Lithofacies, Depositional Environments, and a Stratigraphic Correlation of the Upper Pennsylvanian-aged Paradox and Honaker Trail Formations: A Closer Look at the Rocks from Hand Specimens and Thin Sections*

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Search and Discovery Article #30199 (2011)
Posted November 7, 2011

* Adapted from poster presentation at West Texas Geological Society 2011 Fall Symposium, Midland, Texas, September 28-30, 2011. Please refer to the authors' companion article presented orally at the above-noted WTGS symposium; the title is "Depositional Environments, and West-East Stratigraphic Correlations of Upper Pennsylvanian Honaker Trail Formation, the Paradox Basin, Southeast Utah," Search and Discovery Article #50510 (2011)

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Abstract

The Upper Pennsylvanian Honaker Trail Formation is Missourian-Virgilian in age. It is the uppermost formation of the Hermosa Group. It is composed of cherty, silty carbonates, and calcareous shales, siltstones, and sandstones with no interbedded evaporites. At the end of Pennsylvanian time the Hermosa Sea withdrew from the Paradox Basin, resulting in an unconformity between the Late Carboniferous and overlying Permian strata (Grammer et al., 1996).

Four outcrop sections of the Upper Ismay Member of the Paradox Formation and the Honaker Trail Formation were measured along the San Juan River Canyon in southeastern Utah. Twenty-one sandstone, shale and carbonate lithofacies were identified and combined into seven sedimentary facies. A thorough description of the sedimentary facies was adopted from Mark Williams (2009). The 7 sedimentary facies were assigned to broad depositional tracts that are: 1) continental, 2) transitional, and 3) marine.

The Upper Ismay Member of the Paradox and the Lower Honaker Trail formations (Desmoinesian through early Missourian) are dominated by transitional-marginal marine and open marine carbonates with intermittent tidal flat sandstones and siltstones. The Upper Ismay Member is dominated by marine sediments and it becomes shallower from west to east. The Lower Honaker Trail Formation is characterized by deeper marine deposits on the west and shallow marine to transitional environments on the east. As the cycles transitioned into the Middle Missourian-Virgilian, siliciclastic content increased. The Upper Honaker Trail Formation and the Lower Permian all appear to be predominantly non-marine sands. They consist of very fine- to fine-grained quartz arenites, lithic arenites, and calcareous subarkoses to arkoses. Generally, these transitional to continental sand deposits are dark-brown to red in color from the hematite that occurs mainly as cement or a grain coating, indicating subaerial exposure. These upper cycles were deposited in flood plain, fluvial, and eolian settings.

In the Paradox Basin, cycles are represented as deposits formed by sea level rise and fall and exhibit a deepening to shallowing succession of facies. The Paradox cycles represent a mixed system of carbonates and sandstones that were deposited on the shelf of the Paradox Basin (Grammer et al., 1996).

The Pennsylvanian strata on the Eastern Shelf of the Permian Basin are very similar to those located on the shelf of the Paradox Basin. The results from this study can be directly applied to the deposits on the Eastern Shelf and in North Central Texas.

References

Grammer, G.M., G.P. Eberli, F.S.P. Van Buchem, G.M. Stevenson, and P. Homewood, 1996, Application of high resolution sequence stratigraphy to evaluate lateral variability in outcrop and subsurface – Desert Creek and Ismay intervals, Paradox Basin, *in* M.W. Longman and M.D. Sonnenfield (Eds.), Paleozoic systems of the Rocky Mountain region: Society of Sedimentary Geology, Rocky Mountain Section, p. 235-266.

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Panel #1

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ABSTRACT

The canyons of the San Juan River provide impressive outcrops exposing the Upper Pennsylvanian strata of the Paradox and Honaker Trail Formations, and the Lower Permian Group. These outcrops reveal the Upper Paleozoic geology of the Paradox Basin; the same units are productive in the subsurface. They are the analog to the prolific Greater Aneth Oil Field.

Four vertical sections along the canyon of the San Juan River were measured, sampled, and described. The data collected was used to build detailed stratigraphic columns. Eight depositional environments were identified and they include: fluvial, eolian, beach, lagoon, tidal flat, high energy shoal, proximal open shelf, distal open shelf.

The Upper Pennsylvanian Paradox and the Lower Honaker Trail Formations (Desmoinesian through early Missourian) are dominated by transitional – marginal marine and open marine carbonates with intermittent tidal flat sandstones and siltstones. The Upper Ismay Member is dominated by marine sediments that become shallower from west to east. The Lower Honaker Trail Formation is deeper marine on the west and shallow to transitional environments eastward. As the cycles transitioned into the Middle Missourian – Virgilian, siliciclastic content increased. The Upper Honaker Trail Formation and the Lower Permian all appear to be predominantly non-marine sands. These upper cycles are composed of flood plain, fluvial, and eolian sandstones.

The various lithofacies observed in outcrop sections were bundled into depositional cycles that represent intervals of sea level rise and fall and exhibit a deepening to shallowing succession of facies. These cycles represent a mixed system of carbonates and sandstones that were deposited on the shelf of the Paradox Basin (Grammer and others, 1996). The best reservoir units appear to be shallow marine grain-dominated carbonates and fluvial and eolian sands.

The Pennsylvanian strata on the Eastern Shelf of the Permian Basin are very similar to those located on the shelf of the Paradox Basin. The results from this study can be directly applied to the deposits on the Eastern Shelf and in North Central Texas.

INTRODUCTION

The poster concentrates on the sandstone units of the Honaker Trail Formation that crops out along the canyons of the San Juan River in southeastern Utah (fig. 1). This area has been heavily studied; however the primary objective of previous studies has been the carbonate sections.

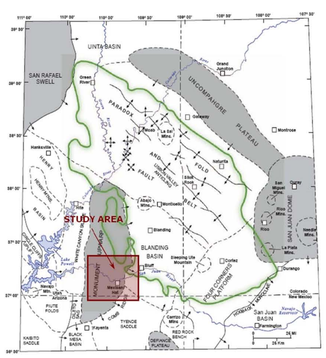


FIGURE 1.—Regional map showing the extent of the Paradox Basin and the major structural features of the Central Colorado Plateau. Location of the study area is shown in the red square (Stevenson and Wray, 2009, modified from Nuccio and Condon, 1996).

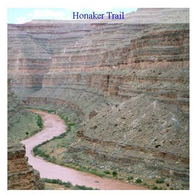
PURPOSE OF STUDY

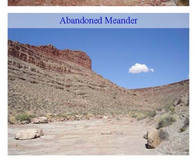
The purpose for the collection of data in the sandstone units of the measured outcrop sections was to determine the following: 1) Identification of lithofacies, 2) organization of lithofacies into sedimentary facies, 3) assignment of sedimentary facies into depositional environments, 4) recognition of cycle types, and 5) correlation between measured outcrop sections. It is the sincere hope that this information and data from the outcrop measured sections and thin sections will add to the store of geologic knowledge in the Paradox Basin and be instrumental to the future discovery of profitable hydrocarbon reserves.

LOCATION OF STUDY AREA

The four outcrops of the Honaker Trail Formation that were measured and described for this study are exposed along the canyons of the San Juan River in southeastern Utah (fig. 2). The Honaker Trail, Raplee Anticline, the Abandoned Meander, and River Mile 9.1 exposures are located on the southwestern boundary of the Paradox Basin. These exposures trend west to east across the Pennsylvanian shelf perpendicular to depositional strike. These locations were chosen for accessibility. The first section measured was the Honaker Trail. This section is the "TYPE" section for all the exposures. The last two measured sections (the Abandoned Meander and River Mile 9.1) were chosen because as of May of 2008, these two sections had never been measured and they were easily accessible by boat from the San Juan River.

FIGURE 2.—Location map showing the four primary measured outcrop sections, Honaker Trail, Raplee Anticline, and River Mile 9.1 with the general sites (yellow stars) along the San Juan River. The vertical measured sections are approximately located at the arrows shown on the map (modified from Google Earth, 2011).





