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Source-Rock Potential of the Lower Permian Supai Formation in the Blackstone Exploration Company Rocking Chair Ranch No. 4 Well, Navajo County, Arizona*

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Abstract

Fifteen drill cutting samples, representing the stratigraphic section between 1415 and 1852 feet in the Blackstone Exploration Rocking Chair Ranch No. 4 well, in the Holbrook Basin of Navajo County, Arizona, were examined for the determination of their source-rock (oil and gas) potential. This was done using the Visual Kerogen Analytical method in combination with Total Organic Carbon analyses.

Visual Kerogen Analysis involves the examining of a rock's organic matter content (types and abundance of components) to determine if the material is oil and/or gas prone (i.e., type of organic material) and to what level of thermal heating the organic constituents have been exposed. The latter is based on the color of trilete spores, pollen, and/or tissue fragments that are interpreted to be **in situ.**

Based solely on Visual Kerogen Analyses, the stratigraphic section between 1415 and 1852 feet was subdivided into three distinct units. Shown as **Units "A"**, **"B"** and **"C"**, these three zones are interpreted to represent the lower Corduroy Sandstone, the Fort Apache Limestone and the Big A Butte Members of the Supai Formation. The Amos Wash Member of the Supai was not, to our knowledge, examined in this study. The three units recognized in this study are interpreted to be at a **Moderately Immature** to **Moderately Mature** stage of thermal maturity.

Total Organic Carbon (**TOC**) analyses indicate that the Fort Apache Limestone member of the Supai has the necessary criteria to be considered as having **GOOD** source-rock potential for the generation of liquid and/or gaseous hydrocarbons. The bulk of the lower Corduroy Sandstone and Big A Butte Members, because of their lithology and low TOC values, are regarded as having a **POOR** source-rock potential. A lower carbonate section, interpreted to be within the lower Corduroy Member, contains an average TOC (%Wt.) content which would define it as having **FAIR** source-rock potential for the generation of gaseous and liquid hydrocarbons. Because of the low levels of thermal maturity, any hydrocarbons that are generated will most likely be minor in amount and of non-commercial interest.

Introduction

Fifteen envelopes of drill cuttings samples, collected between 1415 and 1852 feet in the Blackstone Exploration Rocking Chair Ranch No. 4 borehole (located in Sec. 27, T. 14 N, R. 19 E. of Navajo County, Arizona (Figures 1 and 2), were analyzed for organic matter types and level of thermal maturity. The well cutting samples, along with a suite of well logs, were graciously supplied to the writers by Mr. Carmon Decker Bonanno, owner and operator of the Blackstone Exploration Company, LLC. Unfortunately, the logs did not have any “Formation Tops” marked on them. Consequently, the intervals shown on the attached Induction Electric Log (Figure 3) represent what the writers interpret to be the lower Corduroy Sandstone, Fort Apache Limestone and Big A Butte Members of the Supai. Prior to publication of this manuscript, the senior author sent a copy of our interpretation to The Blackstone Exploration Company, LLC and asked if our “Formation Tops” for the lower Corduroy Sandstone, Fort Apache Limestone and Big A Butte sections were correct. Since we received no comment as to whether this interpretation is correct or in error, the writers assume that our interpretation of the stratigraphic section, between 1415 and 1852 feet in the Rocking Chair Ranch No. 4 well, is essentially correct.

The primary objective of this study was two-fold. The original intent of this study was to examine and identify the various organic matter constituents within the Fort Apache Limestone Member of the Supai. However, after looking at samples from the lower Corduroy Sandstone and Big A Butte Members, it became increasingly clear that the main objective would have to be modified and expanded in order to cover the entire Supai Formation. The second objective was to determine the level of thermal maturity of the Fort Apache Limestone in the Rocking Chair Ranch No. 4 well. This phase of the study, to see if the organic matter had reached a sufficient time-temperature history for the generation of liquid and/or gaseous hydrocarbons, was expanded to include the lower Corduroy and the Big A Butte Members of the Supai.

This manuscript discusses and illustrates the various types of organic matter that were extracted from the drill cutting samples of the lower Corduroy Sandstone, Fort Apache Limestone and Big A Butte Members of the Supai and defines their current state of thermal maturity. The method used to establish the level of thermal maturity, in this study, is based on the spore-coloration technique described by Frank L. Staplin (1969).

Of primary concern was how the organic matter assemblages, including their color changes, varies from one member of the Supai to the other. To illustrate these changes, this report is documented with a series of photomicrographs that show some of the more common organic matter types, including their color rendition, that were observed in the stratigraphic interval between 1415 and 1852 feet. The environment of deposition for the lower Corduroy Sandstone, Fort Apache Limestone and Big A Butte Members of the Supai and the source-rock potential for the generation of liquid and gaseous hydrocarbons (oil and gas) of each are discussed.

An excellent technique to see the changes taking place in the paleo-floral patterns in the members of the Supai Formation is to look at the Visual Kerogen Summary Chart (Figures 4, 5, and 6). Of all the analytical techniques that the geologist can use in putting together a geochemical - organic matter profile for a well-bore, Visual Kerogen Analysis is one of the best and most cost-effective methods available. Using the Visual Kerogen Summary Chart, a geologist can readily see the subtle changes in organic matter (i.e., floral types) that occurred over any geological time interval. The geologist can also observe changes in the thermal maturity history of the well and also changes associated with the depositional environment. The Visual Kerogen Summary Chart is like looking through a “time-window” and being able to observe how the vegetation and associated landscape for a geographical region has changed through geologic-time.

Regarding the Visual Kerogen Summary Chart shown in Figures 4, 5, and 6, please note that Figure 4 shows the raw visual kerogen data generated by the senior writer for the Rocking Chair Ranch No. 4 well prior to any interpretations being made. Figure 5 is the same Visual Kerogen Summary Chart, but here the data have been interpreted as belonging to three distinct stratigraphic units, “A”, “B” and “C”. Can the data on the Summary Chart be interpreted differently? Yes! The interpretation of any data always comes down to the experiences of the analyst and vary from one individual to another. Sample quality, sample preparation, mud additives used in a drilling of the well, number of bit-trips, circulation, and lag time of the well cuttings material in the mud system, as well as the analyst’s expertise, all play a key role as to what will be recorded on the Visual Kerogen Summary Chart and ultimately how it is used.

Figure 6 is the same Visual Kerogen Worksheet as Figures 4 and 5. Here the writers have added a copy of the duel induction log, reduced to the same scale as the interval recorded on the Visual Kerogen Summary Chart. This was done to show how the organic-matter parameters on the Visual Kerogen Summary Chart correlate to the gamma ray and SP curves on the dual induction log. As one can see, the recorded information correlates extremely well with the petrophysical changes illustrated on the well log.

The Holbrook Basin

The greatest part of the Holbrook Basin can be found in southern Navajo and Apache counties of eastern Arizona (Figure 1). It covers a broad area of approximately 20,000 square miles. Smaller portions of the Holbrook Basin extend westward into Coconino County and eastward into western New Mexico. As stated in an online paper from the Arizona Oil and Gas Commission, entitled “Geological Summary of the Holbrook Anticline” in Confidential Report by H.R. 3723, 1996, the Holbrook Basin is almost 200 miles in length and 100 miles in width.

The thickness of the Supai Formation in the Holbrook Basin can be highly variable depending on location. In the Fort Apache area, Winters (1962, p.88, Figure 3) showed the average thickness to be approximately 1100 to 1200 feet. Twenter (1962, p. 135) and Rauzi and Fellows (2003, p. 3, Table 2) reported the Supai Group, within the Holbrook Basin, has an overall thickness of approximately 1700 feet. The thickest portion of the Supai Formation, in the subsurface, was interpreted to be near Holbrook, Arizona. These writers think that the Supai, including those sediments that may have been deposited and long-since eroded, may have reached a thickness of about 2000 feet in some places. The rocks making up the Supai Formation within the Holbrook Basin are dominated by thick deposits of sandstone, siltstone, and mudstone with some dolomitic limestone and interbedded evaporitic sequences in the upper part of the stratigraphic section. The carbonate sequences (dolomite and limestone) are found primarily in the upper half of the Supai (lower Corduroy Sandstone and Fort Apache Limestone Members). Much of what we think might be dolomite, when observed in our visual kerogen slides, appear to be algal (? calcareous algae) in origin. If this is true, then the dolomitization of the calcite-aragonite components of the algae must have been by a biological process as described by Nash, et al. (2011).

Supai Formation (East-Central Arizona)

In east-central Arizona, Winters (1962, 1963) subdivided the Supai Formation into four members. In ascending order, they are: the Amos Wash, Big A Butte, Fort Apache Limestone and Corduroy Sandstone (Figure 7). All of them were named by Winters, except for the Fort Apache Limestone which was recognized, and named, by A. A. Stoyanow (1936).

Winters' (1963) geological examination of the Supai Formation was concentrated on outcrop sections within the Fort Apache Indian Reservation in east-central Arizona. The reservation covers a geographical area that includes parts of Gila, Navajo and Apache counties. In the Fort Apache area, he found the Supai to be composed of about 1300 feet of alternating beds of reddish-brown sandstone, siltstone, mudstone, grayish limestone, evaporites (primarily gypsum) and scattered beds of light-colored mudstone. Winters (1963, p. 8-9) observed that only the upper members of the Supai (i.e., the Corduroy Sandstone and Fort Apache Limestone Members) contained sequences of thin-bedded limestone. The writers are not aware of any carbonate sequences of any significance having ever been reported from the Big A Butte and/or Amos Wash Members of the Supai.

Winters (1963) stated that only the Fort Apache Limestone Member contains, what he considered to be, a good fossil assemblage. In his collection of outcrop material, he recognized 15 genera of pelecypods, 22 genera of gastropods, one species of scaphlopods and a couple of genera of cephalopods. He also recorded echinoids, coral remains, a couple of species of productid brachiopods and the pygidium portion of a trilobite. Winters interpreted his fossil assemblage to be indicative of a shallow, nearshore, marine to brackish-water depositional environment.

Gerrard (1964) examined 17 surface exposures of the Fort Apache Limestone along the Mogollon Rim. His study location extended from the Fort Apache - White River area on the Fort Apache Reservation, west to Oak Creek Canyon south of Flagstaff, Arizona. Gerrard, like Winters (1963), found the Fort Apache Limestone in this region to be dominated by mollusks, foraminifera (including one poorly preserved specimen possibly being a fusulinid), and ostracods. Petrographic studies of the Fort Apache Limestone by Gerrard indicated that the Fort Apache Limestone interval, in his study location, was composed predominantly of dolomite. He interpreted the Fort Apache limestone/dolomite to have been deposited originally as an aragonitic or calcite, allochem-bearing or microcrystalline allochemical mud. Based on his observations, Gerrard (1964), like Winters (1962, 1963), believed the rock type and fossil assemblages were associated with sediments that accumulated within in a shallow, quiet-water, marine environment free of raging currents or harsh wave actions. This type of an environment is perfect for the growth and accumulation of calcareous algae and helps support the writers' observations regarding their interpretations as to the environment of deposition.

Passmore (1969), in her study of the Supai Formation of the Holbrook Basin, worked with subsurface petrophysical data from a series of wells drilled in the area in combination with surface outcrops of the Supai along the Mogollon Rim and the Defiance Uplift. One of her main goals was to investigate the depositional history of the Supai Formation in this area of east-central Arizona. Passmore (1964, p. 3) stated that the Supai in the Fort Apache Reservation area, with surface exposures along the Mogollon Rim, marked the southernmost boundary of the Supai Formation. She also states that the Defiance Uplift area marks the northeastern boundary of the Supai. Based primarily on subsurface well data, Passmore suggested that the thinning of the Supai in the Defiance Uplift area was due primarily to the non-deposition of sediments. She interpreted the absence of some of the Supai Formation, south of the Mogollon Rim, to be caused by recent episodes of erosion.

Based on visual kerogen data obtained from the study of the Rocking Chair Ranch No. 4 well, the writers postulate that much of the erosion of the Supai, and of late Cretaceous and/or Paleocene strata, in east-central Arizona began in concert with various episodes of uplift along the Mogollon Rim during the Late Cretaceous and/or early Paleocene. The presence of Cretaceous to Lower Tertiary angiosperm pollen in the lower Corduroy Sandstone, Fort Apache Limestone and Big A Butte Members of the Supai in the Blackstone Exploration Rocking Chair Ranch No. 4 well suggests that sediments from Cretaceous outcrops (or fractured subsurface units exposed along fault planes) were being stripped, transported and redeposited in the subsurface Supai Formation by ground waters percolating through the sediments and along fracture zones (e.g., by heavy, localized rains). The high concentration of evaporites, common within the upper Supai, was probably very susceptible to the formation of a karst topography. The karst topography undoubtedly included fissures, small nooks and crannies and caves being produced within the subsurface of the Supai members. The writers believe this allowed for the concentration of eroded post-Permian organic debris to collect within these deformed structural and stratigraphic features.

Geologic Age of the Supai Formation, Central Arizona

Based on the work of Winters (1962, 1963), Gerrard (1964), Passmore (1969) and others, the Supai Formation in east-central Arizona is interpreted to be Wolfcampian to Leonardian in age (Figure 7). Gerrard (1964, p. 8, Figure 2) thought that the lower portion of the Supai, the Amos Wash Member, may range in age from Late Pennsylvanian to Early Permian. Because the authors of this manuscript did not, as far as they are aware, examine the Amos Wash Member of the Supai, no comment can be made regarding its age and/or environment of deposition. The one thing that most geologists seem to agree on is that the bulk of the Supai Formation, in the Holbrook Basin of eastern Arizona, is most likely Lower Permian (Wolfcampian to Leonardian) in age.

McGoon (1962) mentioned the presence of carbonaceous (“coaly”) deposits in the lower part of the Supai in the Fossil Creek Canyon area west of Pine, Arizona. He stated that, although the “coal” was badly oxidized, thermal tests performed on the material yielded BTU values of slightly greater than 10,000 units per pound. McGoon interpreted this to be an indication of a bituminous grade of coal. McGoon also mentioned a rock unit containing carbonaceous material (? coal debris) in an outcrop near the base of the Mogollon Rim at Promontory Butte, 24 miles east of the town of Pine. He questioned whether this is the same carbonaceous zone in both locations. As of this date this issue seems to remain unresolved.

If the BTU content of the coalified organic material as reported by McGoon (1962) is accurate, it would be classified, per Teichmuller and Teichmuller (1968, p. 233-267), as a Sub-Bituminous B to a High-Volatile Bituminous C coal. This would indicate that the stratigraphic section is at a **Moderately Immature** to **Moderately Mature** State of Thermal Maturity and has an equivalent Vitrinite Reflectance (%Ro) value of approximately 0.50, $\pm$.05 %Ro. This maturity value is close to what the writers have determined (0.60 %Ro, $\pm$.05 %Ro) based on their visual kerogen assessment (see Figure 10).

Approximately 20 miles south of Holbrook, Arizona, McGoon (1962, p. 90) mentioned the occurrence of carbonaceous zones in two dry holes drilled by The Union-Continental Oil Company. These wells, the Union-Continental Oil, Aztec Land and Cattle Company No. 1 and the Union-Continental Oil, New Mexico and Arizona Land Co. No. 1, had pieces of carbonized “wood” fragments associated with the well cutting samples taken in the Supai Formation. McGoon did not specify exactly where in the Supai Formation that this carbonized material occurred.

McGoon (1962, p. 90, Figure 2) illustrated an instance where a carbonaceous unit (assumed to be the same one he mentions elsewhere in his paper) crosses time lines from the lower Supai (Lower Permian) into the Naco Formation (Upper Pennsylvanian). The writers assume that the carbonized material is within the Big A Butte or Amos Wash Member of the Supai. Whether this carbonaceous unit can be traced over a large regional area is open to question. These carbonaceous units may, in fact, be localized deposits of coalified plant debris and represent local environmental conditions for isolated areas within the Holbrook Basin.

McGoon (1962, p.91), stated that some "carbonized, woody debris" was collected from the New Mexico and Arizona Land Co. No. 1 Well and was supposed to be analyzed for acid insoluble palynomorphs by an unknown laboratory. The object was to see if any fossils could be recovered that might provide geologists with a definitive age date for the deposit. The writers of this manuscript are unaware of any such examination being conducted and/or of any report ever being published.

Acid Insoluble Palynomorphs in the Blackstone Rocking Chair Ranch No. 4 Well

Some of the acid insoluble palynomorphs that these writers observed and photographed during their examination of the well cutting samples, especially the striate bisaccate pollen, are good indicators for sediments that are Permian in age. Other palynomorphs, specifically angiosperm pollen that was extracted from the drill cutting samples, appear to represent contamination from either up-hole cave, contaminants from the drilling mud system or recycled Cretaceous (early Senonian) or Paleocene material brought into the area via subsurface fluids. Per the mud-logger, the Rocking Chair Ranch No. 4 well, as far as is known, was spudded in the Permian. There does not appear to be any Cretaceous or Paleocene aged sediments within the immediate area of the well bore. The drilling fluid used in the well, based on data listed on the mud-log, was a chemical mud. Whether this could provide a host for contaminants indicative of Cretaceous-age sediments remains uncertain. Contamination, due to dirty laboratory apparatus, is also a possibility. However, in this instance, all the beakers and test tubes used to extract the organic debris from the rock cuttings were new and had never been used previously. This leaves us with one last possibility: contamination due to "stratigraphic leakage".

As stated earlier, the most likely scenario regarding the presence of Cretaceous or Paleocene angiosperm pollen in the Supai Group of the RCR No. 4 well is the result of stratigraphic leakage. The writers believe that this is associated with, in part, the uplift of the Mogollon Rim area during the Late Cretaceous and/or Paleocene. The writers postulate that exposed Upper Cretaceous and/or Paleocene sediments, in the surrounding areas where the Blackstone Rocking Chair Ranch No. 4 well was drilled, were and possibly still are being eroded and carried by surface and subsurface waters along drainage systems associated with the numerous faults and fractures that are prevalent within the surface and subsurface strata of the Holbrook Basin. Since the Supai Formation in this area contains a lot of evaporites, including salt, we think that karst topography was probably a common condition that occurred within some portions of the Supai. We also believe that the karst topography, in this part of the Supai, resulted in the formation of scoured-out cavities, hollows and fractures which ultimately served as traps, or catchment basins, for some of the weathered and eroded Upper Cretaceous and/or Paleocene sediments that were transported into the subsurface domain.

Whether the "stratigraphic leakage" of the Upper Cretaceous and/or Paleocene flora (angiosperm pollen) that was seen throughout the Corduroy Sandstone, Fort Apache Limestone and Big A Butte occurs only in the RCR No. 4 well, or throughout the entire Supai Formation in the Holbrook Basin, we do not know. Contamination of Paleozoic age sediments with Cretaceous-age pollen may be more common than previously thought.

The Supai salt karst features in the Holbrook Basin of eastern Arizona has been well documented by the Department of Energy's (DOE) SciTech Connect. A paper by Neal (1994) documented more than 300 sinkholes, depressions, crevices, fissures and other features that occurred along a 70-km (45- mi) dissolution front of the Supai Formation that extended northward into the Holbrook Basin (also called the Supai Salt Basin).

