis of fluvial sediments in

MC-01 shows generally smooth surface textures (Figure 15). Unlike eolian transport, quartz grains subjected to fluvial transport do not have a suite of characteristic surface textures (Krinsley and Donahue, 1968).

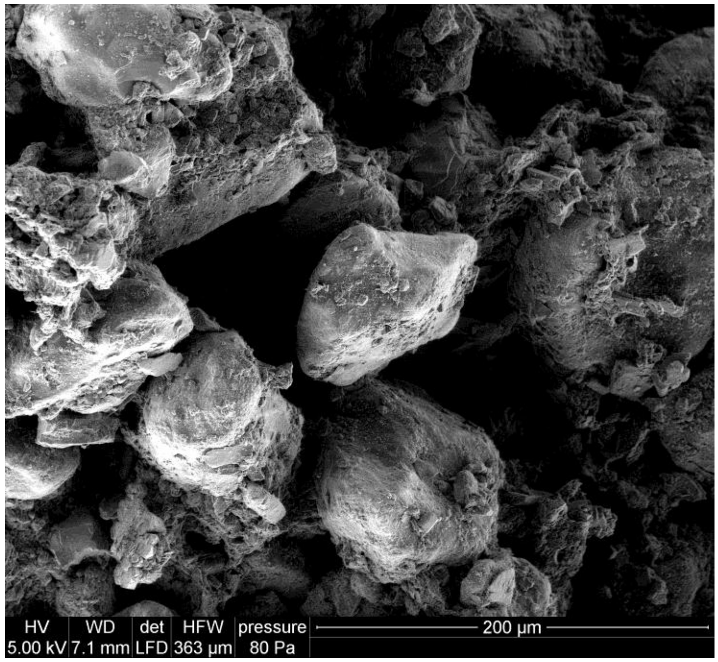

Figure 18. SEM photomicrograph showing clay coatings of fluvial sand grains, MC-01.

Significant diagenetic overprinting of surface textures is shown in SEM images of Rush Springs sediments (Figure 19). Although expected considering the age of the Rush Springs Sandstone, diagenesis makes environmental interpretations from SEM images less conclusive. However, in all samples analyzed none exhibited v-shaped patterns, which are the signature surface texture of the littoral environment (Krinsley and Donahue, 1968; Krinsley and Marshall, 1987; Krinsley and Takahashi, 1962b). This is consistent with an eolian origin for the Rush Springs Sandstone. Additionally, SEM analysis clearly shows a difference in grain roundness between the eolian dune facies assemblage and the fluvial facies of the extradune facies assemblage (Figure 19), with the dune sediments being more rounded than the fluvial facies consistent with the findings of Kuenen (1960).