REGIONAL GEOLOGIC SETTING

The Paradox Basin is a very complex Pennsylvanian-aged intracratonic evaporite basin (Stevenson and Baars, 1986; 1988). The basin is defined by the maximum extent of salt deposited as Paradox Formation during the Middle Pennsylvanian (Baars and Stevenson, 1981; Hite and others, 1984; Nuccio and Condon, 1996) (fig. 1). The basin lies adjacent to the Ancestral Rocky Mountain Uncompahgre Uplift in the eastern Colorado Plateau Province (Stevenson and Baars, 1988). This asymmetrical elongate basin trends northwest-southeast and extends from the northwestern part of New Mexico into east-central Utah. The basin covers an area of approximately 10,245 mi^2 in southwestern Colorado and southeastern Utah (Stevenson and Baars, 1986; 1988). The maximum northwest-southeast length is abut 190 miles and northeast-southwest width is about 95 miles (Nuccio and Condon, 1996).

GEOLOGIC STRUCTURE

The Paradox Basin is surrounded by major uplifts of the Colorado Plateau (fig. 1). It is bounded to the northwest by the San Rafael Swell and the Uinta Basin. On the north and to the northeast the basin is bounded by the Uncompahgre Uplift. The eastern edge is bounded by the San Juan Dome. The Four Corner's Platform and the Hogback Monocline on the eastern edge separate the Paradox Basin from the San Juan Basin (Nuccio and Condon, 1996). The south, southwest, and west are bounded by the Defiance Uplift, Black Mesa Basin, Monument Uplift and the Henry Basin (Wengerd and Matheny, 1958; Nuccio and Condon, 1996).

The tectonic formation of the Paradox Basin is controversial (Trudgill and Artbuckle, 2004). The most accepted theory is that the basin is a pull-apart basin created by strike-slip motion (Baars and Stevenson, 1981). Key basement lineaments (Precambrian through Paleozoic) bound the Colorado Plateau (fig. 3). According to Stevenson and Baars (1986) the basin is heavily faulted, making it more complex structurally and stratigraphically than previously realized (fig. 4). The Paradox Basin was formed by right-lateral extension along two northwest-southeast oriented master faults called the Olympic-Wichita Lineament by (Stevenson and Baars, 1988).

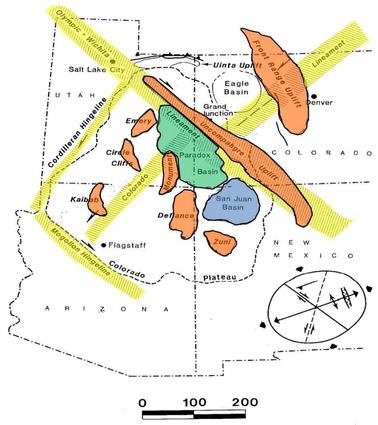


FIGURE 3.—Map showing location of the Colorado Plateau and relationship to major orthogonal set of lineaments. Northwest trending lineaments are right lateral. The stress ellipsoid is oriented such that maximum compressive is directed from the north. (Baars and Stevenson, 1981).

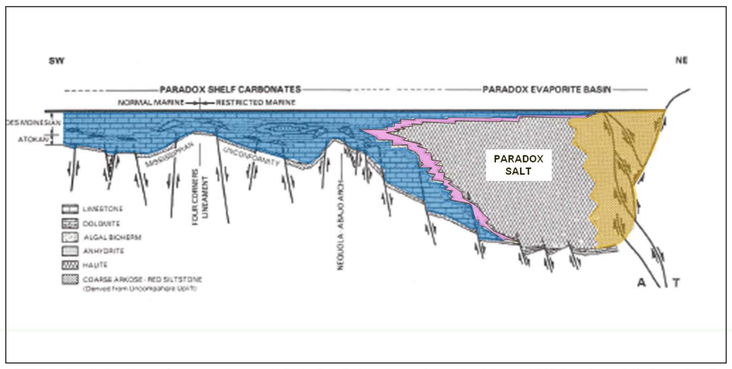


FIGURE 4.—Generalized southwest-northeast cross section across the Paradox Basin illustrating the gross facies relations between the Middle Pennsylvanian shelf carbonates, basinally restricted evaporites, and coarse clastics proximal to the Uncompahgre Uplift Modified from Stevenson and Baars, 1988; (Grammer and others, 1996).

GEOLOGIC STRATIGRAPHY

During the formation of Pangea, North America (Laurasia) collided with the South America-Africa Continent (Gondwana) during the Pennsylvanian Period. This widespread tectonism caused swift, large-scale uplifting of the Uncompahgre Plateau, a segment of the ancestral Rocky Mountains, and subsidence of the northeastern part of the Paradox Basin (Baars and Stevenson, 1981; Nuccio and Condon, 1996).

Most Pre-Pennsylvanian (Cambrian – Mississippian) rocks were eroded away. The weathered erosional surface of the Mississippian Leadville Limestone (fig. 5) was overlain by the Molas Formation, the lowermost Pennsylvanian unit (Stevenson and Baars, 1988). The Atokan Molas Formation was deposited as reworked marine – non-marine material (Goldhammer and others, 1994; Stevenson and Baars, 1988).

Overlying the Molas is the Hermosa Group. It is comprised of three formations from oldest to youngest, the Pinkerton Trail, the Paradox, and the Honaker Trail Formations (Wengerd and Matheny, 1958; Nuccio and Condon, 1996).

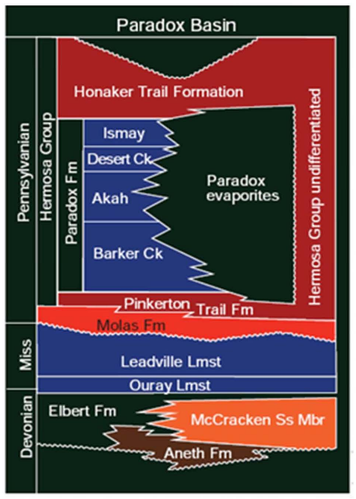


FIGURE 5.—Devonian through Pennsylvanian stratigraphic column illustrating the relationship of the Paradox Formation evaporites and their facies equivalents in the basin (Stevenson and Wray, 2009; from Stevenson, 2006).

GEOLOGIC STRATIGRAPHY (continued)

The Paradox Formation contains all the evaporites in the Paradox Basin. The Paradox Formation is composed of carbonates and siliciclastics interbedded with anhydrite, halite, and potash salts. As many as 40 carbonate – evaporite cycles have been recognized, but most often only 29 are cited in literature (Goldhammer and others, 1996). On the shelf edge these 29 cycles have been grouped into four members of the Paradox Formation that in ascending order are: Barker Creek, Akah, Desert Creek, and Ismay. The Lower and Upper Ismay are separated by a marker bed, the Horn Point Limestone (Grammer and others, 1996). The stratigraphic columns built for this thesis project are based on this marker bed. In the outcrop, the Horn Point is overlain by a siliceous dolomite that is known locally as "Old Yeller" because of its distinctive yellow weathered color (Grammer and others, 1996).

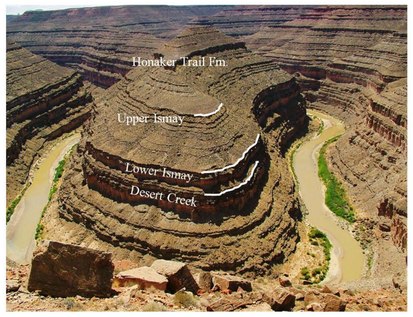


FIGURE 6.—Photograph from the Gooseneck Overlook of the San Juan River showing the Desert Creek, Lower and Upper Ismay, and Lower Honaker Trail sections (Modified from Grammer and others, 1996).

The Honaker Trail Formation is Missourian-Virgilian in age. It is the uppermost formation of the Hermosa Group (fig. 5). It is composed of cherty, silty carbonates, and calcareous shales, siltstones, and sandstones with no interbedded evaporites (fig. 6). As Pennsylvanian time ended, the Hermosa sea withdrew from the Paradox Basin, resulting in an unconformity between the Carboniferous and overlying Permian strata (Grammer and others, 1996). According to Condon (1997), it is unlikely that there is a single limestone that extends throughout the basin that could be used as a datum for the top of the Honaker Trail. Limestones have been observed to thin or grade into sandstone and shale facies in most exposures (Condon, 1997).

