Penn-Perm Stratigraphy and Karst of the Mogollon Rim and Slope, Arizona

W. Norman Kent, 2021

ABSTRACT

Differences exist between the stratigraphy observed in Pennsylvanian and Early Permian strata exposed at the surface along the Mogollon Rim and the equivalent section occurring in wells on the Mogollon Slope. To understand these differences, correlation sections were constructed using surface and subsurface data.

The cross-sections show that the Penn-Perm interval can be divided into two depositional sequences separated by a regional unconformity. In turn, the two sequences are composed of at least twenty-two cyclothems. The cyclothems show depositional environmental change from humid swamp to arid aeolian in a near shore setting.

Sequence 1 is Des Moinesian to Virgil age and is laterally equivalent to the Horquilla Formation of southern Arizona and correlative with the lower part of the Supai Group in the Grand Canyon. Sequence 2 is Wolfcampian to Leonardian age and includes rocks of the Amos Wash, Big A Butte, Corduroy, Schnebly Hill and Coconino Formations and is equivalent to the Esplanade Sandstone and Hermit Shale of the Grand Canyon.

The sequences are affected by two dominant diagenetic processes, acid sulfate diagenesis and evaporite dissolution. Acid sulfate diagenesis changed the color, composition, texture and volume of rocks in both sequences with removal of evaporite units also occurring in Sequence 2.

In the subsurface, both sequences contain abundant pyrite created by bacteria in organic rich, water-saturated, sediments. Some oxidization of sulfides occurred during deposition of the individual cyclothems, and the diagenetic products were incorporated into overlying units. However, much of the diagenesis occurred after lithification.

Sequence 1 contains carbonates, carbonaceous clastics, and coals. These units may be the source of the hydrocarbons, helium, and carbon dioxide in the region's wells.

Sequence 2 is a carbonate / evaporate system. In the subsurface, the halite and intra-halite units are preserved and the salt bodies are surrounded by dolines and non-tectonic faults. In outcrop and near subsurface, erosion has removed the salt beds allowing shallower horizons to collapse forming a founder breccia. Almost half of the depositional thickness of Sequence 2 has been removed at the Mogollon Rim. Mobilization of halite and sulfate salts from Sequence 2 has had a long-term effect on the region's groundwater.

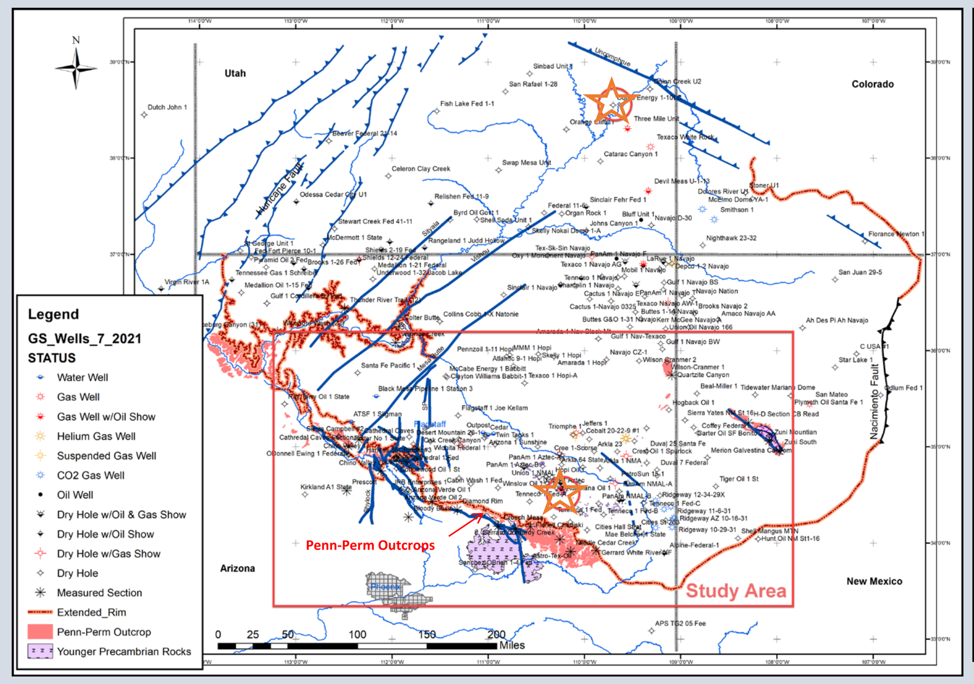


FIGURE 1: THE STUDY AREA IS THE MOGOLLON RIM & SLOPE LOCATED IN THE SOUTHERN PART OF THE COLORADO PLATEAU

The locations of wells in Figure 14 are shown by the stars and circles, Coors Energy 1 at the top & Rocking Chair Ranch 1 at bottom.

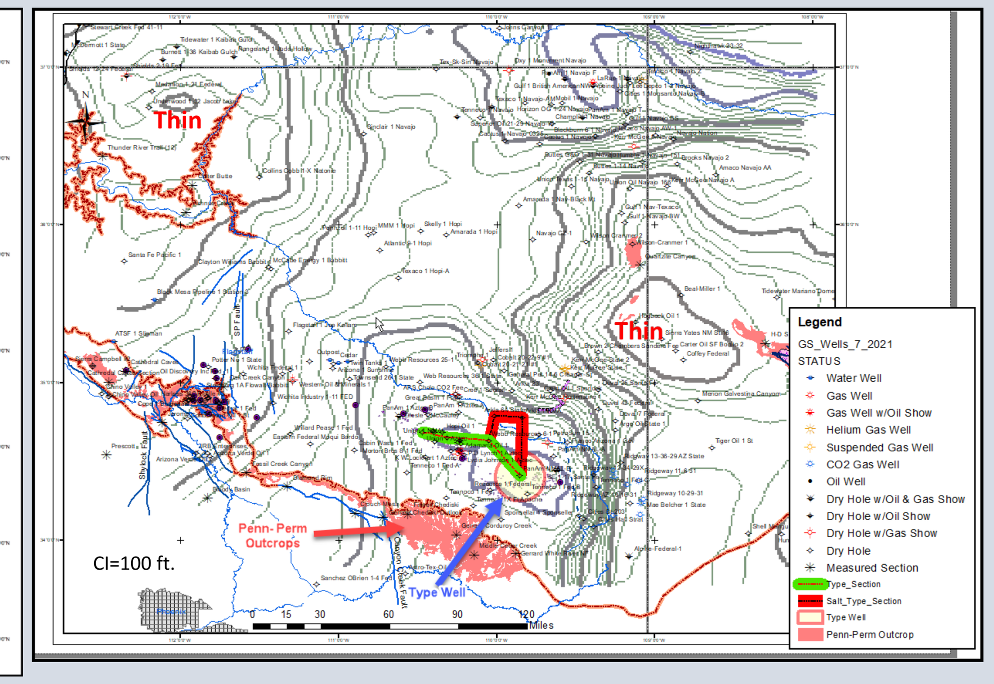


FIGURE 2: PENN-PERM ISOPACHOUS MAP WITH TYPE WELL AND TYPE SECTION LOCATIONS

The data suggests that Paradox Basin and the Pedregosa Basin were connected through, at least, their early (Pennsylvanian) history. The Type Cross Section (Figure 4) is shown in green. The Reference Cross Section (Panel 2, Figure 13) for Sequence 2 is shown in red.

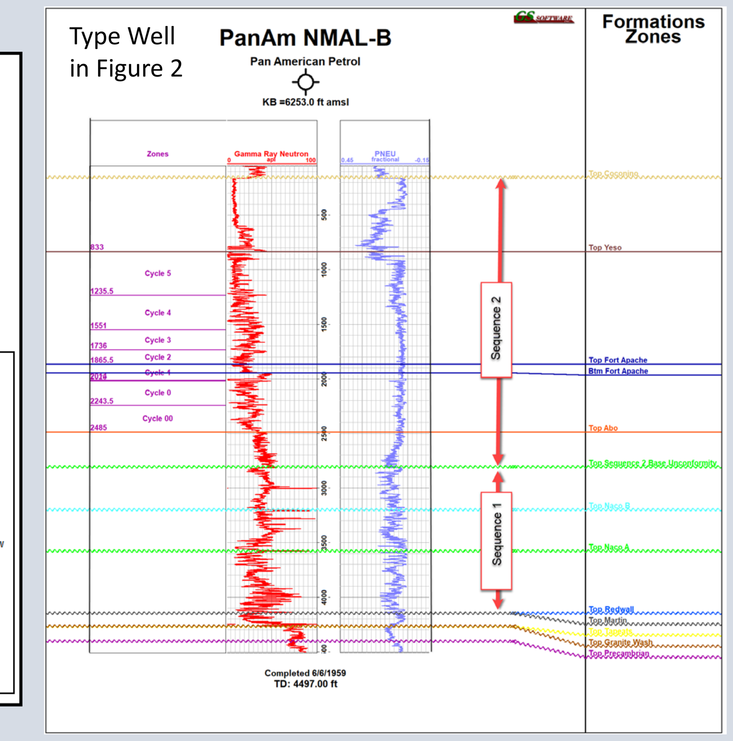


FIGURE 3: CORRELATION TYPE WELL

A Correlation Type Log is defined as the log that exhibits the most complete stratigraphic section in a field or regional area of study (D. J. Tearpock and R. Bischke, 2003).