Geochemistry: Use of Kerogen Data in Petroleum Exploration

Organic Matter Analysis

Visual Kerogen Analyses, also called Organic Matter Analyses, is a technique that allows the geologist to have a general view of what the landscape (including its flora and fauna) was like for any geological time period. In the sampled interval between 1415 and 1852 feet of the Blackstone Rocking Chair Ranch No. 4 borehole, the organic matter suite was uniform with respect to the types of organic matter that were observed. Variations within the organic matter assemblages for the lower Corduroy Sandstone, Fort Apache Limestone and Big A Butte Member of the Supai in the Rocking Chair Ranch No. 4 borehole are illustrated in Figures 14-20.

Individual Visual Kerogen parameters, including the organic matter type, level of thermal maturity (TAI), Preservation (PI), and average organic matter particle size (OMI), are recorded in the Visual Kerogen Summary Chart. In addition, various associated mineral debris observed in the organic matter residue is also recorded. This is shown under the heading "Miscellaneous Data". These individual parameters, shown as numerical values, represent an estimated abundance based on what the analyst observes on the visual kerogen slides. They are relative abundances not measured abundances. Changes in the relative abundance (represented by a change in the numerical value) may be associated with variations in lithology, depositional environment, and geologic age. These parameters are used by the Visual Kerogen Analyst to aid in the recognition, and/or characterization of, the stratigraphic section penetrated by the well bore (depositional intervals, environment of deposition, thermal heating, etc.).

The abundance (numerical value) of the various individual organic-matter parameters represented on the Visual Kerogen Summary Chart are calculations based on the total number of squares (per individual parameter) that have been colored-in. The numerical values are weighted values and derived from observations of the overall total organic-matter assemblage. In this system, or scheme, the greater the number of squares colored-in the higher the percentage for that component on the visual kerogen slide. To calculate the relative abundances of the individual components that are present on the kerogen slide, the total numbers of squares shown colored-in are normalized to the base of 100 percent. This allows the analyst to calculate an estimated percentage value (numerical value) for each of the different Visual Kerogen parameters being recorded. As previously stated, this is only an estimate, not an absolute value.

In this study, the writers have subdivided the stratigraphic section between 1415 and 1852 feet into three Organic Matter units. These units are based on changes that were observed in the overall organic matter assemblage, the level of thermal maturity and the accessory mineral suite as in illustrated in Figures 4, 5, and 6. Please note that the drill-cutting sample, representing the depth of 1415 feet, may represent the base of a different stratigraphic unit. This cannot be proven at this point due to a lack of sample material.

The three organic matter units illustrated on the Visual Kerogen Summary Chart are as follows**: Unit "A,"** 1415 to 1572 feet, **Unit "B."** 1604 to 1697 feet, and **Unit "C,"** 1728 to 1852 feet. Each unit, or zone, will be discussed on an individual basis. Unit "A" is interpreted to represent the lower Corduroy Sandstone Member of the Supai, Unit "B" is interpreted to represent the Fort Apache Limestone Member and Unit "C" is interpreted to represent the Big A Butte Member. The boundary between the lower Corduroy Sandstone and the Fort Apache Limestone is interpreted to be between 1572 and 1604 feet where there is a shift in the level of thermal maturity. It could just as easily have been placed between 1540 and 1572 feet, where there is a noticeable change in the organic-matter particle-size index and a "jump" in the %TOC content (Figures 4, 5, 6, and Table 1). In the Visual Kerogen method one is fortunate if accuracy can be achieved to within one or two samples. This is because of caving, lag time problems, loss of circulation, etc.

Thermal Maturity Analysis

Many different things affect the change in color of organic constituents and not all organic matter matures at the same rate. Thickness of the spores, pollen or tissue, ornamentation and chemical composition all have a bearing on how the various organic matter types mature. The main factor involved in maturation is the ambient temperature to which the organic particles have been subjected. These writers define the level of thermal maturation as the maximum temperature (sustained heat) that the organic matter has experienced since it was first deposited and incorporated into the sediment.

With increased drilling depth, there is usually an associated increase in temperature, pressure (due to overburden and depth), dewatering of the sediment and compaction. All these affect the rate at which the level of thermal maturity occurs. The types and abundance of organic debris trapped within the rock, including its state of thermal maturity, will determine the kinds of hydrocarbons that one can expect to be generated from a given rock unit.

The chemical composition of the organic constituents, their thickness, the geological history they encountered prior to and during deposition, and the environment of deposition itself all affect the color of the organic debris. Staplin (1969) was one of the first to illustrate this in his research on the oil and gas potential of western Alberta and eastern British Colombia when he was employed by Imperial Oil Ltd. of Canada. He demonstrated a direct correlation between a sediment's organic matter content (type of organic constituents) and the type of hydrocarbons one could expect the sediment to yield, based on its current level of thermal maturity (maximum degree of thermal heating). He prepared a series of microscope slides that illustrated various organic matter types and the associated color changes that they underwent with increasing thermal heating. He called these slides his Thermal Alteration Index (TAI) Standards. He established a 1.0 to 5.0 Thermal Alteration Scale which he believed represent all the levels of heating to which an organic matter constituent could be subjected during its burial history. Staplin gave organic matter particles that showed no signs of thermal heating (i.e., constituents that appear colorless or chartreuse to pale-yellow in color) a thermal alteration index value of 1.0. Plant tissue fragments, spores and pollen showing the maximum level of thermal heating were assigned a thermal alteration index of 5.0. These constituents are often poorly preserved, black (opaque) in color and in some cases show signs of being metamorphosed (Figure 8).

Although Staplin's (1969) TAI Slide series (Figure 9) did not have individual slides for his TAI values of 1.0 or 5.0, it was well understood by the analysts who used the Staplin system that he intended those organic constituents having a TAI value of 1.0 would be represented by fresh, unaltered and totally immature organic components. Likewise, Staplin's TAI value of 5.0 was understood to represented spores, pollen and plant tissue fragments that had been heated to such a hot temperature that they were totally burned and black in color. At a TAI of 5.0, commercial quantities of hydrocarbons are no longer produced. Only minor occurrences of high-temperature methane gas and possibly some carbon dioxide will be produced at this level of maturity.

In 1977**,** the senior writer developed a more comprehensive Visual Kerogen Analytical Method and TAI Scale, based on Staplin's original color scheme. Schwab's (1977) classification was based on a 1.00 to 8.00 numerical system. The TAI values are calculated based on the number of boxes colored-in on the Visual Kerogen Chart. The colored-in boxes are averaged, based on the index value given to them. The system allows most of the visual kerogen parameters recorded on the Visual Kerogen Summary Chart to be averaged for any given depth interval or stratigraphic unit, plotted on a map and contoured. Using this system, the organic matter and thermal maturity (heating) trends across any given geographic region, for any geologic age, can be presented in map form. For consistency, the 1.00 to 8.00 index values are applied to all the visual kerogen parameters recorded by analyst.

Schwab's 1.00 to 8.00 Thermal Maturity Scale has been cross-correlated with several other thermal maturation scales (Figures 10 and 11), including the scale used to define Coal Rank. The Thermal Maturity data in the Schwab method, typically plotted on a TAI (index) versus sample depth basis, are cross-correlated with Vitrinite Reflectance (%Ro) values and interpreted to have an accuracy of ±5% for values less than 0.50 %Ro, ±10% for values between 0.50 %Ro and 1.30 %Ro, ±15% for values of between 1.30 and 2.50 %Ro, and ±20% for values above 2.5 %Ro (Figure 12). Because the Thermal Alteration Index (TAI) is based on color and since the visual color value is interpretative and subjective compared to spectral-photometric measurements, there is always going to be an approximate error of around 10% in the TAI indices. In this report, where Schwab's 1.00 to 8.00 TAI values are given for a stratigraphic unit or individual palynomorph, the reader is asked to compare those values with the eight examples of thermally mature palynomorphs illustrated in Figure 13.

Interpretation of the Supai Formation in the Rocking Chair Ranch No. 4 Well

The geochemical interpretation of the Supai Formation that is presented herein is based strictly on visual kerogen and total organic carbon data. The reader should understand that the Organic Matter Units that have been identified are not necessary time-stratigraphic in nature. Rather, they represent stratigraphic rock sequences (sedimentary packets) that can be separated by noticeable changes in their organic matter content, levels of thermal maturity, associated mineral content, and particle-size distribution of the organic matter. They are like "Family Units" that change over time. It is our opinion that the individual Organic Matter Units are controlled almost exclusively by the environmental conditions that prevailed at the time of deposition. Geologic time is also a major factor, but to what extent, the writers do not know.

Organic Matter: Unit "A, " Corduroy Sandstone Member, 1415 to 1572 feet

Figure 14, 15, and 16

Organic Matter

Organic constituents in this part of the stratigraphic section are dominated by high concentrations of algal debris (both tissue and colonial fragments). Particles of Inertinite are common in the sample mixed with slightly less common percentages of unidentifiable plant tissue fragments. Simple, non-trilete spores and fungal debris are also present but in minor amounts. Sporadic occurrences of unidentified bisaccate (gymnosperm) pollen are observed in the samples from 1448 and 1540 feet. Whether the gymnosperm (bisaccate) pollen is in situ, or the result of contamination, we are uncertain (Figures 4, 5, and 6).

The bulk of the mineral debris that was observed in the acid insoluble organic matter residue is interpreted to consist primarily of anhydrite, calcite, aragonite, and dolomite. The average particle size of the organic constituents in this sequence, including the mineral components present in the organic matter assemblage, varies from fine to medium (i.e., between 0.10 and 0.40 mm in size). Tissue fragments with an average particle size larger than 0.40 mm are also present. These larger fragments are very noticeable in the samples from 1415 and 1448 feet. Below 1448 feet, the tissue fragments and other plant constituents are generally smaller in size. Because all the rock cuttings are treated in the same manner during the sample preparation stage, the noticeable changes in the average particle size of the organic constituents was interpreted to be important. Changes in the average particle size of the organic matter, expressed numerically as the Particle Size Index **(PSI)** on the Visual Kerogen Chart, suggest that the stratigraphic section above 1446 feet may represent an entirely different formational unit than that below 1446 feet. We do not have enough sample control above 1415 feet to determine whether this is true or not.

The average PSI for the section between 1446 and 1572 feet is 2.93. The sample from 1415 feet has a PSI of 3.58. When the sample from 1415 feet is included in Unit “A” the average PSI for the sequence, 1415 and 1572 feet, is 3.04. The lower the PSI value, the smaller the average size is of the organic constituents. The overall state of preservation of the organic matter observed in Unit “A” varies from **Good** to **Fair**. Most of the organic material appears to be in situ with little reworking and/or aerial oxidation having taken place.

Thermal Maturity (TAI)

The organic matter constituents in the section between 1415 to 1572 feet are dominantly, i.e. approximately 80%, yellow-orange to orange in color. Approximately 20% percent of the organic constituents are pale yellow to yellow in color. They are interpreted as having a Thermal Alteration Index (TAI) of about 1.5, using the Staplin (1969) spore-coloration technique. This would equate to a Thermal Alteration Index (TAI) of 2.80 on Schwab’s (1977) thermal alteration scale. Both TAI values, Staplin’s and Schwab’s, are equivalent to a Vitrinite Reflectance value of approximately 0.45 %Ro ($\pm$0.05 %Ro).
The organic debris in rock samples from this part of the stratigraphic section is interpreted as being at a **Moderately Immature** stage of thermal maturity (Figures 11 and 12). The reader is asked to compare the color of the organic matter shown in Figures 14 and 15 to Schwab’s 1.00 to 8.00 TAI Standards shown in Figure 13.

Environment of Deposition

From the various organic matter types present in the stratigraphic section between 1415 and 1572 feet, the writers interpret the environment of deposition to be associated with a nearshore, shallow-water environment (i.e., probably with a water depth of less than 10 to 20 meters). Based on the low diversity in organic matter types, including genera and species, the area of deposition is interpreted to have had poor water circulation and may have been associated with a semi-restricted or restricted basin.

The floral elements that were observed in Unit “A” are indicative of a depositional environment that was associated with a non-turbulent, low-energy, sedimentation cycle. The biological dolomitization of calcareous fragments, once larger pieces of algal colonies, was common in this part of the stratigraphic sequence. This biological dolomitization process, as discussed by Nash, et al. (2011), was interpreted to have occurred in the algal components observed in Units “A,” “B,” and “C”. The writers base this supposition on the fact that when observed in transmitted illumination, with a microscope using a 100X magnification objective, many of the tiny rhomboid fragments that we call “dolomite rhombs” exhibit an internal structural network of cells, interpreted to be algal in origin (Figure 16).

From the visual kerogen data, the writers have concluded that the lower Corduroy Sandstone Member of the Supai in the Rocking Chair Ranch No. 4 well was separated from the Fort Apache Limestone by a minor unconformity. We base our interpretation on the occurrence of a slight “jump” in thermal maturity between Units “A” and “B.” It is the writers’ opinion that approximately 150 feet of stratigraphic section are missing between Units “A” and “B” (assuming no hiatus in sediment deposition occurred during this period of geologic-time).

Organic Matter: Unit “B,” Fort Apache Member, 1604 to 1697 feet

Figures 17 and 18

Organic Matter

The organic matter content in Unit “B,” as in Unit “A,” is dominated by large percentages of algal constituents. The type of algal debris is more diverse than what was observed in Unit “A.” Algal components make up over 50 percent of the total organic matter types. They are interpreted to have been colonial in nature and are nearly as well preserved as those observed in Unit “A.” Simple non-trilete algal spores, trilete spores, fungal debris, cuticular plant materials and particles of Inertinite also occur. These, however, are in much lower percentages. Vitrinite-like components (woody debris), which were occasionally observed in Unit “A,” are not observed in this portion of the stratigraphic section (Figures 4, 5, and 6).

As noted above, the preservation of organic matter changes from **Good** to **Fair** in Unit “A” to a predominantly **Fair** condition in Unit “B.” The slight degradation of preservation may be due to a change in the source areas from which the sediments were derived, the overall lithology of the host rock (i.e., the effect of dolomite, pyrite, etc.) and/or changes associated with the depositional environment. The answer was not clear.

Mineral debris associated with the organic matter residue (i.e., particles of calcite, aragonite, anhydrite, and biologically formed dolomite) appears to remain abundant. There is a slight increase in the overall percentage of what we interpret to be pyrite within Unit “B.” Some of the mineral debris the writers may have identified as being pyrite may include spherules of siderite. We cannot always tell what mineral constituents represent pyrite and what represent siderite on the visual kerogen slide. The significance of the pyrite, and/or siderite, if any, is uncertain. The occurrence of these minerals may, however, be an indication that the depositional sequence was deposited in a shallow-water, deltaic type of environment with little turbulence.

If the cutting samples collected from 1415 feet in Unit "A" are considered as representing a separate stratigraphic unit, the overall Particle Size Index **(PSI)** for the organic matter between Units "A" and "B" remains constant and does not seem to indicate any meaningful change in conditions within the depositional environment. Deposition is interpreted to have remained status-quo throughout most of the Fort Apache geologic history. The writers interpret the Fort Apache Limestone to have been deposited within a restricted or semi-restricted basin that had poor water circulation. Standing-water conditions (i.e., ponding), in conjunction with extended periods of evaporation of the water column, may have been common throughout the entire area. The average Particle Size Index **(PSI)** for Unit "B" is 2.99.

Thermal Maturity (TAI)

Organic constituents in the stratigraphic section between 1604 and 1697 feet show a slight increase in their overall level of thermal maturity. The organic matter assemblage continues to be dominated by palynomorphs and tissue fragments that are yellow-orange to orange-brown in color. There are also minor percentages of organic constituents that are pale-yellow to yellow in color, along with some components that exhibit a slightly more orange-brown hue. Using the Staplin Thermal Maturity Scale, the writers interpret this organic matter assemblage to have an average Thermal Alteration Index (TAI) value of 1.7. Using the Schwab 1.00 to 8.00 maturation scale, the level of thermal maturity would be regarded as having an average overall value of 3.00. These maturation values are interpreted as having an equivalent Vitrinite Reflectance (%Ro) value of approximately 0.53 (±0.05 %Ro). The organic debris in Unit "B" is interpreted as being at a **Moderately Immature** to **Moderately Mature** stage of thermal maturity (i.e., near the onset of the so-called "Oil Generation Window" where the generation of hydrocarbons begins as the organic matter increases in its the level of thermal maturity) (Figures 11 and 12).

The mud-logger reported some scattered, faint, golden fluorescence at 1610 feet with no hydrocarbon odor associated with it. The same holds true for the section between 1630 and 1650 feet. In the deeper sample, fluorescence was associated with gas bubbles presumably emanating from the crushed sediments (see MBC WELL LOGGING LLC, 2016).

The notable "jump" in the thermal maturity index (TAI) between Unit "A" and Unit "C" suggests that a major unconformity exists between these two units. This noticeable "jump" may indicate that a substantial portion of either the lower Fort Apache Limestone or the upper Big A Butte is absent in the Blackstone Exploration Rocking Chair Ranch No. 4 well. Based on the calculated differences in the thermal gradient slope, as determined by the TAI values derived for Units "B" and "C," and assuming there is no hiatus in the sedimentation rate, the writers postulate that there may be as much as ~350 feet of stratigraphic section unaccounted for. Whether the missing stratigraphic section has been faulted out, or is the result of a large-scale unconformity between the lower Fort Apache Limestone and the upper Big "A" Butte Members, we do not know. The reader is asked to compare the color of the organic matter shown in Figures 17 and 18 to the TAI Standards shown in Figure 13.

Environment of Deposition

The floral assemblage extracted from rock cuttings in the section between 1604 and 1697 feet was indicative of an organic matter suite having been deposited in a shallow-water environment within a semi-restricted basin having poor water circulation. The water depths associated with Unit "B," as in Unit "A," were probably not greater than 10 to 20 meters. At times, the area of deposition may even have been associated with a shoreline environment. It is certainly possible that some of the colonial algal types may have formed on exposed rocky surfaces and were only visible at low tide.

The writers think the depositional environment within the Holbrook Basin at this time (Early Permian) was relatively calm and may even have experienced stagnant conditions at various times. Fresh water entering the Holbrook Basin in this location was most likely associated with tropical storms that brought heavy precipitation and runoff. Water circulation within the depositional area is interpreted to have been fair to poor, the water currents being sluggish.

Organic Matter: Unit "C," Big A Butte Member, 1728 to 1852 feet

Figures 19 and 20

Organic Matter

The organic constituents making up the floral suite observed in Unit "C" are like those observed in Units "A" and "B." The major difference in this interval compared to the overlying two is the sudden and noticeable increase in the overall abundance of plant and/or algal tissue fragments (including larger percentages of colonial algal debris), coupled with a decrease in the abundance of the constituent Inertinite (Figures 4, 5, and 6). The organic tissue fragments, thought to be mainly of algal origin, are visibly etched on their surfaces by rhomboid-shaped imprints. These we attribute as being due to contemporaneous dolomite and/or calcite crystals. Mineral particles, thought to be composed of anhydrite, dolomite, calcite and pyrite, are common to abundant throughout Unit "C."