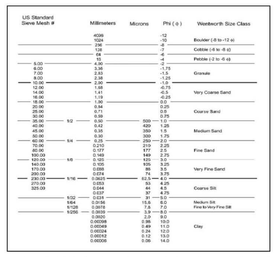
METHODS

During the summer of 2008, the 4 outcrop locations along the San Juan river were measured using a Jacob's staff and a Brunton compass. Field descriptions were recorded as measurements were taken. Described intervals ranged from 1-5 feet or where significant changes of lithologies in the vertical sections were observed.

Samples were also collected at 1-5 feet intervals or at significant changes in the vertical lithologies. A geologic hammer was utilized for taking outcrop samples. Sample size was approximately 2 x 4 inches. The field samples were studied in the laboratory under a low powered binocular microscope to verify field descriptions. The samples were described in the laboratory accordingly: type of rock, color of rock, grain size, sorting, roundness, mineral types, and fossil types. The color of the rock was determined by using the Munsell® ROCK-COLOR CHART (Geological Society of America, 2009).

In addition to outcrop work and low power microscope descriptions of hand samples, 78 thin sections were prepared and studied from the Honaker Trail outcrop section. The thin sections were oriented perpendicular to bedding. The thin sections were stained based on the lithologic assemblages (carbonate vs. sandstone). Samples were labeled with HT, the depths and a C or S at the end. C stands for carbonate and S for sandstone. An example would be HT 33C. Sample was taken at 33' and it appeared to be a carbonate rock. Selected samples were then sent off for thin section preparation. Thin sections were designated as carbonates ("C") were stained with alizarin Red-S and potassium ferricyanide staining. This is used to distinguish iron-free carbonate and iron bearing carbonate minerals. Thin sections designated as sandstones ("S") were stained with sodium cobaltinitrite stain. This stain is used for identifying potassium-feldspar grains.

Grain size, sorting, roundness, sedimentary structures, diagenetic features, matrix, cements, and porosity were noted when applicable. Study of the outcrop samples and petrographic examination of the outcrop thin sections from the Honaker Trail section were necessary to provide a basic framework in order to determine the various lithologies in the other sections. The lithologies and their associated grain size, sorting, and angularity aided in determining the environments of sand and carbonate deposition. Sedimentary structures, digenetic features, fossils, and trace fossils were also studied to aid in interpreting the environment of deposition. Sandstones were classified using the Folk system (Folk, 1968) (fig. 7; 8) and the carbonates were classified using the Dunham method (Dunham, 1962) (fig. 9) and Lucia's modification of Dunham (Lucia, 1995) (fig. 10). A stratigraphic column for each measured section was built using Adobe Illustrator CS4 (plate 1). The stratigraphic columns detail all the descriptions listed above.



US Standard Sieve Mesh #		Millimeters	Microns	PHI (ø)	Wentworth Size Class
		4096		-12	
		1024		-10	Boulder (-8 to -12 ø)
		256		-8	Cobble (-6 to -8 ø)
		128		-7	
		64		-6	Pebble (-2 to -6 ø)
5.00		4.00		-2	
6.00		3.36		-1.75	Granule
7.00		2.83		-1.5	
8.00		2.38		-1.25	
10.00		2.00		-1.0	
12.00		1.68		-0.75	Very Coarse Sand
14.00		1.41		-0.5	
16.00		1.19		-0.25	
18.00		1.00		0.00	
20.00		0.84		0.25	Coarse Sand
25.00		0.71		0.5	
30.00		0.59		0.75	
35.00	5/2	0.50	500	1.0	
40.00		0.42	420	1.25	Medium Sand
45.00		0.35	350	1.5	
50.00		0.30	300	1.75	
60.00	5/4	0.25	250	2.0	
70.00		0.210	210	2.25	Fine Sand
80.00		0.177	177	2.5	
100.00		0.149	149	2.75	
120.00	5/8	0.125	125	3.0	
140.00		0.105	105	3.25	
170.00		0.088	88	3.5	Very Fine Sand
200.00		0.074	74	3.75	
230.00	5/16	0.063	63	4.0	
270.00		0.053	53	4.25	Coarse Silt
325.00		0.044	44	4.5	
		0.037	37	4.75	
	5/32	0.031	31	5.0	
	5/64	0.0156	15.6	6.0	Medium Silt
	5/128	0.0078	7.8	7.0	Fine Silt Very Fine Silt
	5/256	0.0039	3.9	8.0	
		0.0020	2.0	9.0	
		0.00098	0.98	10.0	
		0.00049	0.49	11.0	Clay
		0.00024	0.24	12.0	
		0.00012	0.12	13.0	
		0.00006	0.06	14.0	

FIGURE 7.—Table showing grain size scale for sediments (Folk, 1968).

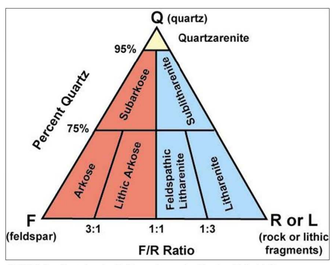


FIGURE 8.—Chart showing Folk's sandstone classification (Folk, 1968).

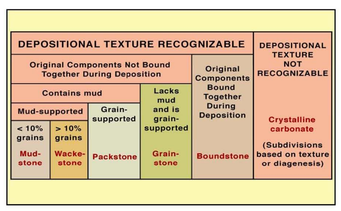


FIGURE 9.—Carbonate classification chart (Dunham, 1962).

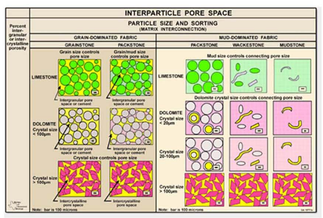


FIGURE 10.—Chart showing carbonate porosity classification (Lucia, 1995).

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Panel #2

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LITHOFACIES

The Honaker Trail and other outcrop sections along the San Juan Canyon consist of many distinctive lithofacies that are described and illustrated with thin sections in the following paragraphs. Lithofacies classification of the sandstone units are based solely on grain size.
The twenty-one lithofacies are:

1. Siltstone (S)
2. Very fine grained sandstone (VSS)
3. Fine-grained sandstone (FSS)
4. Medium-grained sandstone (MSS)
5. Coarse-grained sandstone (CSS)
6. Wackestone (W)
7. Sandy Wackestone (AW)
8. Skeletal Wackestone (SkW)
9. Sandy Skeletal Wackestone (ASkW)
10. Mud-rich packstone (P)
11. Sandy mud-rich packstone (AP)
12. Skeletal mud-rich packstone (SkP)
13. Sandy skeletal mud-rich packstone (ASkP)
14. Grain-rich packstone (P/G)
15. Sandy grain-rich packstone (AP/G)
16. Skeletal grain-rich packstone (SkP/G)
17. Sandy skeletal grain-rich packstone (ASkP/G)
18. Grainstone (G)
19. Skeletal grainstone (SkG)
20. Sandy skeletal grainstone (ASkG)
21. Oolitic grainstone (OG)

The sandstone (SS) lithofacies was further classified into five types on the basis of the composition of the grains and the proportion of the major grain components: quartz (including chert and polycrystalline quartz), feldspars, and rock fragments as determined by examinations of specimens in thin section and they are: Subarkose, Arkose, Sublitharenite, Quartz Arenite, Feldspathic Litharenite**
** no picture taken from thin section.

Shale Lithofacies – (SH).—The Shale Lithofacies (SH) is characterized by fossiliferous, black, gray, green, and brown, blocky, calcareous shales. These samples varied from slightly silty, laminated, brown shales to highly calcareous, fossiliferous, marine, gray shales. The majority are calcareous, fine-grained, light-gray or brown, thinly laminated shales. Another group of shales observed in outcrop were red, green, and purple mottled, calcareous shales. In hand specimen, the mottled samples are red, green, or purple, and contain no fossils. No thin sections were prepared for this facies.

Siltstone Lithofacies – (S).—The Siltstone Lithofacies (S) in outcrop and hand specimen consists of laminated siltstones displaying various colors (dark-red to yellow/brown and light gray to dark olive gray to black). In thin section, the matrix consists of silt-sized clastic grains. The quartz grains include chert and polycrystalline quartz dominate, comprising 80 – 90 percent. Other clastic grains include feldspars, mica, and pyrite. Feldspars compromise less than 5 percent and micas and pyrite are less than 2 percent. Carbonate grains make up 3 – 10 percent of all grains and they include peloids, lithoclasts, and skeletal grains. Ostracods, foraminifera, brachiopods, and crinoids were observed in outcrop. The quartz grains ranged in size from 25 to 125 µm, but 90 percent of the grains are less than 60 µm placing the samples in the siltstone category. The grains are moderate to well sorted and subangular to angular. Carbonate and hematite cements were most common. No porosity was observed in thin section HT 467S.