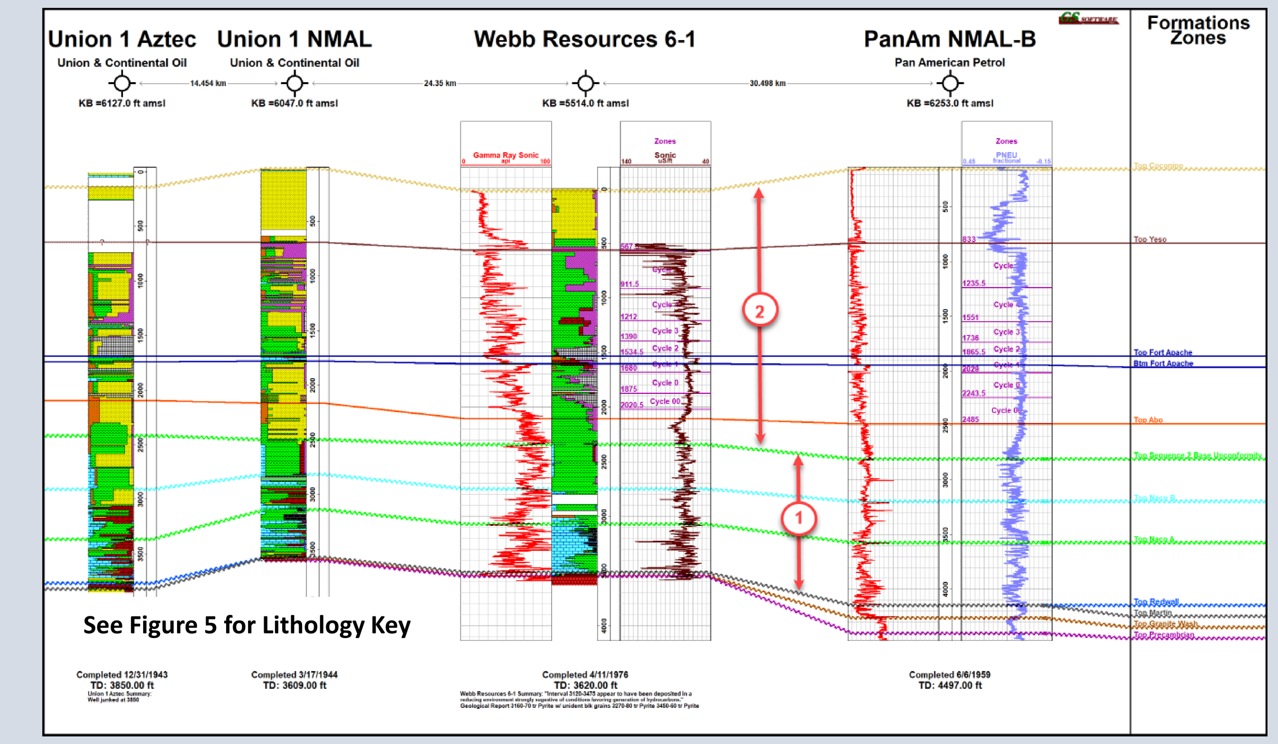


FIGURE 4: TYPE CORRELATION SECTION SHOWING TWO MEGA SEQUENCES

The section datum is the Fort Apache Member, and the section shows markers used in the correlation sections. The Union wells have nearly continuous cuttings and core samples. The Webb Resources well has both sample data and modern logs, while the PanAm well was logged with the old-style logs common to most of the other wells in the area.

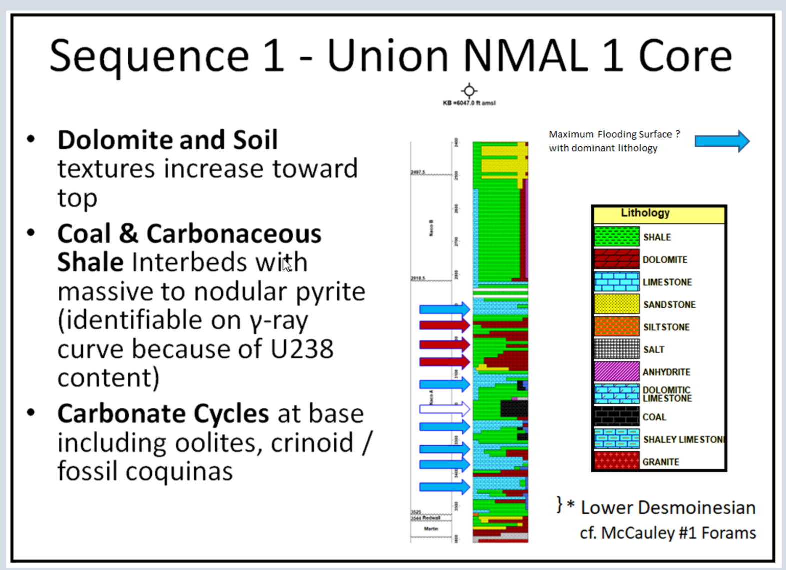


FIGURE 5: LITHOLOGIC LOG FOR CORES, UNION NMAL 1, NACO A & B INTERVALS IN SEQUENCE 1.

The mixed carbonate / clastic cycles are equivalent in age to Formats of Ross, 1973, but no correlation element exists to make a direct comparison. In fact, the cycles could not be correlated with certainty from well to well in the study based on well log character.

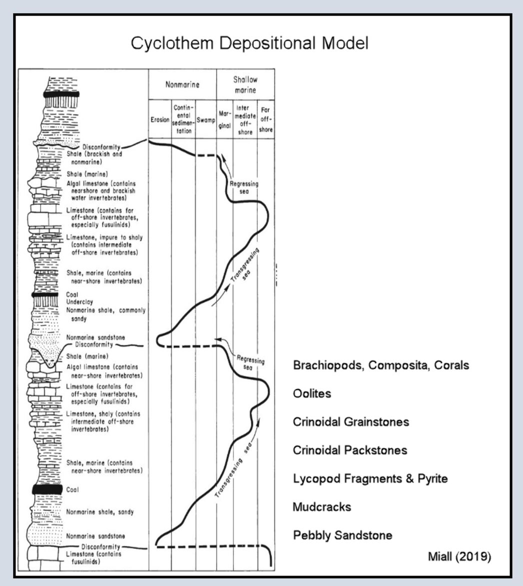


FIGURE 6: CYCLOTHEM MODEL

The generic vertical sequence of the cycles seen in samples Is plotted with the Depositional Model of Miall (2019)

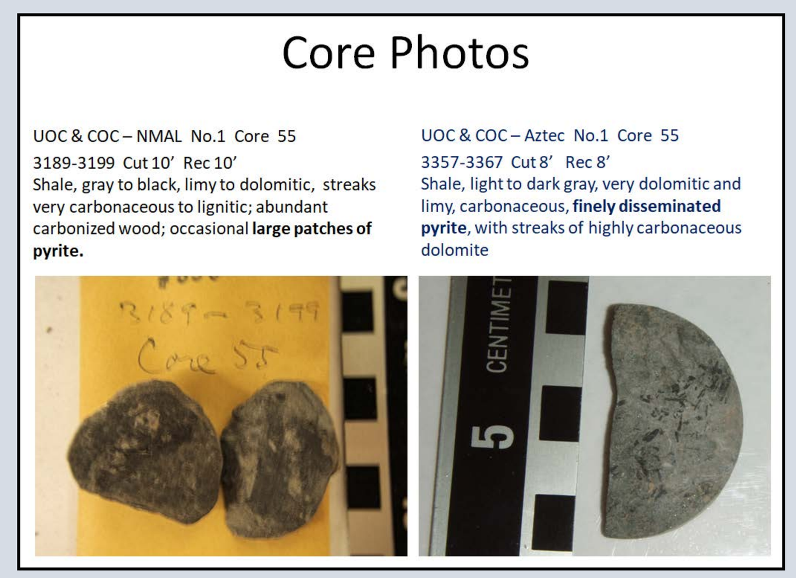
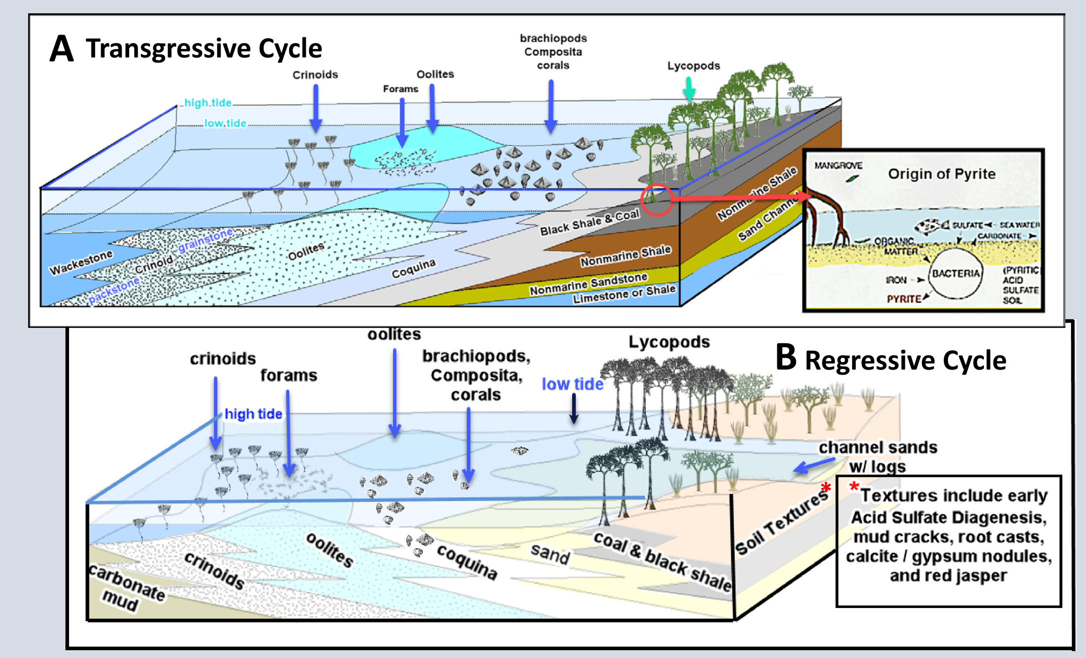


FIGURE 7: CORE SAMPLES FROM UNION WELLS

Core samples from shales in the Union wells of the type section show the abundance of carbonaceous debris and pyrite typical in the subsurface. Although coal and carbonaceous units occur in a few outcrops, they are uncommon. The organic-rich units can be identified on well logs by their high radioactivity as indicated by the gamma-ray log.



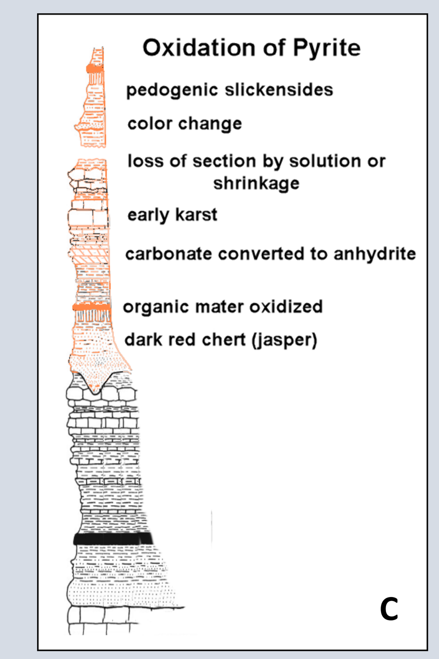


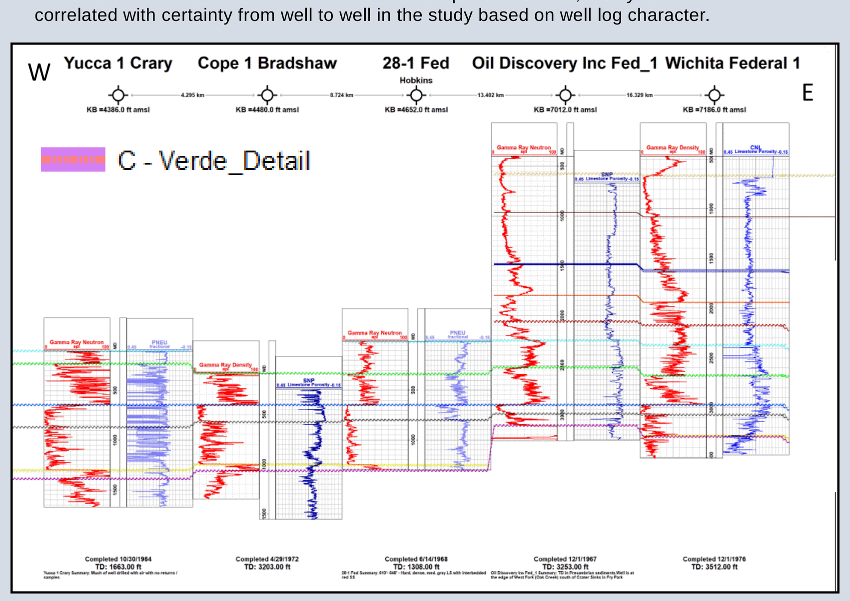
FIGURE 8 A & B: DEPOSITIONAL MODEL SUGGESTED BY THE COMPOSITION AND VERTICAL SEQUENCE OF THE CYCLES. FIGURE 8C: FIGURE MODIFIED CYCLOTHEM MODEL INDICATING POSSIBLE EARLY DIAGENESIS. SEE FIGURE 9.

