The Impact of Facies Heterogeneity on Fluid Storage and Transport in the Lower Burro Canyon Formation, Lisbon Valley, Utah

by

Connor M. Broaddus

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Fort Lewis College

Geosciences Department

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ABSTRACT

In Lisbon Valley, Utah, Early Cretaceous braided stream deposits of the Lower Burro Canyon Formation form the primary host beds for high-grade copper ore bodies that are potential targets for in-situ leach mining. Variations in the lithology, facies associations, and depositional architecture of the Lower Burro Canyon Formation represent major controls on the porosity, permeability, and connectivity of ore host beds, and are poorly understood in this area.

The goal of this study is to constrain and characterize the lithologic (facies-scale), architectural (element-scale) and stratigraphic (member-scale) heterogeneity that exists within the Lower Burro Canyon Formation in Lisbon Valley in the context of its effect on modern fluid storage and transport.

Detailed logging along a closely spaced (less than 150 meters) transect of five drill-cores revealed the presence of 8 major lithofacies within the Lower Burro Canyon Formation, primarily composed of sandstones, mudstones, and pebble conglomerates. Outcrop-based observations and measurements resulted in the description of 4 distinct architectural element types. Quantitative porosity and permeability data are limited, with existing data showing porosities ranging from approximately 11-22% and permeabilities ranging from approximately 20-325 millidarcies.

INTRODUCTION

Heterogeneity in lithology and stratigraphic architecture form primary controls on the porosity and permeability of rocks deposited by fluvial systems (Miall, 1988). In Lisbon Valley, Utah, disseminated copper ore bodies are hosted by sand-dominated beds of the Lower Burro Canyon Formation. These deposits are currently being mined through traditional open-pit, heap-leach methods, but are being considered as potential targets for in-situ leach mining.

The Lower Burro Canyon Formation was deposited during the Early Cretaceous by braided fluvial systems draining the Sevier Highlands to the west and Mogollon Highlands to the south. This unit exhibits significant lithologic heterogeneity throughout its range, varying in composition between mudstone, sandstone, and pebble conglomerate. It also exhibits heterogeneity in depositional architecture, ranging from mudstone-dominated, floodplain architectural styles to sandstone and conglomerate-dominated, amalgamated channel-complex architectures. These heterogeneities exist at the scale of Lisbon Valley, and have important implications for fluid storage and transport in the Lower Burro Canyon Formation.

The success or failure of in-situ leach mining depends on the ability of leaching fluids to move through rocks and come into contact with ore minerals (Briggs, 2015). In sedimentary hosted deposits (such as those of the Lower Burro Canyon Formation in Lisbon Valley), fluid movement and storage is dependent on the depositional and diagenetic characteristics of the sediments themselves. Previous work detailing the Lower Burro Canyon Formation in Lisbon Valley has focused primarily on the paragenetic sequence for this unit (Altinok, 1998), but places little emphasis on its lithologic and architectural character.

The primary purpose of this project was to fill the gap in existing knowledge regarding the lithologic and architectural character of the Lower Burro Canyon Formation in Lisbon Valley. Detailed lithofacies and architectural element classification schemes were developed, and the general stacking pattern of elements was interpreted for the Lower Burro Canyon Formation from panoramic photography. Quantitative porosity and permeability assessments were performed for each lithofacies using mercury injection porosimetry. These results of these efforts represent a crucial input in the feasibility assessment process for the development of an in-situ mining operation in Lisbon Valley.

The results of this study have implications beyond that of the in-situ mining feasibility assessment process. The observed set of lithofacies and upward progression of architectural elements give some insights into the fluvial style of the Lower Burro Canyon Formation depositional system. The results of this study may also have implications for the paleogeography of this region during the Early Cretaceous.

BACKGROUND

Paradox Basin and Salt Diapirism

Lisbon Valley is one of a series of northwest-trending anticlines, associated synclines, and extensional faults collectively known as the "Paradox Fold and Fault Belt" (Figure 1) (Baars & Stevenson, 1981). The Paradox Fold and Fault Belt formed through a progression of geologic processes that began with the deposition, loading, and diapirism of Pennsylvanian evaporite deposits known as the Paradox Formation.

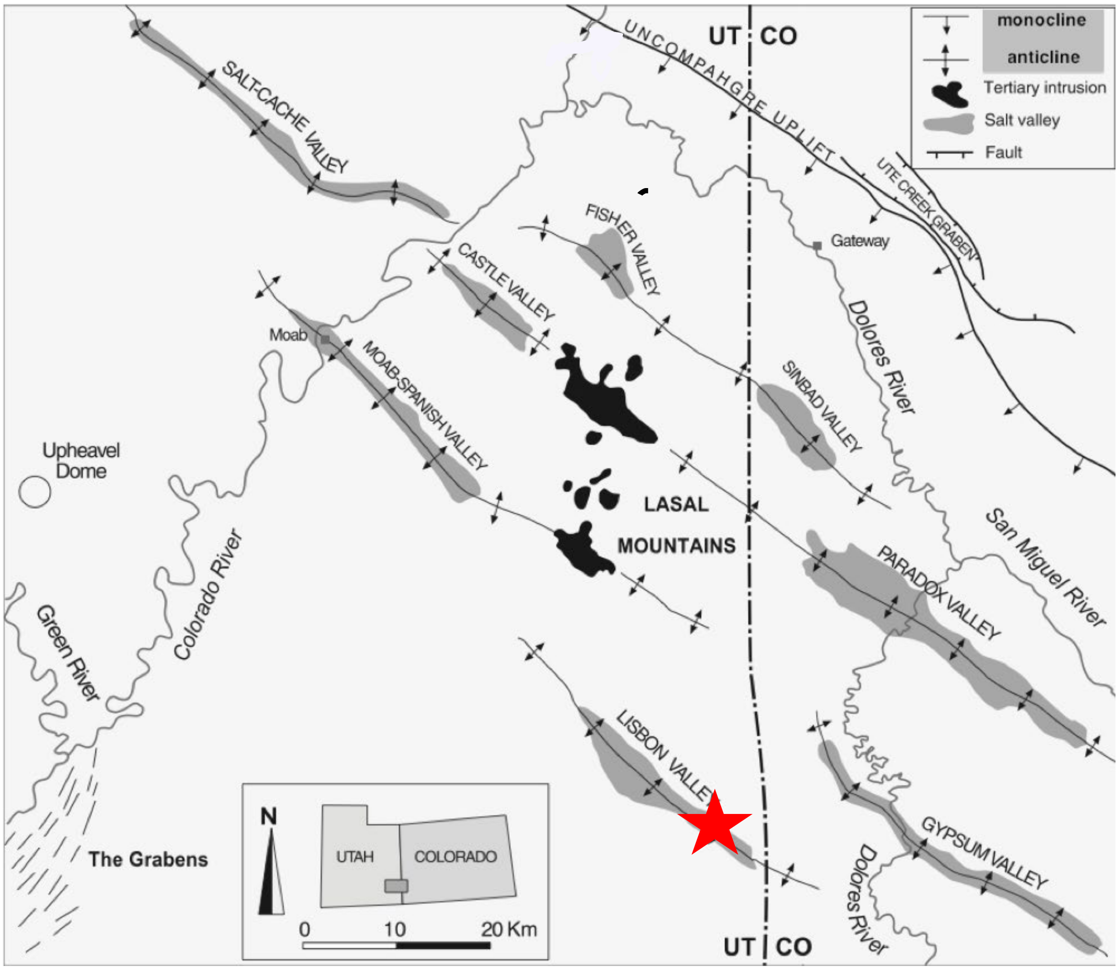

Figure 1: Feature map of the Paradox Basin showing the locations of major salt anticline structures in the region. From Gutierrez (2004). Note the location of the Colorado River, which forms the arbitrary dividing line between the Burro Canyon Formation and the Cedar Mountain Formation. Red star marks the study area.

The Paradox Basin is an intraforeland flexural basin formed in response to the basement-involved Uncompaghre uplift of the Ancestral Rocky Mountain orogeny (Barbeau, 2003). Overthrusting of the northwest-trending Uncompahgre uplift created rapid subsidence of the Paradox Basin, resulting in the deposition of coarse-grained arkosic sediments proximal to the uplift, and deposition of evaporite sequences up to 8000 feet thick in medial parts of the basin (Baars & Stevenson, 1981). These evaporite beds (and interbedded silts and shales) are known as the Paradox Formation.

Subsidence in the Paradox Basin began to slow during the Permian, as coarse-grained arkosic sediment shed from the Uncompahgre Uplift prograded outward to fill and eventually overtop the basin. Coarse terrestrial clastics, now known as the Cutler Group, were deposited atop thick Pennsylvanian evaporite beds, creating an enormous overburden which eventually led to the mass flowage of underlying salt (Baars & Stevenson, 1981).

Salt movement and density contrasts resulted in the upward rise of the Paradox Formation along elongated salt walls (anticlines), folding the rocks above and forming large anticlines with deformed salt cores. In many of these structures, the salt cores have since been dissolved by fluids and transported elsewhere, resulting in large scale collapse along steeply dipping normal faults (Baars & Stevenson, 1981). These faults run roughly parallel to the crest of the anticlines and represent important controls on fluid movement (both ancient and modern) and resource distribution in the Paradox Basin (Thorson, personal communication, 2018).