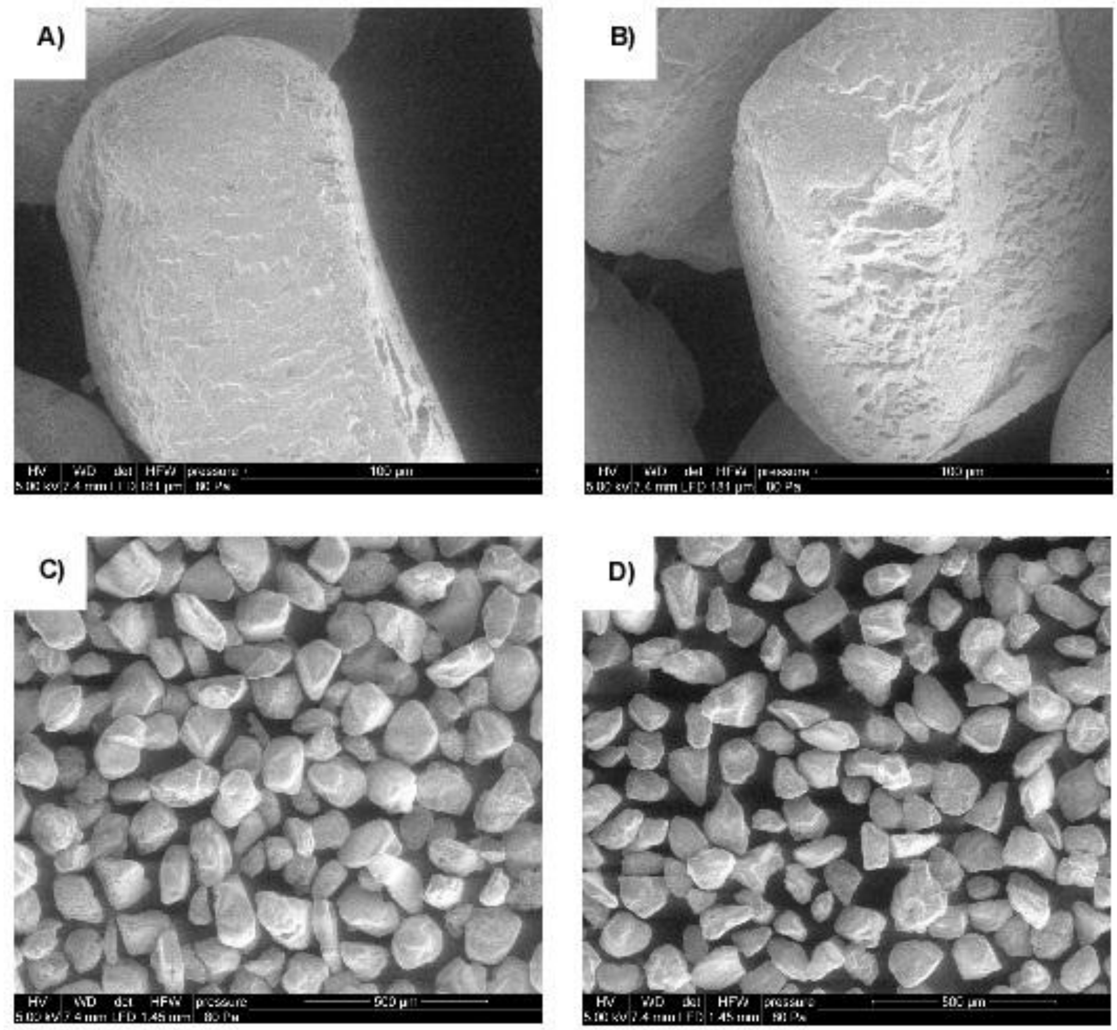

Figure 19. SEM photomicrographs of Rush Springs Sandstone. Showing interpreted diagenetic effects on grain surface texture (A & B), sample from location OL-07. Variation in grain angularity between C) eolian dune facies, sample from OL-05 and D) fluvial facies, sample taken from MC-01.

Climbing Bedforms

One characteristic feature of erg sediments is the presence of laterally extensive, smooth, parallel surfaces that sharply truncate cross-bedding (Stokes, 1968). These surfaces divide the sandstones into cross-bedded “packages” of roughly even thickness. Two processes have been suggested for the formation of these bounding surfaces within the eolian environment (Kocurek, 1988). Stokes (1968) proposed a model from which these parallel surfaces were caused by erosion of dune sediments to the water table, where the increased cohesion caused by the moisture prevented further erosion. Stokes-type surfaces arise from erosional processes where the erg is cannibalized by wind that has not reached its sediment carrying capacity (Mountney, 2006). An alternative to the Stokes model was proposed in which bounding surfaces result from the systematic migration of bedforms at non-positive angles of climb causing either erosion or sediment bypassing (Rubin and Hunter, 1984).

Brookfield (1977) identified three other types of bounding surfaces in eolianites that arise from bedform migration (Figure 20). The surfaces recognized by Brookfield (1977) form a surface hierarchy within eolianites. Eolian surface hierarchy consists of first order, second order, and third order surfaces, later renamed interdune surfaces, superposition surfaces and reactivation surfaces respectively (Kocurek, 1996). Interdune surfaces result from climbing of interdunes over the adjacent downwind dune/draa (Figure 20), these surfaces are planar and appear horizontal (Brookfield, 1977). However, the surfaces indeed climb, at very low angles, if net sedimentation occurred (Rubin and Hunter, 1982). Interdune surfaces are found in the Rush Springs Sandstone (Figure 21).