Very Fine Grained Sandstone Lithofacies – (VSS).—The very fine grained sandstone lithofacies (VSS) consists of dark red to yellow/brown, and light gray to gray/brown laminated sandstones. The VSS lithofacies are classified on the basis of the composition of the grains, matrix, and the proportion of the major grain components. The matrix is composed of quartz (including chert and polycrystalline quartz), feldspars, and rock fragments as determined by examinations of specimens in thin section.

Fine-Grained Sandstone Lithofacies – (FSS).—The fine-grained sandstone lithofacies (FSS) consists of pale red to light gray laminated sandstones. In thin section the FSS lithofacies were all subarkoses as described above. The quartz grains range in size from 62 to 500 µm but 90 percent were 175 µm. Grains are moderately to well sorted, and subangular to angular. The quartz grains exhibited slight to strongly undulose extinction. Carbonate and hematite cement was most common. Interparticle porosity and porosity along laminations was observed in thin section. The feldspars appeared to be altered and partial dissolution of the feldspars is well shown by the blue epoxy within the porous areas (interparticle porosity). Thin section HT 542S is a fine grained peloidal subarkose (FSS).

Medium-Grained Sandstone Lithofacies – (MSS).—The medium-grained sandstone lithofacies (MSS) consists of dark-red to yellow/gray sandstones. The MSS lithofacies in thin section are calcareous subarkoses HT 533S (fig. 11) and quartz arenites HT 735S (fig. 14) as described above. The MSS lithofacies contains no carbonate grains. The quartz grains of the subarkoses ranged in size from 62 to 500 µm and 90 percent were 300 µm. Grains are well sorted, and subangular to angular. The quartz grains exhibited straight to slightly undulose extinction. Carbonate and hematite cement were most common in subarkoses and silica cement in the quartz arenites. Interparticle porosity and intraparticle porosity is observed in thin section.

Coarse-Grained Sandstone Facies – (CSS).—The coarse-grained sandstone lithofacies (CSS) lithofacies is a sandstone where the grain size range in size from 0.5 to 1.0 mm in outcrop and 90 percent were 0.75 mm. The coarse-grained Sandstone Facies (CSS) consists of dark red to yellow to gray sandstones. The CSS lithofacies are calcareous subarkoses and quartz arenites as described above. Thin sections were prepared, but no pictures taken.

Wackestone Lithofacies – (W). — The wackestone lithofacies (W) HT 273C consists of olive black to olive gray limestones. The grain types for the W lithofacies consist of pellets, peloids, and intraclasts. Sedimentary structures observed were some burrowing, with pellets filling the burrows. In outcrop elongated to nodular chert nodules are common.

Sandy Wackestone Lithofacies – (AW).—The sandy wackestone lithofacies (AW) consists of olive brown to olive gray limestones HT 217C (fig. 15). The common grain types consist of pellets, peloids, glauconite, and intraclasts. Clastic grains includes abundant common quartz grains, chert, feldspars (orthoclase and plagioclase), and mica. The quartz grains range in size from 25 to 125 µm, with straight to slightly undulose extinction. Sedimentary structures observed are pellet-filled burrows. In outcrop elongated to nodular chert nodules are common.

Skeletal Wackestone Lithofacies – (SkW).—The skeletal wackestone lithofacies (SkW) HT 109C consists of olive-gray limestones. The grains types consisted of pellets, peloids, glauconite, intraclasts, skeletal grains, pelcypods, ostracods, brachiopods, bryozoa, and crinoids. Clastic grains include abundant common quartz grains, chert, feldspars, and mica. Sedimentary structures are burrowing and bioturbation. In outcrop elongated to nodular chert nodules were common.

Sandy Skeletal Wackestone Lithofacies – (ASkW).—The sandy skeletal wackestone lithofacies (ASkW) HT 453C consists of yellow to brown to olive gray limestones. The grains types consist of pellets, peloids, glauconite, intraclasts, skeletal grains, pelcypods, ostracods, brachiopods, bryozoa, and crinoids. The clastic grains include abundant common quartz polycrystalline quartz, chert, feldspars (orthoclase, plagioclase, and microcline), mica, and pyrite. Quartz grains range in size from very fine to coarse (25 to 700 µm). They were poorly to well sorted, angular to rounded, with straight to strongly undulose extinction. Sedimentary structures observed were cross bedding and burrowing. In outcrop elongated to nodular chert nodules were common.

Mud-Rich Packstone Lithofacies – (P).—The mud-rich packstone lithofacies (P) consists of light gray to olive gray limestones. In outcrop elongated to nodular chert nodules are common. The common grain types are intraclasts, pellets, and peloids. Sedimentary structures include burrowing. No thin sections were prepared for this lithofacies.

Sandy Mud-Rich Packstone Lithofacies – (AP).—The sandy mud-rich packstone lithofacies (AP) consists of light to dark olive gray limestones that contain abundant quartz grains and micrite, but are grain supported. The common grain types are quartz, (common, polycrystalline, and chert) lithoclasts, pellets, and peloids. Sedimentary structures recorded from outcrop are burrowing and linear chert nodules. No hand samples or thin sections were prepared for this lithofacies.

Skeletal Mud-Rich Packstone Lithofacies – (SkP).—The skeletal mud-rich packstone lithofacies (SkP) consists of yellow to brown to olive-gray limestones. Carbonate grain types are intraclasts, pellets, peloids, and skeletal grains. The fossils include ostracods, trilobites, foraminifera, brachiopods, bryozoa, and crinoids. No thin sections were prepared from hand specimens for this lithofacies.

Sandy Skeletal Mud-Rich Packstone Lithofacies – (ASkP).—The sandy skeletal mud-rich packstone lithofacies (ASkP) HT 578.^{5}C (fig. 16) consists of yellow to gray to olive-gray very sandy limestones. It contains a substantial amount of calcite in the form of shell fragments and as cement between the quartz grains. The clastic grains are subangular to subrounded common quartz, polycrystalline quartz, orthoclase, and plagioclase. The quartz grains are single detrital crystals and they show straight-to strongly undulose extinction. The fossils identified are ostracods, trilobites, pelcypods, gastropods, foraminifera, brachiopods, bryozoa, and crinoids.

Grain-Rich Packstone Lithofacies – (P/G).—The grain-rich packstone lithofacies (P/G) HT 312C is a carbonate rock where the common grain types are non-marine carbonate grains; intraclasts, pellets, and peloids. A grain-rich packstone is a carbonate rock that contains mud, but is grain supported. It contains less than 50 percent mud. In the Grain Rich Packstone lithofacies (P/G), the micrite matrix contains mud. That prevents it from being classified as a grainstone.

Sandy Grain-Rich Packstone Lithofacies – (AP/G).—The sandy grain-rich packstone lithofacies (AP/G) HT 414S consist of a yellow to gray limestone. This rock is a very sandy limestone. It contains a substantial amount of calcite as cement between the quartz grains. Subangular to subrounded common quartz, polycrystalline quartz, orthoclase, and plagioclase are present with calcite cement and peloids.

Skeletal Grain-Rich Packstone Lithofacies – (SkP/G).—The skeletal grain-rich packstone lithofacies (SkP/G) HT 358C consists of yellow to gray to olive-gray limestones. The grain types consisted of pellets, peloids, glauconite, intraclasts, and skeletal grains. The fossils include pelcypods, ostracods, brachiopods, bryozoa, and crinoids. Clastic grains include abundant common quartz grains, chert, feldspars, and mica. Sedimentary structures observed are burrowing and bioturbation. It contains a substantial amount of calcite in the form of shell fragments and as cement between the quartz grains. Subangular-subrounded common quartz, polycrystalline quartz, orthoclase, and plagioclase are present with calcite cement.