Lisbon Valley Mining District

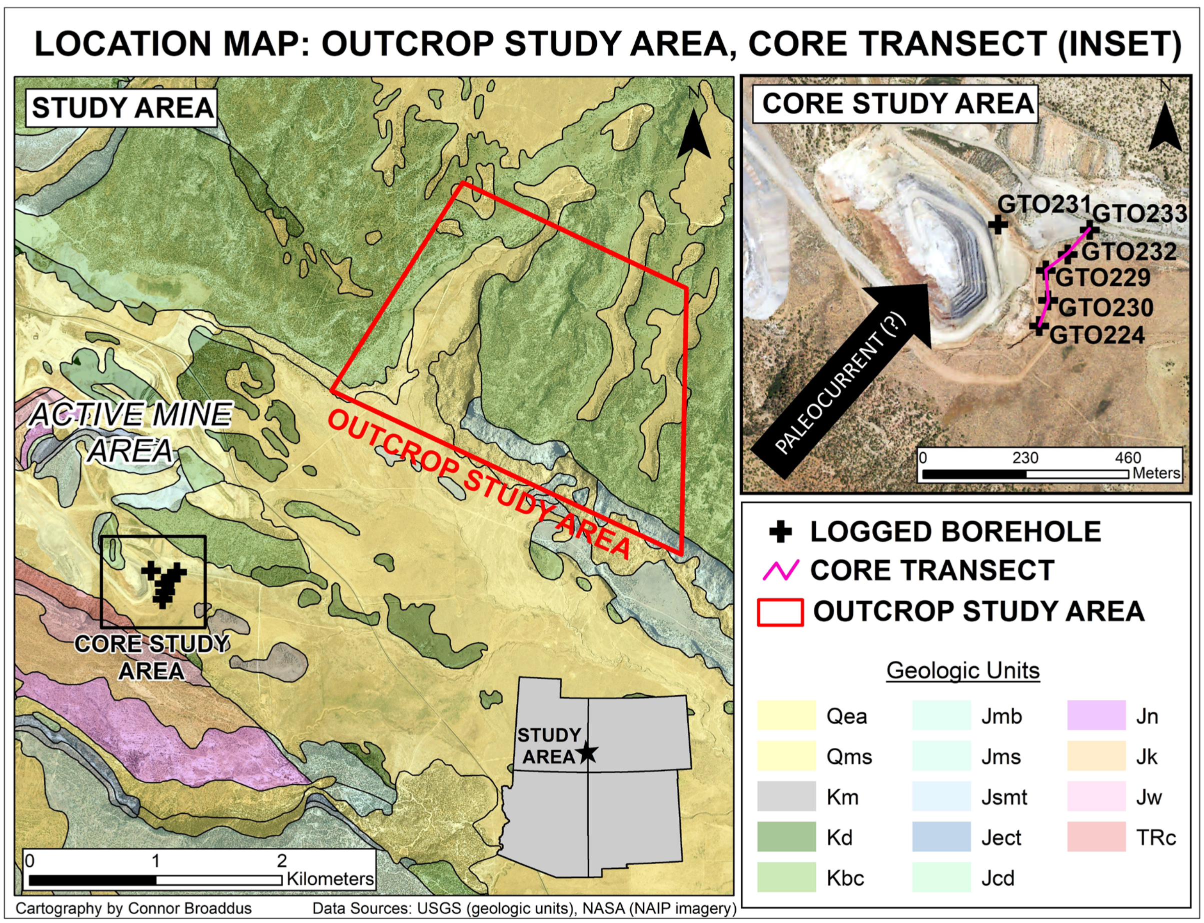

Figure 2: Study area map centered on Lower Lisbon Valley. Geology (USGS) is overlain on NAIP aerial imagery. Inset map shows the locations of logged core. Polygon at bottom right of main map shows study area location within the Four Corners region.

The Lisbon Valley Mining District is located in the Paradox Basin approximately 60 miles south of Moab, Utah, and is situated atop a doubly-plunging, northwest-trending anticline that developed as a result of Paradox diapirism (Figure 2). The northeastern flank of the anticline is offset roughly 1000 feet along a steeply dipping normal fault (Krahulec, 2006). This fault is roughly continuous near the center of the anticline, but diverges into a series of splays at the northwest and southeast tips of the anticline. Copper (and associated vanadium, silver, and iron) mineralization is concentrated in porous and permeable sedimentary units immediately adjacent to these faults.

Commercial copper mining has occurred in the Lisbon Valley District for well over a century (Krahulec, 2006). Early workers, such as those of the Big Indian Mine, concentrated on deposits at the northwestern end of the anticline, while later operations, such as the Blackbird Mine, were focused along splays at the southeastern end of the structure. Current operations are focused on 3 major splays of the Lisbon Valley Fault near the southeastern tip of the anticline.

The exposed stratigraphy of the Lisbon Valley Mine includes beds ranging from Jurassic to Cretaceous in age, and is shown in the stratigraphic column in Figure 3. Triassic, Permian, and older rocks are not exposed at the surface in the southeastern portion of the valley, but exist in the subsurface at this location.

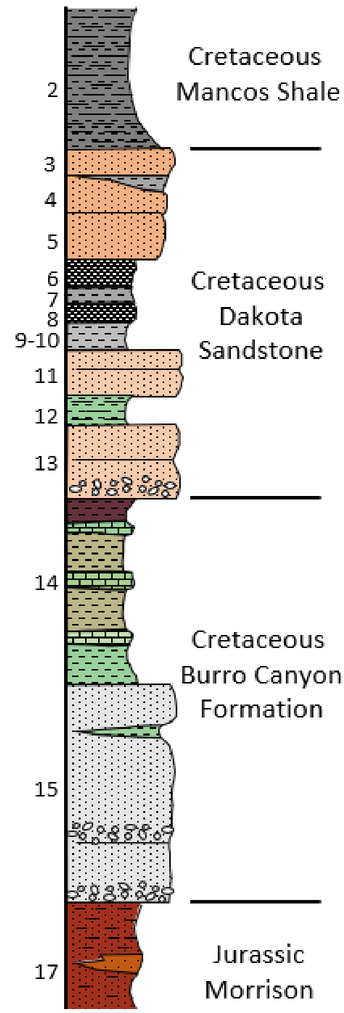

Figure 3: Generalized column of exposed stratigraphy of Lisbon Valley, Utah. Bed number nomenclature used by the mine is included to the left of the column.

The primary copper ore hosting beds in Lisbon Valley are the Lower Burro Canyon Formation (Bed 15) and the Dakota Sandstone (Bed 13). Thick, impermeable shales of the Mancos Shale overlie these coarse-grained, high-permeability units, creating a significant fluid seal (vertical permeability barrier) that directly overlies reservoir rocks. The green mudstones of the upper Burro Canyon Formation may also create a barrier to fluid transport, though the nature of this barrier is uncertain due to the occurrence of mineralization in beds of the overlying Dakota Sandstone (Thorson, personal communication, 2019).

Though an important ore hosting bed in Lisbon Valley mine workings, the Dakota Sandstone is outside of the scope of this project and is therefore not discussed in the following sections. It should be noted, however, that the mineralization observed in the lower beds of the Dakota Sandstone is an important chapter in the story of fluid movement, and will require further study.

Historic and current mining efforts in Lisbon Valley have consisted primarily of large-scale, open-pit operations. However, ore distribution within the Lower Burro Canyon Formation is highly variable, and is difficult to predict due to the multitude of factors and timing of events that could control its distribution. Additionally, regional dips in the southeast end of the valley result in increased ore depths toward the southeast. Because of these factors, the Lisbon Valley Mining Company is assessing the viability of in-situ leach recovery as a means of mining deposits situated at the southeastern end of Lisbon Valley.

In-situ leach mining is a modern resource extraction process that provides a means for recovering metals from an ore body without the need to excavate the ore body itself. In-situ leach mining uses a series of boreholes and pumps (called injection wells) to force solutions, such as water or dilute acid, through the natural fluid pathways of an ore body (Briggs, 2015). Soluble target metals are dissolved into the now "impregnated" solution, which is then pumped out of the rock by a series of recovery wells. The impregnated solution can then be processed by methods similar to those used in traditional heap-leach operations.

In-situ leach mining allows for the development of large, low-grade copper deposits that would not otherwise be economical to mine, such as those found at the southeast end of Lower Lisbon Valley. The effectiveness and productivity of an in-situ leach mining operation, however, are directly dependent on the solution's ability to circulate through the ore body (Briggs, 2015). The feasibility of any in-situ leach mining operation is thus determined by those factors which control fluid movement through the rock, such as permeability, porosity, and sand-body connectivity. In the Lower Burro Canyon Formation, these factors are highly variable, and are poorly understood in terms of major trends and possible controls.

Burro Canyon Formation

The Burro Canyon Formation is a package of sedimentary rock found across much of western Utah, eastern Colorado, and northern New Mexico. It is bounded by unconformities and marks the beginning of the Cretaceous section for much of its range. The Burro Canyon Formation is widely considered to be age equivalent to the Cedar Mountain Formation of northern and central Utah, with the Colorado River serving as an arbitrary demarcation line between the two units (Stokes, 1952; Miller, 2016). It is underlain by the Salt Wash Member of the Jurassic Morrison Formation, and overlain by the Cretaceous Dakota Sandstone (Young, 1975).

The Burro Canyon Formation was deposited by braided to meandering fluvial systems carrying water and sediment shed from the Sevier Highlands to the west and the Mogollon Highlands to the south (Miller, 2016) (Figure 1). The Sevier orogeny began approximately 140 Ma (at the onset of the Cretaceous) when a large fold and thrust belt was uplifted across western North America as a result of the subduction of the Farallon Plate beneath the North American Plate (DeCelles, 2004). This uplift resulted in the development of the Sevier Highlands and a corresponding flexural foreland basin, termed the Rocky Mountain Foreland Basin, along the eastern flank of the mountains. A large coastal plain divided the proximal and distal portions of the basin, and The Burro Canyon Formation was deposited by fluvial systems flowing from the southwest to the northeast across this coastal plain (DeCelles, 2004). The Mogollon Highlands were uplifted in central Arizona and southern New Mexico during the Early Cretaceous as a thermotectonic rift shoulder of the Bisbee Basin. Sediment shed from the north slope of the Mogollon Highlands was deposited by streams which eventually merged with those draining the Sevier Highlands, resulting in the deposition of the Burro Canyon Formation (Miller, 2016.)

Paleocurrent orientation is poorly understood in the Burro Canyon Formation across much of its range. Regional drainage directions suggest paleocurrents that run roughly southwest to northeast (Craig, 1982). Individual paleocurrent studies (Lewis et al., 2018; Miller, 2016) located outside of the Paradox Basin corroborate this idea, with transport directions that are dominantly southwest to northeast or south to north. However, the paleocurrent orientation of this unit in regions affected by Paradox salt diapirism is very poorly constrained.