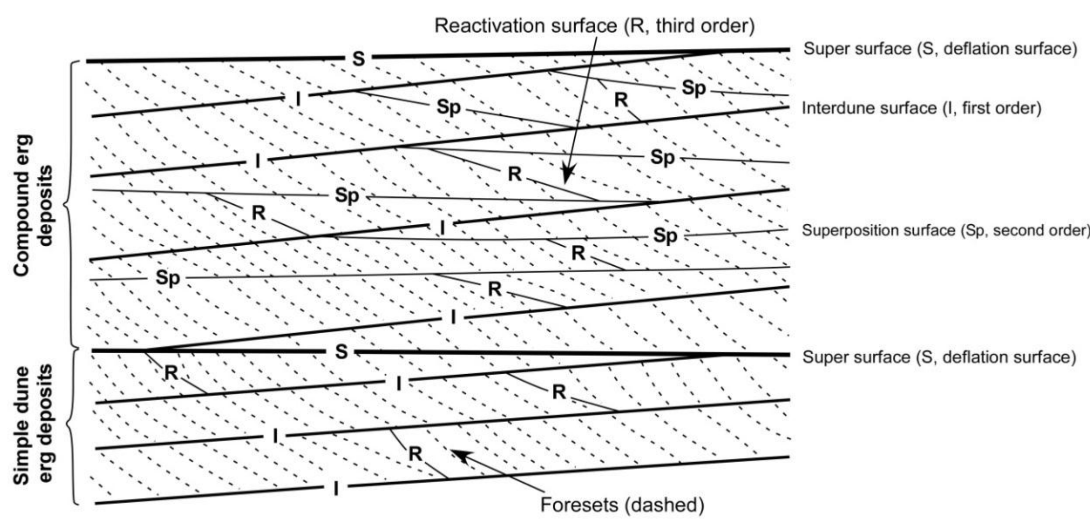

Figure 20. Schematic drawing illustrating eolian bounding surface hierarchy. Note that second order surfaces are missing from the simple dune model. Figure modified from Boggs Jr. (2006) after Kocurek (1988).

Figure 21. Outcrop photo with interpreted surface hierarchy annotated, MS-19. Showing interpreted interdune surface (yellow dashed line), superposition surface (red dashed line) and reactivation surfaces (gray dashed lines). Note that superposition surface dips downwind and downlaps onto the interdune surface. Trees in the background are approximately 3-6 m tall. Compare with Figure 20.

Superposition surfaces arise from the migration of superimposed dunes down the leeward slope of larger draas (Figure 20). These surfaces dip downwind at moderate angles and are planar or convex up surfaces that may be truncated by interdune surfaces (Brookfield, 1977; Loope and Rowe, 2003). Superposition surfaces are also found within the Rush Springs Sandstone (Figure 21).

Reactivation surfaces bound bundles of cross laminations (Brookfield, 1977). They may be truncated by both interdune and superposition surfaces (Figure 20). Reactivation surfaces form from periodic changes in wind direction due to eddying on the lee side of large bedforms. Reactivation surfaces are found in the Rush Springs Sandstone as well (Figure 21).

Eolian surface hierarchy is found in the Rush Springs Sandstone (Figures 21). The presence of superposition surfaces in the Rush Springs Sandstone implies that the erg was, at least at times, characterized by compound, transverse bedforms, where smaller dunes were superimposed on larger draas (Brookfield, 1984; Kocurek, 1984; Rubin and Hunter, 1982). The recognition of surface hierarchy in the Rush Springs Sandstone supports an eolian interpretation and aids in ancient erg reconstruction.

Erg Reconstruction

Dune/Interdune Stacking Patterns

Within the study area, eolian deposition dominated Rush Springs sedimentation; however, the character of deposition clearly changed through Rush Springs time. The lower Rush Springs is dominated by eolian sand sheet deposits with small dunes migrating over large flats. By middle Rush Springs time, migrating bedforms had grown larger, both vertically and laterally. However, the interdune facies assemblage has a similar thickness throughout the same period. A vertical thickening trend of the preserved dune facies assemblage is especially apparent at Red Rock Canyon State Park (MS-12, Figure 22). Mountney (2006) observed a similar thickening of