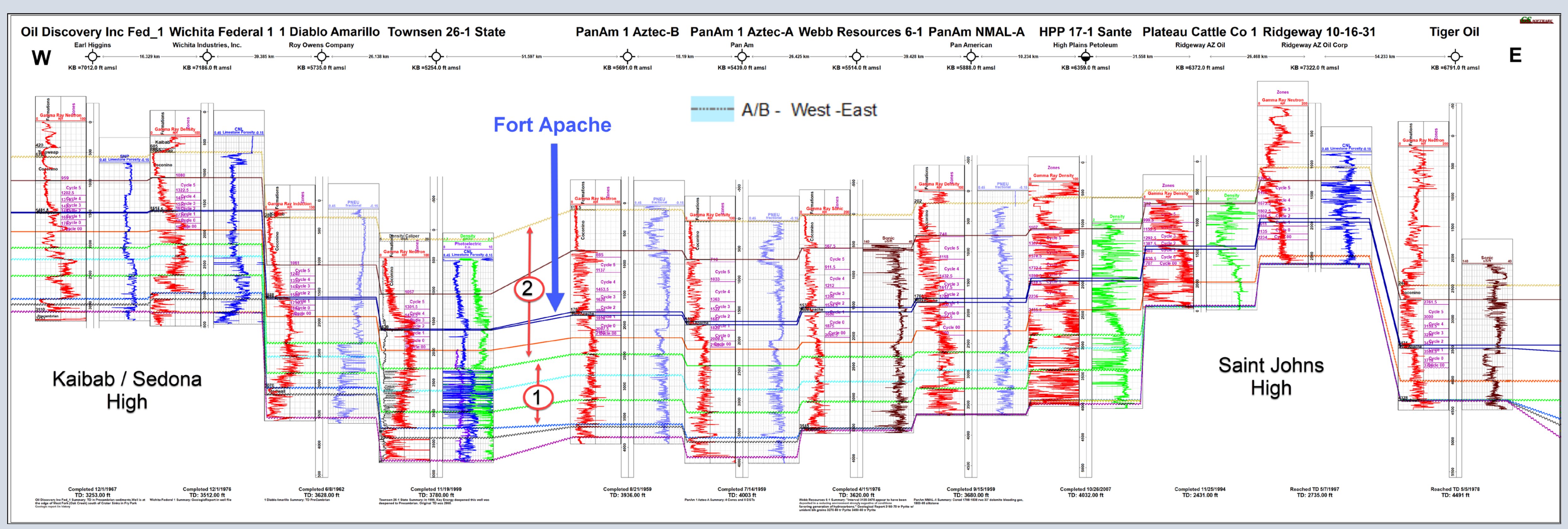
The composition and textures of the carbonate units are visually similar to vertical sequences of the underlying Redwall Limestone (Kent & Rawson 1980). Additional complexity is supplied by the interstratified marginal marine and / or non-marine pyritic-acid-sulfate clastic units where large amounts of pyrite formed. The components required for acid sulfate soil formation are shown in the in-set of Figure 8A, image, *Origin of Pyrite,* from https://www.qld.gov.au/environment/land/management/soil/acid-sulfate/explained.
As shown in Figure 8B, acid sulfate soils are common in mangrove and saltmarsh areas and underlie floodplains, levees and back swamps. During regressions the oxidization of pyrite creates a diagenetic overprint on the depositional facies. Figure 8C illustrates some of the observed diagenetic changes to the cyclothem model.

FIGURE 9: PHOTOGRAPH OF BOTTLE BEND LAGOON – MURRAY RIVER, AUSTRALIA

https://www.riverspace.com.au/item/bottle-bend-lagoon-restoration/
Bottle Bend Lagoon is a modern example of acid sulfate diagenesis in wetland soils. Partial drying of the area due to low flow in the Murray River resulted in the soil pH dropping from near neutral to below 3 in under four months. When pyrite is exposed to water and oxygen either by natural processes or anthropogenic activities, it is exothermically oxidized to sulfuric acid, a highly corrosive oxidant. The abundance of pyrite in the subsurface and its absence in outcrop along with the abundance of iron oxides and the absence of organic material in outcrop suggest that this oxidization reaction is a significant diagenetic event for these rocks. The Bottle Bend Lagoon example suggests that this type of diagenesis occurred during the regressive events between cycles at the landward edge of each cycle. Because of the remnant coal units, like those at Fossil Creek Canyon, not all of the pyrite diagenesis was early and much of it may have occurred with the development of the Mogollon Rim and Slope.

Locations of the West – East Cross Sections are shown in Figure 11.





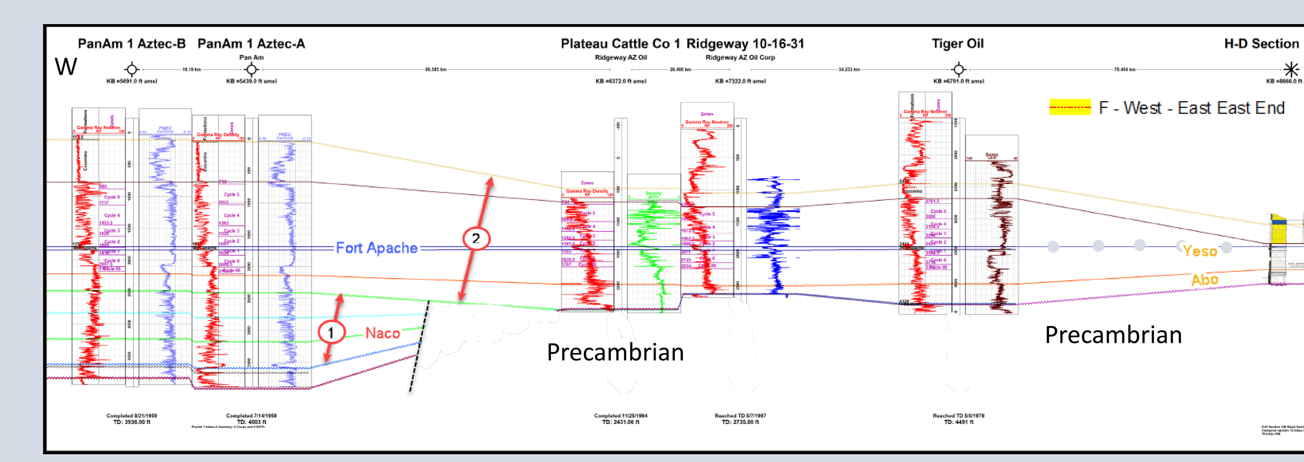
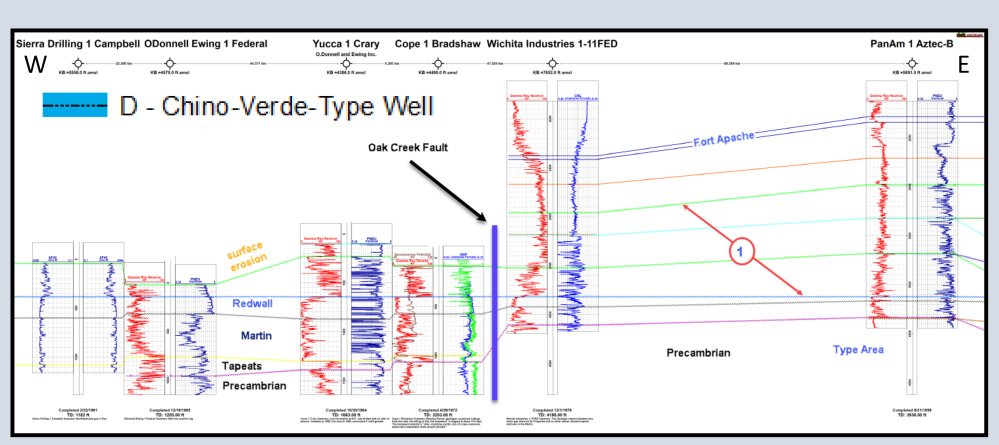


FIGURE 10 F: WEST – EAST ACCESSORY SECTION FROM WEST END OF FIGURE 10A TO OUTCROPS OF THE ZUNI UPLIFT

The well data is tied to a measured section of Huddle and Dobrovolny (H-D),1945. The cross section with the Fort Apache Member datum shows Sequence 1 (Naco) truncated at the Saint Johns Dome and Sequence 2 correlative with the Yeso and Abo Formations in outcrop.



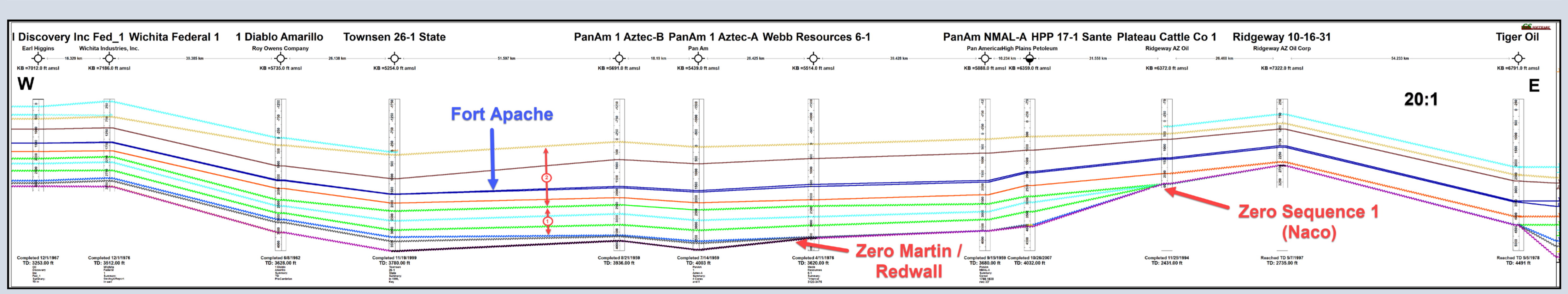
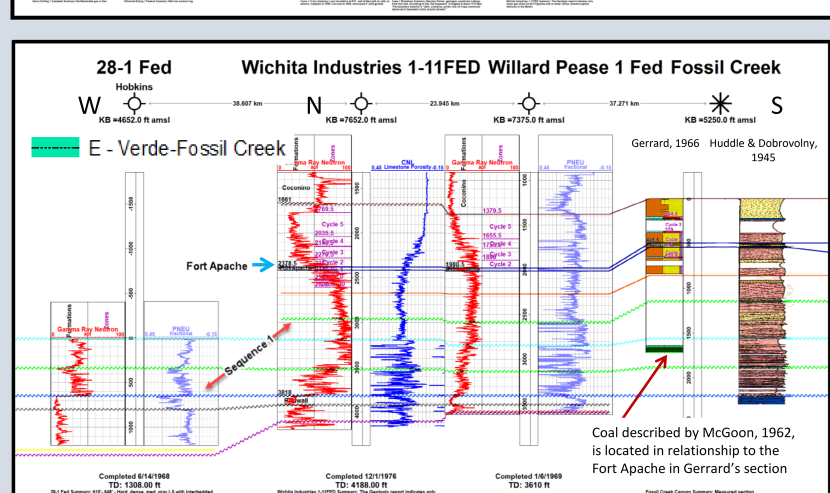