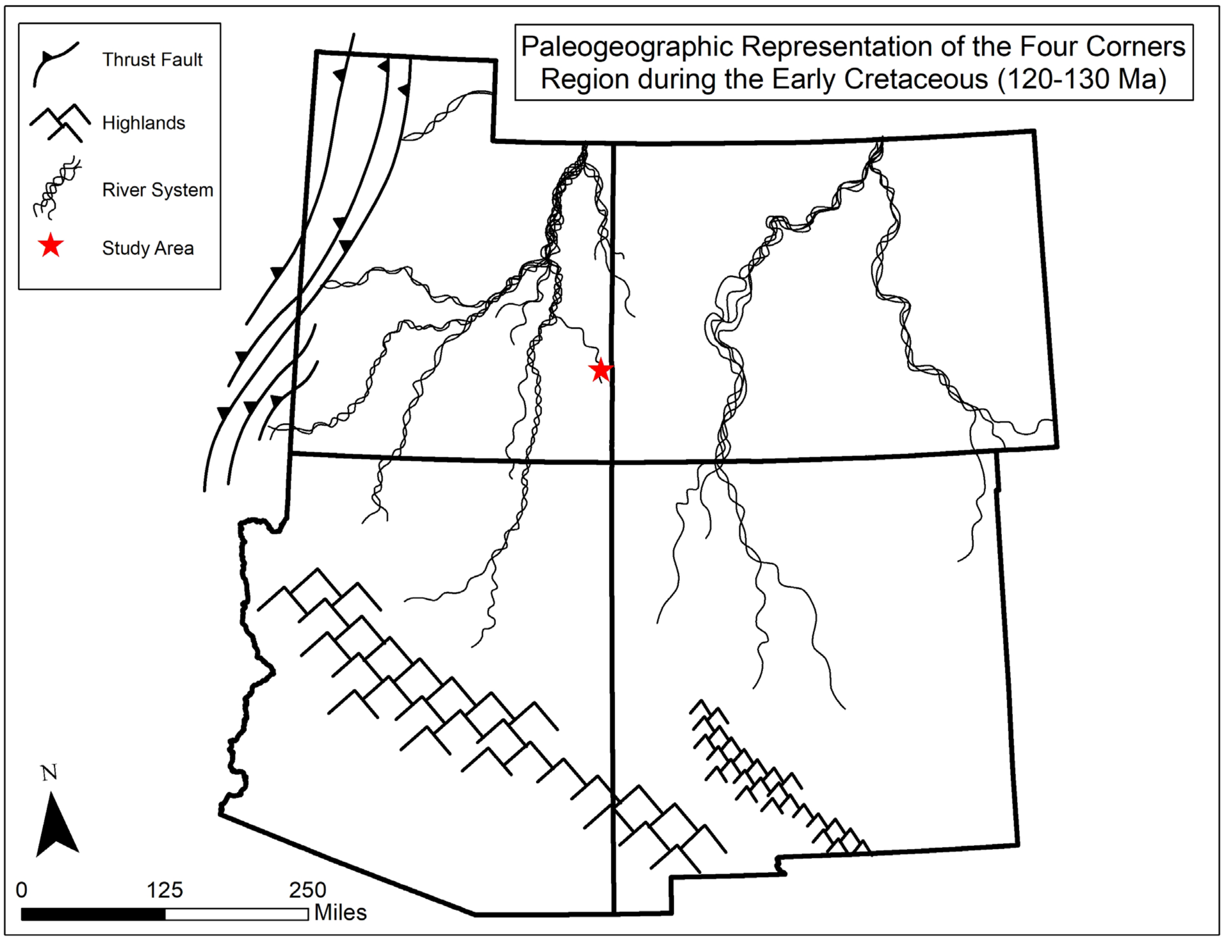

Figure 4: Paleogeographic representation of the Four Corners region during the deposition of the Burro Canyon Formation. Note the dominant drainage direction is roughly southwest to northeast. Based on the work of Dr. Ron Blakey.

Coarse-grained sandstone and conglomeratic sandstone dominate the lower portion of the formation, and are interbedded with green silty mudstone and some red siltstone. The Upper Burro Canyon Formation consists primarily of green calcareous mudstone, with rare isolated beds of sandstone and conglomeratic sandstone (Craig, 1982). Thickness of the Burro Canyon Formation ranges from 0 – 90 meters. Because the Lower Burro Canyon Formation forms the primary ore hosting beds in this location, this unit will be the focus of this study.

The Lower Burro Canyon Formation exhibits significant lithological heterogeneity in Lisbon Valley. Sorting ranges from very poorly sorted to very well sorted, and grain size ranges from clay to gravel. This heterogeneity is fractal in nature, occurring at scales ranging from individual laminae and cross bed sets to the scale of the entire Lower Burro Canyon Formation. In order to fully characterize this heterogeneity, it is necessary to consider the various scales at which the rock can be considered roughly homogenous.

Fluvial Heterogeneity & Permeability

Previous studies have shown that significant heterogeneity exists at multiple scales in rocks deposited by fluvial systems. Miall (1988) suggested a six-fold hierarchy of bounding surfaces that divides heterogeneity into scales ranging from the member/submember level (at the largest scales) down to the scale of individual lithofacies. A recent study by Lewis et al. (2018) focused on the Burro Canyon formation defined two major scales of heterogeneity in fluvial reservoir rocks: reservoir-scale heterogeneity defined by the stacking pattern of architectural elements, and element-scale heterogeneity defined by the stacking pattern of lithofacies. This investigation will use a similar hierarchy, focusing on the heterogeneities observed at the lithofacies scale (centimeters), the facies association / architectural element scale (meters), and at the member scale (tens of meters) (Figure 5).

Though often difficult to quantify, heterogeneities in fluvial reservoir rocks can have significant and important qualitative effects on permeability. At the lithofacies scale, variations in composition, sorting, and sedimentary structures form the primary controls on permeability. Clay has the ability to clog pores and pore throats, effectively limiting the porosity and permeability of clay-dominated lithofacies and lithofacies that contain clay. Porosity and permeability in poorly sorted deposits is also inhibited by pore clogging grains (though not necessarily clays). Coarse-grained, well-sorted, massive sandstones represent the most permeable lithofacies types, while fine-grained mudstones represent nearly impermeable barriers to fluid movement.

At the architectural element scale, the observed association of lithofacies controls the overall permeability of the element and its distribution throughout. The degree of amalgamation of sand dominated lithofacies is also a major control on architectural element porosity and permeability. Element geometries (vertical and lateral dimensions, upper and lower contact types) control the connectivity of sand-bodies at the member scale.

At the member scale, variations in the stacking frequency of sandstone bodies, referred to as the amalgamation ratio, represent a major control on vertical permeability. Similarly, variations in the lateral continuity (or horizontal width) of sandstone bodies represent a major control on lateral permeability.

By characterizing the heterogeneity that exists within the Lower Burro Canyon Formation at the lithofacies-scale, the architectural element scale, and the member scale, interpretations and predictions can be made regarding the overall connectivity and permeability of ore-hosting beds that are targets for in-situ leach mining efforts. These observations also provide key insights into the depositional setting for the Lower Burro Canyon Formation in this location, with paleotopographic implications for the Paradox Basin during the Early Cretaceous.

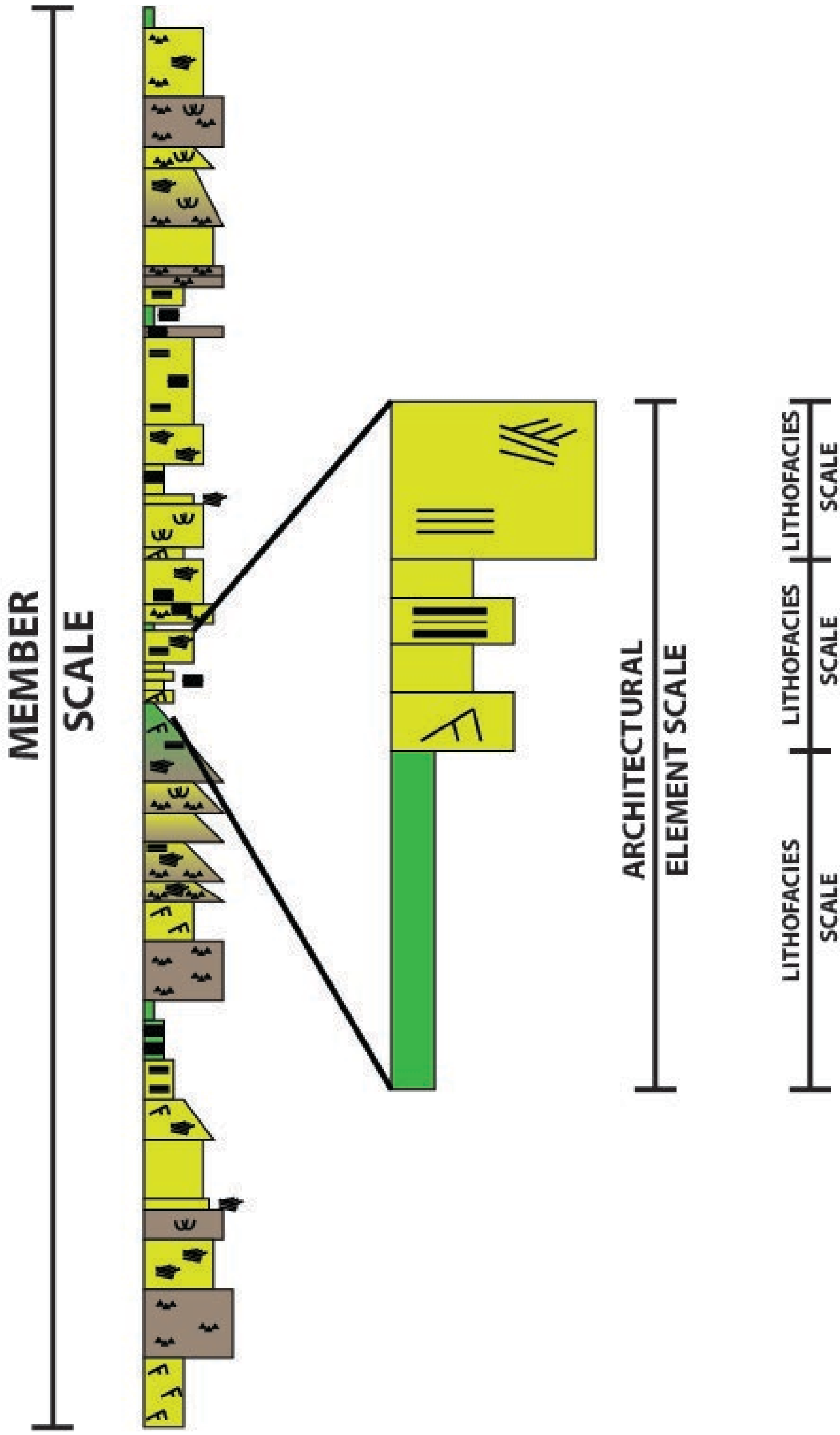

Figure 5: Stratigraphic column schematic depicting the three scales of heterogeneity that will be considered in this study. Note that the stratigraphic column at right is an inset of the column at left, vertically exaggerating the architectural element and lithofacies scales (which are actually much smaller than the member scale).

METHODS

Lithofacies-Scale Efforts

The Lower Burro Canyon Formation has been extensively cored in Lisbon Valley as a part of mineral exploration efforts by the Lisbon Valley Mining Company. Cored intervals typically include the entire Burro Canyon Formation, as well as the overlying Dakota Sandstone and some of the underlying Brushy Basin member of the Morrison Formation. Intervals assumed to be the Lower Burro Canyon Formation were slabbed by mine workers prior to the initiation of this project, with all core being of 2.5 inch diameter.

To capture the lithofacies-scale heterogeneity that exists within the Lower Burro Canyon Formation in this location, a core transect consisting of five drill cores was established and logged in detail. The transect trends roughly southwest to northeast (parallel to the assumed paleocurrent orientation), with core spacing averaging 60 meters (Figure 2).

Each core was logged in detail (smallest unit ~ 5 centimeters) for lithology, grain size, grain shape, sorting, sedimentary structures, degree and type of cementation, and bounding surfaces. Observations were recorded to paper logs, which were digitized in Adobe Illustrator for correlation interpretations and to increase readability, although certain data was excluded in the digital logs for this same reason.