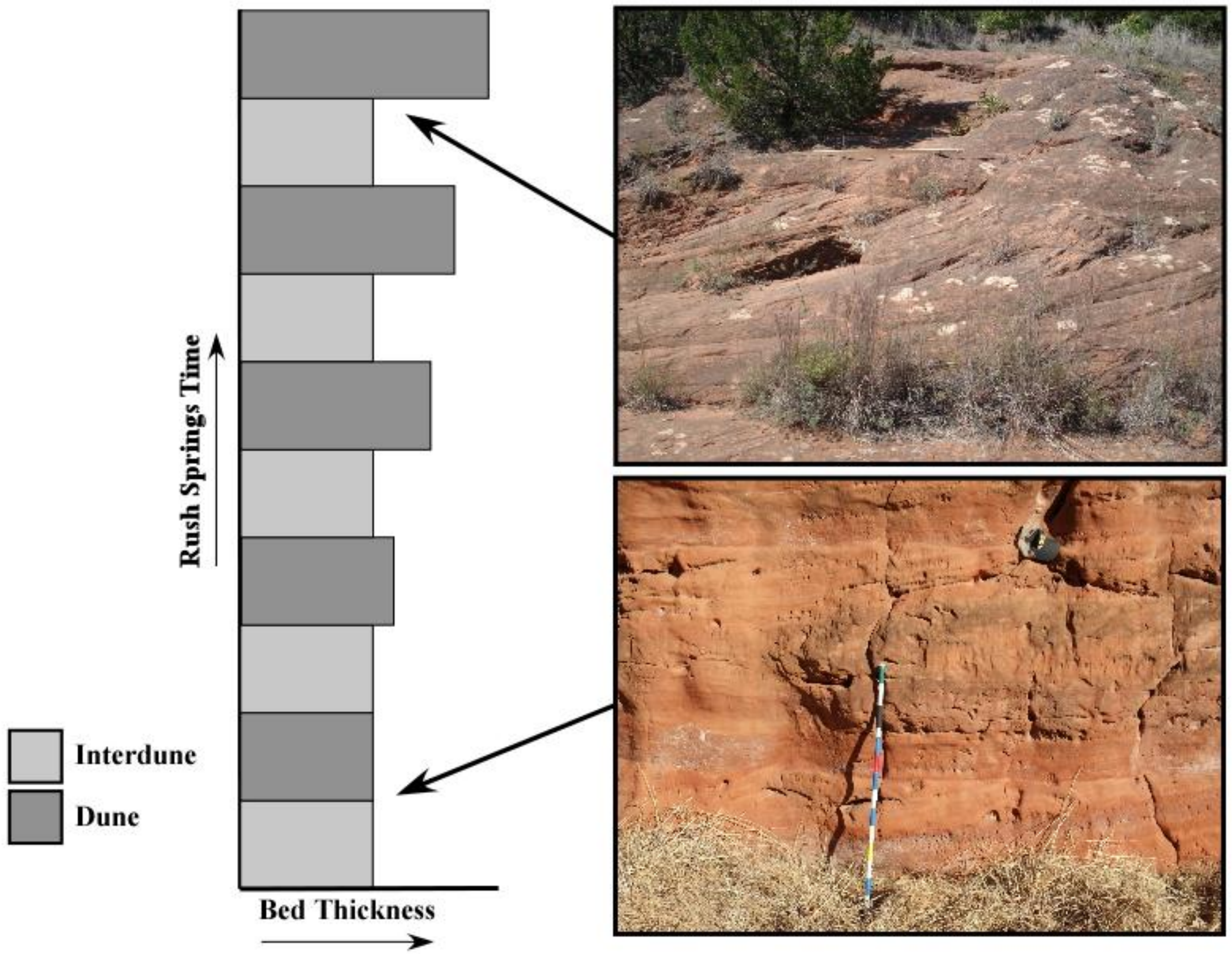

Figure 22. Generalized stacking patterns of Rush Springs eolian facies in Red Rock Canyon State Park, showing a progressive thickening of preserved eolian dune sediments through time, the result of increases in sand supply and in the angle of bedform climb. Lower photo (MS-12), upper photo (OL-01).

preserved dune cross sets in eolianite sequences bounded by deflationary super surfaces in the Cedar Mesa Sandstone of Utah. Mountney (2006) interpreted the thin cross-bedded sets to have been preserved from a time where small, isolated, and disorganized bedforms migrated across vast interdune and sand sheet areas during a time of erg construction. Mountney (2006) proposed that deposition by small, disorganized bedforms during early regression transitioned into large, organized bedforms during the middle to late regression (erg accumulation) representing the natural progression of an erg's life, before being deflated.

An overall increase in cross-bedding thickness of preserved dune deposits in the Rush Springs Sandstone is attributed to an increase in sediment supply, creating larger bedforms, and an increase in the climb angle of those bedforms. Increased sand supply is most likely a result of climate change (drying) or eustacy (regression) rather than tectonics, because uplift in the area had ceased by Rush Springs time (Johnson, 1989a).