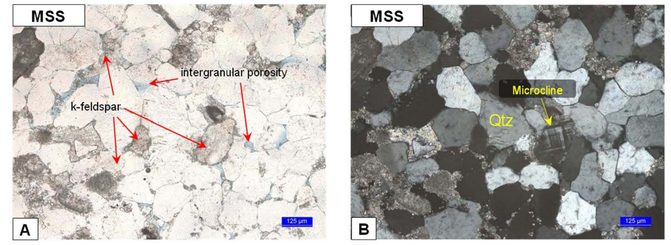
Sandy Skeletal Grain-Rich Packstone Lithofacies – (ASkP/G).—The lithofacies designation for this rock is a sandy skeletal grain-rich packstone (ASkP/G) HT 697C (fig. 17) and HT 275C. This sample is a very sandy limestone; it contains a substantial amount of calcite in the form of shell fragments. It has subangular to subrounded common quartz, polycrystalline quartz, and orthoclase and plagioclase are present with calcite cement. The quartz grains show straight to strongly undulose extinction. The fossils identified include brachiopods, bryozoa, and crinoids.

Skeletal Grainstone Lithofacies – (SkG).—The skeletal grainstone lithofacies (SkG) consist of yellow to gray to olive-gray limestones. Burrowing was observed in outcrop. The grain types consist of ooids, peloids, pellets, foraminifera, ostracods, gastropods, brachiopods, bryozoa, crinoids, and skeletal grainstones that in thin section are algally encrusted. Chert replaced the original component of most fossils.

Sandy Skeletal Grainstone Lithofacies – (ASkG).—The sandy skeletal grainstone lithofacies (ASkG) consists of yellow to gray to olive-gray limestones. The carbonate grain type for this lithofacies is the same as above. What distinguishes this lithofacies from the others is that it contains a substantial amount of clastic grains, quartz being the most dominant (>5 percent) of the total grains. The clastic grains include quartz (common, polycrystalline, and chert), feldspars (orthoclase, plagioclase, and microcline), mica and pyrite.

Oolitic Grainstone Lithofacies – (OG).—The oolitic grainstone lithofacies (OG) HT 655C (fig. 18) consist of light-gray to dark-olive gray grain supported carbonate rocks. The carbonate grain types for this lithofacies are pellets, peloids, and ooids cemented with micrite or sparite, a calcareous mud. In figure 18, the ooids are micrite with faint concentric laminations. The sediment is grain-supported and cemented by sparite. The original center has been replaced with silica, common quartz. No porosity was observed in thin section.

FIGURE 11.—Photomicrograph(s) of a medium grained calcareous subarkose. The lithofacies designation is a calcareous medium grained sandstone (MSS).

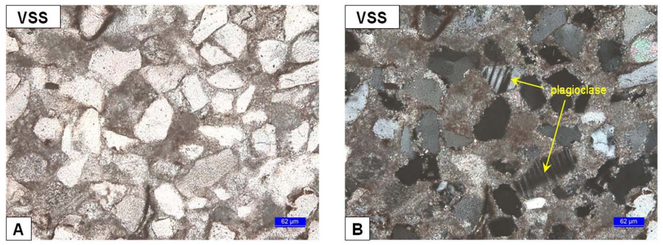


A. Thin section view under plain light (HT 533S) B. Thin-section view under crossed nicols (HT 533S).

Subarkose

The subarkoses were pale red to green/brown. In thin-section they consisted of very fine clastic grains. Quartz is dominant (75-95%). Other clastic grains include chert, feldspars (orthoclase, plagioclase, and microcline), mica, pyrite, and carbonate rock fragments. Feldspars make up 5-25%, rock fragments, micas and pyrite are less than 15%. The carbonate rock fragments make up less than 10% and include peloids, intraclasts, and skeletal grains (ostracods, foraminifera, brachiopods, and crinoids). The clastic grains range in size from 25 – 150µm but 90% were 88µm. Grains are well sorted, and subangular – angular. The quartz grains exhibited straight – slight undulose extinction. Carbonate and hematite cement were most common. No porosity was observed and no pictures were taken in thin-sections of the VSS lithofacies.

FIGURE 12.—Photomicrograph(s) of a calcareous very fine grained arkose. The lithofacies designation is a very fine grained sandstone (VSS).

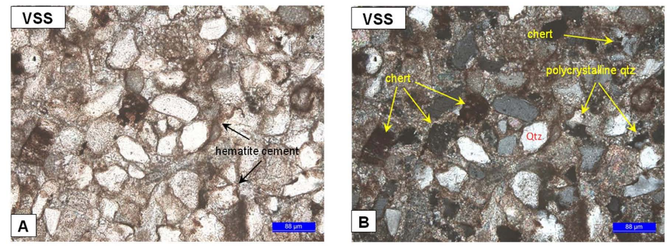


A. Thin section view under plain light (HT 470S) B. Thin-section view under crossed nicols (HT 470S).

Arkose

The arkoses were dark red to moderate brown sandstones. By definition (Folk, 1974), arkoses should have a feldspar to rock fragment ratio of 3:1 to 1:1. Quartz grains comprise at least 25% of the sample and other clastic grains include: chert, feldspars (orthoclase, plagioclase and microcline), mica, pyrite, and carbonate rock fragments. Feldspars make up at least 25%. Rock fragments, micas and pyrite comprise less than 15%. The carbonate grains make up less than 10%, and include: peloids, intraclasts, and skeletal grains (ostracods, foraminifera, brachiopods, and crinoids). The quartz grains range in size from 25 – 150µm but 90% were 88µm. Grains are poorly to moderately sorted, and subangular – angular. The quartz grains exhibited straight – slight undulose extinction. Carbonate and hematite cement were most common.

FIGURE 13.—Photomicrograph(s) of a very fine to fine-grained calcareous sublitharenite. The lithofacies designation is a calcareous fine-grained sandstone (VSS).



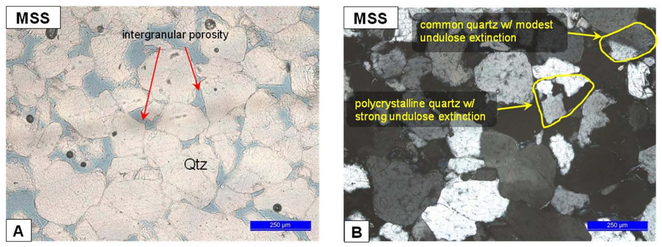
A. Thin section view under plain light (HT 599S) B. Thin-section view under crossed nicols (HT 599S).

Sublitharenite

Sublitharenites found in this facies are dark-red to olive gray sandstones. The dominant matrix grain type is quartz, but they contain more rock fragments in addition to other minerals. Quartz grains comprise 75 to 95 % of the sandstone. Rock fragments, micas and heavy minerals make up 5 to 25%, and feldspars constitute less than 15%. The carbonate grains make up less than 10% that includes peloids, intraclasts, and skeletal grains (ostracods, foraminifera, brachiopods, and crinoids). Calcite and hematite cement is very common. In thin section the quartz grains range from 25 to 150µm, but 90% were 88µm. Grains are poorly to moderately sorted, and angular to subangular.

The quartz grains exhibit straight to slight undulose extinction.

FIGURE 14.—Photomicrograph(s) of a medium grained quartzarenite. The lithofacies designation is a medium grained sandstone (MSS).

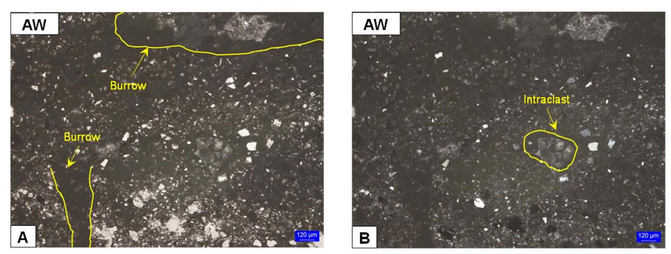


A. Thin section view under plain light (HT 735S) B. Thin-section view under crossed nicols (HT 735S).

Quartzarenite

The quartzarenite are yellow to gray sandstones. The dominant grain types in the thin section are single detrital quartz. Quartz grains comprise more than 95 percent of the sandstone matrix. Feldspars make up less than 5 percent, and rock fragments, micas and heavy minerals make up an additional 1 percent. No carbonate grains were found in this rock type in any of the measured sections. In thin section the quartz grains ranged in size from 177 to 500µm, but 90 percent were 300µm. Grains are well sorted, and subangular to rounded. The quartz grains exhibit straight to strongly undulose extinction. It is slightly cemented with silica cement.