Core-based observations were used to classify and characterize the existing lithofacies heterogeneity for the Lower Burro Canyon Formation in this location. Lithofacies were defined according to lithology and characteristic sedimentary structures, and nearly all can be equated with the lithofacies scheme of Miall (1988). This standardized scheme enjoys widespread use and allows comparison to other fluvial systems in different locations. During the classification process, emphasis was placed on those characteristics thought to affect fluid storage and transport, such as mud content and sorting.

Petrographic analysis of select lithofacies was made possible by opportunistic sampling of thin sections that were collected and prepared by University of Arizona student Alex Whitehead. Although these samples were not collected for the express purpose of this project, they represented various lithofacies within the Lower Burro Canyon Formation and were collected from the same cores that were logged in this study. To characterize the micro-scale features that may be affecting lithofacies porosity, we described select thin sections for features including lithology, grain size, grain shape, sorting, presence or absence of clays, cementation, and sedimentary structures (if visible). Although sedimentary structures were often not visible in thin section, corresponding hand samples were used to confirm the lithofacies classifications of each thin section.

To determine the quantitative fluid storage and transport characteristics of each of the identified lithofacies, representative samples of each lithofacies were collected for laboratory-based mercury-injection porosimetry testing. Samples were collected and prepared by geologists at the Lisbon Valley Mine and involve removing a small diameter “plug” from the drill core, in the direction perpendicular to the hole itself (long dimension of sample is roughly parallel to bedding). Porosimetry testing was performed by PoroTechnology Reservoir Evaluations Laboratory and funded by the Lisbon Valley Mining company. Testing results include porosity as a percentage and permeability in millidarcies.

Architectural Element-Scale Efforts

The Lower Burro Canyon Formation is exposed to varying degrees in the cliffs that form the rim of Lower Lisbon Valley. The degree of exposure is determined by the lithology for any given location; sandy, more amalgamated sections are well-exposed in vertical cliffs, while sections dominated by isolated sand bodies and clay tend to form slopes covered by large (up to 10 meters in diameter), fractured blocks of sandstone. This style of terrain is poorly suited for stratigraphic section measurement, as a majority of the section is either covered by rockfall or is dangerously exposed.

Architectural element-scale heterogeneity has the most significant effect on fluid storage and transport capacity in fluvial deposits (Miall, 1988). Characterizing the dominant architectural element styles in the Lower Burro Canyon Formation is therefore essential to the purpose of this project, despite the challenges associated with outcrop-based section measurement in this location. To address these challenges, field-based efforts focused on identifying and measuring individual architectural elements, rather than measuring entire sections.

Architectural element classifications were made based on the observed assemblage of lithofacies, geometries (including dimensions), and bounding surfaces. Because the study area characteristics inhibit section measurement, the element classification scheme that was developed for this project is intentionally generalized relative to many other architectural studies. Rather than attempting to identify individual macroforms (such as a single channel-fill or a single fluvial bar), elements were grouped based on characteristics important to fluid storage and transport, such as sand body connectivity.

Once the element classification scheme had been defined, specific elements considered representative examples of each element type were selected for more detailed observation. Dimensional measurements of each element type were made with a measuring tape, including average thickness and lateral extent. The lithofacies assemblages and bounding surfaces were observed and recorded for each element type.

System-Scale Efforts

To determine the fluid storage and transport characteristics of the Lower Burro Canyon Formation as a whole, petrophysical heterogeneity must be investigated at not only the scale of lithofacies and architectural elements, but also at the scale of the entire member. Member-scale permeability and porosity is determined by the degree of amalgamation of permeable rock types (sandstones) (Zhang, et al. 2017), and the stacking patterns of the various architectural elements (Miall, 1988).

To determine the degree of amalgamation of permeable rock types within the Lower Burro Canyon Formation, amalgamation ratio was calculated from core using the scheme designed by Zhang et al. (2017). Although this scheme was developed for use submarine channel systems, the authors note the potential for its application to other channelized depositional systems, such as braided fluvial deposits. Amalgamation ratio was

$$\mathbf{A/R} = \frac{\text{NUMBER OF SAND ON SAND SCOUR SURFACES}}{\text{TOTAL NUMBER OF SCOUR SURFACES}}$$

Figure 6: Equation used for the calculation of amalgamation ratio (A/R)

calculated for the entire length of each core, using the equation in Figure 6. Calculations involve only those contact surfaces identified as scours in core, rather than all contact surfaces. This method was chosen because many of the contacts within the Lower Burro Canyon Formation are gradational in nature, and have permeability affects that are also gradational and difficult to predict. Additionally, these gradational contacts show aggradation rather than amalgamation, whereas scour surfaces represent erosion and reworking of sediment. Sand body amalgamation is analogous to vertical connectivity, and plays a key role in determining fluid storage and transport characteristics, as well as being an important indicator of flow regimes and accommodation space.

To characterize the stacking patterns of architectural elements within the Lower Burro Canyon Formation, a panoramic image was captured of a particularly well exposed outcrop face that is oriented roughly parallel to the orientation of the core transect. This is also one of the outcrops used for identification and classification of the existing architectural element types. The photographs were captured from one location and stitched together using a basic, free software called AutoStitch. This software is extremely easy to use and produces visually appealing stitched panoramas, but lacks the control features of some more advanced stitching softwares. The resulting image is less robust geometrically than some other outputs may be (and thus should not be used for detailed photogrammetry work), but still allows for the recognition of major stratigraphic surfaces, architectural elements, and the characterization of stacking patterns. The stitched panorama was used for exactly this purpose; major surfaces were traced onto the image using Adobe Illustrator, which allowed the identification of architectural elements present in this outcrop. Areas of uncertainty were investigated further during field study to confirm surface locations and element designations.

To support outcrop-based work in the identification of stacking patterns, correlation interpretations were made for the core transect from the digitized core logs. The top of the Lower Burro Canyon Formation served as the datum for these efforts. This datum is considered much more regular and planar than surfaces within the unit or the lower contact. Correlation efforts focused on large packages of sediment (either individual elements or groups of elements) rather than individual surfaces. Because of the poor lateral continuity of scour surfaces and fine-grained intervals, these surfaces show very little correlation.

RESULTS

Lithofacies

Contacts between lithofacies within the Lower Burro Canyon Formation are often gradational in nature, and the section in this area is dominated by normally graded beds that rapidly fine upward from basal scour surfaces. Eight major lithofacies were defined within the Lower Burro Canyon Formation on the basis of lithology, grain size, and sedimentary structures. These lithofacies are listed, qualitatively described, and assigned abbreviated facies codes in Table 1 below.

Table 1: Lithofacies Classification Scheme

Facies Code	Lithofacies Description	Grain Size	Sedimentary Structures	Miall (1978) Equivalent	Miall (1978) Interpretation
Fms	Green Mudstone	Mud-Silt	Flat Lamination	Fm	Overbank or drape deposits
Fss	Red Mudstone - Siltstone	Mud, Silt, Sand	Root Traces	Fsc	Backswamp deposits
Mds	Mud-Draped Siltstone - Sandstone	Mud, Silt, VF-F Sand	Planar Lamination Ripple Lamination with Mud Drapes	Fl	Overbank or waning flood deposits
Srl	Ripple Laminated Sandstone	F-M Sand	Ripple Lamination	Sr	Current ripples (lower flow regime)
Spl	Planar Laminated Sandstone	VF-M Sand	Planar Lamination	Sh	Planar bed flow (upper flow regime)
Scb	Cross-bedded to Massive Sandstone	VF-VC Sand with some Pebbles	Trough and Planar Cross Stratification	St, Sp	Dunes, linguoid bars, transverse bars, sand waves
Sgi	Interbedded Sandstone & Pebble Conglomerate	M-VC Sand, Pebbles, Rip-up Clasts	Trough and Planar Cross Stratification	Gp, Gt	Minor channel fills, longitudinal bars
Grc	Pebble Conglomerate with Rip-up Clasts	VC Sand, Pebbles, Rip-up Clasts	Crudely Bedded, some Trough Cross Stratification	Se	Scour fills

The Green Mudstone lithofacies is composed primarily of clay to silt-sized grains, with the occasional interbed of fine-grained sand. This lithofacies is defined by its small grain size, green color (due to the presence of reduced iron), and flat laminated structure. Figure 7 is a photomicrograph showing a representative example of this lithofacies.

The Red Mudstone-Siltstone lithofacies is composed primarily of silt-sized grains, with some clay and sand-sized grains. This lithofacies occasionally includes root traces, is commonly flat-laminated, and varies in color from reddish-orange to grey.

The Mud-Draped Sandstone lithofacies is composed primarily of sand and clay sized grains. This lithofacies is characterized by the presence of thin (< 1 mm) clay layers that are interbedded with fine grained sand and extend laterally for no more than approximately 5 cm. Figure 8 is an outcrop image that includes a representative example of this lithofacies.

The Ripple Laminated Sandstone lithofacies is composed primarily of fine to medium grained sand (with some clay) and is characterized by the presence of small current ripple sedimentary structures. These ripples are occasionally mud-draped, with the mud fraction being the primary difference between this lithofacies and the Mud-Draped Siltstone-Sandstone lithofacies.

The Cross-bedded to Massive Sandstone lithofacies is composed primarily of quartz sand grains and chert pebbles, with very little mud. This lithofacies is characterized by its coarse-grained nature and poor sorting. Cross-bedding (planar and/or trough) is common, though not necessarily characteristic (massive sandstones are included in this lithofacies). Figure 9 is photomicrograph depicting a sample considered representative for this lithofacies.

The Planar Laminated Sandstone lithofacies consists of very fine to medium-grained sand, and is characterized by the presence of planar lamination. This lithofacies is relatively homogenous and is dominated by quartz grains with very little mud or chert. Figure 10 includes two photomicrographs of the planar laminated sandstone lithofacies, both taken from the same thin section. These images highlight a number of features, including the growth of opaque mineralization in pore spaces and the variability in degree of quartz overgrowth cementation.

The Interbedded Sandstone and Pebble Conglomerate lithofacies is characterized by its poor sorting, and is composed primarily of quartz sand, chert pebbles, and some rip-up clasts. This lithofacies occasionally contains planar lamination or cross-bedding.

The Pebble Conglomerate with Rip-up Clasts lithofacies is characterized by its coarse grain sizes and extremely poor sorting. This lithofacies is composed of quartz sand, chert pebbles, and rip-up clasts that vary in abundance. Examples dominated by rip-up clasts have mud fractions so high that they are nearly matrix supported. Other examples contain no rip-up clasts at all. Figure 11 includes a representative photomicrograph of the Pebble Conglomerate with Rip-up Clasts lithofacies. This image highlights the presence of clays within the pore spaces between quartz grains, as well as the poorly sorted nature of this lithofacies in general.