FIGURE 10 A: MAIN WEST – EAST CORRELATION SECTION FROM WEST OF FLAGSTAFF ARIZONA TO EAST OF THE NEW MEXICO BORDER WITH WELL CONTROL
FIGURE 10 B: MAIN WEST – EAST CORRELATION SECTION WITHOUT WELL DATA AT A SCALE OF 20:1



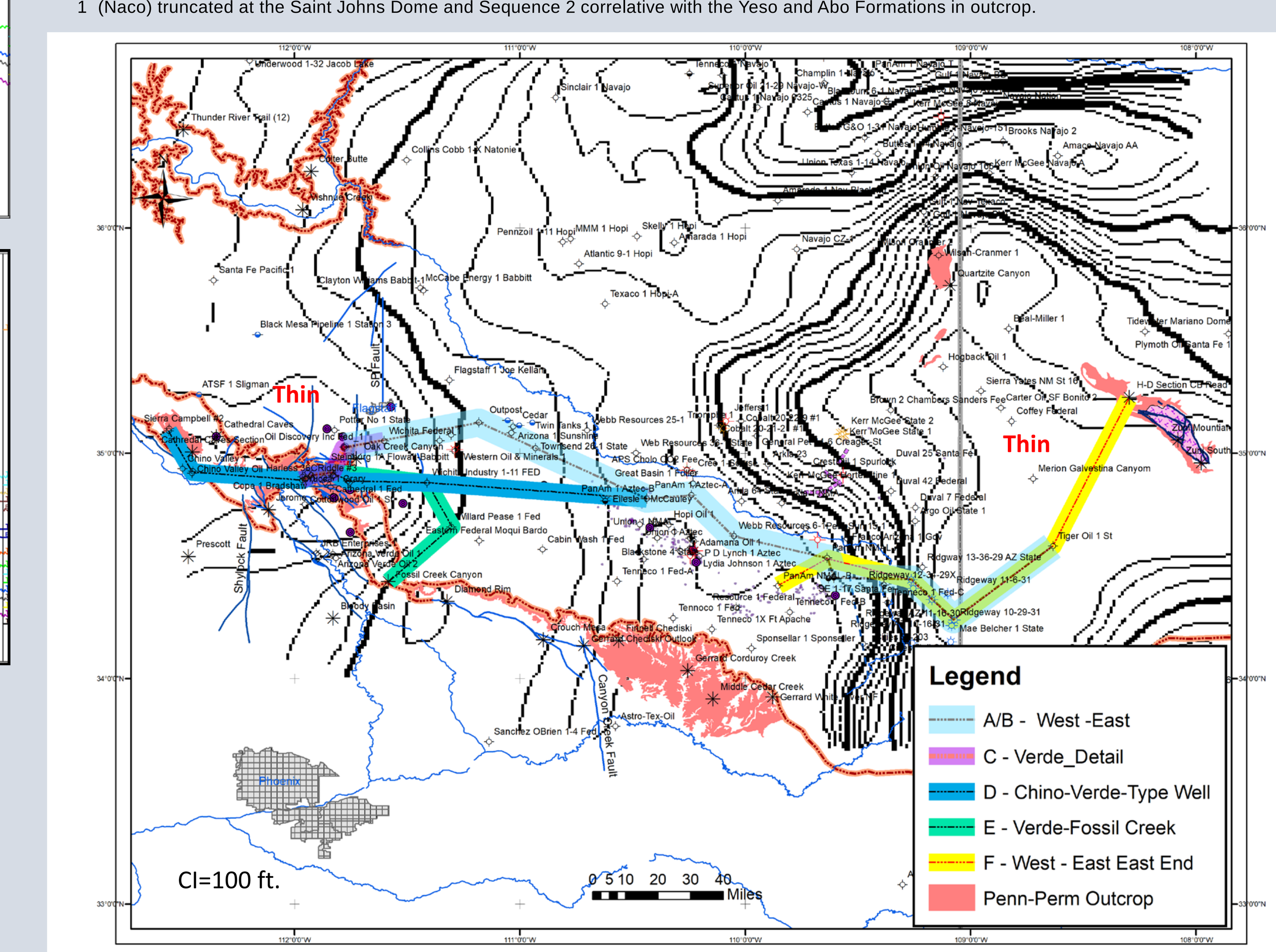


FIGURE 11: INDEX MAP FOR THE WEST – EAST CORRELATION SECTION AND ACCESSORY SUBSECTIONS WITH SEQUENCE 1 ISOPACHOUS CONTOURS

FIGURE 10 C: WEST– EAST ACCESSORY SECTION CONNECTING THE END OF FIGURE 10A TO THE WELLS IN THE VERDE VALLEY WEST

The top of the Redwall is the datum for the sections in Figures 10C, 10D, & !0E. The wells in Section 10C show the distinctive well log character of the clastic – carbonate cycle's at the base of Sequence 1

FIGURE 10 D: WEST– EAST ACCESSORY SECTION FROM THE TYPE WELL TO SECOND WELL AT THE END OF FIGURE 10A

This accessory section illustrates that the basal units of Sequence 1 can be correlated to wells and outcrops of the Chino Valley / Black Mesa area. The cross section indicates that Hughes (1952) interpretation the rocks north of Chino Valley as Pennsylvanian (Desmoinian / Virgil) age was correct. The section also suggests pre-Pennsylvanian displacement on the Oak Creek Fault supporting the Holm and Cloud (1990) interpretation that the Oak Creek Fault should be included in a "system of faults on southern Colorado Plateau that have deformed Phanerozoic strata by reactivation of ancestral fractures in the Precambrian basement (Holm & Cloud, 1990, Page 1014). They base this interpretation on measured sections on opposite sides of the Oak Creek Fault in which the thickness of the section between the Fort Apache and the Coconino Sandstone are different.

FIGURE 10 E : WEST – EAST ACCESSORY SECTION FROM FOSSIL CREEK CANYON OUTCROP TO THE NORTH END OF VERDE VALLEY

At the Fossil Creek Canyon location, the measured sections of Gerrard, (left side) Huddle & Dobrovolny (right side) are shown (Gerrard, 1966; Huddle & Dobrovolny, 1945). The location of the coal beds of McGoon (1962) are shown relative to Gerrard's section.

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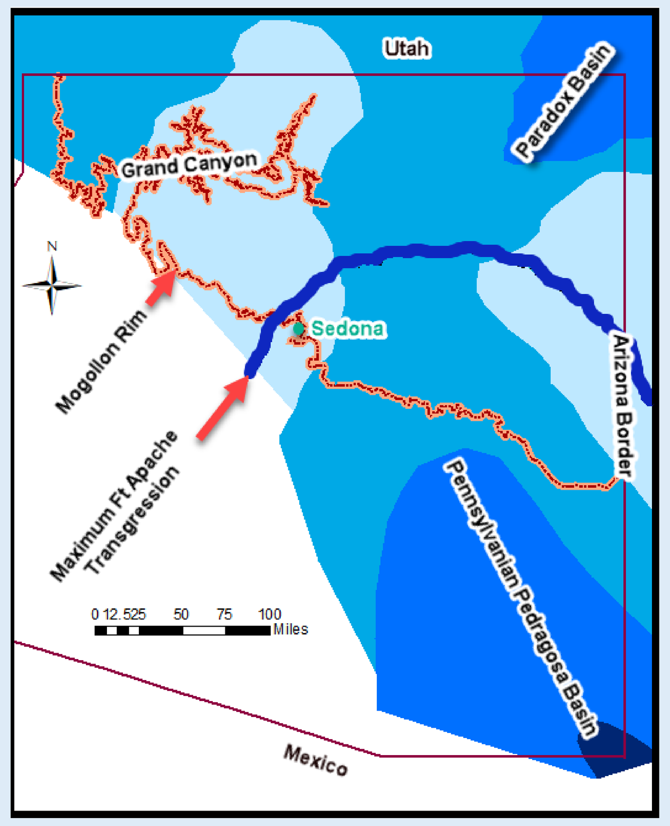


FIGURE 12: PENNSYLVANIAN - PERMIAN PALEOGEOGRAPHY

Regional correlations indicate that marine water covered most of eastern Arizona during the Pennsylvanian. The data is less definitive for the Permian sea. The northern limit of the Fort Apache Member may indicate the maximum transgression to the north by shallow sea water.