Paleocurrent

Paleocurrent data is consistent with published paleocurrent data for the Whitehorse Group (Kocurek and Kirkland, 1998) taken further north which had a mean transport direction of 219° (S39W). Reeves (1921) also reported dips to the southwest in his study of the Rush Springs Sandstone. After correcting for Guadalupian paleogeography, paleocurrent data from the Rush Springs Sandstone indicates easterly/northeasterly paleowinds. Paleocurrent data from the Rush Springs Sandstone, coupled with a lack of perthite grains in the Whitehorse Group (Nelson, 1983), which are typical of sediments from the Wichita Uplift (Ham et al., 1964), call into question a southern provenance for the Rush Springs Sandstone (Fay, 1962; O'Brien, 1963). Instead, a sediment source to the present day northeast, possibly the Ozark Uplift, is favored as suggested by Moussavi-Harami (1977) and Suneson and Johnson (1996). Paleocurrent data from the Rush Springs Sandstone is in close agreement with paleocurrent data taken from Paleozoic eolian sandstones in the western United States (Loope et al., 2004; Peterson, 1988; Rowe et al., 2007), as well as atmospheric circulation models (Parrish and Peterson, 1988). These observations and models indicate that the accumulation of eolian sand was controlled by the regional atmospheric circulation patterns of Pangea. Paleocurrent data from the Rush Springs Sandstone (Figure 17) coupled with the paleogeography of the region (Figure 1) suggests that the Wichita Uplift may have aided in construction of the Rush Springs Erg and controlled its thickness by acting as a barrier to dune migration further downwind. A similar scenario can be observed at Great Sand Dunes National Park, Colorado, where the Sangre de Cristo Mountains have trapped Holocene dunes (Marin et al., 2005).

Nature of the Rush Springs Contacts

The Rush Springs Sandstone is conformable with the stratigraphic units above and below it. The lower contact with the Marlow Formation is clearly gradational in MC-01 and at MS-03. The gradational contact suggests a progressive change from marine and marginal-marine deposition during Marlow time to sabkha and eolian sand sheet deposition with small, isolated dune fields during the earliest Rush Springs time, which eventually gave way to large dune fields in the central and southeastern part of the study area.

The upper contact of the Rush Springs Sandstone with the Moccasin Creek Gypsum Member of the Cloud Chief Formation is also conformable marked by its gradational change. A gradational change from gypsiferous sandstone to sandy gypsum (siliciclastic sabkha/shallow marine deposits) in the upper Rush Springs Sandstone into gypsum (restricted marine), of the Moccasin Creek Gypsum Member of the Cloud Chief Formation is very clear in MC-01 in the westernmost part of the study area. A similar change is observed in outcrops of the eastern part of the study area.

The basal contact of the Weatherford Bed with the Rush Springs Sandstone is unconformable. At MS-08, red-orange colored cross-bedded sandstone of the dune facies assemblage, grades into massive bedded fine grained sandstone (Figure 23). This massive sandstone is overlain by the Weatherford Gypsum. The contact is planar and sharp. An interval about 30 cm thick of white-gray to gray-green silty-sandstone is found in the very upper part of the Rush Springs Sandstone. This color change in the Rush Springs Sandstone at MS-08 indicates possible gleying. A similar relationship between the Weatherford Bed and the underlying Rush Springs Sandstone can be observed in the western portion of the study area in MC-01 (Figure 23). In the core, wavy laminated sands of the arenaceous sabkha subfacies of the extradune facies assemblage are sharply overlain by gypsum of the Weatherford Bed.

Massive and convolute bedding in the sandstone below the Weatherford Bed (Figure 7B and 23B) suggests that eolian activity in the Rush Springs Sandstone ceased leading up to Weatherford deposition. This cessation in eolian transport resulted from a decrease in sand supplied to the erg, causing dune deflation, due to a rising water table that accompanied a transgression. The mechanism is similar to the one proposed by Stokes, (1968) and described by Loope (1985) to explain extensive bedding planes in eolian sandstones. The Weatherford Bed of the Rush Springs Sandstone is analogous to the marine limestones interbedded with fluvial and eolian sandstones of the Cutler Group in the Paradox Basin of Utah (Jordan and Mountney, 2010) and the Page Sandstone in Arizona (Blakey et al., 1996). During Weatherford time, restricted marine or playa inundation probably proceeded from the erg margin in the west, where sabkha and restricted marine facies dominate below the Weatherford Bed, towards the erg center in the central and eastern portion of the study area, where eolian facies dominate below the bed. Dune/interdune sedimentation waned and deflation occurred ahead of this transgression.