FIGURE 15.—Photomicrograph(s) of a wackestone. The lithofacies designation is a sandy wackestone (AW). This rock has micrite, intraclasts, and angular to subangular common quartz grains. It shows no porosity.

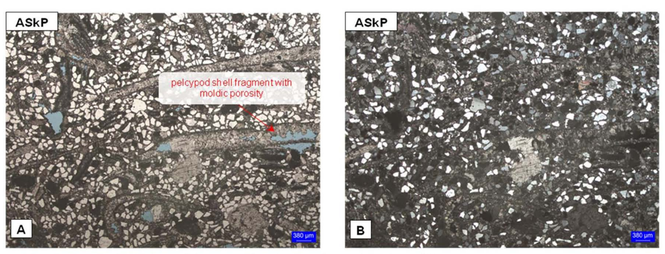


A. Thin section view under plain light (HT 217C) B. Thin-section view under crossed nicols (HT 217C).

Sandy Wackestone

Figure 15 is grain types consist of pellets and intraclasts. Clastic grains includes abundant common quartz grains, chert, feldspars (orthoclase and plagioclase), and mica. Sedimentary structures observed in thin-section are pellet-filled burrows.

FIGURE 16.—Photomicrograph(s) of a packstone. The lithofacies designation is a sandy skeletal packstone (ASkP). This rock is a very sandy limestone; it contains a substantial amount of calcite in the form of shell fragments and as cement between the quartz grains.

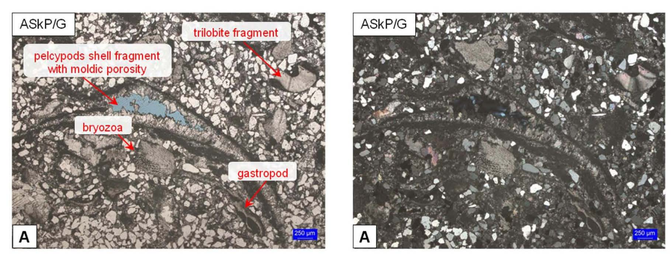


A. Thin section view under plain light (HT 578.^{5}C) B. Thin-section view under crossed nicols (HT 578.^{5}C)

Sandy Skeletal Mud-Rich Packstone

In this sample subangular to subrounded common quartz polycrystalline quartz, orthoclase, and plagioclase are present with calcite cement. The quartz grains are single detrital crystals. They show straight to strongly undulose extinction. The fossils identified include brachiopods, bryozoa, crinoids, ostracods, and trilobites. The blue-colored areas between the grains represent porosity. One of the pelcypod shells display secondary moldic porosity with blocky calcite cement.

FIGURE 17.—Photomicrograph(s) of a very sandy fossiliferous grain-dominated packstone. The lithofacies designation is a very sandy fossiliferous grain-dominated packstone (ASkP/G).

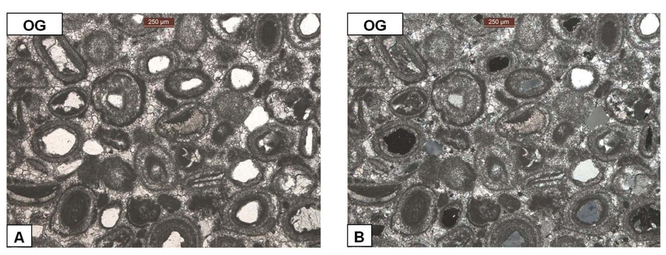


A. Thin section view under plain light (HT 697C) B. Thin-section view under crossed nicols (HT 697C).

Grain-Rich Packstone

This sample is a very sandy limestone. It contains a substantial amount of calcite in the form of shell fragments and as cement between the quartz grains. The blue colored areas between grains represent porosity. Subanglar-subrounded common quartz, polycrystalline quartz, orthoclase, and plagioclase are present with calcite cement. The quartz grains are single detrital crystals. They show straight to strongly undulose extinction. The fossils identified here include brachiopod, bryozoa, crinoids, ostracods and a trilobite. This pelcypod shell has secondary moldic porosity with blocky calcite cement.

FIGURE 18.—Photomicrograph(s) of an oolitic grainstone (OG). The ooids are well developed with both concentric and radial structure. Common quartz grains are in the center of the ooids.



A. Thin section view under plain light (HT 655C) B. Thin-section view under crossed nicols (HT 655C).

Grainstone

Oolitic Grainstone Lithofacies – (OG) consist of light-gray to dark-olive gray grain supported carbonate rocks.

LITHOFACIES, DEPOSITIONAL ENVIRONMENTS, AND A STRATIGRAPHIC CORRELATION OF THE UPPER PENNSYLVANIAN-AGED, PARADOX AND HONAKER TRAIL FORMATIONS: A CLOSER LOOK AT THE ROCKS FROM HAND SPECIMENS AND THIN SECTIONS

Panel #3

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SEDIMENTARY FACIES

A thorough description of the sedimentary facies in the Honaker Trail Formation was presented by Mark Williams (2009). As much of his information is directly applicable to this study, his sedimentary facies are adopted herein. The 21 lithofacies that were described in the previous section were combined into seven facies. The sedimentary facies are listed from continental to most distal marine: MHS (Mottled Heterolithic Sandstone and Shale), LCS (Large-Scale Cross-Bedded Sandstone), PWS (Planar- to Wavy -Bedded Sandstone), LMCS (Laminated Muddy Carbonate-Siliciclastic Sandstone), ASB (Amalgamated Carbonate-Quartz Sandy Beds), DSP (Diverse Skeletal Wackestone to Packstone), DCM (Displacive Cherty Mudstone to Wackestone).

Each facies type may contain several lithofacies and one type of lithofacies could be found in more than one sedimentary facies type. The sedimentary facies are subdivided into three types of depositional environments: continental, transitional, and marine (fig. 18). The details of the description, interpretation, depositional environment, and energy regime are summarized in the following paragraphs. The depositional environment of the sedimentary facies was generally interpreted by studying the data collected from outcrop descriptions, examination of hand specimens, and where applicable, thin sections. The scheme used for describing the outcrops and hand specimens includes: color of sample, grain size, sorting, grain shape (roundness), sedimentary structures, fossils, or trace fossils. Mineral composition is rarely useful in determining depositional environment, but composition of cements can be a valuable criterion.