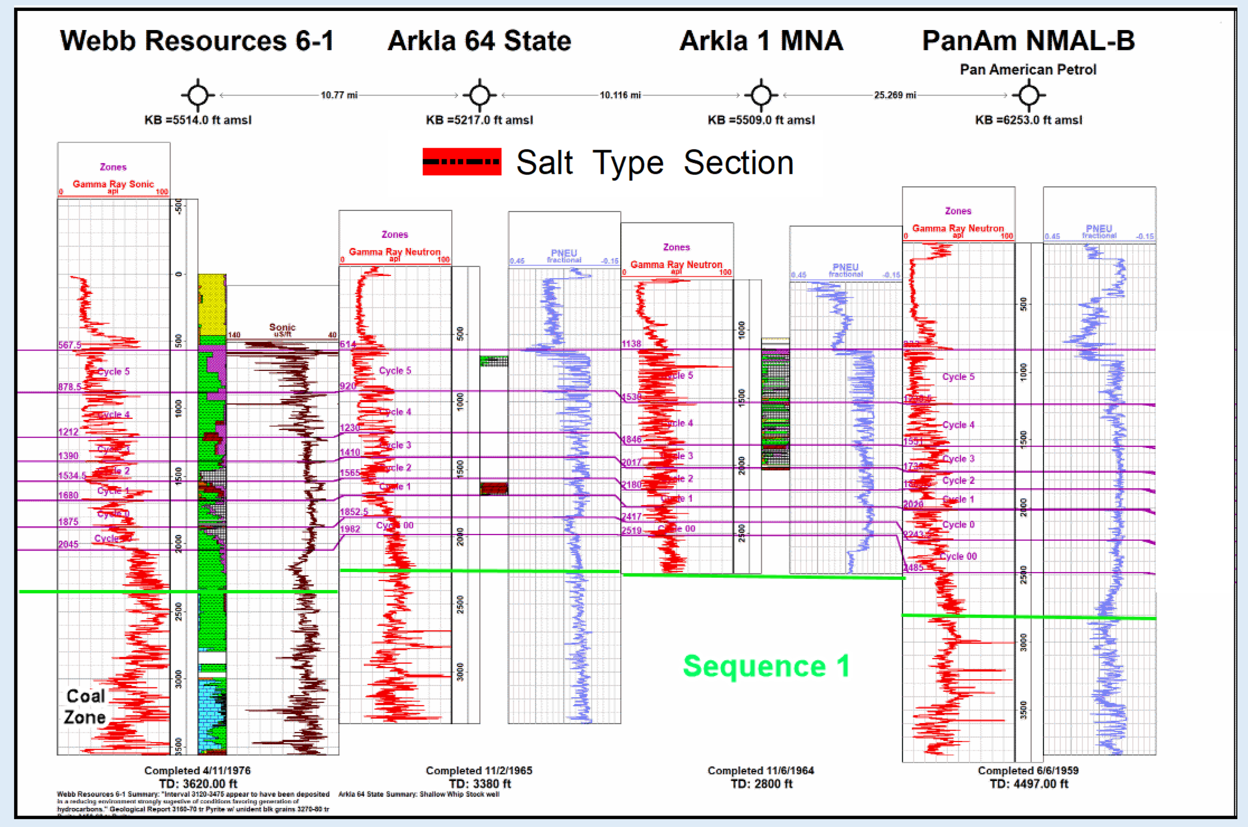


FIGURE 13: REFERENCE TYPE SECTION FOR SEQUENCE 2

The Reference Section connects the Type Section to the Salt Cycles developed by the Arkla Exploration Company in their wells and used in publications by The Arizona Geological Survey (Rauzi, 2000). These correlation markers were supplemented by the author to identify units below the Arkla zones. Figure 14 A & B provide an alternate way that the salt cycles may be defined with perhaps more genetic significance.

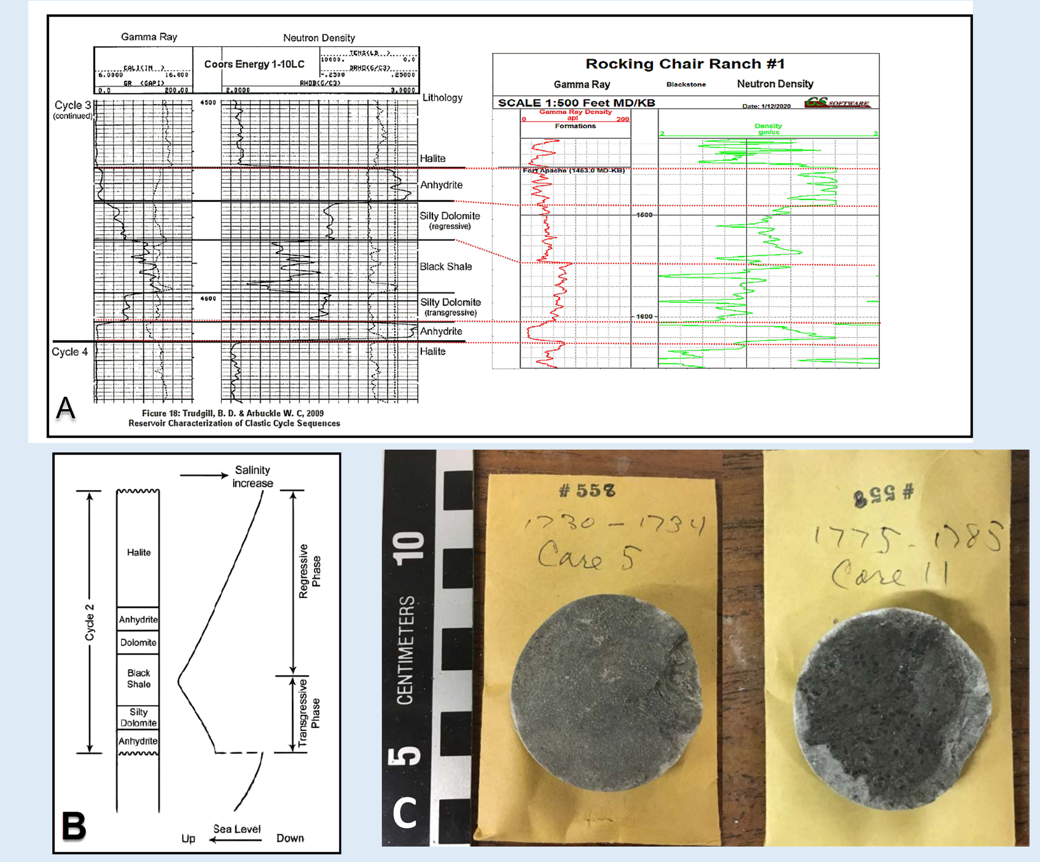


FIGURE 14A: PARADOX BASIN SALT CYCLE COMPARISON

Correlation of clastic cycle sequence from Coors Energy 1-10LC, Paradox Basin, Utah (B. D. Trudgill and W. C. Arbuckle, 2009) with Rocking Chair Ranch #1, near the center of the study area (see Figure 1 for well locations). The Fort Apache interval in the Rocking Chair Ranch #1 on the right shows a similar vertical lithologic sequence to the Paradox Basin well.

FIGURE 14B: PARADOX BASIN VERTICAL SALT SEQUENCE

(Figure 17 from B. D. Trudgill and W. C. Arbuckle, 2009, OFR 543, Utah Geological Survey)

FIGURE 14C: UNION OIL 1 NMAL CORE SAMPLES

Core samples from cycle 2 (Fort Apache) showing organic-rich silty sandstone and dolomitic sandstone with disseminated pyrite.

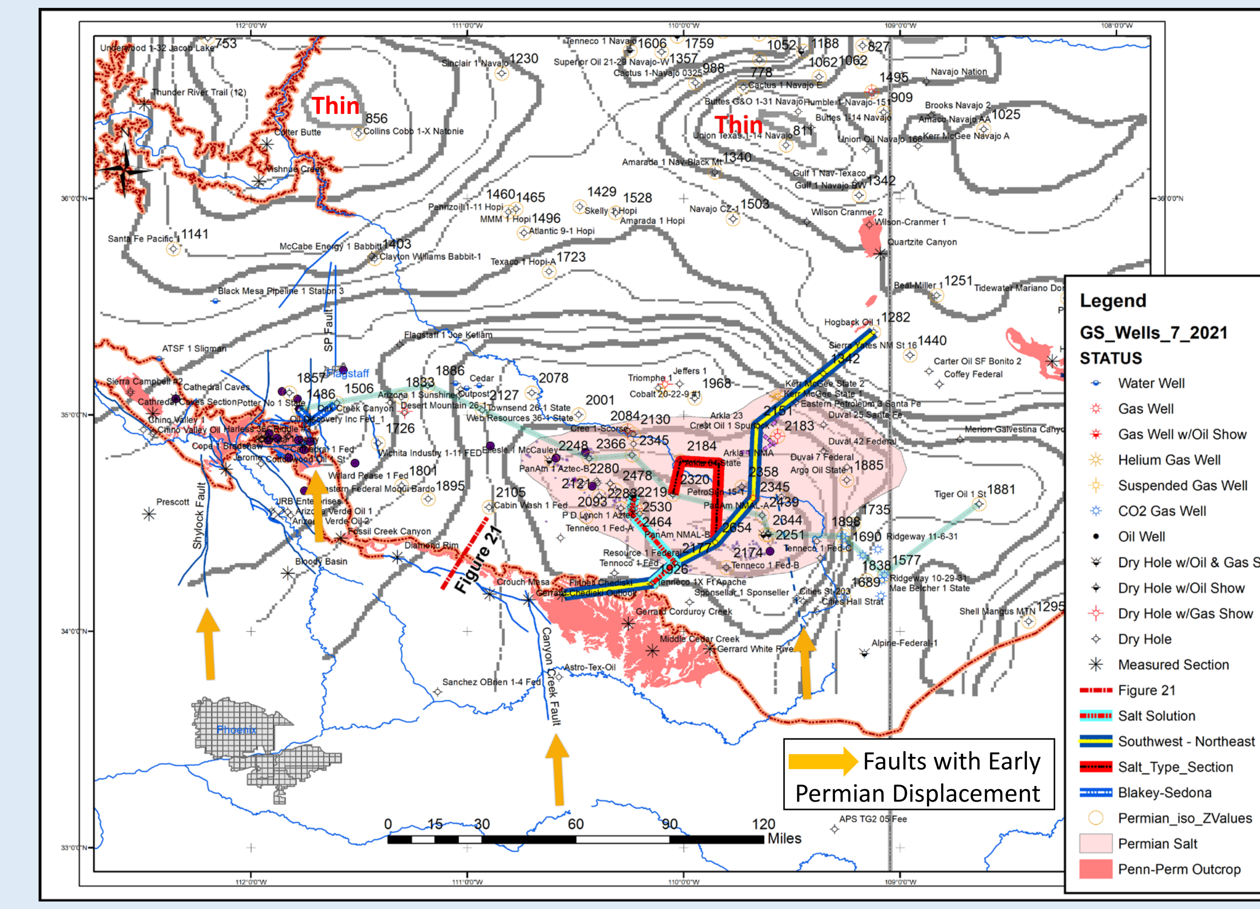


FIGURE 15: ISOPACH MAP OF SEQUENCE 2 ILLUSTRATING LOCATION OF THE SOUTHWEST-NORTHEAST AND ACCESSORY CROSS SECTIONS

The arrows indicate the locations of the Shylock, Oak Creek, Canyon Creek, and Saint Johns Faults, from west to east. These faults all show displacement that occurred in Early Permian time (Finnell, T. L. (1962), Holm, R. F., & Cloud, R. A. (1990), and this study).