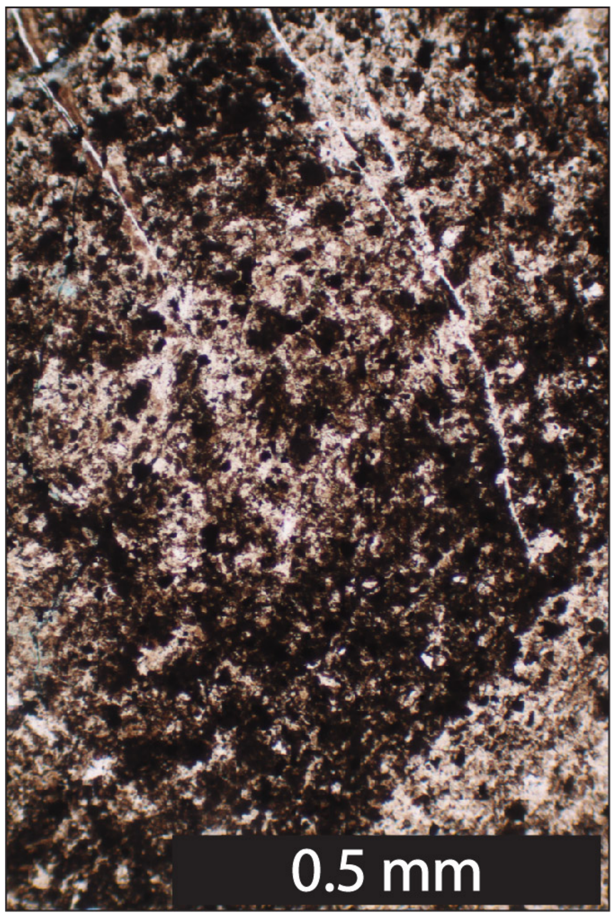

Figure 7: Photomicrograph of the Green Mudstone Lithofacies. Note the flat laminated clays and absence of porosity (would appear blue due to epoxy coloring)

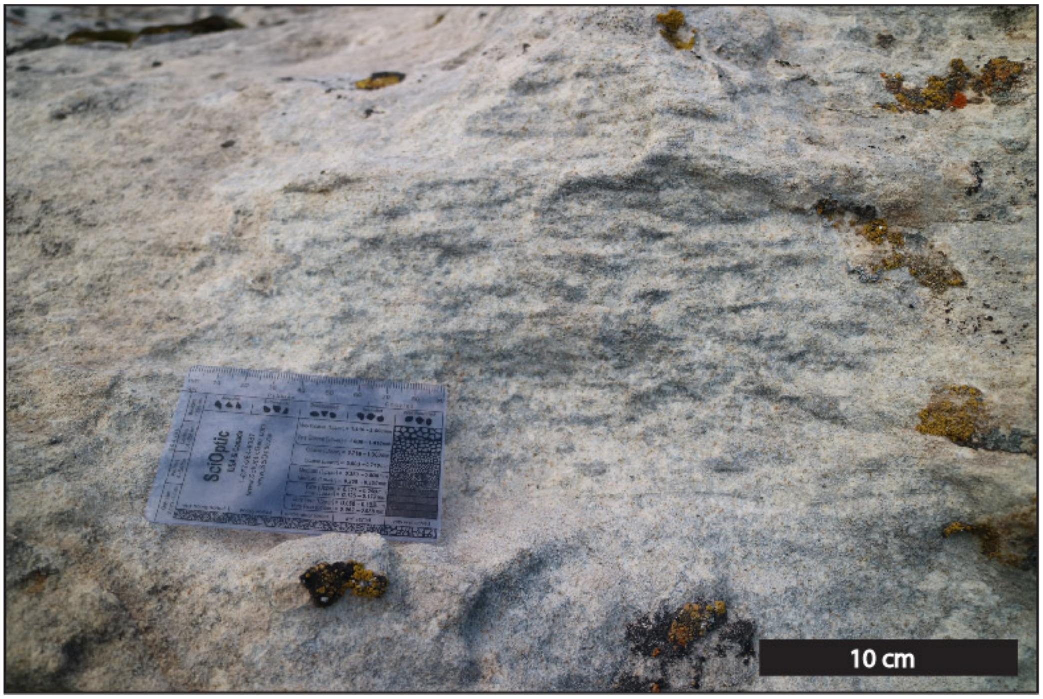

Figure 8: Outcrop image of the Mud-draped Sandstone Lithofacies. Note the presence of thin, interbedded muds (darker laminae / blebs) in a matrix of dominantly fine-grained sand.

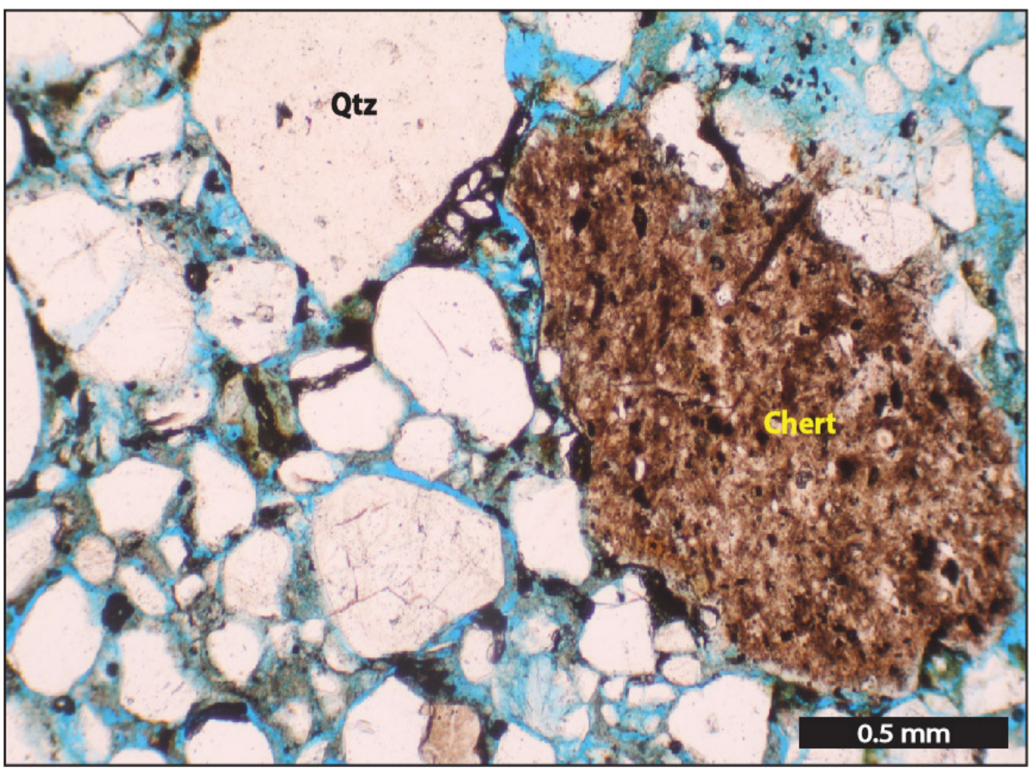

Figure 9: Photomicrograph of the Cross-bedded to Massive Sandstone Lithofacies. Note the poor degree of sorting, relatively high porosity (blue epoxy). Opaque grains are assumed to be copper mineralization.

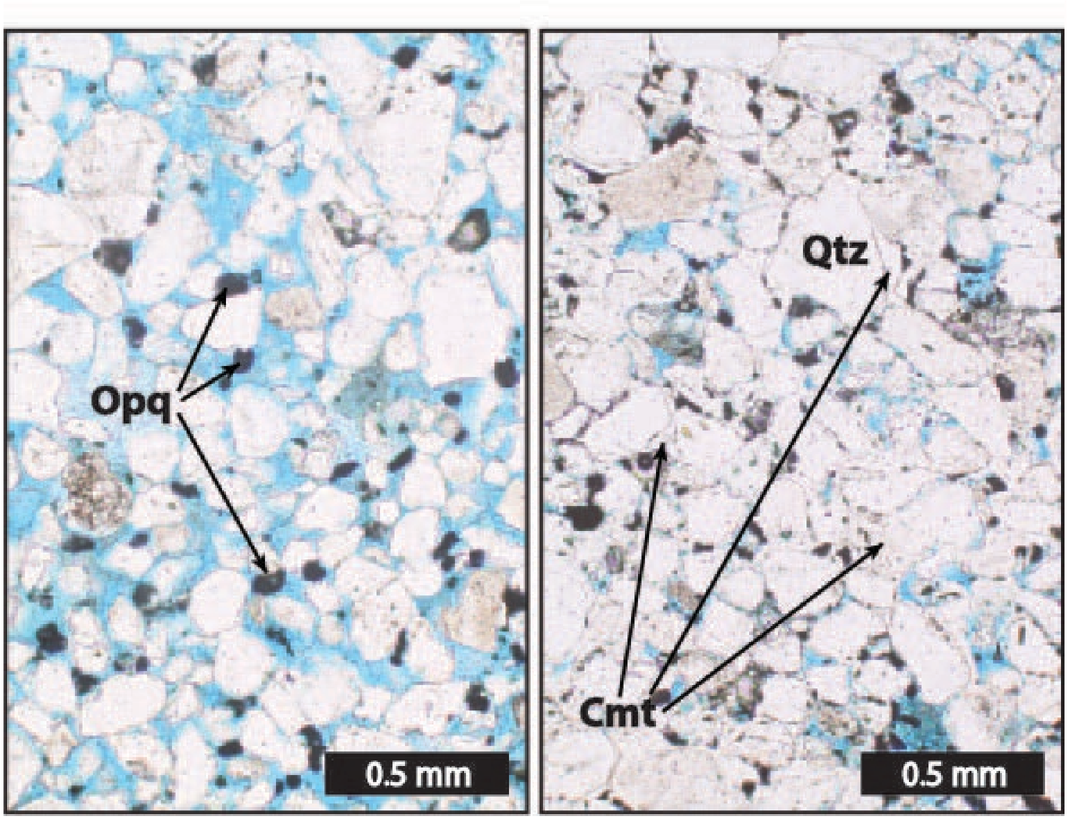

Figure 10: Photomicrographs of the Planar Laminated Sandstone lithofacies taken at 40x magnification. Note the variability in porosity (blue epoxy) associated with quartz overgrowth cementation (Cmt), in contrast to the lack of variability in the opaque mineralization (Opq), assumed to be copper sulfides.