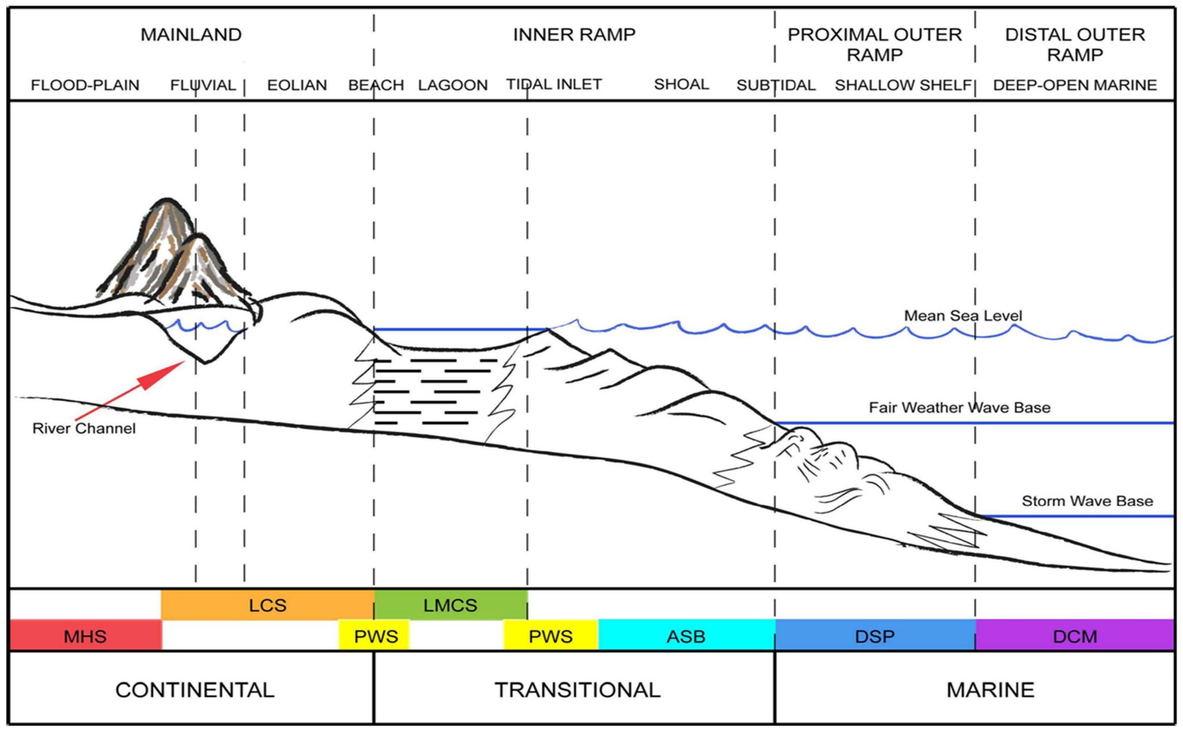
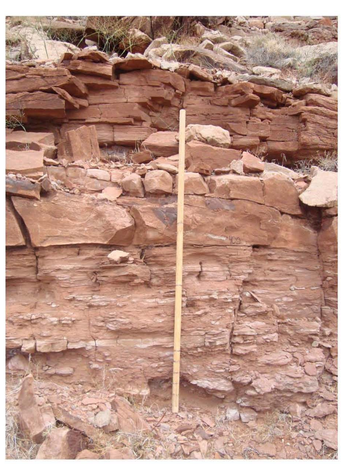


FIGURE 18.—Diagram illustrating primary depositional environments and facies types.

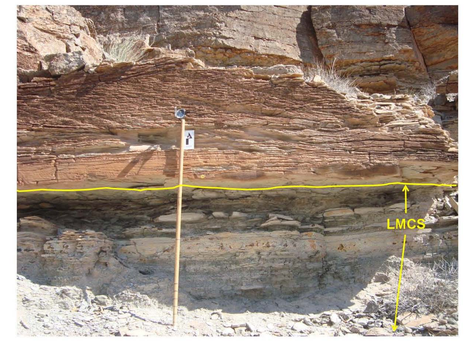
- ***Mottled Heterolithic Sandstone and Shale (MHS)*** is described as a mottled purple to olive green to light gray, interbedded shale, siltstone, and sandstone in varying proportions. Grain size ranges from fine-grained to coarse-grained lithic and feldspathic arenites. Common sedimentary structures are thin, low-angle to horizontal laminations, ripple cross lamination, and medium- to small-scale trough or planar tabular cross-bedding. The abundance of very fine- to fine-grained quartz, the presence of wind ripples, and common association of these beds with the LCS beds suggests that much of the sand is reworked from an eolian source. The arkosic sandstones within the upper part of the section are interpreted as fluvial, probably derived from the Uncompahgre Uplift. The depositional environment is interpreted as lagoon to flood-plain. Energy is low to moderate.



- ***Large-Scale Cross-Bedded Sandstones (LCS)*** is described as light gray to buff, very fine- to fine-grained quartz arenites and lithic arenites. Up to 40% mica, calcite, and shale are present. Cross beds very from low-angle and symmetrical. to high-angle, and tabular cross beds. Sedimentary structures include black silicified rhizoliths. The presence of red and brown, hematite stained quartz sand grains resulted from differential oxidation in a subaerial environment. The depositional environment is interpreted as eolian. Energy is high.

SEDIMENTARY FACIES (continued)

- ***Laminated Muddy Carbonate - Siliciclastic Sandstone (LMCS)*** is described as light gray to tan, silty and sandy carbonate mudstones and wackestones with less than 50% clastic grains. The LMCS facies is dominated with ostracods and lesser amounts of fenestrate bryozoans and gastropods. Silt and shale content increases upward resulting in increased fissility and bedding character from thickly bedded to platy bedded. Mud-cracked crypt-algal laminites are common. Purple bioturbated mudstones also common. Post depositional sedimentary structures are abundant and include mud cracks, rhizocretions, petrified wood, auto-brecciated horizons, and burrows along bedding planes. The predominance of horizontal bedding and fine grain size suggest deposition under low-energy conditions. Fossils are scarce and are limited to ostracods. Burrows, mud cracks and algal laminites are evidence for very shallow water with periodic subareial exposure. The frequent and transitional association of these deposits with MHS beds suggests evidence for a very shallow subtidal to intratidal to supratidal environment. The replacement of ostracod skeletal material by iron-oxide-rich chert suggests depositional conditions within a playa lake or a restricted shallow lagoon that is ultimately exposed and desiccated. The overall depositional setting ranges from playa lake, restricted shallow water lagoon to intertidal to supratidal (tidal flat). Energy regime is low to moderate.



- ***Planar - to Wavy - Bedded Sandstone (PWS)*** is described as white, laminated- to thin-bedded, very fine- to fine-grained, micaeous, shaley and calcareous quartz arenites. Sedimentary structures include wave oscillatory, bidirectional (herringbone) to combined-flow currents, ripple laminae, subhorizontal planar, low-amplitude wavy beds, and medium- to thick-bedded hummocky cross stratification. Burrow traces and structureless bioturbated beds are common. Trochoidal and symmetrical ripple cross lamination suggest a shallow water, wave-dominated marine, nearshore settings, or a partially submerged coastal dune where eolian processes redeposited sand in a shallow marine setting. The overall depositional setting ranges from tidal inlet to wave-dominated upper shoreface. Energy regime is low to moderate.

- ***Amalgamated Carbonate - Quartz Sandy Beds (ASB)*** range from thin- to massive-bedded. Facies consist of ooid, pelletal, bioclastic, and coated-grain skeletal packstones to grainstones, and very fine- to fine-grained lithic to sublithic arenites. Fossils are primarily foraminifera, algal fragments, broken crinoids and bryozoans. ASB beds are largely composed of carbonate grains, the ration of quartz sand to carbonate allochems varies widely, making it very difficult to distinguish between sandstones and limestones. The abundance and variety of skeletal and nonskeletal grains, combined with the lack of mud, are indicative of high-energy currents. Scours and graded bedding indicate the currents were erosional. This suggests a variety of intertidal to fair-weather wave base environments; including shoreface, offshore marine shoal and intertidal settings. The majority of the sand was reworked from an eolian environment. Very fine- to fine-grained clastic sands are intercalated with carbonate grains suggesting that the sand was blown directly into the environment or has been reworked from eolian dunes adjacent to paleoshoreface. The overall depositional setting ranges from very shallow marine to beach/shoal. Energy regime is high.

- ***Diverse Skeletal Wackestone to Packstone (DSP)*** range from thin- to thick-bedded (11'-20'), skeletal wackestones to packstones. The sedimentary structures include wave ripples, and low-angle migrating seaward bars. Chert replacement of fossil structures is common. Fossils consist of crinoid stems, whole brachiopods, fenestrate bryozoans, fusalinids, encrusting foraminifera, sponges, gastropods, horn corals, and echinoderm fragments. The skeletal diversity of the DSP facies suggests normal marine circulation and salinity. Unbroken fossils indicate that they could not have been transported long distances. Interbedding of the DSP beds is evidence for gradually shallowing water depth. The presence of higher energy grain-rich topset beds indicates continued shallowing. Erosional surfaces and toplapping suggests exposure to currents near fair weather wave base. The overall depositional setting ranges from subtidal to shallowing/shoaling upward. Energy regime is low to moderate.

- ***Displacive Cherty Mudstone to Wackestone (DCM)*** dark to medium gray, laminated- to thick-bedded, cherty mudstone to wackestone. Sedimentary structures include rare thin laminae of silt to sand and broken skeletal debris. Chaetetes mounds that occur near base of DCM beds are 3'- 5'. Chert is abundant and is typically dark gray oblate nodules. This facies was probably deposited on a protected marine shelf below wave base within the photic zone. It is located at the base of a shoaling succession of carbonates, suggesting a deep to open marine environment. The abundance and displacive character of chert along bedding planes suggests early precipitation along preferred permeability pathways. The presence of glauconite is evidence for a reduction is sedimentation rate. The overall depositional setting ranges from deep to open marine. Energy regime is low.