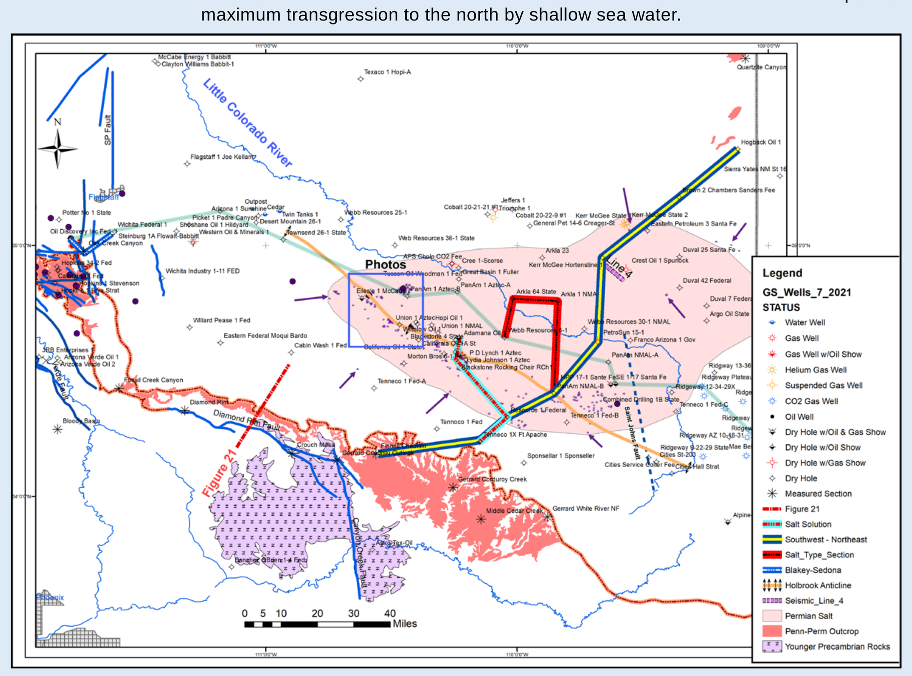


FIGURE 16: DETAIL OF FIGURE 15:

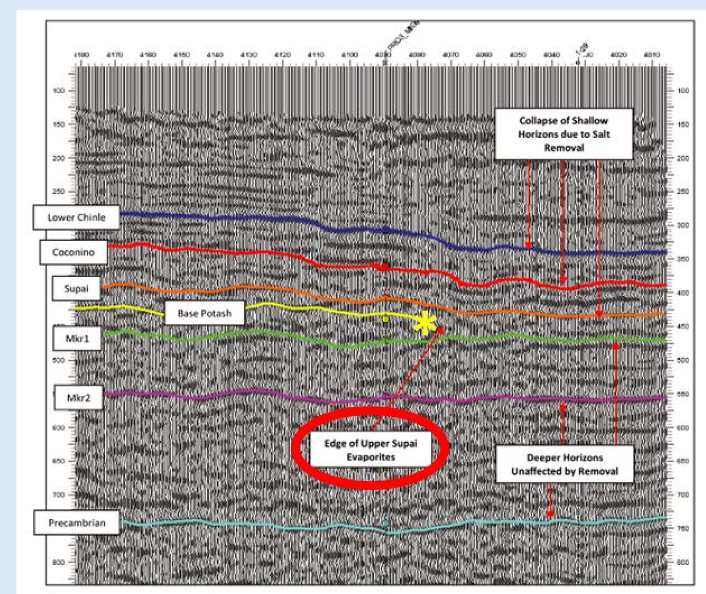
The sinkholes surrounding the residual salt body are indicated by purple dots indicated by arrows and the larger dolines are indicated by the larger black circles.
The photographs of Figure 17 illustrate the area enclosed by the blue box.
The seismic line (purple & black line) shown in Figure 18 crosses the Main Southwest – Northeast Cross Section (dark blue line with yellow center) near the north edge of the salt body.
The Accessory Southwest – Northeast Cross section in Figure 23 is shown by the light blue line with red center.

From Google Earth

From Neal, Johnson and Lindberg, 2013

FIGURE 17: PHOTOS OF KARST

The images show only a fraction of the surface features.



https://www.sec.gov/Archives/edgar/data/1477032/000095012311103797/c26091exv99w1.htm

FIGURE 18: SEISMIC LINE 4

The seismic line acquires by American West Potash shows the collapse of shallow beds into the space created by salt removal. Note that strata below the base of salt are unaffected by the karst induced faulting.

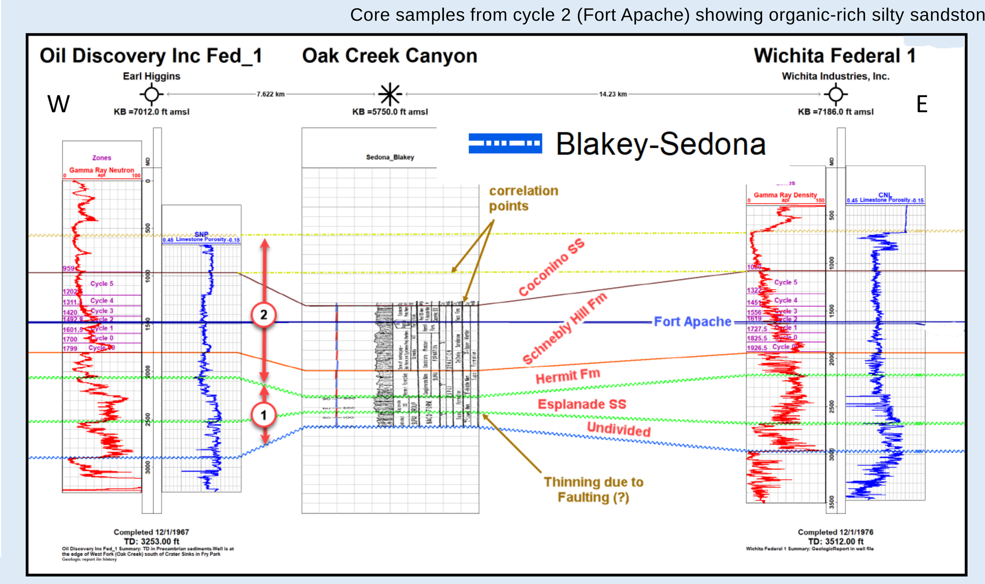


FIGURE 19: WEST END OF W-E SECTION WITH MEASURED SECTION BY BLAKEY, 1990.

All of the salt cycle correlation markers are present in the area of the Oak Creek Canyon near Sedona, as well as the Fort Apache and other intra-halite units. This suggests that the Rim outcrops are part of a regional founder breccia created by salt removal and that the dramatic scenery is typical karst topography. The cross section illustrates the difficulty of lithostratigraphy in diagenetically altered rocks. The stratigraphic interpretation is further complicated by the faulting that was active when these rocks were deposited. These conclusions are demonstrated by Blakey's section which includes the correlations of four previous interpretations. See Figures 15 for location..

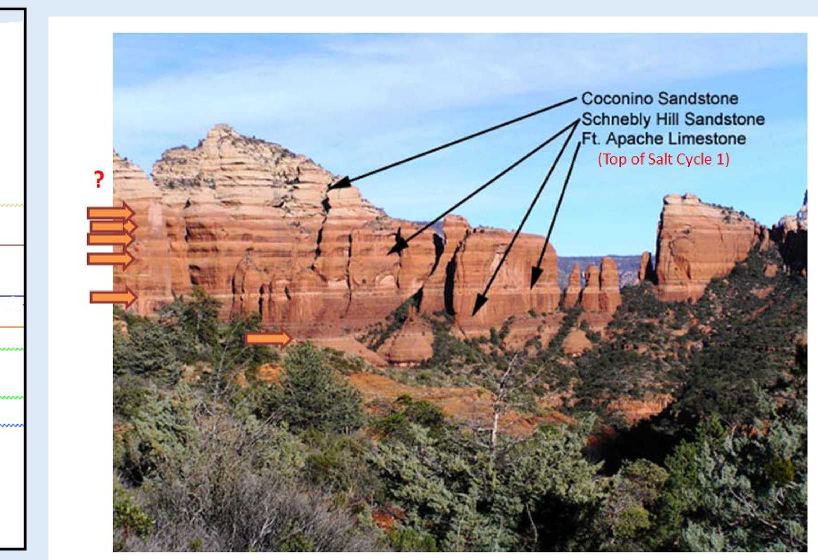


FIGURE 20: MOGOLLON RIM NEAR SEDONA

Outcrops shows karst topography and color cyclicity of the strata above and below the Fort Apache Marker bed. The color cyclicity continues through most of the Coconino Sandstone.
Note that most of the fore-ground is below the base of salt cycle 1.
Photograph from
https://www.google.com/url?sa=i&source=images&cd=&ved=2ahUKEwiO9NmMxc7kAhV8JDQIHffmAxcQjRx6BAgBEAU&url=http%3A%2F%2Fwww.arizonaruins.com%2Fsedona%2Fsedona_geology.html&psig=AOvVaw1ua9vMDNpG_1B29t_nixMn&ust=1568489562957552

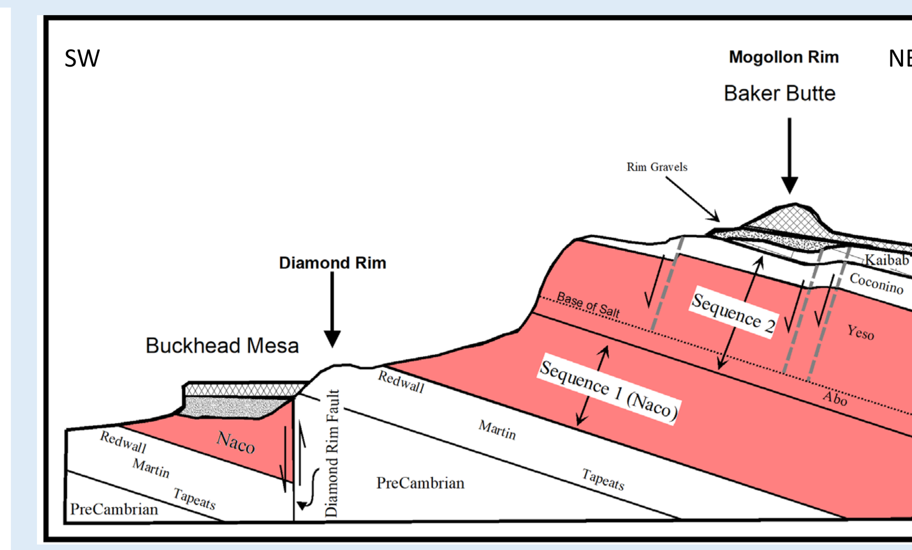
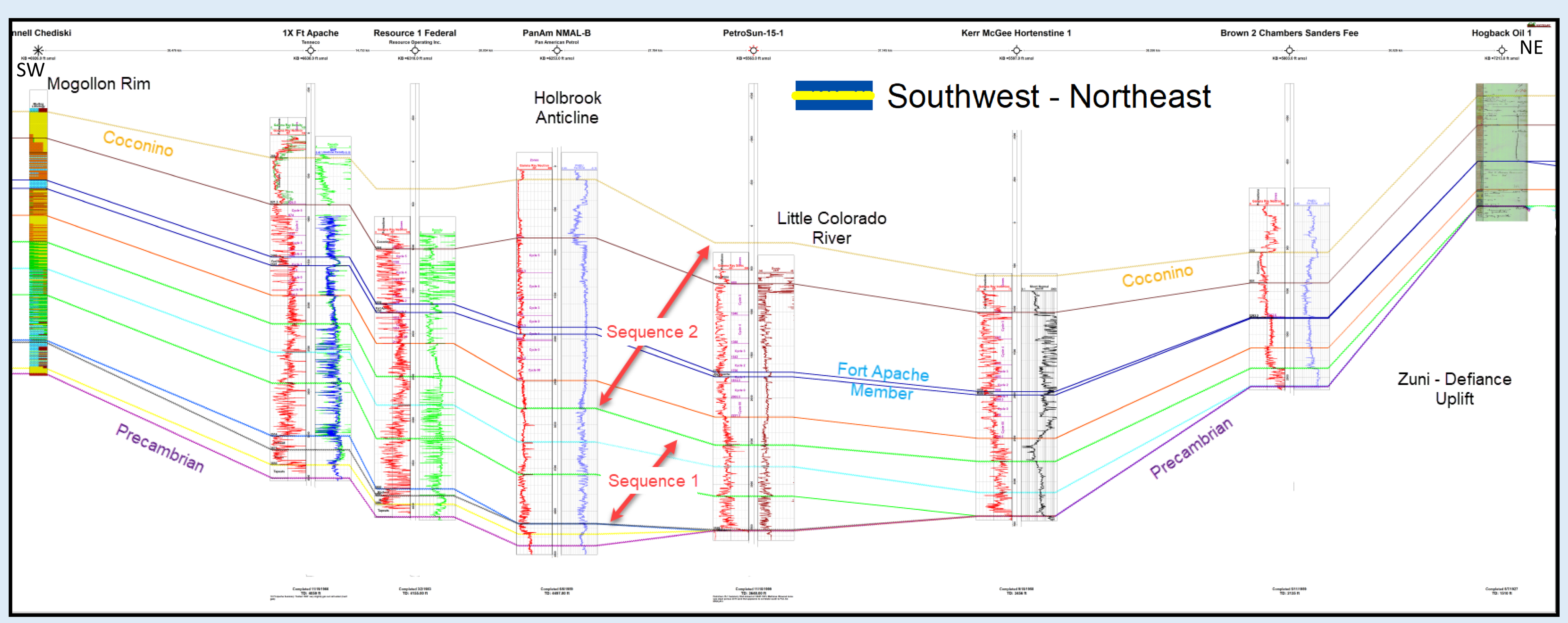