The sudden appearance and common occurrence of dolomite and/or calcite "rhombs," etched onto the surface of the organic tissue or embedded in the organic debris, are very noticeable within this portion of the stratigraphic section. Just what the sudden onset and abundance of algal tissue etched by dolomite/calcite means geologically, we do not know. It is our contention that this change is most likely coupled with changes in sediment provenance, depositional rates, sediment transport, and water conditions (i.e., circulation, oxygen content, depths, eH, ORP, pH., etc.). As stated above, we believe it has something to do with changes in the sedimentation cycle, water depth and possibly the regional configuration of the Holbrook Basin during the Early Permian. The change is very dramatic and clearly visible on the Visual Kerogen Summary Chart (Figures 4, 5, and 6).

Not only can a major change in the associated mineral debris be observed (see column entitled Miscellaneous Data on the Visual Kerogen Summary Chart Figure 5), but there is also a noticeable change in the state of preservation of the organic debris. This we think, as previously stated, reflects a major change in the climate and/or depositional environment from what was observed in Unit "B" (the Fort Apache Limestone). It is also our opinion that this change serves as supporting evidence for the occurrence of a major hiatus between these two members of the Supai Formation. Whether the major change between the Fort Apache Limestone and Big A Butte Members of the Supai was associated with a massive tectonic event and/or climatic change (i.e., uplift along the Mogollon Rim, changes in the magnetic poles, or intense changes in the weather patterns), we do not know.

We postulate that the Holbrook Basin was a slightly deeper water basin during the deposition of the Big A Butte cycle and that it may have had a better water circulation pattern than occurred during deposition of the overlying Fort Apache Limestone. The fact that there was a much greater abundance of algal tissue fragments in the Big A Butte Member of the Supai Formation than what was seen in Fort Apache Limestone suggests that the organic matter suite in this unit was probably as "lipid-rich" or even more so as that of the overlying Fort Apache Limestone . In this study, it is easy to see that the organic matter assemblage, in total, is directly tied to the lithology of the stratigraphic units. The writers think that the changes recognized in the organic matter assemblage recorded for the lower Corduroy Sandstone, the Fort Apache Limestone, and the Big A Butte Members of the Supai were directly associated with pronounced changes (regional and local) in the environment of deposition (climate, water type, depth and circulation, vegetation patterns, etc.). The writers also think that these changes can be used to recognize the presence of unconformities, disconformities and/or faults.

The average particle size of the organic matter and mineral debris, is essentially the same as that observed in Unit "A". The Particle Size Index **(PSI)** is 3.04.

Thermal Maturity (TAI)

Of notable interest on the Visual Kerogen Chart are the differences observed between Units "B" and "C". Not only is there a noteworthy change in the composition of the organic matter suite, but there is also a noticeable elevation in the level of thermal maturity. The organic constituents in Unit "C" were more yellow-orange to orange-brown in color than those extracted from Unit "B." Additionally, there are also moderate percentages of organic constituents having an orange-brown color rendition. The thermal maturity level, as determined using Staplin's (1969) TAI scale and Schwab's (1977) thermal maturity scale, is indicative of an organic matter suite that would be classified as being **Moderately Mature**. The TAI value, using the Staplin (1969) scale, would be between 1.7 to 1.8. On the Schwab (1977) scale, it would have a TAI value of 3.20. Both these values would be correlative to a Vitrinite Reflectance of, or near, 0.60 % Ro (+0.05) (Figures 11 and 12).

This visible "jump" in thermal maturity is significant and may reflect a change in the lithology (including sediment provenance and deposition) and/or geologic time. Compare the color of the organic matter shown in Figures 19 and 20 to the TAI Standards shown in Figure 13.

Environment of Deposition

The organic-matter assemblages observed in Unit "C" are interpreted to have been deposited in a different environment than that of Units "A" and "B." The writers interpret the stratigraphic sequence between 1728 and 1852 feet in the Rocking Chair Ranch No. 4 well to have been deposited in a slightly deeper water environment than that of the lower Corduroy Sandstone and Fort Apache Limestone Members. The Holbrook Basin may have been somewhat of a semi-restricted basin at various times during its history, but we think it had more of an open-sea setting at this time than that which existed during Fort Apache time. The organic matter suite suggests that the environment of deposition probably had better water circulation than that which prevailed during the Fort Apache depositional cycle.

The algal assemblage in Unit "C" is interesting. Many of the forms are bizarre when compared to those observed in Units "A" and "B." A detailed study of the algal debris within the Big A Butte section could provide biostratigraphers with an additional set of parameters that could be useful in helping to recognize and correlate this particular time-stratigraphic unit. Whether the changes we describe are local in nature, or occur on a regional scale, we do not know. We would need to look at more wells and examine many more drill cutting samples to verify these observations and our hypotheses.

Hydrocarbon Potential of the Supai Formation in the Blackstone Rocking Chair Ranch No. 4 Well

In determining the hydrocarbon source-rock potential of any given rock, geologists have the option of using several techniques. Figure 21, modified from an illustration by Tissot and Welte (1978, p. 465, Table V.1.5), shows some of the more commonly used methods for the characterization of source rocks. The most important screening method the geochemist can use to determine source-rock potential is the Total Organic Carbon analysis. No matter how good the rock might look, it is the Total Organic Carbon content that defines whether a rock can be “classified” as having a **Poor**, **Fair**, **Good** or **Excellent** source potential for the generation of liquid and/or gaseous hydrocarbons. Total Organic Carbon content, abbreviated as **TOC %Wt**., is the method by which “organic-carbon richness” is measured.

Geochemists, in past studies, have found that rocks composed predominantly of carbonates (limestone) require only about half as much TOC, compared to a clastic rock (shale and mudstone), to be considered as being **“Good”** source rocks. Of all the analytical techniques used to identify source rocks and source-rock potential, this is the one essential data point that must be acquired. A good discussion of the **Carbon Cycle** and **Sources of Organic Carbon** can be found in Tissot and Welte (1978, p. 3-13, Figures 1.1.6, 1.1.7).

All fifteen drill cutting samples from the Supai Formation that were examined for Visual Kerogen were sent to National Petrographic Inc., a geological service company in Houston, Texas, for TOC analyses. Total Organic Carbon values that were generated and recorded by National Petrographic Inc. are shown in Table 1. These TOC values are recorded and illustrated on a TOC Summary Chart (Figure 22). This is how the TOC %Wt. would normally be plotted. In rock samples with very low TOC values that show slight, almost undetectable differences in values, they are best plotted using a semi-logarithmic graphing paper, as illustrated in Figure 23.

As seen in the Total Organic Carbon profile, the Fort Apache Limestone and the Big A Butte Members of the Supai Formation, as illustrated in Figure 23, are more similar in their signature (TOC pattern) than the Corduroy Sandstone and Fort Apache Limestone . Of interest is the repetitive nature (cyclic pattern of the TOC signature) of the TOC %Wt. content in Units “B” and “C.” The writers interpret the cyclic nature of the TOC signatures in the profile for the Fort Apache Limestone and Big A Butte Members to be associated with, or reflect changes in, the depositional environment (i.e., water temperature, currents, depth, oxygen content, vegetation, etc.) within the Holbrook Basin.

As shown in Table 1, all samples had a TOC value of less than 0.50 %Wt. This means that none of the clastic rocks (i.e., those dominated by shale, mudstone, or sandstone) can be considered as having an effective source-rock potential. When we apply the rule; “carbonates need to contain only half the amount of TOC in them, compared to clastic rocks, to be considered as having effective source-rock qualities”, the TOC data show that the carbonate sequences within the Supai Formation are the most likely to have served as the primary source for any hydrocarbons (gaseous and liquid) that might be produced at this location.

Recent data, posted on the Internet by MBC Well Logging LLC (2016), regarding the Blackstone Exploration Rocking Chair Ranch No. 4 well, show that the stratigraphic section between 1385 and 1438 feet is a carbonate. This may be part of the lower Corduroy Sandstone. Likewise, the section between 1580 and 1650 feet which the writers interpret to be the Fort Apache Limestone (referred to as Unit "B" in this report) is also a carbonate.

The carbonate section within what we interpret to be the lower Corduroy Sandstone, specifically the cuttings sample from 1415 feet, has an average TOC value of 0.26 %Wt. If our data are correct, this interval would be interpreted as having a "**Poor"** to "**Fair"** source-rock potential.

The Fort Apache Limestone section, between 1580 and 1640 feet, has an average TOC value of 0.33 %Wt. It is the only member of the Supai Formation that meets the requirements for being considered as having effective source-rock potential for the generation of liquid and/or gaseous hydrocarbons.

The dominantly clastic portion of the lower Corduroy Sandstone Member of the Supai Formation, represented by the interval from 1446 to 1540 feet, has an average TOC content of 0.24 %Wt. The Big A Butte Member, represented by the interval from 1728 to 1852 feet, has an average TOC content of 0.36 %Wt. These stratigraphic intervals are composed chiefly of shale, mudstone and sandstone with some sections having major accumulations of evaporites. Neither of these stratigraphic intervals is considered to have any source-rock potential for the generation of commercial quantities of liquid or gaseous hydrocarbons.

Palynological Floral Elements Observed in Drill Cuttings Samples from the Rocking Chair Ranch No. 4 Well

Definitive paleontological data for the Supai Formation in the Holbrook Basin of eastern Arizona, based on acid insoluble palynomorphs, is essentially non-existent in the literature. To our knowledge nothing has been reported with respect to the Corduroy Sandstone, Fort Apache Limestone and Big A Butte Members of the Supai Formation. The paleontological data present herein, as far as these writers know, are new. The writers have no knowledge of these fossil forms, especially the algal material, having been documented, mentioned or illustrated in any previous publications.

Of special interest is the algal debris that is common to abundant throughout the upper three members of the Supai Formation. These constituents are generally well preserved, possibly because they are associated, in part, with an evaporitic sequence. The writers believe that many of the algal colonies were originally calcareous in nature. We are also of the opinion that much of the calcium carbonate (Calcite-Aragonite) of the algal debris has been dolomitized by biological means and converted to some other form of carbonate. Because of the acid treatment used in the preparation of the Visual Kerogen slides (i.e., concentrated Hydrochloric and Hydrofluoric acid), any algal colonies that were initially calcareous in nature, and unaltered, are interpreted to have been destroyed during the organic-matter extraction process.

Although many of the algal forms retain exquisite detail, the writers have not made any attempt to identify these forms. Our reason is that we have nothing to compare these forms to. They are very small, sometimes fragmented, and do not seem to fit into any of the taxonomic categories that algal specialists use for identification. This, plus the fact that many algae are polymorphic, makes their identification impossible.

The best that can be done with the little information that we currently have is to make the readers aware of their presence and abundance and to illustrate several of the more common types that occur in the various members of the Supai Formation.

[**NOTE:** Many of the algal remains are interpreted to be fragments of the fossil calcareous blue-green algae ***Girvanella*** whose extant representative***, Plectonema***, was identified by Riding (1977). Riding's paper provides a good discussion of the two genera, their environmental habitat and geologic occurrence. In addition to being found in fresh water and marine environments, Cameron (1960) states that the algal genus ***Plectonema*** is commonly found in the soil of the Sonoran Desert in Arizona. The writers assume that the fossil algal genus ***Girvanella,*** like ***Plectonema,*** was also an inhabitant in the soil landscape of the Pennsylvanian-Permian of the area that is currently being discussed.]

Palynomorphs having specific time-stratigraphic value are present in the Supai samples of the Rocking Chair Ranch No. 4 well. Some of these are illustrated in Figures 24 and 25. Fossil striate-bisaccate pollen grains of gymnosperm origin and commonly found in Upper Pennsylvanian and Permian sediments, were observed in several of the samples that we examined. The fossil bisaccate pollen, illustrated in Figure 24 A, B, closely resembles the genera ***Striatoabietites* sp.** and ***Protohaploxypinus* sp.** as illustrated by Hart (1969, p. 280). There are also some palynomorphs that resemble the genus ***Schopfipollenites* sp.** (Figure 24 C, D). Although rare in our samples, these palynomorphs, if identified correctly and in situ, could be used to support the Early Permian age that has already been established for this part of the stratigraphic section. [**NOTE:** Utting, et al., 2004, found a similar group of saccate palynomorphs in the Upper Pennsylvanian Red Tank Member of the Bursum Formation at Carrizo Arroyo in central New Mexico.]

The common occurrence of fossil angiosperm pollen in the cutting samples from the Supai Formation is not only perplexing but may have significance when it comes to understanding the geological tectonic history of the area. As mentioned earlier, angiosperm pollen is a common constituent in all the samples that were examined. Normally one would interpret contaminants coming from younger sediments to have been introduced through mud additives used in the drilling of the well or possibly the result of up-hole cave. Since the drilling mud used in the Rocking Chair Ranch No. 4 well was a chemical mud, we believe that the angiosperm pollen is coming from a different source. The Rocking Chair Ranch No. 4 borehole spudded, to our knowledge, in the Permian. If that is true, then the possibility of up-hole contamination, due to caved sediments of Cretaceous and/or Paleocene age material, can be ruled out. That leaves only two possible sources for the contamination; contamination due to stratigraphic leakage or contamination due to poor handling in the laboratory (i.e., contamination during sample preparation). Since all the glassware used in the laboratory was new and unused, this rules out laboratory contamination. The writers think that the angiosperm pollen most likely came from sediments that are Upper Cretaceous and/or Paleocene in age. It is also our opinion that the palynomorphs are contaminants that were introduced into the stratigraphic section by "stratigraphic leakage..

Whether the angiosperm pollen was introduced along major fracture zones associated with faulting, we do not know, but it certainly is a possibility. A single trilete spore interpreted as belonging to the genus ***Cirratriradites*** *sp*. (shown in Figure 25) was observed in the well cuttings sample from 1852 feet (i.e., the section interpreted as representing the Big A Butte Member of the Supai Formation). The trilete spore has been severely altered and is interpreted to have been subjected to extremely high temperatures. Where the trilete spore came from, what its geologic-age is and whether it is truly indicative of a thermally derived level of maturity (versus being burned due to volcanism), we do not know.

Each member of the Supai Formation that was examined has been represented by a series of photographic plates that show the typical fossil assemblage that occurs within that stratigraphic unit. Because the writers were not given the “Formation Tops” for the Corduroy Sandstone, Fort Apache Limestone, and Big A Butte Members of the Supai Formation, (normally marked on the Dual Induction Electric Log by the geologist), they have relied on the visual kerogen data, as presented on the Visual Kerogen Summary Chart, to pick the “tops” of the various members of the Supai Formation that occurs in the Rocking Chair Ranch No. 4 well. Regardless of where the actual boundaries occur between these three members, (the Corduroy Sandstone, Fort Apache Limestone and Big A Butte), there is definitely an organic-matter assemblage, accompanied by a well defined thermal maturity gradient, associated with each of them. The notable differences in the organic matter assemblages within the Supai Formation are interpreted to be primarily associated with environment changes in deposition (including eustatic variations in sea level) that occurred throughout the Early Permian. Whether these changes in the floral pattern are of a local nature, regional in extent, and/or time-related, we do not know.

Conclusions

1). The stratigraphic section between 1415 and 1852 feet in the Blackstone Exploration Company Rocking Chair Ranch No. 4 borehole, located in Navajo County, Arizona, was divided into three individual organic-matter units based on Visual Kerogen data (i.e., organic matter types, thermal maturity and associated mineral debris). These are designated as Units **“A,” “B,”** and **“C”** by the writers and correspond to the lower Corduroy Sandstone, Fort Apache Limestone and Big A Butte Members of the Supai Formation. The Amos Wash Member of the Supai was not examined in this study.

2). Thermal maturity levels for the stratigraphic section between 1415 and1852 feet in the Blackstone Exploration Company Rocking Chair Ranch No. 4 well are as follows: The stratigraphic section between 1415 and 1572 feet (the lower Corduroy Sandstone), Unit “A,” is interpreted as being **Moderately Immature**. The stratigraphic sequence between 1604 and 1697 feet (the Fort Apache Limestone), Unit “B,” is also regarded as being **Moderately Immature to Moderately Mature**. The well section from 1728 to 1852 feet (the Big “A” Butte Member of the Supai), Unit “C”, is interpreted to be **Moderately Mature**.

3). In the Rocking Chair Ranch No.4 well the lower Corduroy Sandstone Member of the Supai has been interpreted to be separated from the Fort Apache Limestone Member by a small unconformity. Approximately 150 feet of section is interpreted to be missing at the lower Corduroy-Fort Apache boundary. The Fort Apache Limestone Member is also interpreted to be separated from the Big A Butte Member of the Supai by an unconformity and/or fault. Here, an estimated 350 feet of stratigraphic section is interpreted to be missing.

4). Occurrences of striate bisaccate pollen, possibly belonging to the genera *Striatoabietites* sp. and *Protohaploxypinus* sp., in the samples between 1415 and 1852 feet in the Blackstone Exploration Company Rocking Chair Ranch No. 4 well, if in situ, may help to support the Early Permian age date already designated for this portion of the Supai Formation.

5). The occurrence of angiosperm pollen grains within the organic matter extracts from the Supai are interpreted to be the product of “stratigraphic leakage.” These forms are clearly out of place and are thought to have been derived from Upper Cretaceous and/or Paleocene sediments that were eroded and re-deposited during the various tectonic sequences associated with the uplift of the Mogollon Rim. The angiosperm pollen is thought to be associated with a karst topography and introduced into the surface and subsurface rock formations by waters percolating through the strata along faults and fractures.

6). Total Organic Carbon (TOC %Wt.) values, measured for the well cutting samples of the Blackstone Exploration Company Rocking Chair Ranch No. 4 borehole, indicate that the carbonate sequences at 1385 to 1438 feet and 1580 to 1640 feet, are the only two stratigraphic sections that can be classified as having source-rock potential for the generation of gaseous and/or liquid hydrocarbons.

7). Based on the visual kerogen data (organic--matter type and thermal maturity) that was obtained from the Blackstone Exploration Company Rocking Chair Ranch No. 4 borehole, the limestone unit of the lower Corduroy Sandstone at 1385 to 1438 feet, and the Fort Apache Limestone at 1580 to 1640 feet, are interpreted to be within the early thermal maturity stages of hydrocarbon generation. Because of their low levels in thermal maturity, the writers believe these units will not source commercial quantities of liquid or gaseous hydrocarbons in the Blackstone Rocking Chair Ranch No. 4 well.

8). The striking resemblance and recurring nature of the TOC profiles (signatures) for the Fort Apache Limestone and the Big A Butte Members of the Supai Formation in the Blackstone Exploration Company Rocking Chair Ranch No. 4 well suggest that these two units may have been deposited under similar environmental conditions (depositional environment).

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Dedications

This manuscript is dedicated to the late Dr. Halsey W. Miller, who passed away just a few days before this paper was published. A co-author of this manuscript, Dr. Halsey Miller was Professor of Invertebrate Paleontology at the University of Arizona, Tucson, Arizona while the senior author was working on his Masters of Science Degree (M.S.) in Geology (1961-1963). An outstanding educator, Halsey remained a lifelong friend to me, to my family and to those he taught.