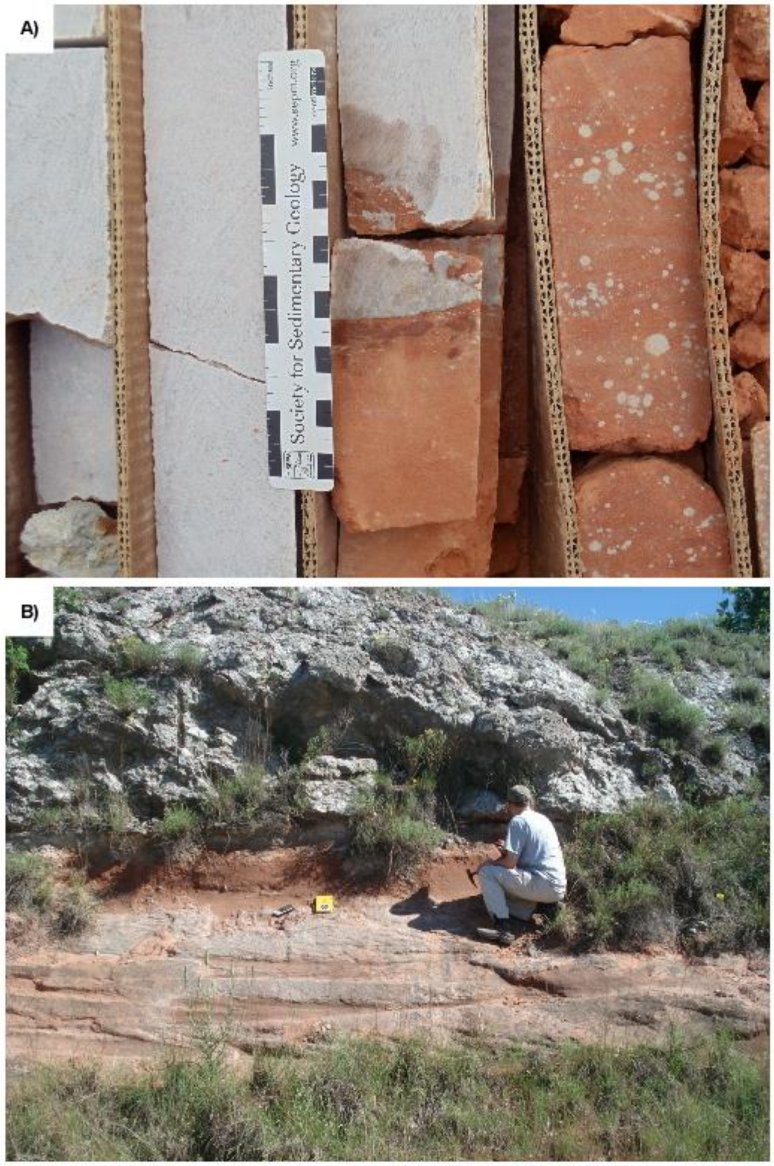

Figure 23. Contact between the Rush Springs Sandstone and the Weatherford Bed. A) MC-01 (erg margin) showing laminated sandstone (coastal sabkha) sharply overlain by the Weatherford Gypsum. B) MS-08 (erg center), cross-bedded sandstone overlain by massive sandstone, which is overlain by the massive gypsum of the Weatherford Bed. Note the very sharp, planar contact between the two and the color change in the sandstone immediately below the contact.

Rush Springs Facies Model

The Rush Springs Sandstone of western Oklahoma represents a semi-arid/arid depositional system that can be broken up into three paleoenvironmental belts from southeast to northwest across the study area. These are: erg center, erg margin and extradune environments respectively (Figure 24).

Paleoenvironmental Interpretations

The middle Rush Springs was deposited in large, transverse, occasionally compound bedforms as evidenced by superposition surfaces in the surface hierarchy of the Rush Springs Sandstone (Figure 21). Interdunes of the Rush Springs Erg were at least periodically wet due to the presence of freshwater carbonates, root casts, and ripples of subaqueous origin. The accumulation of interdune flat sediments and interbedding of dune facies within interdune facies reinforces this interpretation (Kocurek and Havholm, 1993). However, the presence of wet interdune deposits does not necessarily mean that the dunes formed in a humid climate (Hunter, 1981). Periodically moist interdunes could have resulted from seasonal precipitation variations due to monsoonal circulation that arose from the continental configuration of Pangea (Loope et al., 2001; Parrish, 1993; Parrish, 1995).

Thickness of preserved cross-bed sets bounded by interdune surfaces in the Rush Springs Sandstone have an observed maximum thickness of 6.1 m at OL-06, where three such sets can be observed (average set thickness = 4.85 m). Rubin and Hunter (1982) gave an equation to calculate dune height from preserved cross-bed set thickness, bedform index (wavelength/height), and downcurrent depositional extent of the set. Unfortunately, outcrops were not laterally continuous enough for the exact downcurrent extent to be determined for the Rush Springs Sandstone. However, preserved cross-bed thickness is only a small fraction of original bedform height (Rubin and Hunter, 1982), so dunes and draas of the Rush Springs Erg were probably on the order of several tens of meters high.