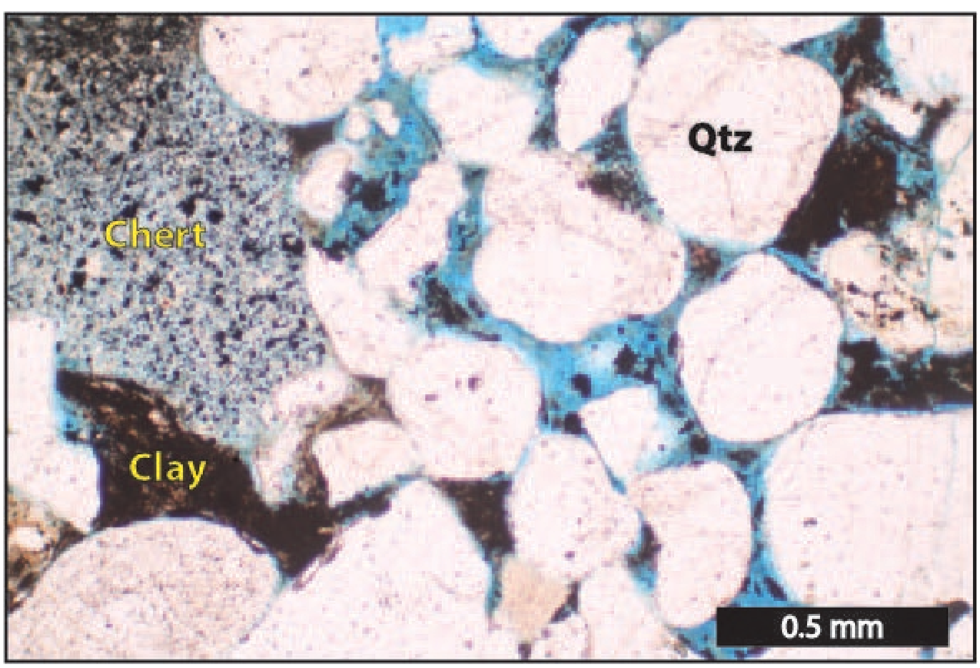

Figure 11: Photomicrograph of Pebble Conglomerate with Rip-Up Clasts lithofacies at 40x magnification. Note the abundance of clays in the pore space (blue) between grains of quartz (Qtz) and chert sand.

Quantitative Porosity and Permeability Testing

Mercury injection porosimetry was performed on representative samples collected from core for each of the 8 lithofacies that were defined. Results include percent porosity, permeability in millidarcies, density in grams per cubic centimeter, and a drainage composite, which plots injection pressure (in psi) against wetting phase saturation in cumulative percent pore volume. The resultant porosity and permeability values were compiled in a table format (Table 2) and cross plotted for each lithofacies, shown in Figure 12. Sample depth locations for porosimetry testing are indicated by the colored stars on the stratigraphic columns in Figure 16. Porosity ranges from ~ 11% to ~ 22%, and permeability ranges from ~ 20 millidarcies to ~ 350 millidarcies. Planar Laminated Sandstone and Ripple Laminated Sandstone lithofacies exhibit the greatest porosities and permeabilities.

Table 2: Quantitative Porosimetry Results

Lithofacies	Porosity (%)	Permeability (mD)	Supporting Observations
Pebble Conglomerate with Rip-Up Clasts	17.86 %	190.38 mD	Rip-up clasts, extremely poor sorting
Planar Laminated Sandstone	16.72 %	325.55 mD	No rip-up clasts and very little clay
Ripple Laminated Sandstone	21.89 %	323.38 mD	No rip-up clasts and very little clay
Ripple Laminated Sandstone	10.67 %	20.19 mD	Abundant recemented fractures, some clay between grains
Massive to Cross-bedded Sandstone	12.37 %	150.57 mD	Rip-up clasts, poor sorting

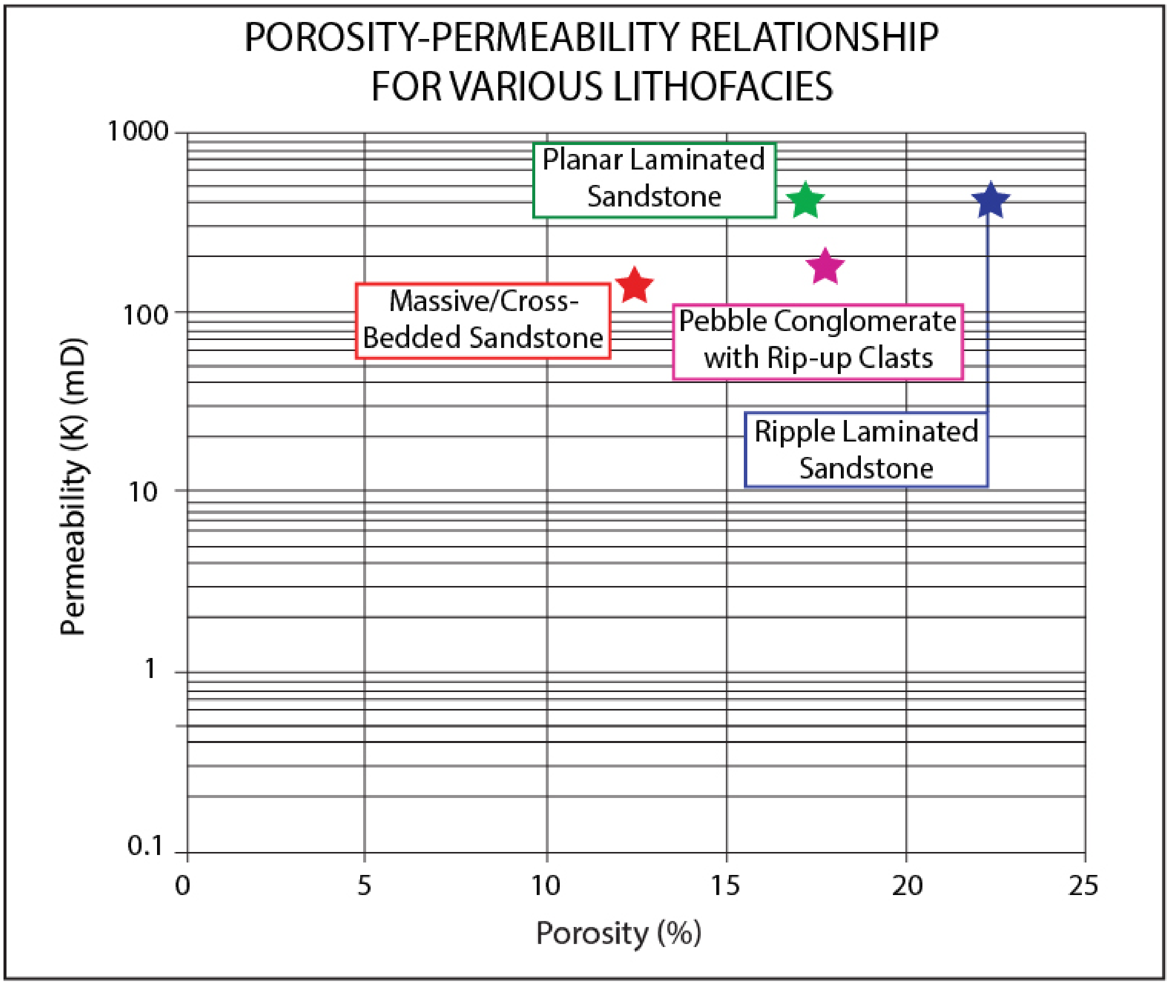

Figure 12: Crossplot showing the relationship between porosity and permeability for four of the eight identified lithofacies. Sand dominated lithofacies with little to no mud exhibit the highest porosities and permeabilities, while poorly sorted, higher energy lithofacies containing rip-up clasts exhibit lower porosities and permeabilities.

The observed set of lithofacies can be easily compared to the lithofacies scheme designed by Miall (1988), and Table 1 includes columns denoting these facies equivalencies. By determining these equivalencies, the vertical stacking patterns of lithofacies (facies associations) can be interpreted for architectural elements using the scheme developed by Miall (1988).

Architectural Elements

Architectural elements are defined by their bounding surfaces, lithofacies assemblages, scales, and lithosome geometries (Miall, 1988). Outcrop observation and measurements in the Lower Burro Canyon Formation revealed the presence of four different architectural element types, listed and described in Table 3. These element types are intentionally categorically broad and include a number of the more specific element types defined by Miall (1988).

Table 3: Architectural Element Scheme

Element Code	Element Name	Constituent Lithofacies	Bounding Surfaces	Geometry
ACC	Amalgamated Fluvial Bar / Channel Fill Complex	Grc, Sgi, Scb, Spl minor Srl	Erosive, irregular concave base with either gradational or eroded, irregular concave top	Amalgamated lenses, dune forms, and sheet-like bodies with abundant basal scour, combine to form sheets up to 12m thick and of varying lateral extent
ICC	Isolated Fluvial Bar / Channel Fill Complex	Grc, Sgi, Scb, Spl minor Srl, Mds near top	Erosive, irregular concave base with gradational top. Tend to be connected laterally	Isolated lenses, dune forms, and sheet-like bodies with abundant basal scour. Individual bodies up to 3m thick and upt to 15m in lateral extent
LSS	Laminated Sheet Sand	Spl, Srl, Mds, Fss minor Scb, Sgi near base	Erosive, planar to slightly concave base with eroded planar or irregular or concave top	Sheet-like sand bodies that extend up to >1000m laterally, range from 3-9m thick
FPF	Floodplain Fines	Fms, Fss, Mds Minor Spl interbeds	Gradational base with eroded irregular, concave, convex, or planar top	Typically well laminated, envelopes other elements, otherwise tends to drape surfaces within elements. Some thin interbedded sheet sands.

The amalgamated fluvial bar / channel-fill complex element is by far the most dominant architectural element type observed within the Lower Burro Canyon Formation at this location. It exhibits significant lithologic heterogeneity and consists primarily of conglomeratic to sandy lithofacies with some interbedded mudstones and siltstones. This element type is characterized by an abundance of irregular internal scour surfaces that contain green clay rip-up clasts and range from 1-5 cm thick. Graded beds are typically bounded by these scour surfaces (Figure 13) and consist of the facies progression described in Table 3. This element type is most common within the lower portion of the Lower Burro Canyon Formation, often forming laterally continuous, well connected sand bodies up to 12 meters thick.

Isolated fluvial bar / channel-fill complexes consist of primarily the same lithofacies that are observed within the amalgamated fluvial bar / channel-fill complexes but are encased by floodplain fines and lack the abundant and laterally extensive scour surfaces observed in the latter. Beds commonly fine upward from a basal scour surface through the entire progression of lithofacies listed in Table 3, eventually grading into the green siltstone and mudstone facies that make up the floodplain fines element type. This element type is most dominant within the upper portion of the Lower Burro Canyon Formation, and forms sand bodies averaging 3 meters in thickness that are isolated both laterally and vertically.

Laminated sheet sands are defined by their planar, laterally continuous geometries. They consist primarily of fine to medium grained, sand-dominated lithofacies, and often exhibit inverse grading. This element is relatively homogenous in composition when compared to the other element types, and most commonly occurs in the lower reaches of the Lower Burro Canyon Formation. Connectivity of this element type varies, and depends primarily on the proximity of this element to other sand-dominated elements (often forms the base or cap for amalgamated fluvial bar / channel complex element). Thickness averages 6 meters. Figure 14 is an image showing the typical lithofacies progression in an outcrop considered representative of this element type.