FIGURE 21: DIAGRAMMATIC SKETCH OF THE MOGOLLON RIM

The area shaded in color corresponds to the equivalent area in the map of Figure 1. The volcanic rocks and Rim Gravels are shaded with textures (Redrawn from H.W. Peirce, Damon, & Shafiqullah, 1979). The sketch illustrates the founder breccia developed above the base of salt. The Rim Gravels and volcanic units show that salt solution occurred prior to and contemporaneously with the Rim formation.



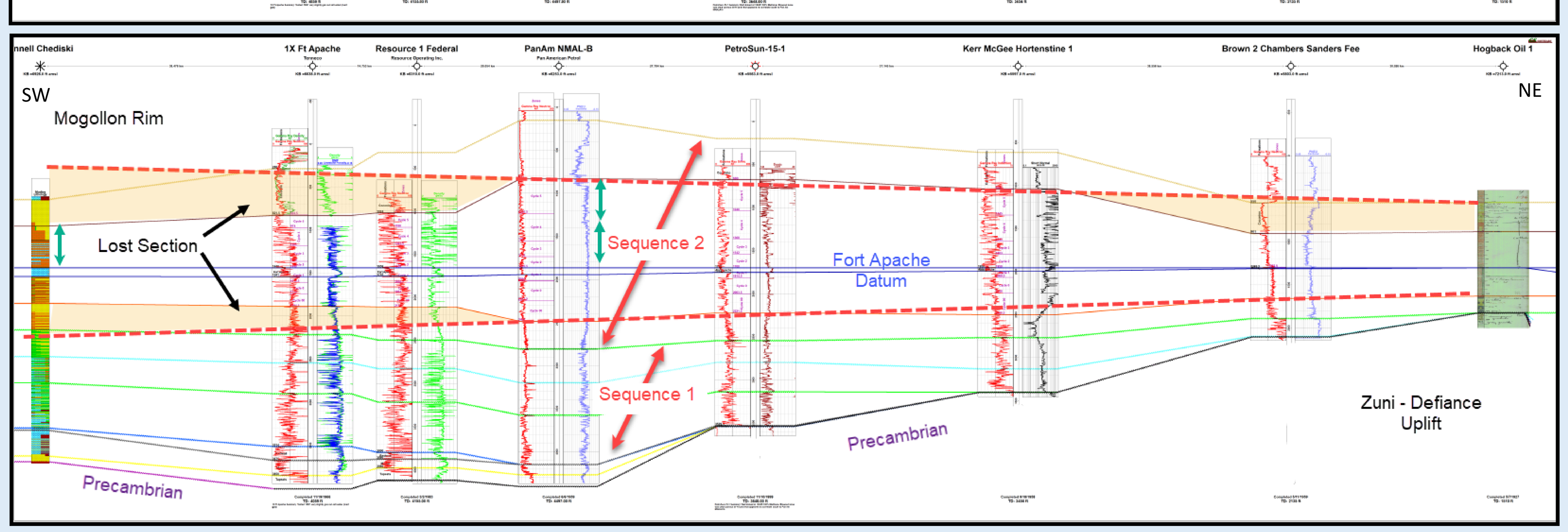


FIGURE 22A: SOUTHWEST – NORTHEAST STRUCTURAL CROSS SECTION FROM THE MOGOLLON RIM TO THE DEFIANCE UPLIFT

The section shows the Cambrian through Pennsylvanian strata truncated at the north edge of the Mogollon Slope at the Zuni – Defiance Uplift

FIGURE 22B SOUTHWEST – NORTHEAST STRATIGRAPHIC CROSS SECTION – FORT APACHE MEMBER DATUM

The section shows the Cambrian, Devonian, and Mississippian units and Sequence 1 on-lapping the Zuni – Defiance Uplift.
However in Sequence 2, the intra-salt units like the Fort Apache Member thicken southward, but the total thickness of Sequence 2 thins toward the south. The evidence provided above indicates that the southward thinning is the result of salt solution and removal of material from the section. Extending the red dashed lines from the tops and bottoms of the total section in the wells within the salt body toward the northeast and southwest provides an estimate of the post-deposition, post-compaction thickness of Sequence 2. The Coconino Formation is excluded from this exercise because its thickness is affected by surface erosion. The difference between the current tops and bottoms of Sequence 2 in wells outside of the salt body to the red dashed lines indicates the amount of thickness of the dissolved salt or "Lost Section" (orange shaded area). Note that the orange shaded areas correlate to the map areas with the highest density of sinkholes / dolines and to the south flank of the Holbrook Anticline. The seismic line in Figure 18 also occurs above the area of the lost section at the northeast end of this figure.

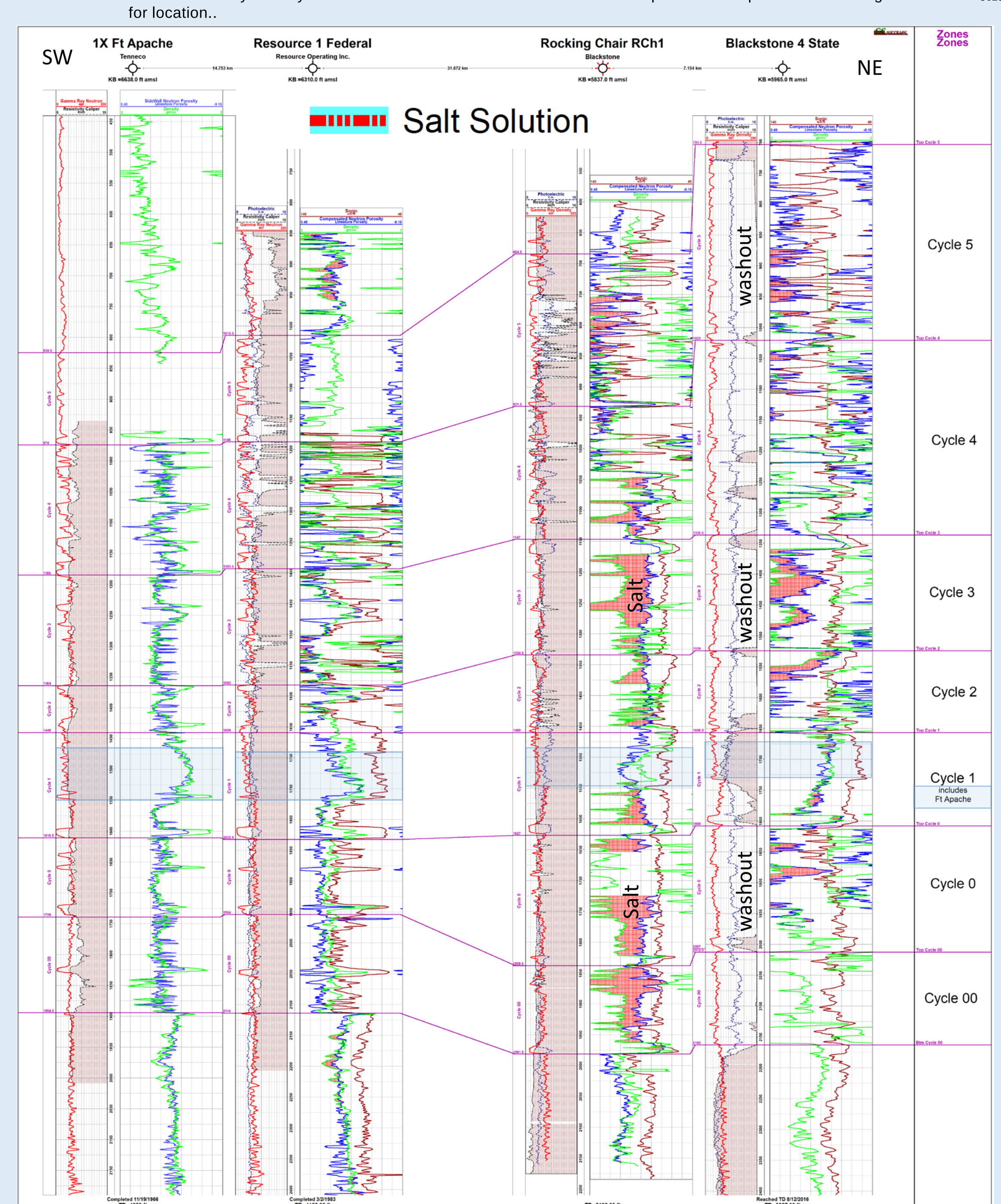


FIGURE 23: ACCESSORY SW – NE STRATIGRAPHIC CROSS SECTION – SEQUENCE 2 ONLY – TOP CYCLE 1 DATUM (INCLUDES FT. APACHE MEMBER)

A Southwest - Northeast Section to better illustrate the continuity of markers despite the loss of the salt beds. This section relies on a more modern well log suite than the Main Southwest – Northeast Section in Figures 22A/22B and illustrates the continuity of the intra-salt units and the loss of evaporite units. The Neutron – Density crossover (red shaded intervals between the green and blue curves on the right of the depth tract) indicates the presence of halite. The unshaded parts of the caliper curve on the left of the depth track is an indication of washed-out or oversized bore hole. These wells were drilled with native (fresh) water which resulted in solution of the salt intervals as shown by the large hole volume or salt wash-out. Integration of all of the geophysical logs indicate that although the inter-halite units thicken southward, the total thickness decreases due to loss of the halite and other evaporite content within the strata.