Also recognized is Ms. Dorothy Buffham (deceased) and Dr. Virgil R. Baker (deceased). It was Ms. Buffham who, 68 years ago, first encouraged the senior author to pursue a career in geology/paleontology and it was Dr. Virgil R. Baker who, at Arizona State University, Tempe, Arizona, brought the Science of Geology to life in a such a unique way that it forever captured the excitement and interest of the writer.

Michael Smith would also like to acknowledge the invaluable guidance of his Graduate School Supervising Professors which prepared him to participate in and contribute to a wide variety of geological research projects over the last 50 years. The late Dr. Roger L. Kaesler at the University of Kansas inspired a lifelong interest in micropaleontology and many related topics. Insight, guidance and encouragement from the late Dr. F. Earl Ingerson at the University of Texas led to a rewarding career, including many years involving applied geochemical research, with the petroleum industry and the U.S. Department of the Interior.

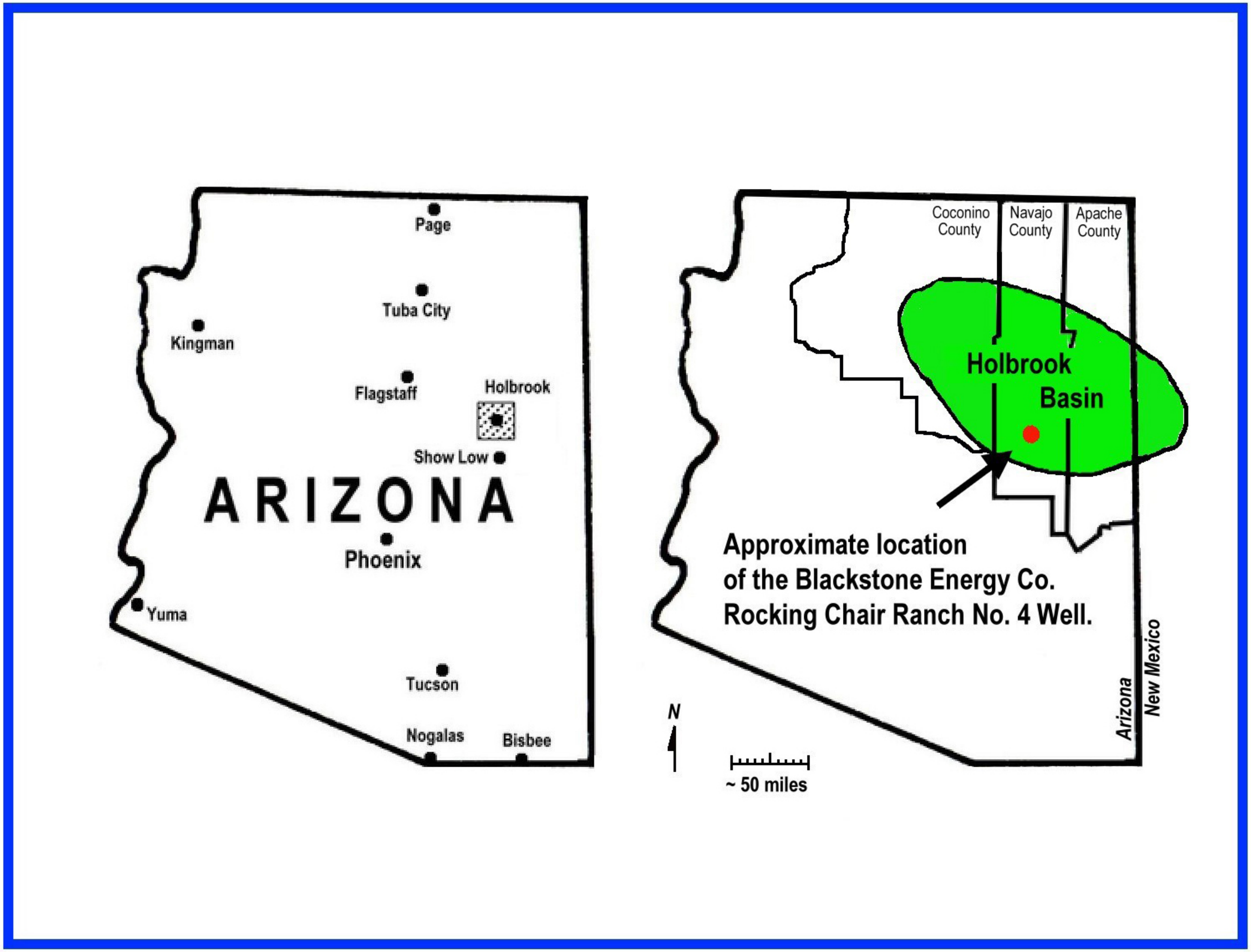


Figure 1. Location map showing the Holbrook Basin in eastern Arizona.

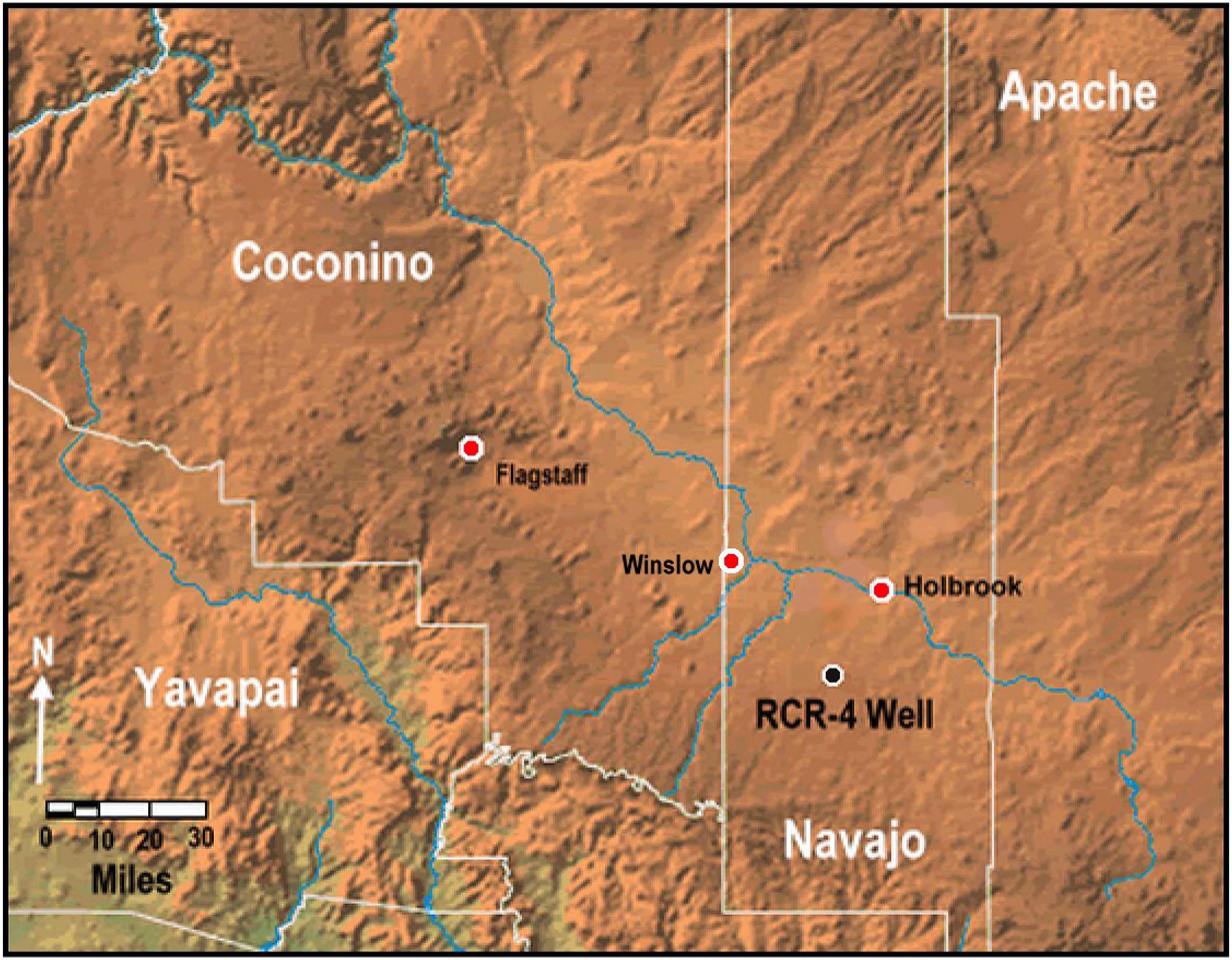


Figure 2. Map of northern and central Arizona showing the general location of the Rocking Chair Ranch No. 4 well, Section 27, T.14N, R.19E.

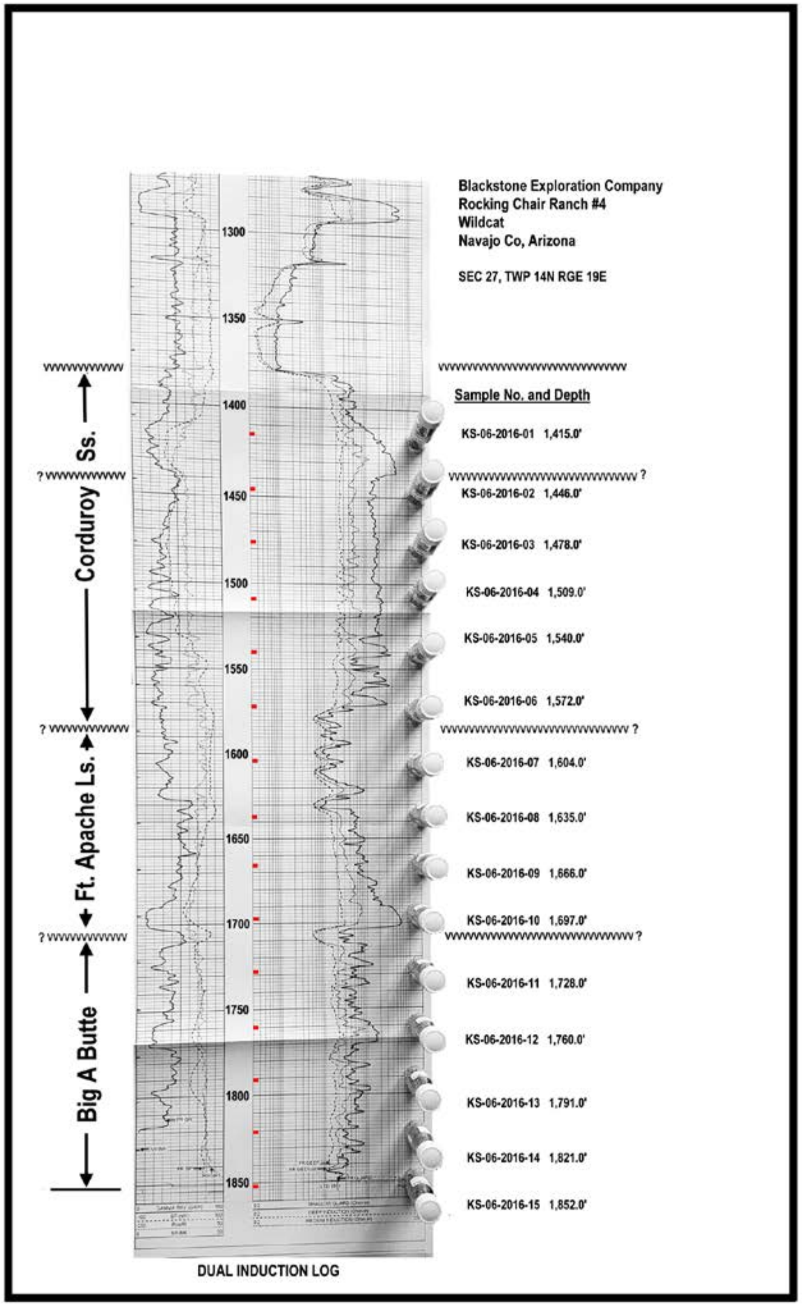
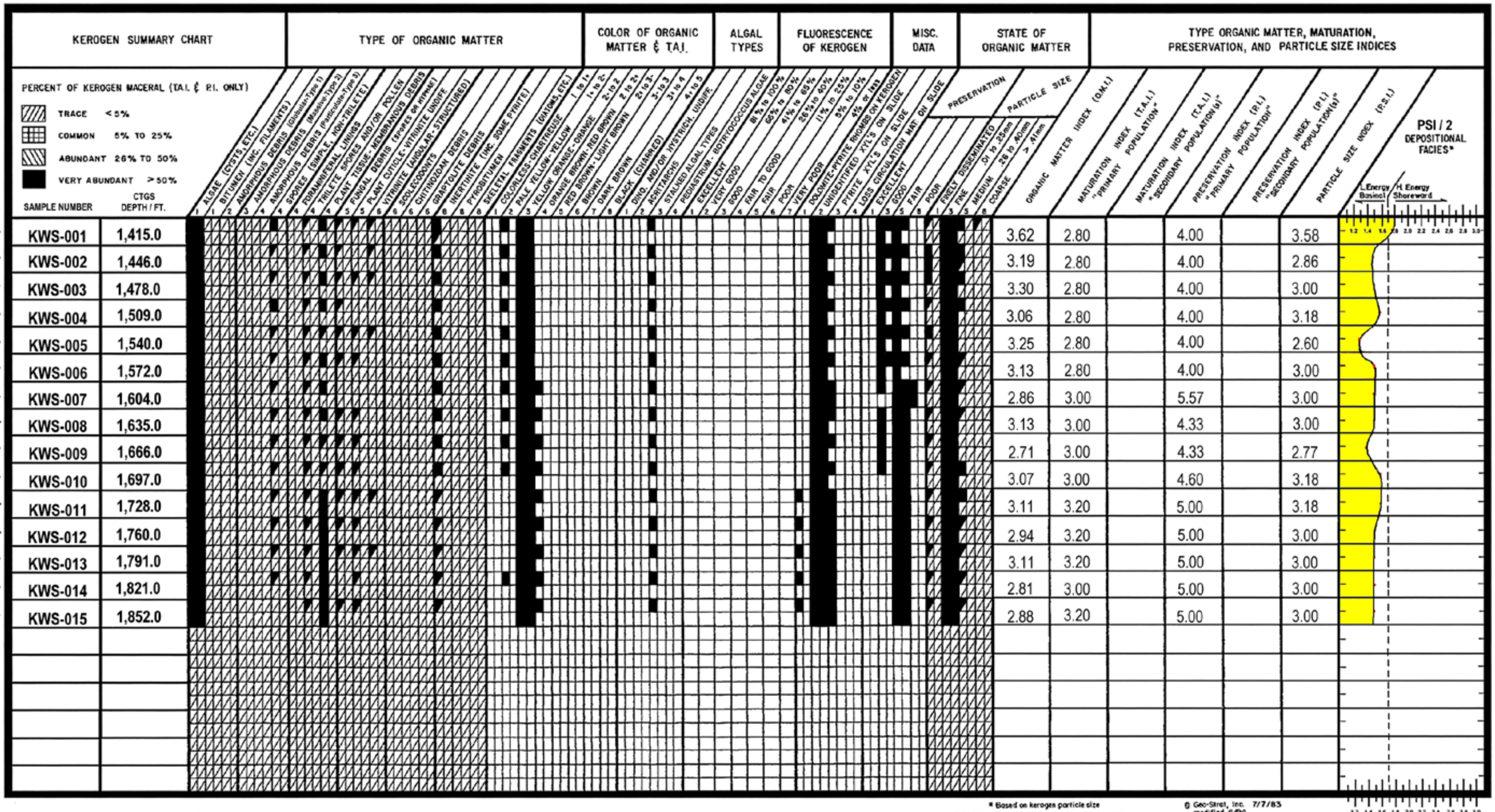


Figure 3. Annotated dual induction log of stratigraphic interval of Rocking Chair Ranch No. 4 well (RCR-4).

Blackstone Expl. Co., Rocking Chair Ranch # 4, Navajo County, Arizona

SEC 27, TWP 14N, RGE 19E.



	Sample Number	CTGS Depth / Ft.	Organic Matter Index (O.M.I.)	Maturation Index (T.A.I.) "Primary Population"	Maturation Index (T.A.I.) "Secondary Population(s)"	Preservation Index (P.I.) "Primary Population"	Preservation Index (P.I.) "Secondary Population(s)"	Particle Size Index (P.S.I.)
+	KWS-001	1,415.0	3.62	2.80		4.00		3.58
+	KWS-002	1,446.0	3.19	2.80		4.00		2.86
+	KWS-003	1,478.0	3.30	2.80		4.00		3.00
+	KWS-004	1,509.0	3.06	2.80		4.00		3.18
+	KWS-005	1,540.0	3.25	2.80		4.00		2.60
+	KWS-006	1,572.0	3.13	2.80		4.00		3.00
+	KWS-007	1,604.0	2.86	3.00		5.57		3.00
+	KWS-008	1,635.0	3.13	3.00		4.33		3.00
+	KWS-009	1,666.0	2.71	3.00		4.33		2.77
*+	KWS-010	1,697.0	3.07	3.00		4.60		3.18
*+	KWS-011	1,728.0	3.11	3.20		5.00		3.18
*+	KWS-012	1,760.0	2.94	3.20		5.00		3.00
*+	KWS-013	1,791.0	3.11	3.20		5.00		3.00
*+	KWS-014	1,821.0	2.81	3.00		5.00		3.00
*+	KWS-015	1,852.0	2.88	3.20		5.00		3.00

* indicates ?siderite in sample
+ indicates anhydrite and/or dolomite in sample

Figure 4. Organic matter content and thermal maturity (raw data).