Figure 13: Outcrop image showing a basal contact of the amalgamated fluvial bar / channel complex element, seen here as an irregular scour surface capping the floodplain fines element (tape measurer is approximately 30cm in diameter)

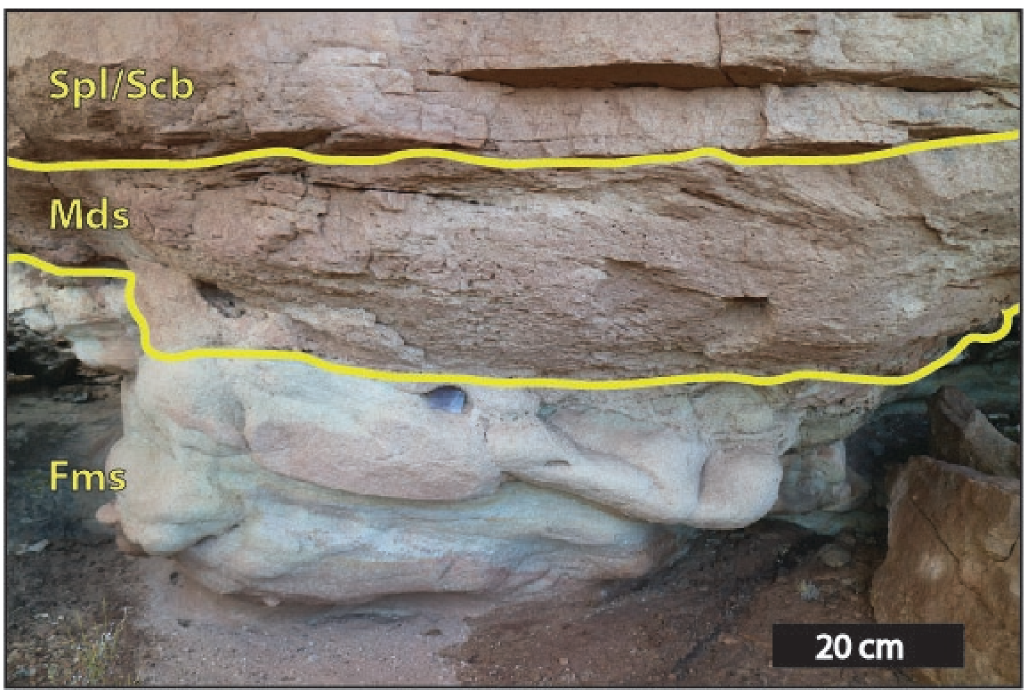

Figure 14: Outcrop image showing the vertical progression of lithofacies typically observed in the laminated sheet sand element. Note the interbedded sand bodies within the Green Mudstone lithofacies (Fms). Mds = Mud draped sandstone, Spl = Planar Laminated Sandstone, Scb = Cross-bedded to Massive Sandstone.

Floodplain fines consist of the green mudstone and gray to green siltstone lithofacies, with occasional interbedded fine-grained sandy lithofacies. This element typically encases or is incorporated within the other element types, rather than forming a distinct geobody. This element is far more dominant in the upper reaches of the Lower Burro Canyon Formation, eventually becoming the dominant element type as the section progresses upward into the Upper Burro Canyon Formation.

Panoramic photography corroborated the presence of these 4 elements by highlighting the outcrop styles of major architectural element types (Figure 15). Additionally, panoramic photography (along with general outcrop observations) depict the upward progression of elements (stacking patterns) for the Lower Burro Canyon Formation at the member scale. The unit generally progresses from more amalgamated, sand dominated architectural styles (in the lower portion) to less amalgamated, floodplain fines-dominated architectural styles.

Amalgamation Ratio

Amalgamation ratio was calculated for the entire Lower Burro Canyon Formation for each of the five cores in the transect, according to the scheme modified from Zhang et al (2017) (Figure 2). Values for individual cores range from 0.38-0.87, with an average of 0.67. Figure 16 includes stratigraphic columns for the five cores in the transect, with the associated amalgamation ratio for each core labeled at the top of the column.

Thickness Trends

Thickness of the Lower Burro Canyon Formation ranges from 30 – 54 meters in the 6 cores that were logged (Figure 16). Because of the close spacing of cores in the transect (average 60 meters), regional thickness trends could not be identified using the data acquired in this study. The thicknesses identified in this study parallel those identified in previous studies for the Lower Burro Canyon Formation over the axis of Lisbon Valley.

Stratigraphic sections measured by Altinok (1998) have thicknesses ranging from 10 to 50 meters and were widely distributed across lower Lisbon Valley and into surrounding areas unaffected by Paradox diapirism. These sections show an increase in thickness of the Burro Canyon Formation over the Lisbon Valley salt anticline; sections measured directly over the anticline have thicknesses up to 50 meters, while adjacent sections measured over the corresponding syncline are as thin as 10 meters (Altinok, 1998).

Figure 15: Panoramic photograph of an outcrop of Lower Burro Canyon Formation. Photograph is oriented roughly parallel to the assumed paleocurrent orientation.

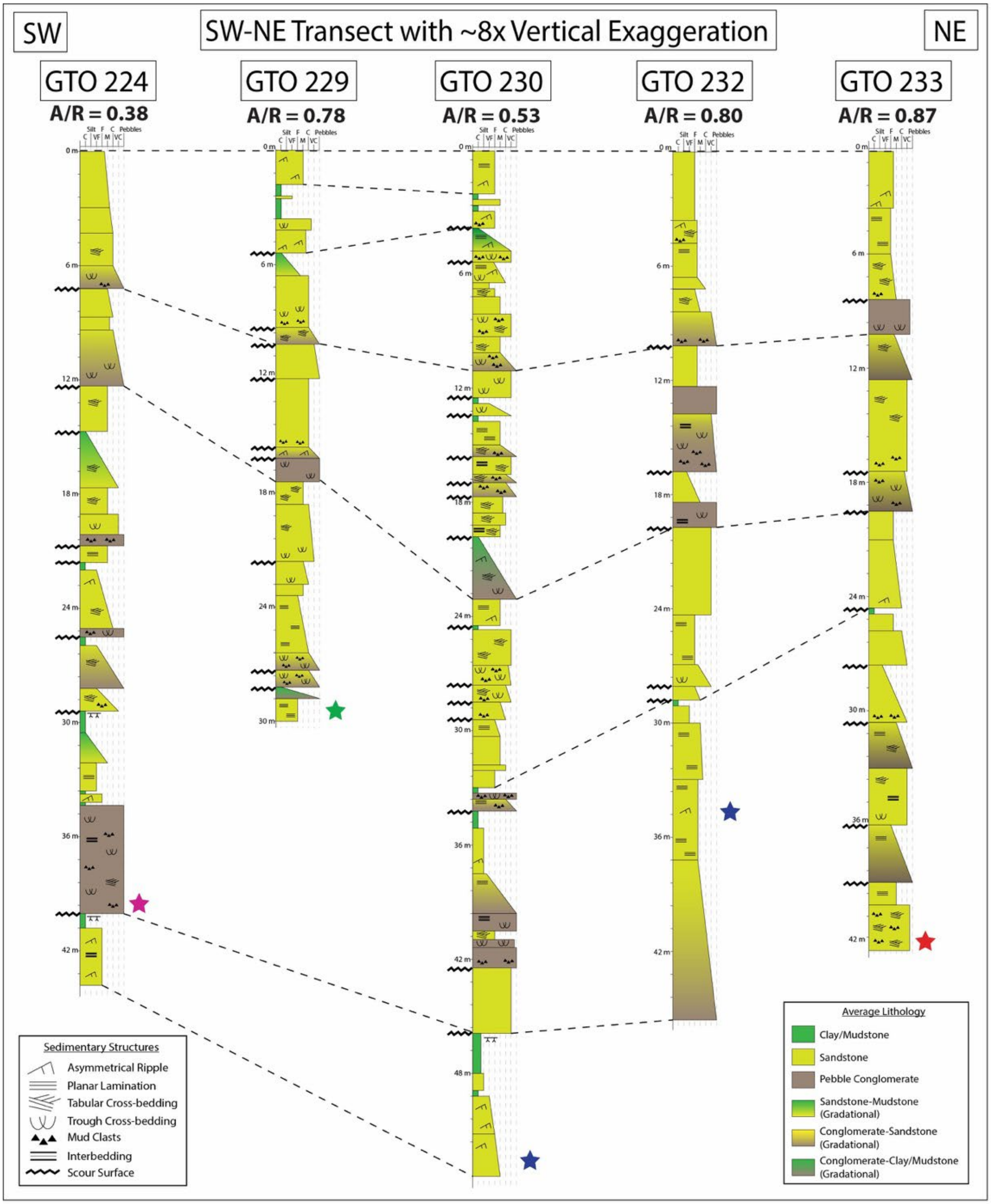

Figure 16: Core transect from GTO224 to GTO233, oriented roughly southwest to northeast, parallel to the assumed paleocurrent direction. Datum is the top of the Lower Burro Canyon Formation. Vertically exaggerated by a factor of 8.

DISCUSSION

Depositional Interpretations

The Lower Burro Canyon Formation was deposited by sandy braided to meandering river systems across a broad coastal plain (Craig, 1982). The abundance of scour surfaces, rip-up clasts, and the high degree of sandstone amalgamation suggest a high energy system with relatively low accommodation space that underwent repeated avulsions.

At the scale of Lower Lisbon Valley, the Lower Burro Canyon Formation exhibits an overall decrease in degree of amalgamation and an increase in the proportion of fine-grained lithofacies as the section progresses upward. The dominant architectural element style also shifts from amalgamated fluvial-bar / channel complexes to isolated fluvial-bar / channel complexes as the section progresses upward (Figure 15). These gradational changes in lithology and architectural style are interpreted here to represent a shift in the depositional system from a higher energy, braided fluvial system (at the base) to a lower energy, meandering fluvial system (at the top).

Assuming equal rates of sediment input, the interpreted changes in fluvial planform style could be the result of a relative increase in the rate of generation of accommodation space over time. Increased accommodation space would theoretically decrease the overall degree of amalgamation, leading to a decrease in the proportion of fine-grained lithofacies that are remobilized during avulsions and scour.

Lithofacies-Scale Permeability Trends

Porosity and permeability of lithofacies within the Lower Burro Canyon Formation are controlled primarily by the degree of sorting and the abundance of mud. Grain shape and grain size form secondary and tertiary controls.