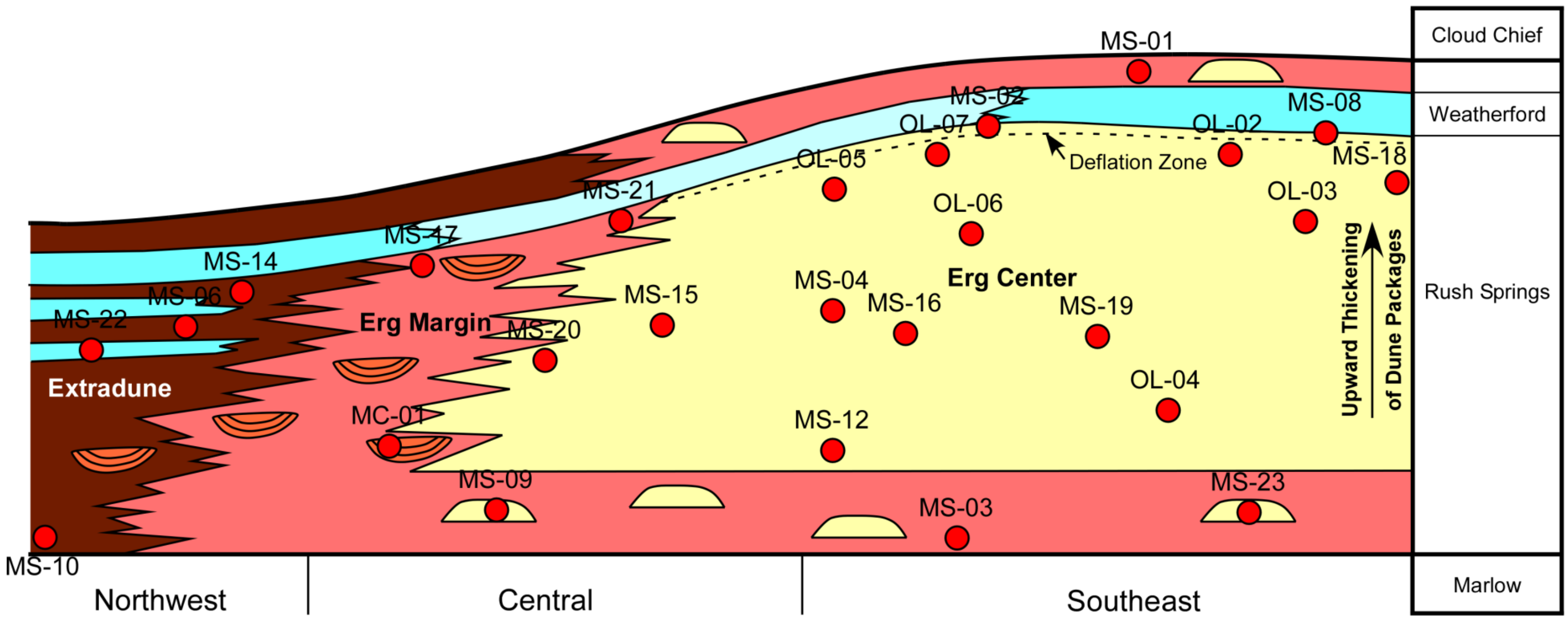

Figure 24. Idealized 2D facies model of Rush Springs Sandstone from northwest to southeast across the study area, with locations of facies observations. Figure flattened on the Marlow/Rush Springs contact, figure not to scale. Note thinning of Rush Springs Sandstone towards the north. Facies are: restricted marine/playa (blue), eolian dune/interdune (yellow), eolian sand sheet (pink), fluvial (orange), sabkha (brown).

MC-01 represents the margin of the Rush Springs sand sea, as indicated by the temporal shift in depositional environments represented within the core, and the interfingering nature of the facies. The sequence of environmental change in MC-01 is: 1) marine/marginal marine deposition (Marlow Formation), gradually giving way to sabkha and eolian sand sheet deposition in the lowest Rush Springs, 2) eolian dune/interdune deposition in the lower-middle Rush Springs, 3) fluvial deposition in the middle Rush Springs interval, 4) eolian dune/interdune deposition re-established in the upper-middle Rush Springs, 5) eolian sand sheet and sabkha deposition dominating the upper Rush Springs with occasional restricted marine/playa lake inundations, and 6) the gradual change to restricted marine deposition at the top of the Rush Springs (Moccasin Creek Gypsum Member of the Cloud Chief Formation, Figure 13). Similar relationships between fluvial, sabkha and erg deposits have been described in other erg margin systems (Clemmensen et al., 1989).