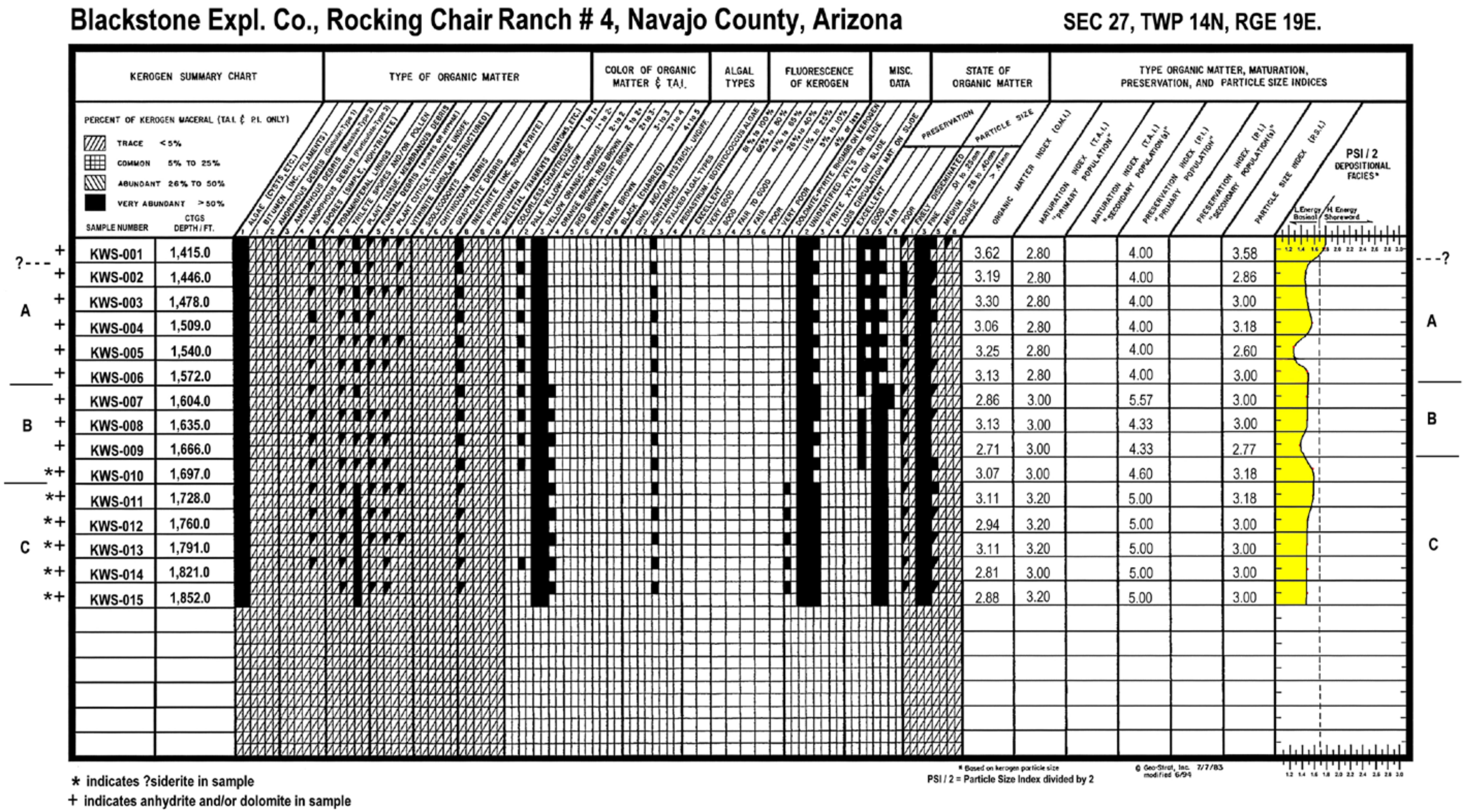


Figure 5. Organic matter content and thermal maturity (data interpreted).

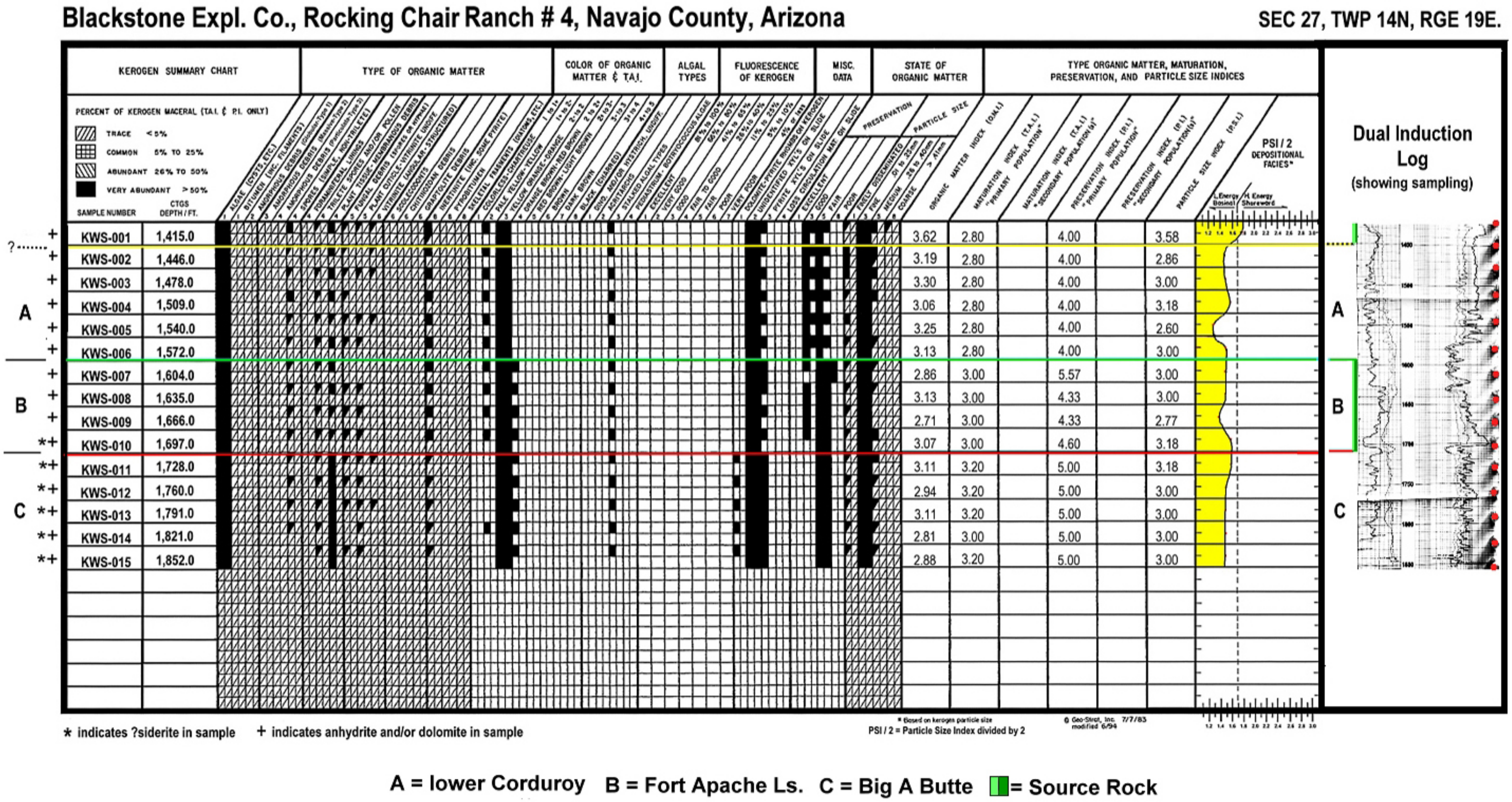


Figure 6. Organic matter content and thermal maturity (interpreted data with dual induction log).

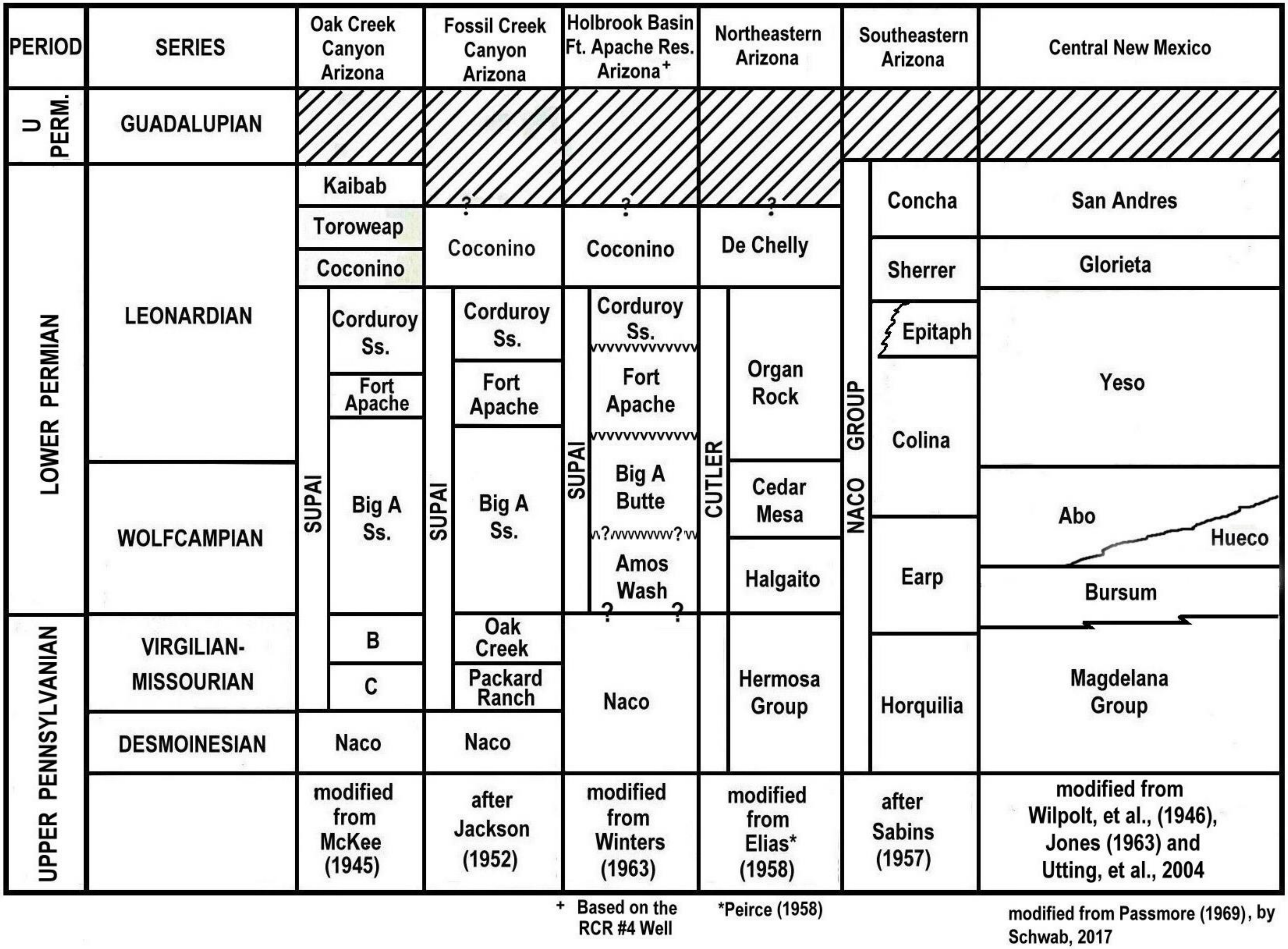


Figure 7. Correlation of Pennsylvanian and Permian stratigraphic units across northern, eastern, southeastern Arizona and central New Mexico.

THERMAL ALTERATION INDEX - TAI	ORGANIC MATTER COLOR	ASSOCIATED HYDRO-CARBONS
1. None	Fresh, Yellow	Wet or Dry
2. Slight	Brownish Yellow	Wet or Dry
3. Moderate	Brown	Wet or Dry
4. Strong	Black	Dry Gas
5. Severe	*Black	Dry gas to barren

* with additional evidence of rock metamorphism

Figure 8. Thermal maturation system developed by Frank L. Staplin (1969).

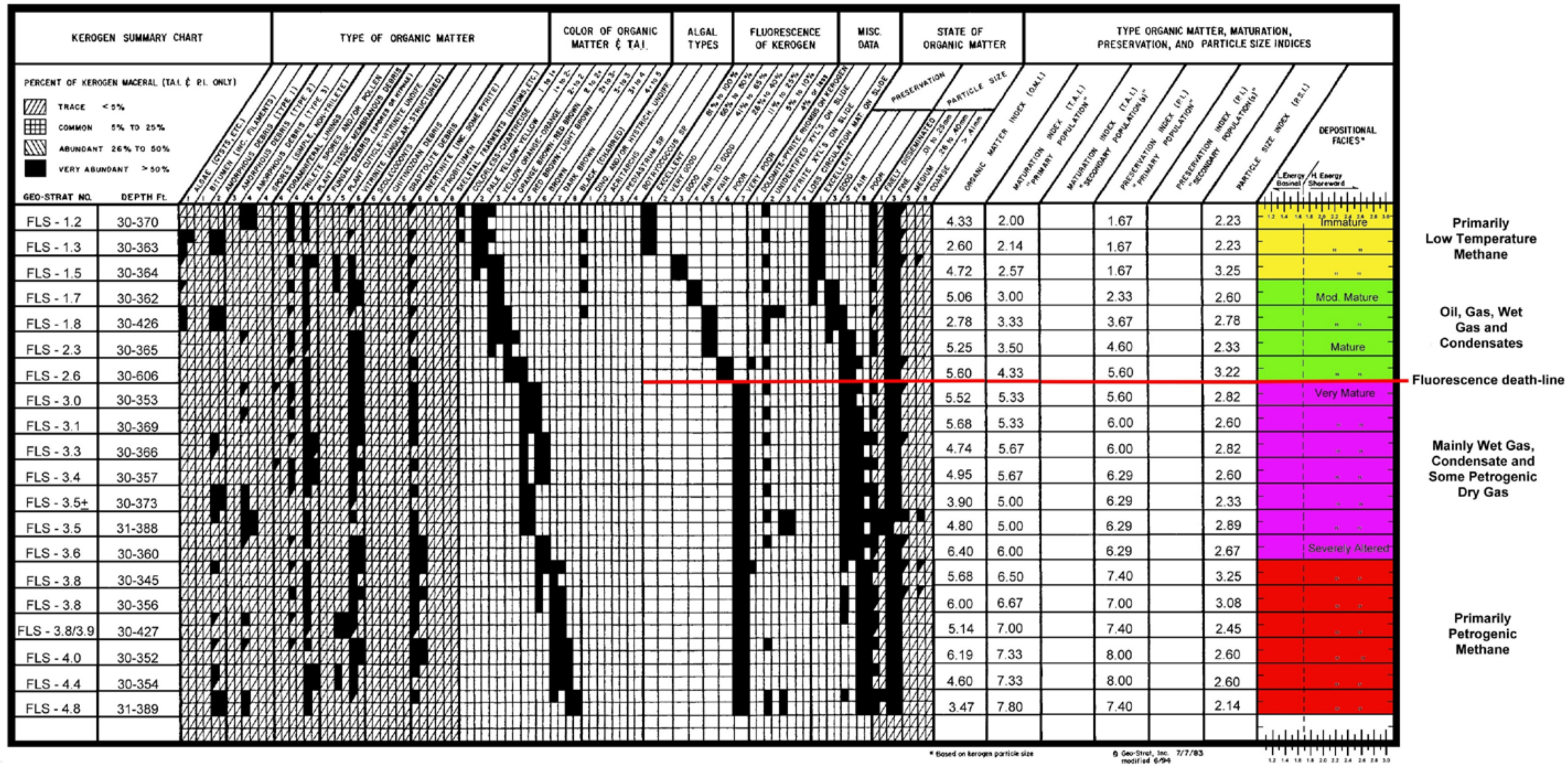


Figure 9. Interpretation of Staplin's TAI standards by Schwab (1983).

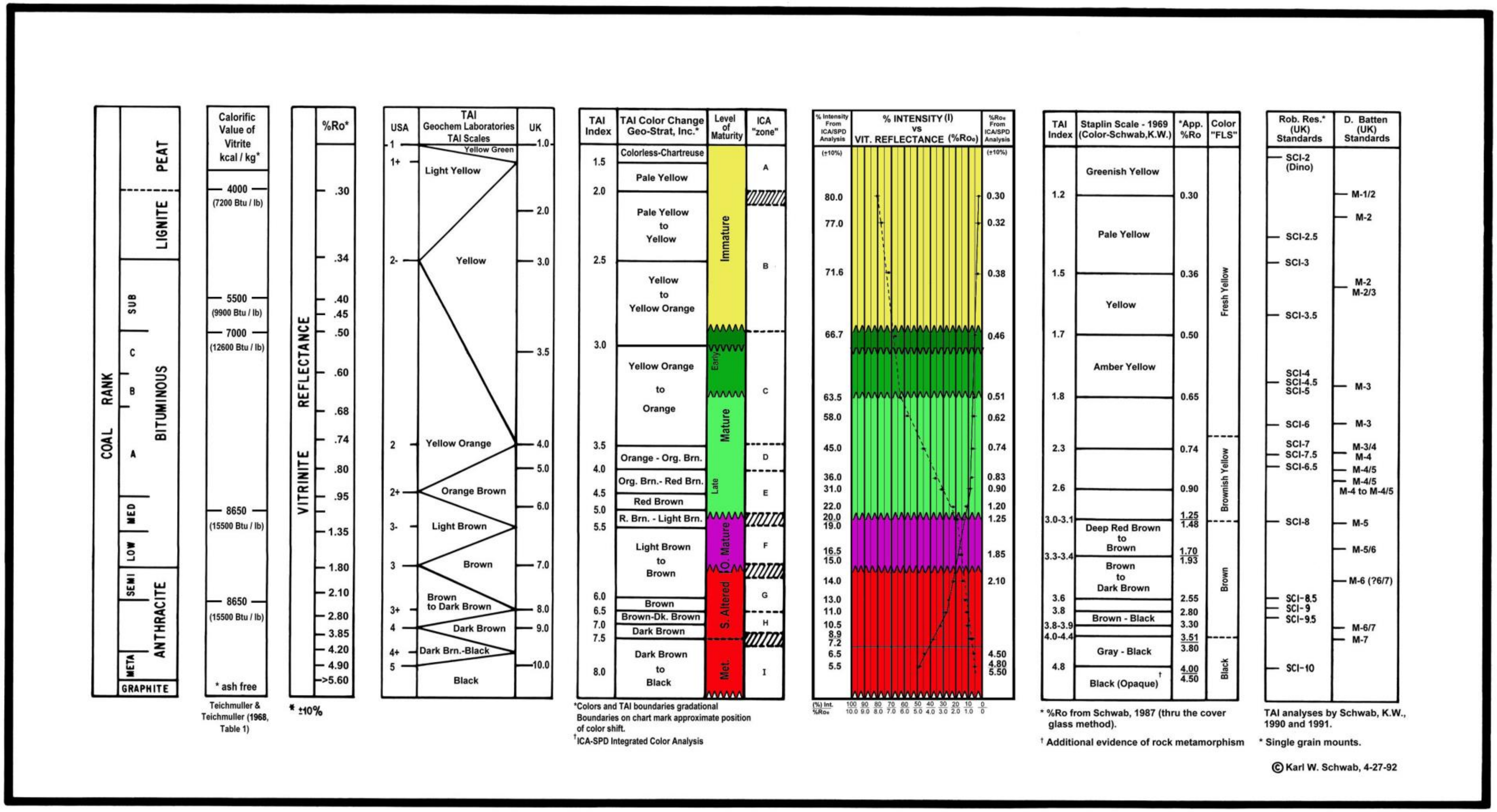


Figure 10. Comparison of thermal maturity scales (cross-correlation measurements) made by Schwab (1992).