Well sorted sandy lithofacies tend to be the most porous and permeable facies within the Lower Burro Canyon Formation, and include the planar-laminated sandstone, ripple-laminated sandstone, and cross-bedded sandstone lithofacies (Figure 12). These facies dominate the Lower Burro Canyon in this location and are primary constituents in the amalgamated and isolated fluvial bar / channel complex architectural elements (Table 3). These facies contain little to no mud, with grain shape varying from well-rounded to sub-rounded (sub-angular clasts in some Cross-bedded to Massive Sandstone lithofacies) (Figure 9, Figure 10).

Fine grained lithofacies (such as Green Mudstone and Red Mudstone-Siltstone) tend to be the least porous and permeable facies within the Lower Burro Canyon Formation (Figure 12). These facies are dominated by silts and clays, and are poorly sorted, often containing sand and occasionally pebbles. Green Mudstone and Red Mudstone-Siltstone associate with the occasional interbed of Planar Laminated Sandstone to form the “floodplain fines” architectural element. These facies also form the bounding surfaces for both the isolated and amalgamated fluvial bar / channel complexes (Table 3).

Coarse grained lithofacies (such as the Pebble Conglomerate with Rip-up Clasts, the Interbedded Sandstone & Pebble Conglomerate, and some Cross-bedded to Massive Sandstone) have variable porosities and permeabilities that seem to be tied more closely to sorting and angularity than to grain size (Table 2). These lithofacies were deposited rapidly by high energy, turbulent water, and often contain green clay rip-up clasts that vary in abundance (Figure 11).

In some examples of Pebble Conglomerate with Rip-up Clasts, rip-up clasts are so prevalent that the rock becomes nearly matrix-supported. Other examples of this lithofacies contain almost no mud clasts at all. These rip up clasts represent a major control on permeability; compaction has deformed the clay rip-up clasts, forcing them into the pore spaces between grains and closing off pore throats (Figure 11). Examples of this lithofacies with abundant rip-up clasts are predicted to have extremely low permeability for this reason.

Although less abundant than in the Pebble Conglomerate with Rip-up Clasts lithofacies, rip-up clasts are also relatively common in the Interbedded Sandstone and Pebble Conglomerate lithofacies and affect the overall porosity and permeability in a similar manner (though to a lesser extent). Rip-up clasts are relatively uncommon in the Cross-bedded to Massive Sandstone lithofacies, but are still observed (Figure 9). A more important control on porosity and permeability in this lithofacies is the degree of sorting. Some examples contain abundant chert clasts, which tend to be larger and more angular than the quartz sand grains. The increased angularity and decreased sorting associated with increasing proportions of chert fragments likely have the effect of decreasing overall permeability (Figure 9).

Element-Scale Permeability Trends

The permeability of each architectural element type is a function of the types of lithofacies that make up the element, the vertical progression of those lithofacies, and the degree of amalgamation of sandy, permeable lithofacies.

Amalgamated fluvial bar/ channel complexes are the most dominant architectural element in the Lower Burro Canyon Formation (Figure 15, Figure 16), and are highly porous and permeable. These elements are dominated by sandy lithofacies (Table 3), with the proportion of sand controlled primarily by the degree of amalgamation. Amalgamation results in the removal of the upper portions of normally-graded sedimentary packages through scour, and thus preferentially decreases the proportions of fine-grained lithofacies within each package. This process results in highly amalgamated sand bodies which tend to be relatively coarse-grained with only small proportions of fine-grained lithofacies in the form of thin drapes and/or rip-up clasts.

Isolated fluvial bar / channel complexes are much less permeable than the amalgamated fluvial bar / channel complexes, though porosities are roughly equivalent. Permeability is inhibited primarily by the lack of amalgamation within the elements themselves. Sand bodies tend to fine upward from a basal scour through the entire progression of lithofacies, before eventually grading into the floodplain fine architectural element (Figure 16). Lithofacies near the stratigraphic top of these associations (Green Mudstone, Red Mudstone-Siltstone) tend to be much less permeable than those in the basal and medial sections (Planar Laminated Sandstone, Cross-bedded to Massive Sandstone, Interbedded Sandstone and Pebble Conglomerate), and result in lower permeability overall for these elements.

Laminated sheet sands are the most porous and permeable elements in this location, primarily due to their low degree of heterogeneity and sand-dominated constituent lithofacies (such as Planar Laminated Sandstones, and Ripple Laminated Sandstones). The lack of scour surfaces in these elements serves to increase the element scale permeability relative to the amalgamated fluvial bar / channel complexes.

Floodplain fines represent the least porous and permeable architectural elements within the Lower Burro Canyon Formation. This can be attributed to the high proportions of fine-grained (clay and silt dominated) constituent lithofacies which have very small pore and pore throat sizes. This element forms major barriers to permeability between sandy architectural elements, specifically with respect to the isolated fluvial bar / channel complex element, which it tends to envelope (Figure 15). The permeability of the floodplain fines element is highly variable, due to its poorly sorted nature and tendency to contain thin, fine grained sheet sands. Despite this petrophysical heterogeneity, characterizing and quantifying the permeability of this element will be an integral part of detailed in-situ recovery evaluations.

In-Situ Recovery Implications

Sand body connectivity depends on both lateral and vertical connectivity. Lateral connectivity of sand bodies is primarily dependent on the architectural element type, while the vertical connectivity of sand bodies is dependent on amalgamation ratio, element type, and the lithology of bounding surfaces. Of the element types that were identified in this location, the amalgamated fluvial-bar / channel complex element has the highest vertical and lateral sand body connectivity (Figure 15). The overall connectivity of sand bodies in the Lower Burro Canyon Formation will determine the optimal density of wells (as well as necessary volumes and rates of injection for solution) needed for the in-situ recovery process.

Floodplain fines elements tend to envelope the more permeable sand-dominated elements, occasionally occurring within these elements as scour surfaces (Figure 13, Figure 15). The geometries of this element thus serve to compartmentalize the reservoir, as well as to create vertical flow baffles within the sand bodies themselves. As a result, permeability of floodplain elements and fine grained lithofacies are primary controls on reservoir connectivity and should be investigated in detail. Depending on injection pressure, the permeability of these rocks may or may not be greater than the capillary entry pressure of fluids used for in-situ recovery efforts.

The presence of Laminated Sheet Sand elements within the Lower Burro Canyon Formation creates the potential for confined zones of extremely high permeability. The presence of these high permeability “streaks” has the potential to concentrate fluid flow through these elements, essentially limiting fluid transport to one bed. This is an important consideration for in-situ recovery efforts, as these elements could have a significant effect on the pathways that leaching fluids and pregnant solutions use to travel through the rock.

Thickness Trends

Core logs and stratigraphic sections measured in this study show no definitive trends in the thickness of the Lower Burro Canyon Formation due to a lack of dispersion (thickness trends were not the primary scope of this study). Previous studies have identified definitive changes in thickness across the major structures in Lisbon Valley, the implications of which are discussed below.

Stratigraphic sections measured by Altinok (1998) have thicknesses ranging from 30 to 130 feet and were widely distributed across lower Lisbon Valley and into surrounding areas unaffected by Paradox diapirism. These sections show an increase in thickness of the Burro Canyon Formation over the Lisbon Valley salt anticline; sections measured directly over the anticline have thicknesses up to 130 feet, while adjacent sections measured over the corresponding syncline are as thin as 30 feet (Altinok, 1998). The thicknesses observed in this study are similar to those measured by Altinok (1998) over the axis of Lisbon Valley.

Thickness trends observed in the Lower Burro Canyon Formation contrast with those of sedimentary rock units deposited prior to the Cretaceous, which show a depositional thinning over the axis of the major structures (Lingrey, 2018), suggesting a topographic high in this area during their deposition. The shift from a topographic high to a topographic low denotes a significant structural and tectonic shift in this area, but is beyond the scope of this study.

The observed thickness trends have important implications with respect to the timing of salt diapirism and the topography during the Early Cretaceous. The increased thickness of the Burro Canyon Formation over the axis of the major structures in Lisbon Valley suggests that this area was a topographic low during its deposition. Although the paleocurrent orientation at the time of Burro Canyon deposition is poorly constrained for this location as is, this local topographic variation creates another complicating factor that must be considered/constrained in future studies.

CONCLUSIONS

This project sought to characterize the facies heterogeneity, stratigraphic architecture, and degree of sandstone amalgamation for the Lower Burro Canyon Formation in Lisbon Valley, Utah. Secondary goals included interpreting the general fluvial planform style (braided, meandering, or anastomosing), and discussing the implications of thickness trends identified in past studies (and supported by this study).

A total of eight lithofacies were identified within the Lower Burro Canyon Formation, and consist primarily of sandstones, mudstones, and pebble conglomerates with various textures, maturities, and interbeddings. Lithofacies characterization is the first step in the construction of a static reservoir model, and will be the foundation of in-situ recovery feasibility evaluation efforts. Fine grained lithofacies exhibit significantly lower permeabilities than sand-dominated lithofacies, but exhibit (preliminary) quantitative permeabilities that would characterize them as permeability baffles, rather than barriers. These lithofacies are primary controls on fluid flow in this unit and should be a major focus of future efforts.

A total of 4 architectural elements were identified, ranging from highly amalgamated, sand and conglomerate-dominated associations to mud-dominated floodplain associations. The section is generally dominated by amalgamated and sheet sand elements, with isolated and floodplain elements forming less prominent (but petrophysically significant) associations. This assemblage of architectural elements creates laterally continuous/connected, relatively thick (up to 12m for ACC) sand bodies – ideal for in-situ recovery efforts.

Degree of sandstone amalgamation shows significant variability between wells, and between core and outcrop. Outcrop based efforts suggest that sandstone amalgamation is relatively high in the Lower Burro Canyon Formation (average A/R > 0.50), and generally decreases up section. Although core-based efforts corroborate a high degree of sandstone amalgamation in this unit (A/R up to 0.89), vertical amalgamation trends for individual cores are less conclusive than outcrop observations would suggest. This discrepancy could be due to the concave nature of scour surfaces in ACC elements, which enhance vertical connectivity between sand-bodies by pinching out floodplain elements (and can be difficult to identify in core).

Amalgamation trends, architectural element types and geometries, and lithofacies associations suggest a variable fluvial planform style for the Lower Burro Canyon Formation. The relative decrease in ACC elements and increase in ICC and FPF elements as one progresses up section in the Lower Burro Canyon Formation (and especially from the Lower to the Upper Burro Canyon Formation) suggest a gradual shift from a braided to a meandering fluvial planform style. More detailed architectural work would be necessary to confirm this interpretation.

Thickness trends in sections measured by Altinok (1998) show an axial thickening of the Burro Canyon Formation with respect to the structural trend of Lisbon Valley. Thicknesses measured in this study, though not widely dispersed, are similar to (and even thicker than) those measured by Altinok. These thickness trends suggest an axial increase with respect to local accommodation space in Lisbon Valley at the time of Burro Canyon deposition, contradicting thickness trends observed in this unit in Moab Valley (Altinok, 1998).

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