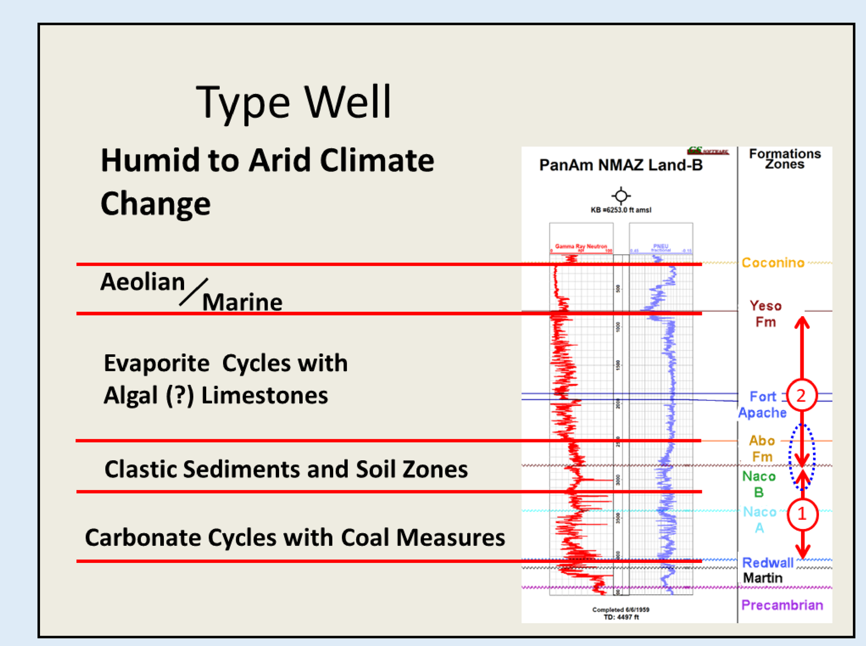


FIGURE 25: SUGGESTED PALEO CLIMATES

At its base, Sequence 1 includes thin karst deposits similar to the Molas Formation of the San Juan Basin. The unit grades upward into dominantly carbonate cycles with textures similar to the underlying Redwall Limestone. The coal inter beds suggest a warm humid depositional environment. These cycles gradually become dominated by clastic sediments and soil zones. Although the two sequences are separated by major regional unconformity, the transition between them appears to be gradual. Sequence 2 grades vertically from terrigenous clastics into cycles of evaporites separated by organic carbonates and clastic units and finally into marine and aeolian sandstone beds. The transition from marine to aeolian sandstone suggests a final transition to a semiarid or arid environment.

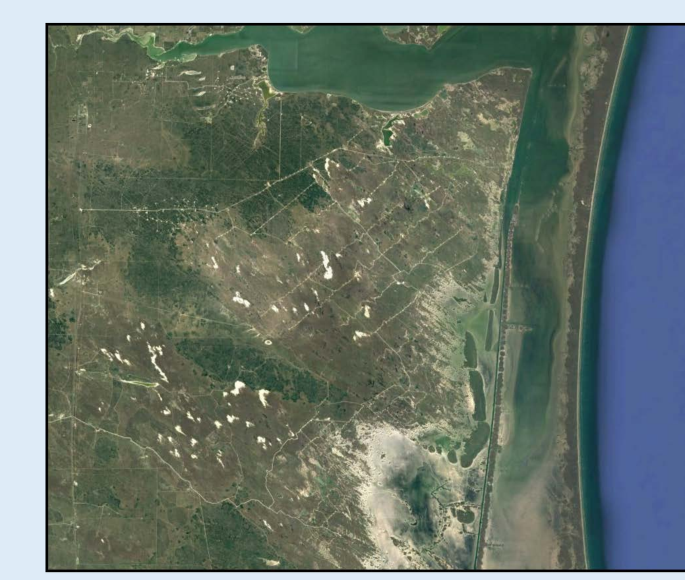


FIGURE 26: DEPOSITIONAL SETTING

The absence of organic material in the Penn-Perm strata of the Mogollon Rim and the abundance of iron oxide have been important contributors to the traditional interpretation of the depositional environments for these units. However, if the composition and textural changes caused by acid sulfate diageneses are recognized and the absence of organic sediments are accepted as are result of that process, then these units appear more similar to other cyclic Upper Carboniferous / Permian rocks of North America. Although the coastal area near Corpus Christi (above figure) provides a visually similar, possible modern analogue consisting of estuaries, lagoons, abundant vegetation, and sand dunes, acid sulfate soils are not known to be present there.

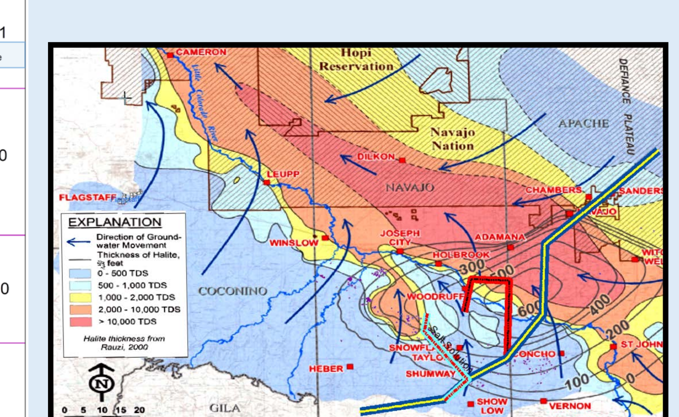


FIGURE 24: DISTRIBUTION OF TOTAL DISSOLVED SOLIDS, THICKNESS OF HALITE, AND DIRECTION OF GROUND WATER MOVEMENT DOWN THE MOGOLLON SLOPE

The contoured salt body in this figure is the pink shaded area of Figure 15, above. The locations of the cross sections in figures 13, 22 and 23 are indicated by the corresponding colored lines. The map is taken from McGavock, 2014, AHS / AIPG Symposium.

CONCLUSIONS

- The Penn-Perm Interval can be divided into two Sequences composed of at least 22 cyclothems.
- During deposition the climate changed from warm humid to warm semiarid.
- Lithotrophic bacteria caused precipitation of abundant pyrite in the organic rich sediments.
- Correlations between outcrops and subsurface wells is difficult because:
  - Pyrite oxidation caused diagenetic metamorphosis of the sediments changing their color, texture and altering component minerals or removing them;
  - Depositional cycles were cannibalistic (e.g. Red Jasper in the basal conglomerates originated in previous cycles);
  - Ground water flow removed large volumes of stratigraphic interval – up to half of Sequence 2;
  - Identifying founder breccias in outcrop is difficult.

ACKNOWLEDGEMENT

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The Author thanks the Geological Survey of the State of Arizona for access to the State Sample Repository.

References Cited

American.West.Potash. (2011). Preliminary Economic Assessment American West Potasy - Holbrook Basin Project. Retrieved from https://www.sec.gov/Archives/edgar/data/1477032/000095012311103797/c26091exv99w1.htm

Blakey, R. C. (1990). Stratigraphy and geologic history of Pennsylvanian and Permian rocks, Mogollon Rim region, central Arizona and vicinity. *Geological Society of America Bulletin, 102*, 1189-1217.

Finnell, T. L. (1962). *Recurrent Movement on the Canyon Creek Fault, Navajo County, Arizona*. Washington D. C.: United States Government Printing Office

Gerrard, T. A. (1966). Environmental Studies of the Fort Apache Member, Supai Formation, East-Central Arizona. *AAPG Bull, 50*(11), 2434-2463.

Holm, R. F., & Cloud, R. A. (1990). Regional significance of recurrent faulting and intracanyon volcanism at Oak Creek Canyon, southern Colorado Plateau, Arizona. *Geology, 18*(10), 1014-1017. doi:10.1130/0091-7613(1990)018<1014:Rsorfa>2.3.Co;2

Huddle, J. W., & Dobrovolny, E. (1945). *Late Paleozoic Stratigraphy of central and Northeastern Arizona*.

Hughes, P. W. (1952). Stratigraphy Of Supai Formation, Chino Valley Area, Yavapai County, Arizona. *AAPG Bull, 36*(4), 635-657.

Kent, W. N., & Rawson, R. R. (1980). *Depositional Environments of the Mississippian Redwall Limestone in Northeastern Arizona.* Paper presented at the Paleozoic Paleogeography of the West-Central United States, Rockymountain Paleogeography Symposium 1.

McGavock, E. (2014). *The Padre Canyon Evaporites, Coconino County, Arizona*. Paper presented at the AHS / AIPG Synposium, Prescott, Arizona.

McGoon, D. O. J. (1962). *Occurrences of Paleozoic Carbonaceous Deposits in the Mogollon Rim Region*. Paper presented at the New Mexico Geological Society 13th Annual Fall Field Conference Mogollon Rim.

Miall, A. D. (2019). Chapter 8 - The Southern Midcontinent, Permian Basin and Ouachitas. In A. D. Miall (Ed.), *The Sedimentary Basins of the United States and Canada (Second Edition)* (pp. 369-399): Elsevier.

Neal, J. T., Johnson, K. S., & Lindberg, P. (2013). *Variations in Evaporite Karst in the Holbrook Basin, Arizona*. Paper presented at the The 13th Multidisciplinary Conference on Sinkholes and the Engineering & Environmental Impacts of Karst, Carlsbad, New Mexico, USA.

Peirce, H. W., Damon, P. E., & Shafiqullah, M. (1979). An oligocene (?) colorado plateau edge in arizona,. *Tectonophysics, 61*(1-3), 1-24. Retrieved from https://doi.org/10.1016/0040-1951(79)90289-0.

Quensland.Government. (2019, December 11, 2019). Acid sulfate soils explained. Retrieved from https://www.qld.gov.au/environment/land/management/soil/acid-sulfate/explained

Rauzi, S. L. (2000). *Permian Salt in the Holbrook Basin, Arizona*. Arizona Geological Survey

Riverspace. (2020). Bottle Bend Lagoon Restoration. Retrieved from https://www.riverspace.com.au/item/bottle-bend-lagoon-restoration/

Ross, C. A. (1973). Pennsylvanian and Early Permian depositional history, southeastern Arizona. *Am. Assoc. Petroleum Geologists Bull., 57*, 887-912.

Tearpock, D. J., & Bischke, R. E. (2003). *Applied Sbsurface Gological Mpping with Structural Methods* (Second ed.): Prentice Hall PTR.

Turdgill, B. D., & Arbuckle, W. C. (2009). *Reservoir Characterization Of Clastic Cycle Sequences In The Paradox Formation Of The Hermosa Group, Paradox Basin, Utah (OFR-543)*. Utah Department of Natural Resources

Unknown. (2007). Coconino and Schnebly Hill layers, with Ft. Apache Limestone running through the middle of Schnebly Hill. Retrieved from https://www.google.com/url?sa=i&source=images&cd=&ved=2ahUKEwiO9NmMxc7kAhV8JDQIHffmAxcQjRx6BAgBEAU&url=http%3A%2F%2Fwww.arizonaruins.com%2Fsedona%2Fsedona_geology.html&psig=AOvVaw1ua9vMDNpG_1B29t_nixMn&ust=1568489562957552