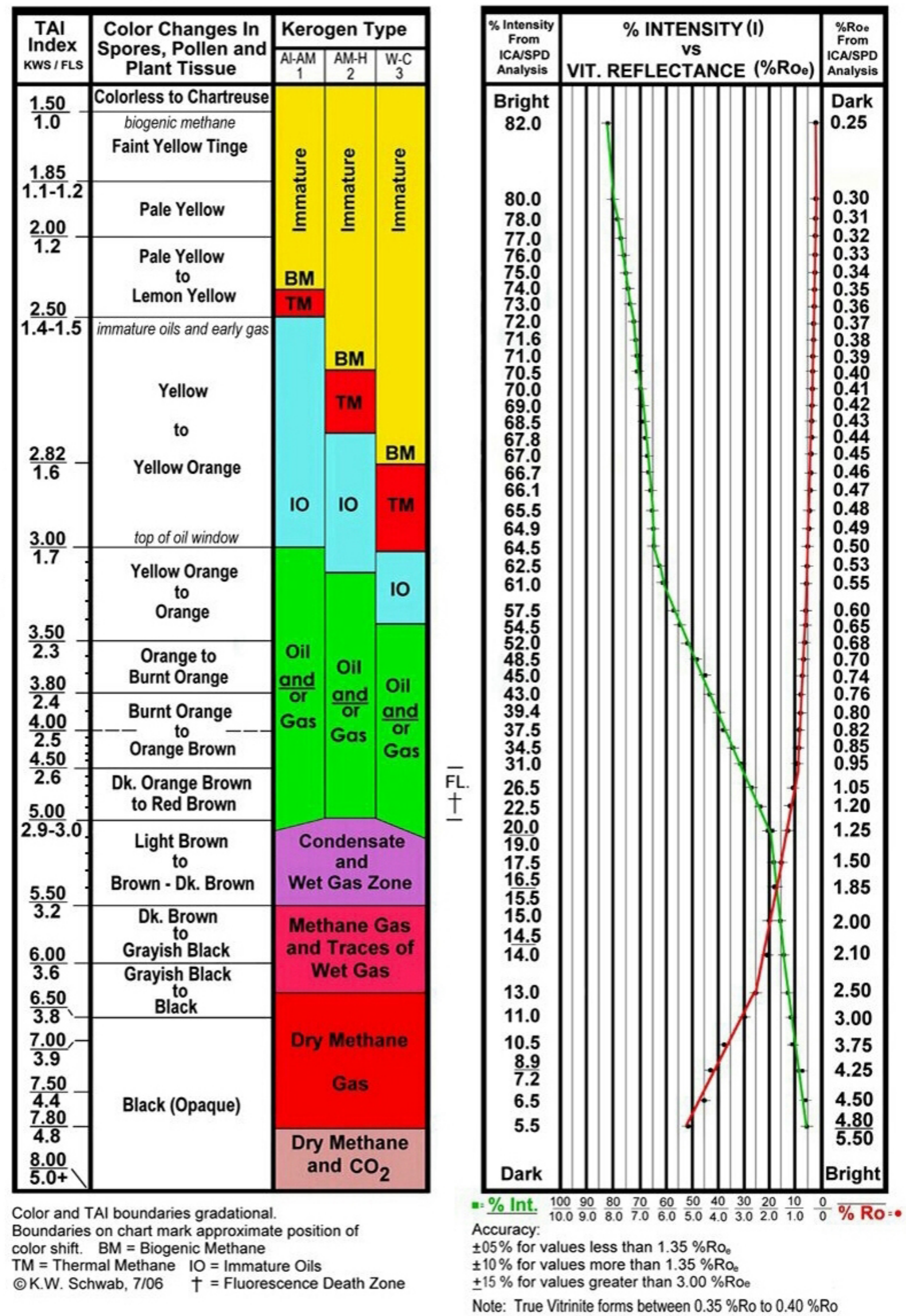


Figure 11. Correlation of TAI, intensity (I), and approximate vitrinite reflectance (%Roe) values.

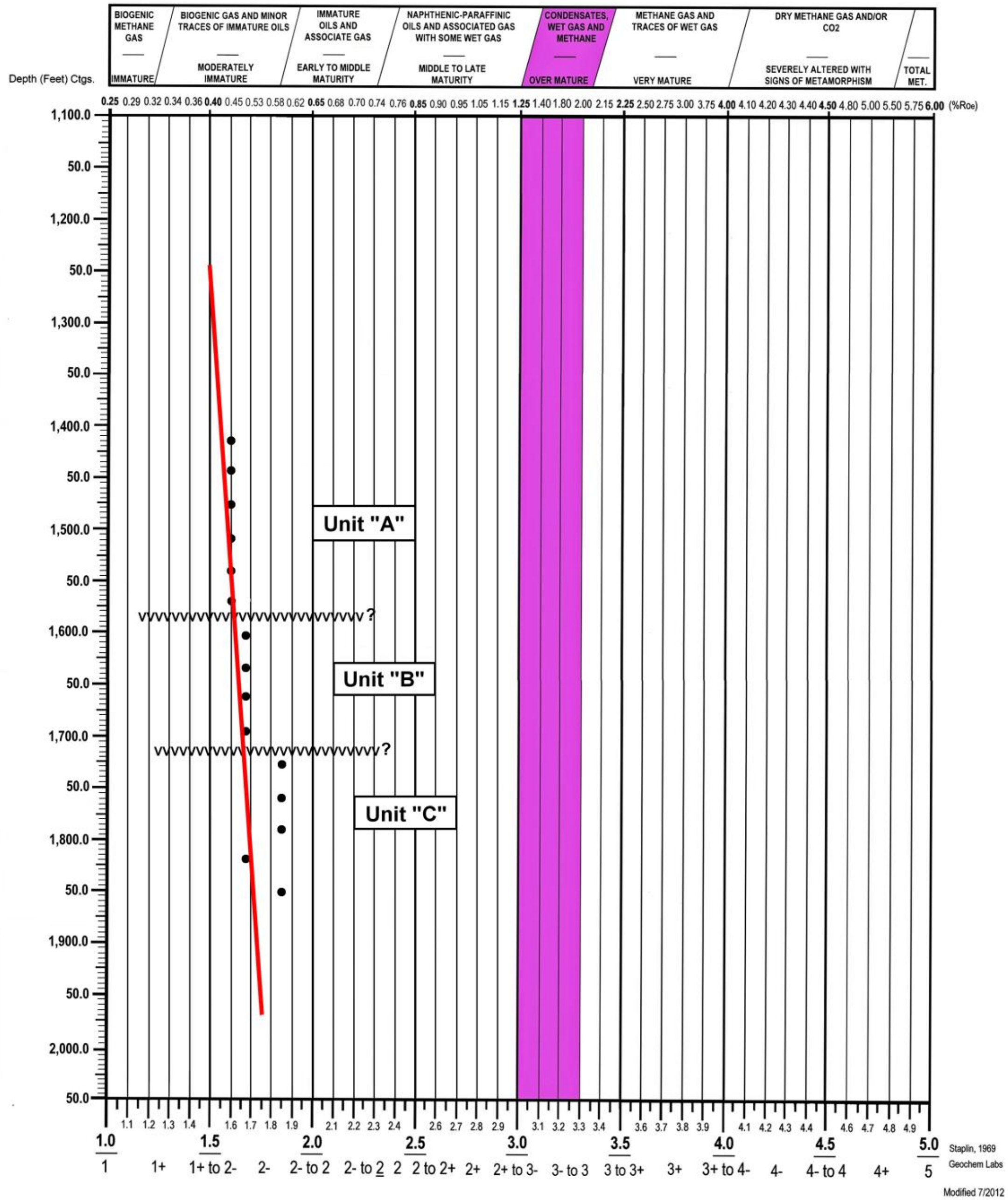


Figure 12. TAI - %Ro well profile of the Supai Formation in the RCR No. 4 well.

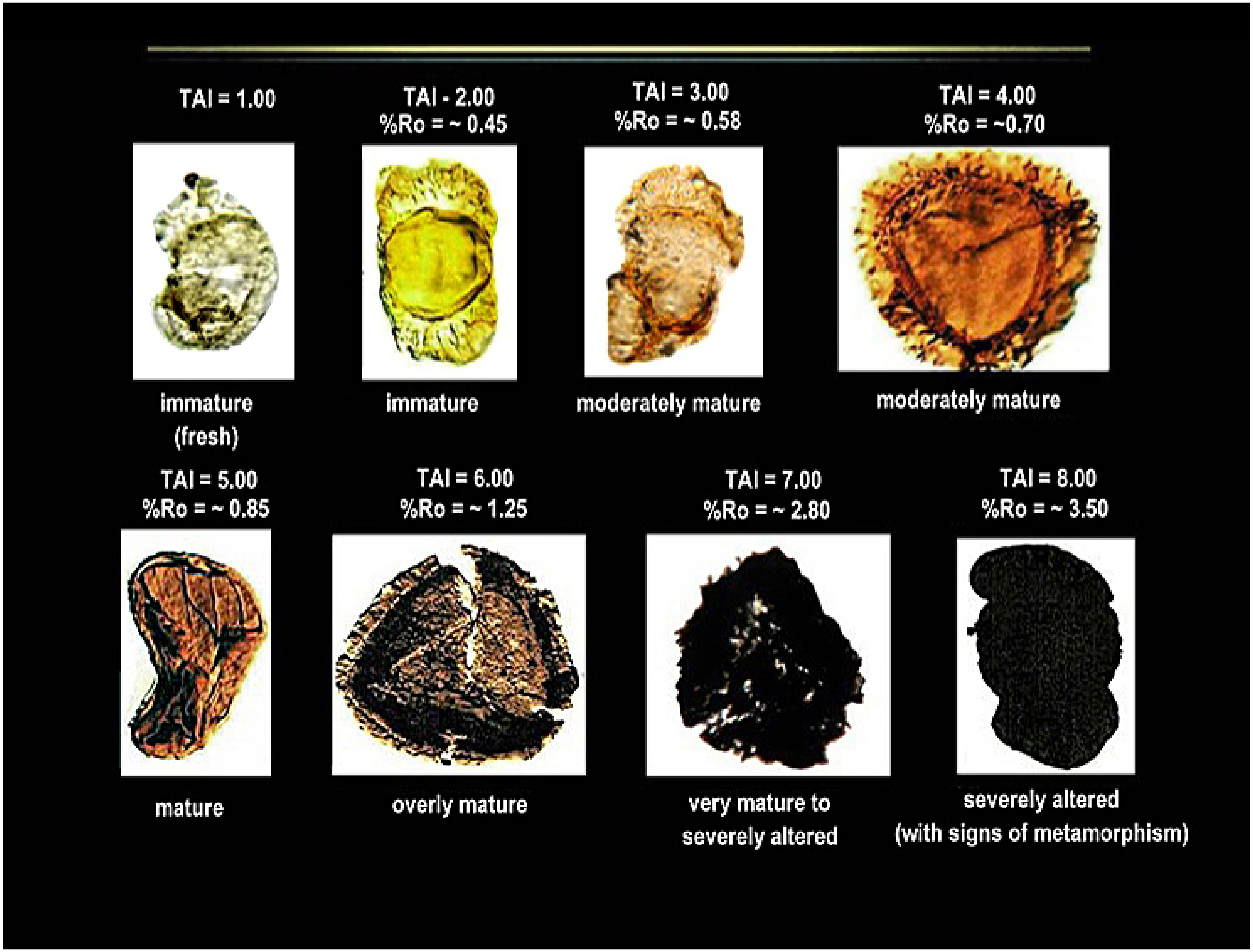


Figure 13. Thermal maturation of organic matter, as related to changes in the color of the trilete spores, pollen, and tissue fragments (Schwab, 1977).

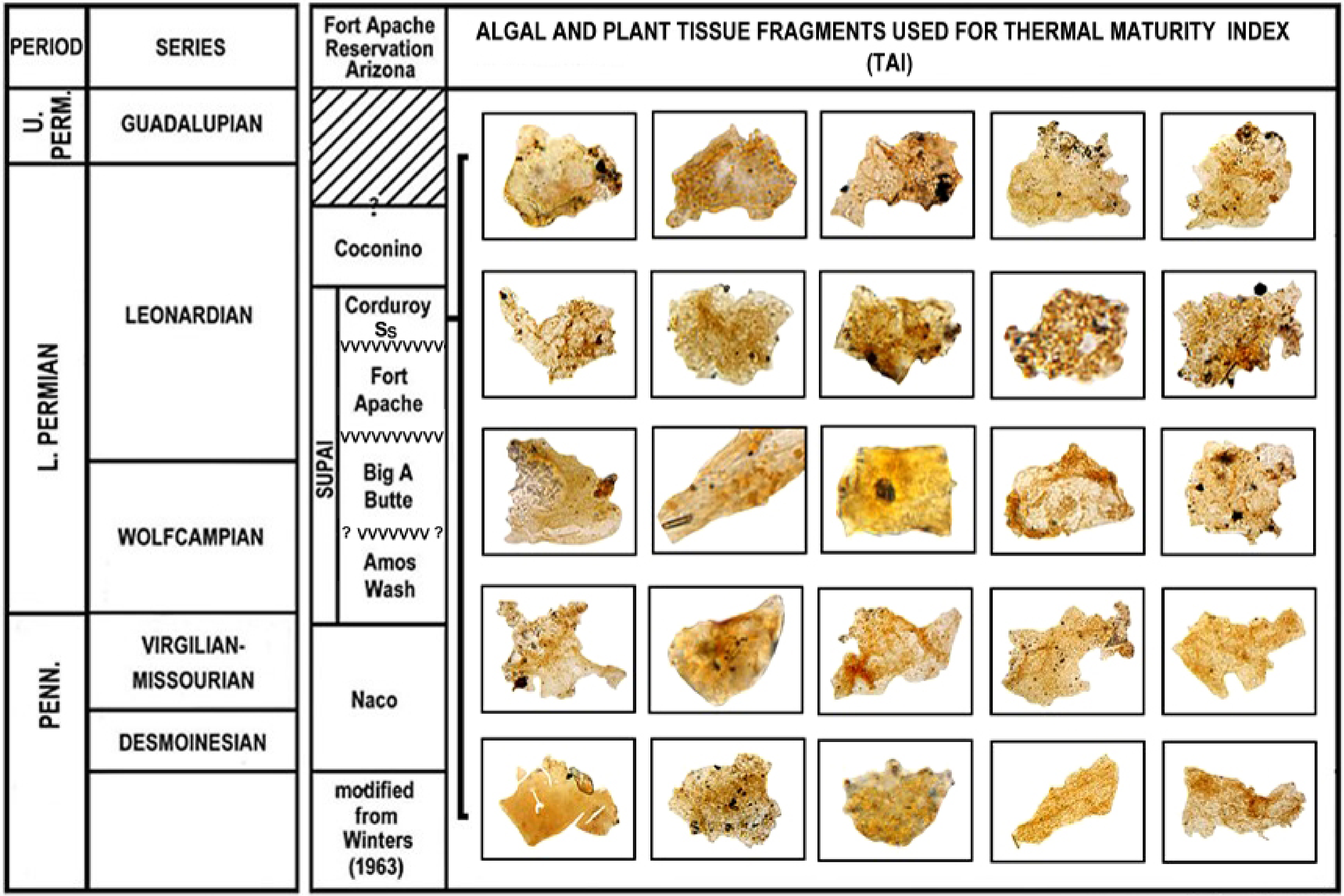


Figure 14. Corduroy Sandstone TAI assemblage, based of study of RCR-4.

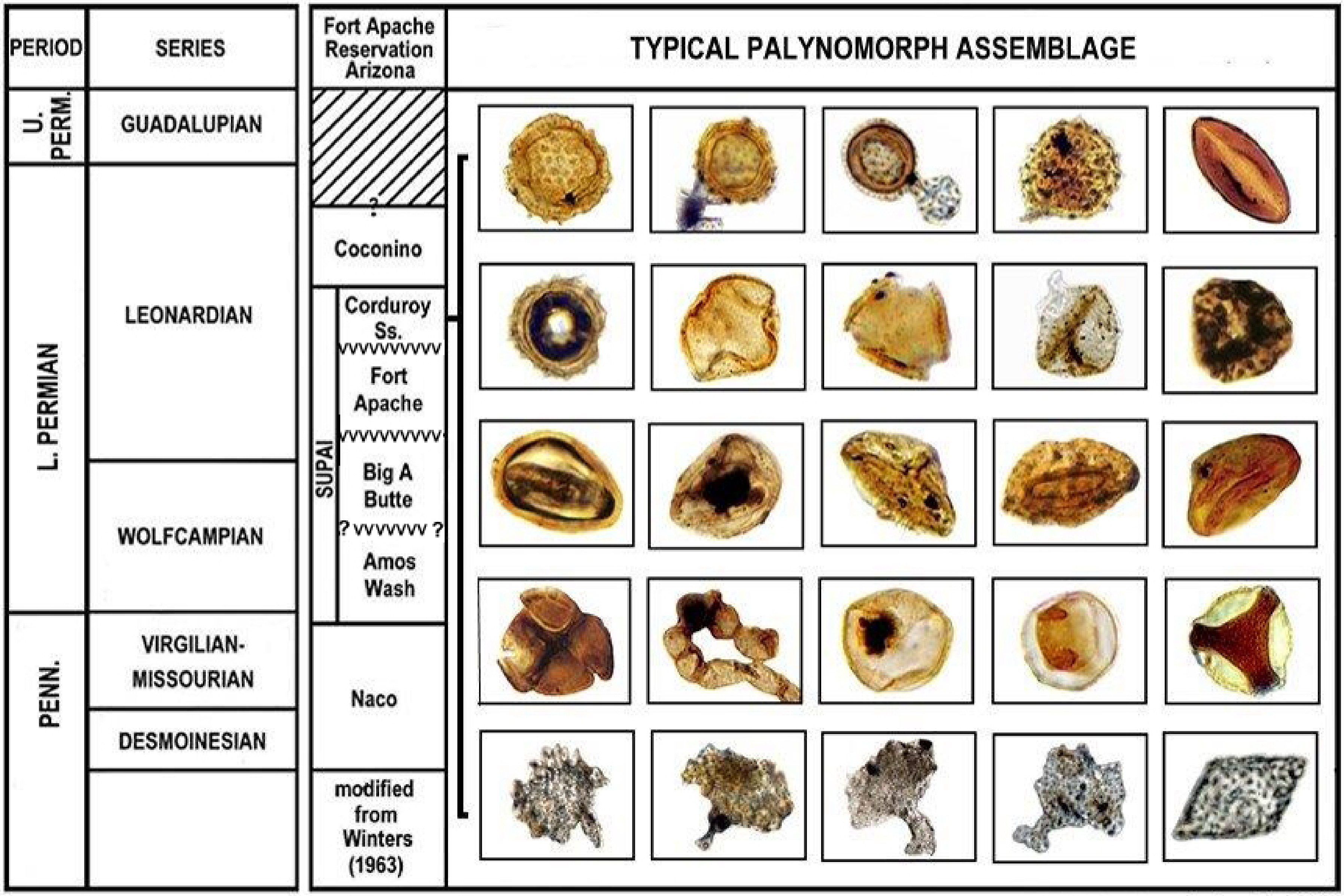


Figure 15. Corduroy Sandstone palynomorph assemblage, based on study of RCR-4.