LITHOFACIES, DEPOSITIONAL ENVIRONMENTS, AND A STRATIGRAPHIC CORRELATION OF THE UPPER PENNSYLVANIAN-AGED, PARADOX AND HONAKER TRAIL FORMATIONS: A CLOSER LOOK AT THE ROCKS FROM HAND SPECIMENS AND THIN SECTIONS

Panel #4

GREAT WESTERN DRILLING CO.

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THE UNIVERSITY OF TEXAS OF THE PERMIAN BASIN

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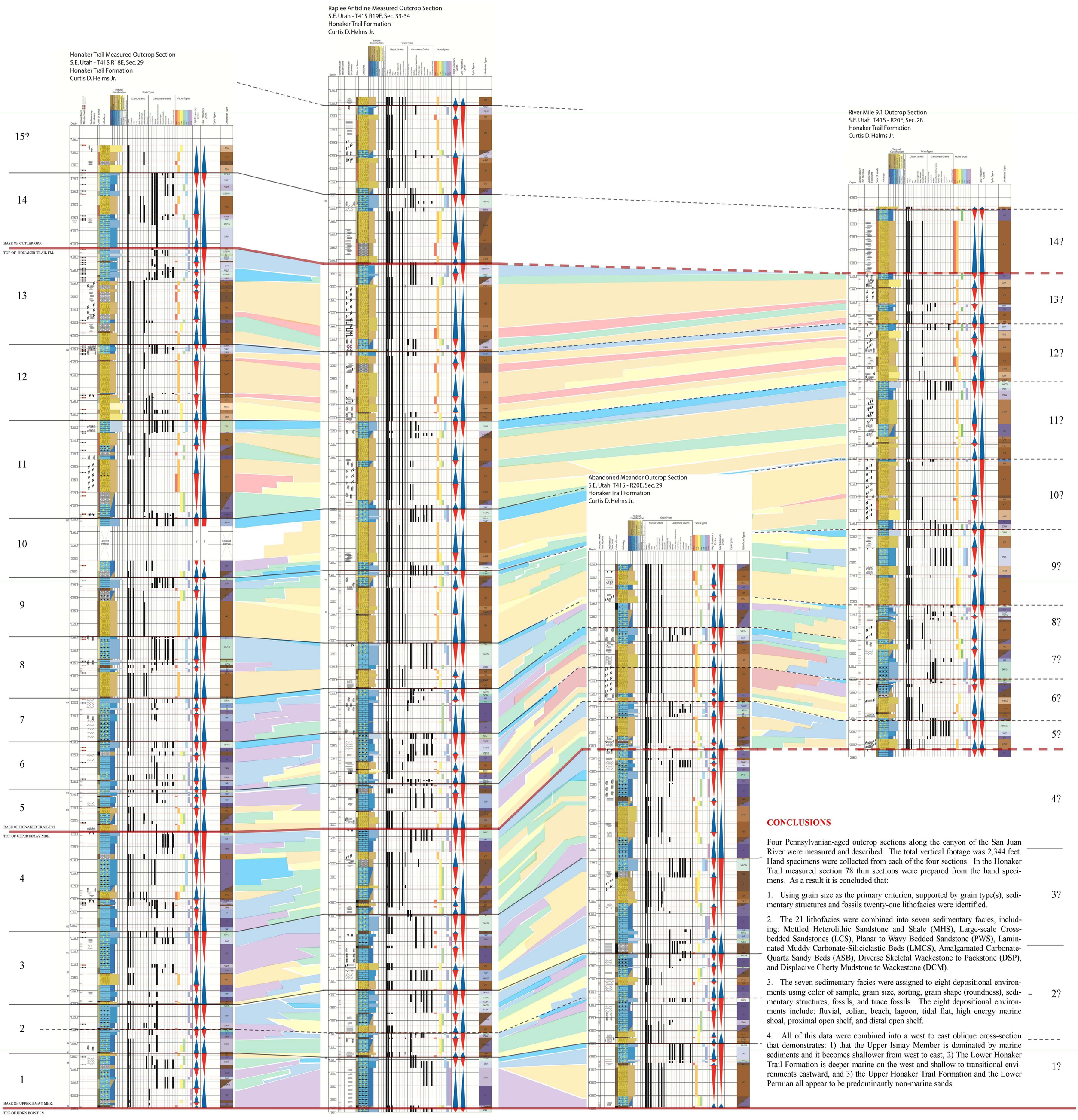


CONCLUSIONS

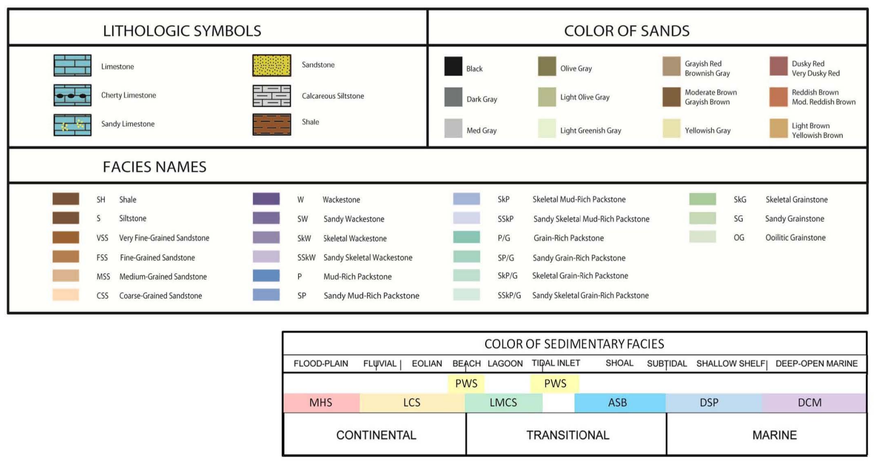
Four Pennsylvanian-aged outcrop sections along the canyon of the San Juan River were measured and described. The total vertical footage was 2,344 feet. Hand specimens were collected from each of the four sections. In the Honaker Trail measured section 78 thin sections were prepared from the hand specimens. As a result it is concluded that:

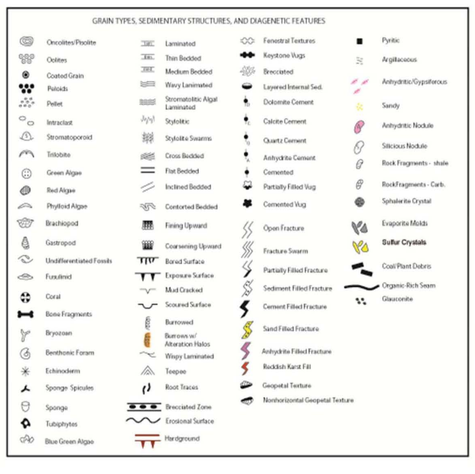
1. Using grain size as the primary criterion, supported by grain type(s), sedimentary structures and fossils twenty-one lithofacies were identified.

2. The 21 lithofacies were combined into seven sedimentary facies, including: Mottled Heterolithic Sandstone and Shale (MHS), Large-scale Cross-bedded Sandstones (LCS), Planar to Wavy Bedded Sandstone (PWS), Laminated Muddy Carbonate-Siliciclastic Beds (LMCS), Amalgamated Carbonate-Quartz Sandy Beds (ASB), Diverse Skeletal Wackestone to Packstone (DSP), and Displacive Cherty Mudstone to Wackestone (DCM).

3. The seven sedimentary facies were assigned to eight depositional environments using color of sample, grain size, sorting, grain shape (roundness), sedimentary structures, fossils, and trace fossils. The eight depositional environments include: fluvial, eolian, beach, lagoon, tidal flat, high energy marine shoal, proximal open shelf, and distal open shelf.

4. All of this data were combined into a west to east oblique cross-section that demonstrates: 1) that the Upper Ismay Member is dominated by marine sediments and it becomes shallower from west to east, 2) The Lower Honaker Trail Formation is deeper marine on the west and shallow to transitional environments eastward, and 3) the Upper Honaker Trail Formation and the Lower Permian all appear to be predominantly non-marine sands.





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