The Guadalupian was a time period marked by the last gasps of the Gondwanan glaciation (Rygel et al., 2008). It was also marked by a decrease in the magnitude of sea-level fluctuations (Haq and Schutter, 2008) and climate changes (Montanez et al., 2007). It was a period of continental drying within the midcontinent as seen within the floral record (Looy, 2007) and paleosols (Tabor et al., 2002) by the increasing frequency of evaporite beds. This is reflected in the Late Paleozoic of the midcontinent with cyclothems dominating the Pennsylvanian (Heckel, 1986) and increasingly less marine influence and greater drying through the Permian deposits. Thus the Rush Springs may mark the most harsh conditions of this Paleozoic trend within the midcontinent.

CHAPTER VI

CONCLUSION

The sedimentary structures, textures, surface hierarchy, paleocurrent data, the presence of root casts, and the absence of marine fossils all support the interpretation that the Rush Springs Sandstone (Permian/Guadalupian) of western Oklahoma represents an ancient erg-erg margin depositional system rather than the shallow marine/marginal marine origin that has been suggested previously (Al-Shaieb, 1988; Davis, 1955; Nelson, 1983; O'Brien, 1963; Tanaka and Davis, 1963).

Based on facies distributions the Rush Springs Sandstone can be divided into three paleoenvironmental belts across the study area. They are: erg center (southeast), erg margin (central) and extradune (northwest). Deposition by large eolian bedforms was generally confined to the middle part of the Rush Springs Sandstone in the central and southeastern portion of the study area. From early Rush Springs time until Weatherford time, eolian bedforms became larger and more organized due to an increase in sediment availability. The Rush Springs Erg was characterized by compound eolian bedforms several tens of meters high and wet/damp interdunes. The scarcity of fluvial deposits observed in outcrop suggests that fluvial systems rarely penetrated into the central portion of the Rush Springs Erg. Eolian sedimentation ceased from an absence of sand supply attributed to a rising water table accompanying the formation of a restricted marine/saline lake during Weatherford time. Although eolian deposition occurred after

Weatherford time, large scale eolian deposition was not a factor in the Rush Springs Sandstone post-Weatherford time.

The new facies model for the Rush Springs Sandstone presented here has paleogeographic and paleoclimatic implications for western Pangea during the Guadalupian. This model may also help lead to a geologic solution for arsenic mitigation within the Rush Springs aquifer of western Oklahoma.

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VITA

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Master of Science

Thesis: SEDIMENTOLOGY OF THE RUSH SPRINGS SANDSTONE (PERMIAN/GUADALUPIAN), WESTERN OKLAHOMA: EVIDENCE OF AN ERG-ERG MARGIN DEPOSITIONAL SYSTEM

Major Field: Geology

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Title of Study: SEDIMENTOLOGY OF THE RUSH SPRINGS SANDSTONE (PERMIAN/GUADALUPIAN), WESTERN OKLAHOMA: EVIDENCE OF AN ERG-ERG MARGIN DEPOSITIONAL SYSTEM

Pages in Study: 70 Candidate for the Degree of Master of Science

Major Field: Geology

Scope and Method of Study:

Deposits of the Rush Springs Sandstone (Permian/Guadalupian) of western Oklahoma were studied through measuring section, grain-size analysis via CILAS 1180 laser particle-size analyzer, thin section analysis, and SEM data.

Findings and Conclusions:

The Rush Springs Sandstone (Permian/Guadalupian) of western Oklahoma has traditionally been interpreted as a shallow marine/fluvial-deltaic unit. Based on 23 measured sections and a 177 m core, a new model for the Rush Springs Sandstone is presented. I interpret the Rush Springs Sandstone as an ancient erg-erg margin depositional system. Based on facies relationships, the Rush Springs Sandstone can be divided into three paleoenvironmental belts in west-central Oklahoma. These belts are erg center, erg margin and extradune environments. Outcrop observations suggest that the central portion of the Rush Springs Erg was characterized by compound eolian bedforms several tens of meters high with wet/damp interdunal areas. Paleocurrent data from the Rush Springs Sandstone is in agreement with paleocurrent data from Late Paleozoic eolian sandstones in the Colorado Plateau, and indicates that regional atmospheric circulation controlled eolian deposition in western Pangea.

ADVISER'S APPROVAL: Dr. Jim Puckette