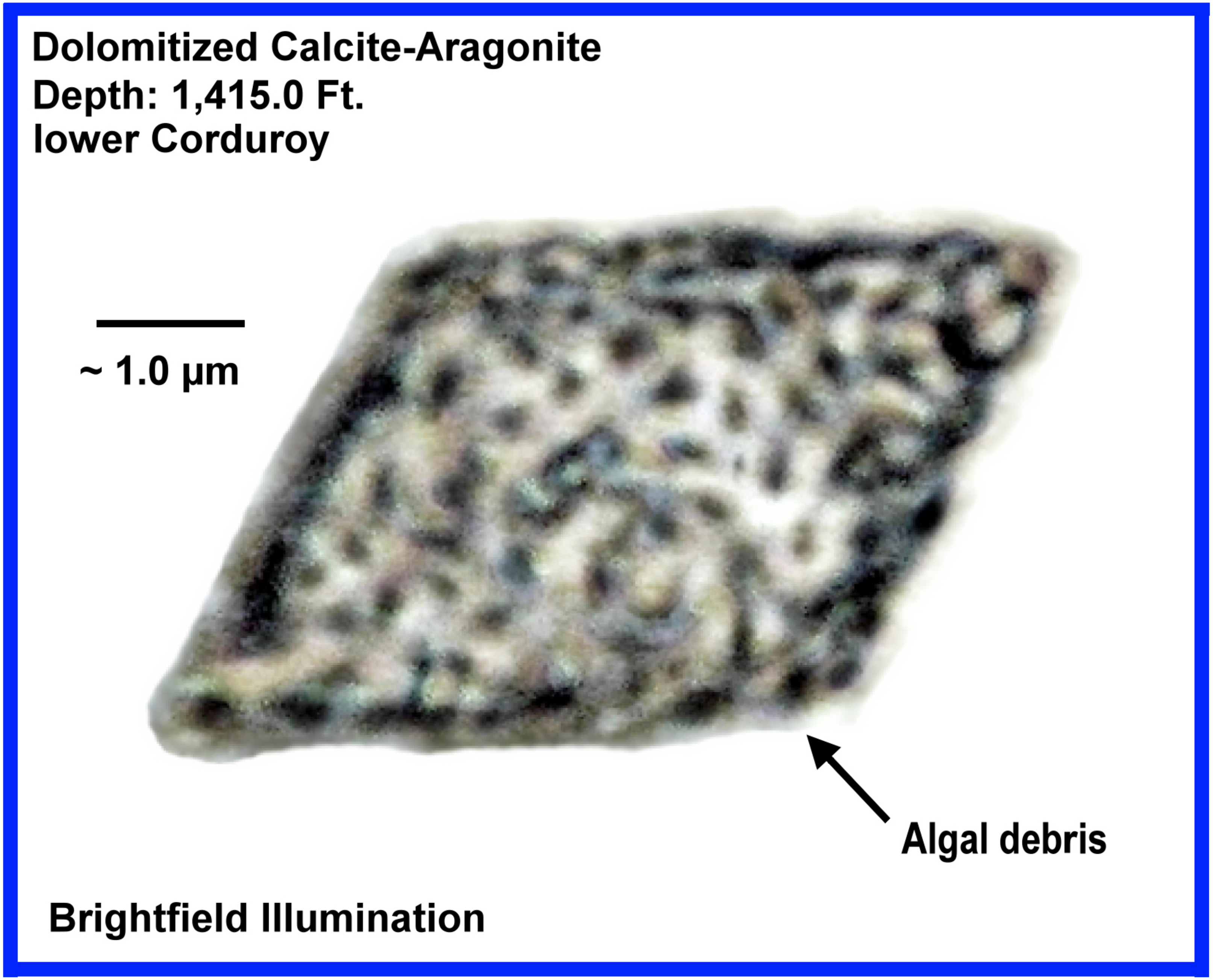


Figure 16. Domitized calcite-aragonite, lower Corduroy Sandstone.

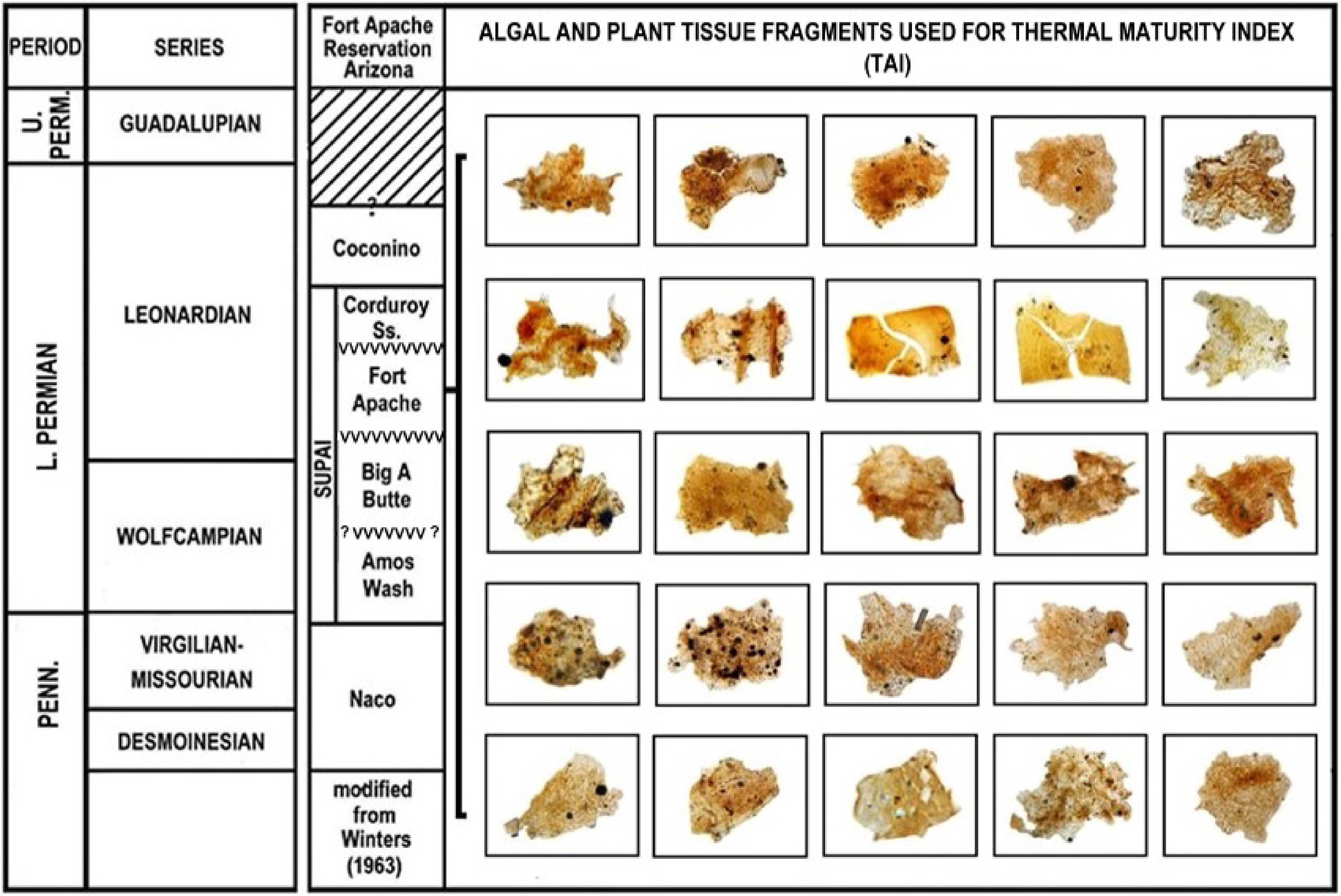


Figure 17. Fort Apache Limestone TIA assemblage, based on study of RCR-4.

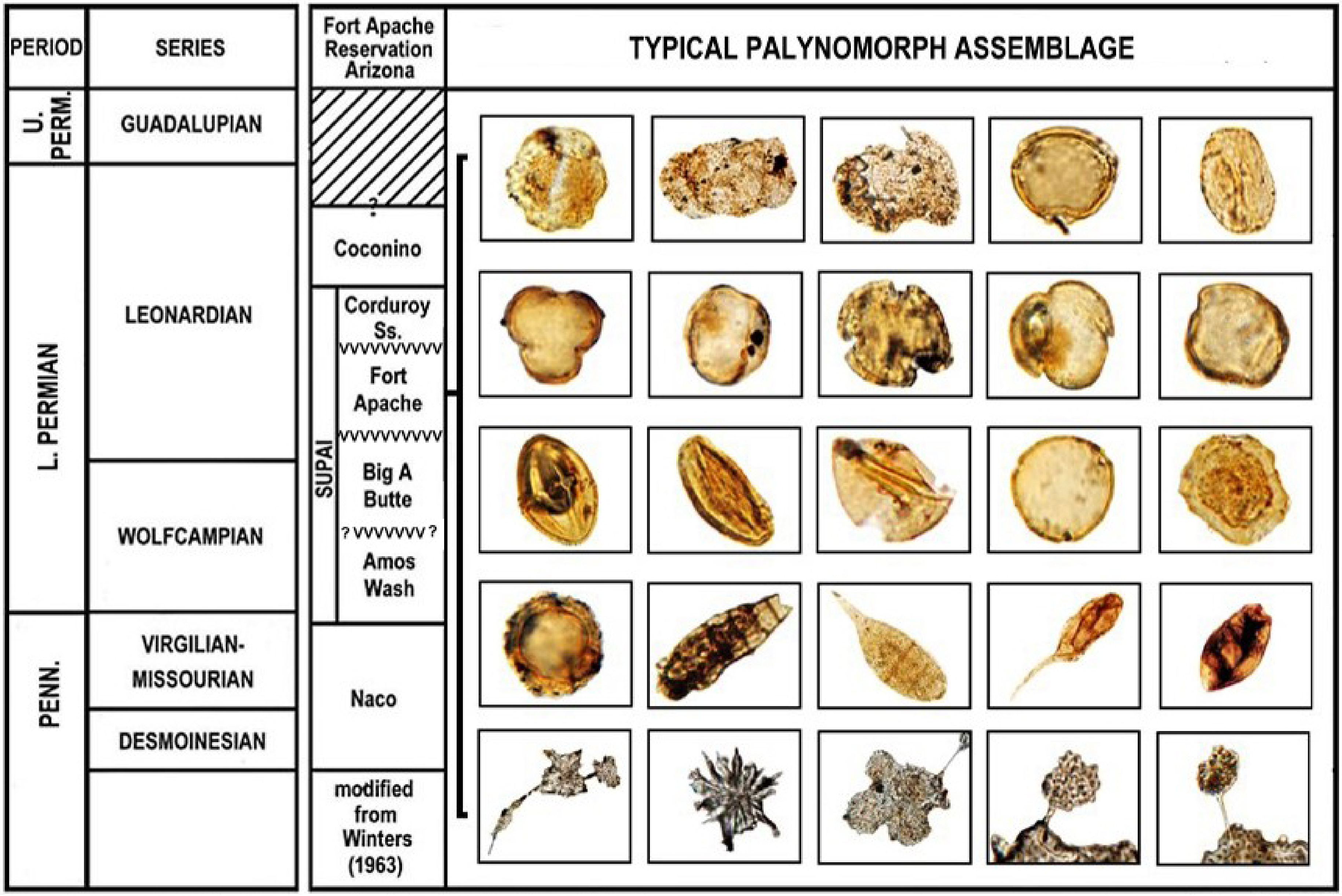


Figure 18. Fort Apache Limestone palynomorph assemblage, based on study of RCR-4.

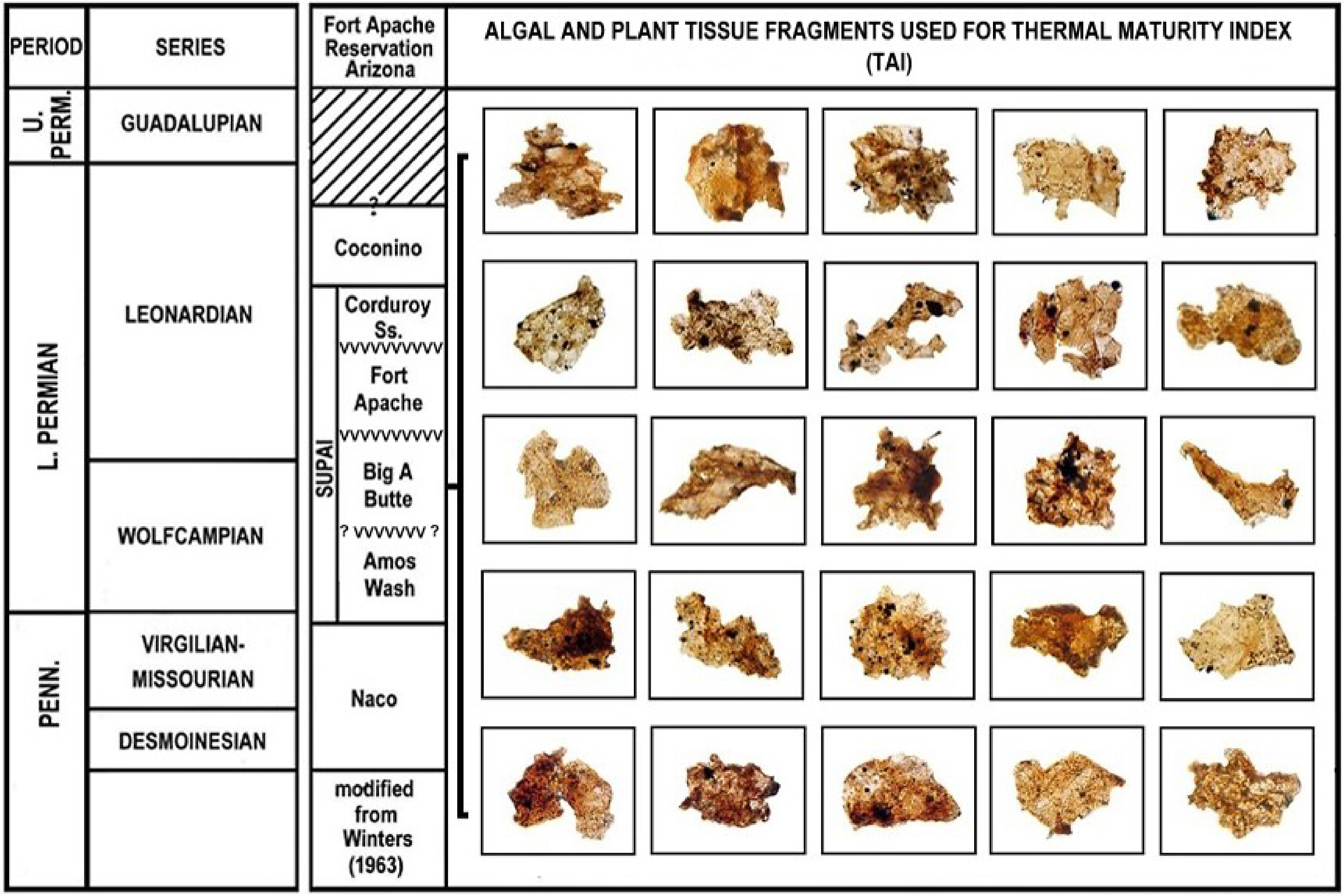


Figure 19. Big A Butte Member TIA assemblage, based on study of RCR-4.

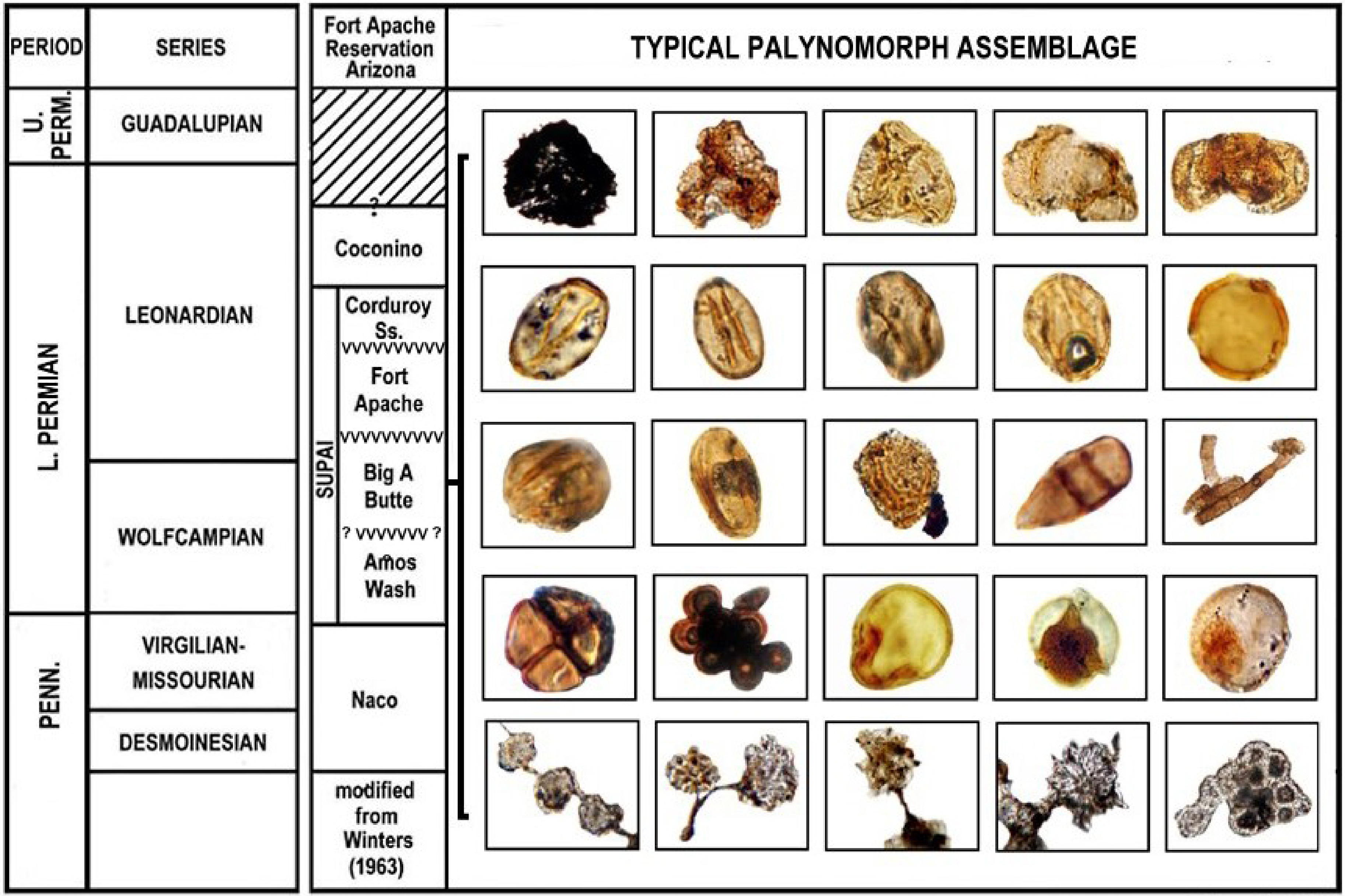


Figure 20. Big A Butte Member palynomorph assemblage, based on study of RCR-4.

METHOD OF ANALYSIS		Abundance or "richness" of organic matter	Quality of organic matter (i.e., type, proneness to oil and/or gas	Level or degree of thermal maturity	Correlation between source-rock and petroleum	Subjectivity in analysis-data; ctgs. (H) High (M) Moderate (L) Low	Analysis based on: (B) Bulk sample (S) Selected OM type	Type of measurement: (E) Estimated (S) Spot (W) Whole grain
CLASS	**TYPE**							
Chemical (on rock)	Total Organic Carbon % TOC	● Excellent to V. Good				M-L	B	
Optical Microscopy	Transmitted light (Visual Kerogen - spore coloration)		● Excellent to V. Good	● Excellent to V. Good		M-L	S	E
	Transmitted light (spectral photometer) ICA - SPD		● Good to Fair	● Excellent to V. Good		L	S	S
	Transmitted light (Image Analysis-ICA)		● Good to Fair	● Excellent to V. Good		L	S	S-W
	Reflected light Vitrinite Reflectance-%Ro		● Low (Limited use)	● Excellent to V. Good		M-L	S	S
	Fluorescence		● Excellent to V. Good	● Good to Fair		M-L	S	E-W
Pyrolysis (on rock)	Rock - Eval	● Good to Fair	● Good to Fair	● Good to Fair		M-L	B	
	C_R/C_T, etc...		● Low (Limited use)	● Low (Limited use)				

Efficiency: ● Excellent to V. Good ● Good to Fair ● Low (Limited use)

Figure 21. Most commonly used methods for the characterization of source rocks. Modified from Tissot and Welte (1978).

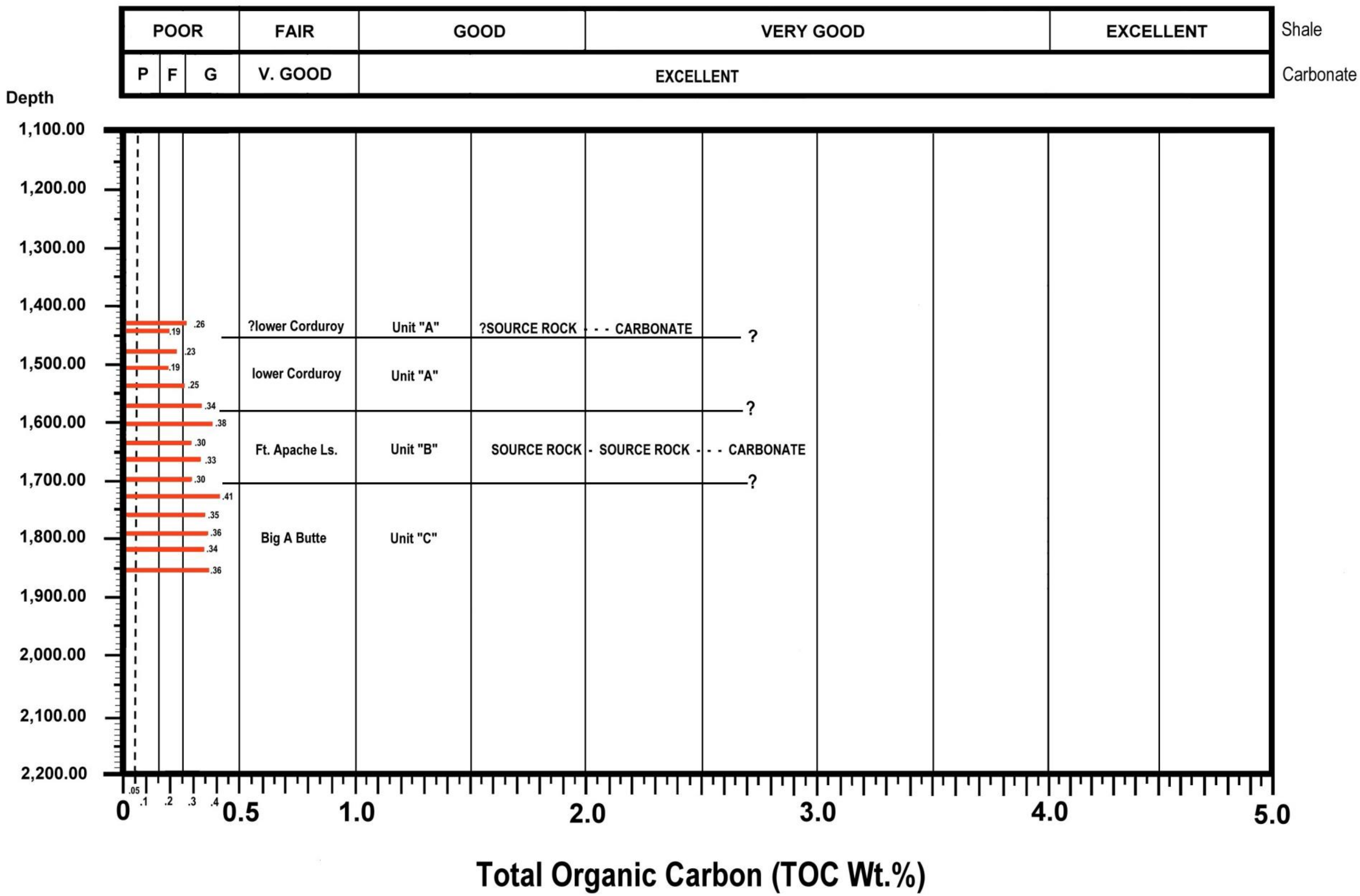


Figure 22. Total organic carbon (TOC %Wt.) profile of the Supai Formation in the RCR No. 4 well.

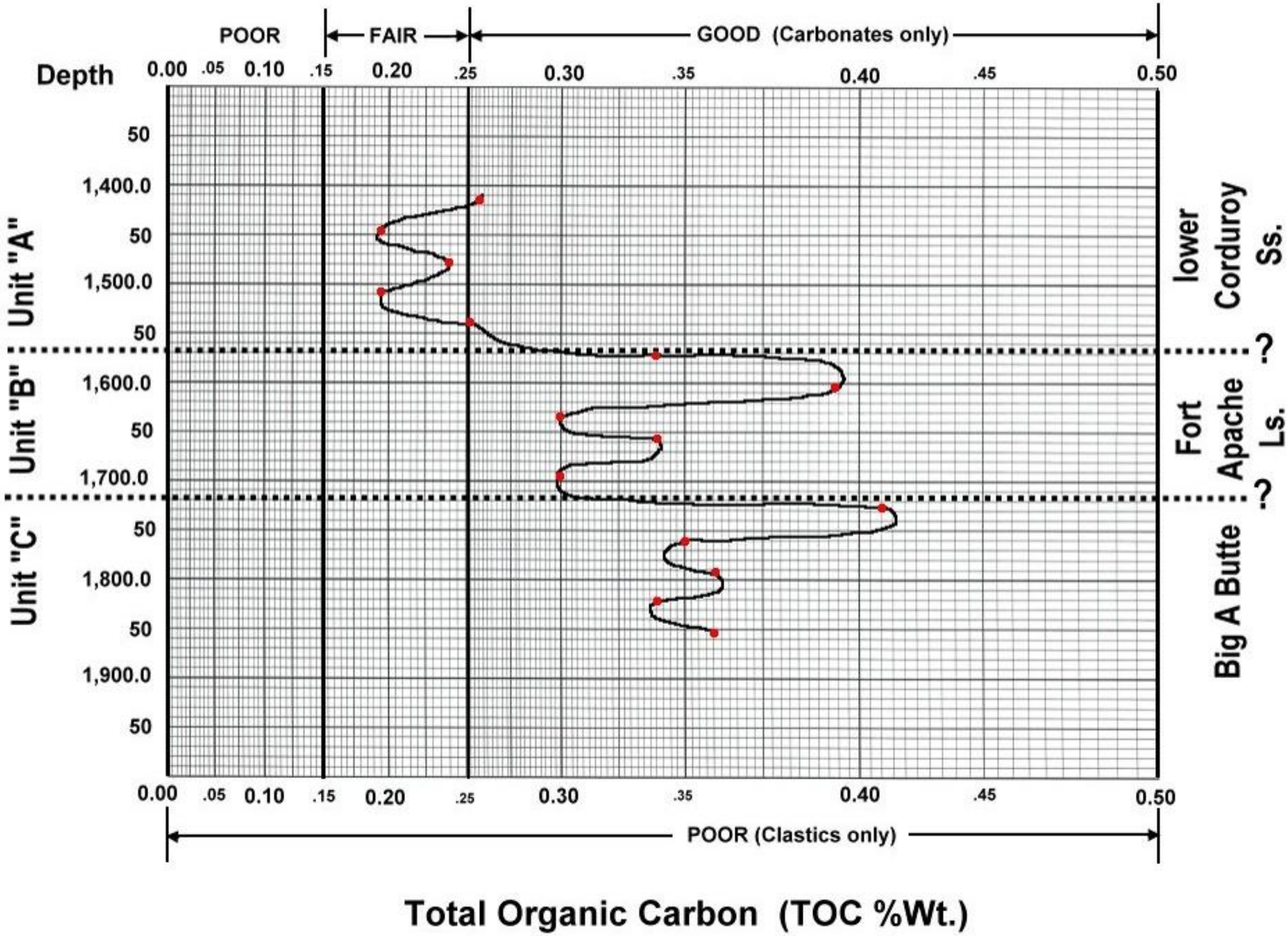


Figure 23. TOC profile of the RCR No. 4 well. Note the rhythmic variations in the TOC content through this portion of the Supai Formation.

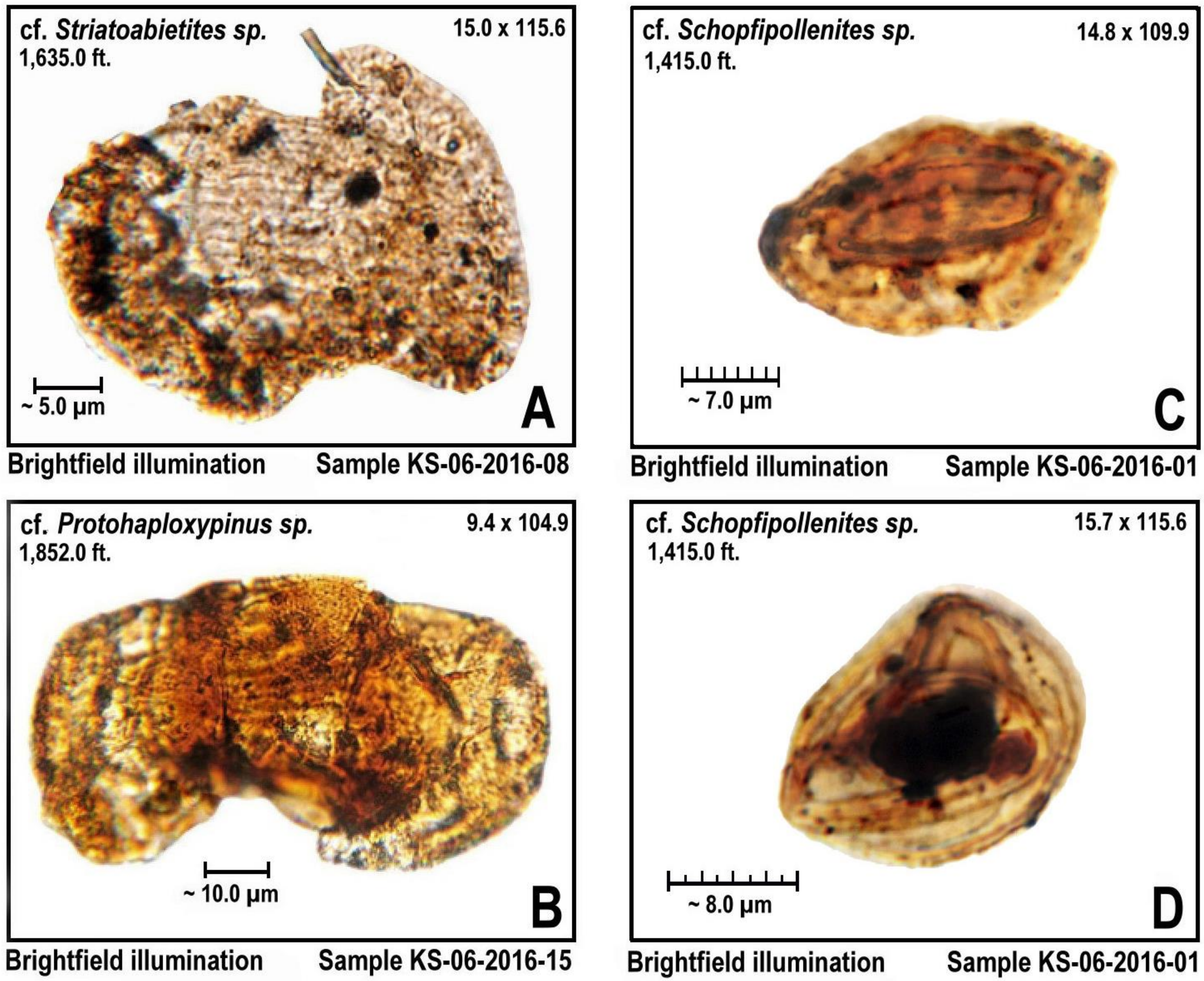


Figure 24. Striate bisaccate pollen and other palynomorphs from the RCR No. 4 well.

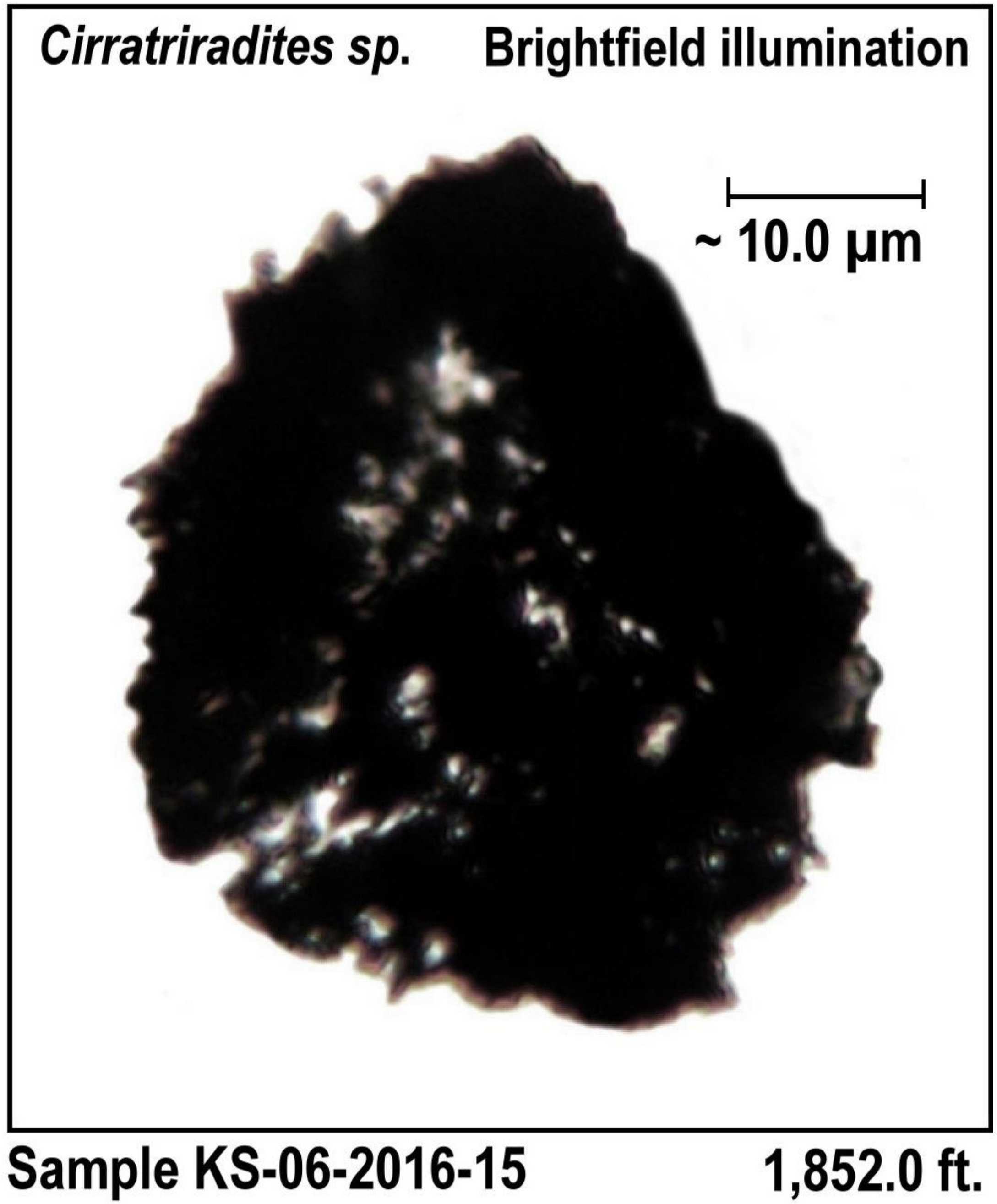


Figure 25. The trilete spore *Cirratriradites* sp.

Unit	Well	Sample ID	Sample Depth	Leco TOC(%)	Avg. TOC (%Wt.)
	Blackstone Rocking Chair RN-4	KS-06-2016-01	1415.0	0.26	
	Blackstone Rocking Chair RN-4	KS-06-2016-02	1446.0	0.19	
Unit "A"	Blackstone Rocking Chair RN-4	KS-06-2016-03	1478.0	0.23	0.24
	Blackstone Rocking Chair RN-4	KS-06-2016-04	1509.0	0.19	
	Blackstone Rocking Chair RN-4	KS-06-2016-05	1540.0	0.25	
?------	Blackstone Rocking Chair RN-4	KS-06-2016-06	1572.0	0.34	------?
	Blackstone Rocking Chair RN-4	KS-06-2016-07	1604.0	0.38	
Unit "B"	Blackstone Rocking Chair RN-4	KS-06-2016-08	1635.0	0.30	0.33
	Blackstone Rocking Chair RN-4	KS-06-2016-09	1666.0	0.33	
	Blackstone Rocking Chair RN-4	KS-06-2016-10	1697.0	0.30	
	Blackstone Rocking Chair RN-4	KS-06-2016-11	1728.0	0.41	
	Blackstone Rocking Chair RN-4	KS-06-2016-12	1760.0	0.35	
Unit "C"	Blackstone Rocking Chair RN-4	KS-06-2016-13	1791.0	0.36	0.36
	Blackstone Rocking Chair RN-4	KS-06-2016-14	1820.0	0.34	
	Blackstone Rocking Chair RN-4	KS-06-2016-15	1852.0	0.36	

Samples processed by National Petrographic Services, Inc., Houston, Texas

Table 1. Total Organic Carbon (TOC %Wt.) values recorded for the Rocking Chair Ranch No. 4 well.