Placoderm Desmid-Like Microalgae in Outcrop Samples Collected from the Lower Eagle Ford Shale of Terrell and Val Verde Counties, Texas*

Karl W. Schwab[1], Geoffrey S. Bayliss[2], Michael A. Smith[3], and Nelson B. Yoder[4]

Search and Discovery Article #50523 (2011)
Posted December 12, 2011

*Manuscript received October 12, 2011; accepted October 18, 2011.

[1]Consultant, Houston, Texas (karlwschwab@sbcglobal.net)
[2]Geochem Laboratories, Houston, Texas
[3]The G-2 Group, Grand Prairie, Texas
[4]Integrated Exploration Services, La Porte, Texas

Abstract

The remnants of what are interpreted to be the fossilized cellulose sheaths of placoderm desmid-like algae are common constituents within the lower Eagle Ford Shale in outcrop samples collected from two outcrop exposures along U. S. Highway 90, located respectively in Terrell and Val Verde Counties, Texas. Similar forms, although not illustrated in this paper, have also been observed in core and well cuttings samples from the lower Eagle Ford Shale of Webb and La Salle Counties, Texas. These particular algal types are commonly found in association with high concentrations of the freshwater colonial algae *Botryococcus braunii* in our organic matter residue. Simple non-trilete spores (interpreted as belonging to the cyanobacteria), trilete spores, pollen, degraded dinoflagellates, and foraminifer linings are also present, but in minor percentages.

To our knowledge this is the first reported occurrence of desmid-like microalgae found in, and reported from, the lower Eagle Ford Shale of Texas. The widespread occurrence and abundance of these fossils, especially within the organic-rich zone of the lower Eagle Ford Shale facies, may provide geologists with new and important information regarding the paleo-depositional conditions that prevailed during Cenomanian time.

Introduction

The presence of what are interpreted as being the skeletal remains of placoderm desmid-like algae in the lower Eagle Ford Shale of south Texas is considered to be important, especially in helping to get a better understanding of the various environments that may have been involved during its depositional history. All extant species of desmids have only been reported from, and are considered restricted to, a freshwater habitat. Although a few desmids have supposedly been reported from a brackish-water environment, the bulk of the genera and species are all indicators of a freshwater system. Phycologists study desmids because they are extremely sensitive to pollution and are often used in determining the trophic state of a water body. Most desmid species are associated with slightly acid, oligotrophic waters. Other species prefer a more alkaline condition and are commonly found in mesotrophic and eutrophic waters. Today, as in the geologic past, desmids reach their highest level of abundance in the late summer and autumn when temperatures are warm and sunshine is plentiful.

This study is based on the examination of organic matter (commonly referred to as visual kerogen) extracted from lower Eagle Ford Shale outcrop samples collected from two exposures along or near U.S. Highway 90, one in Val Verde County and the other in Terrell County, Texas (Figure 1). The first outcrop area, designated as location "A" on the location map, is located approximately 1 mile south of U. S. highway 90 and 2.5 to 3.0 miles west of the Terrell - Val Verde County line in a cobble strewn river bed, known locally as Lozier Canyon. It is the same location illustrated by Donovan et al., (2011, p. 39 and 41). The second location, a roadside cut designated as "B" on the location map, is approximately 7 miles west of the town of Comstock, Texas (Figure 1).

The intent of this paper is to inform our colleagues, especially those who work in the petroleum industry, what desmids are, why they are important and how they can be used to better understand depositional environments. The presence of what we interpret to be desmid-like algae may help geologists, palynologists, and sedimentologists better understand the water conditions, and perhaps circulation patterns, that existed in a given area for a particular point in time. The data presented in this paper should be of particular importance to those who are involved in trying to reconstruct the various environmental habitats associated with the ancestral Texas Gulf Coast region during Cenomanian time.

What Are Desmids?

Desmids are a particular group of algae that live in an exclusively freshwater environment. They are characterized, in part, by having chloroplasts and having chlorophyll *a* and *b* as the predominating pigments. All desmids are flowerless and lack leaves, stems, and roots. They are commonly found in shallow, calm, clear water. Desmids, according to Wehr and Sheath (2003, p.838), represent a group of unicellular and filamentous green algae that give rise to nonflagellated, amoeboid gametes whose reproduction is carried out through the process of conjugation. Currently, there is no agreement on how to subdivide the desmids into orders and families. Rather than getting into a lengthy discussion on the classification of desmids, the writers suggest that those interested in the taxonomy of these particular algal forms read Gerrath (2003, p. 353-365) and Brook (1981, p. 1-26).

Brook (1981, p. 78), in discussing the construction of the cell wall of placoderm desmids (desmids whose vegetative cells consist of two parts), states that walls of these algal types are multi-layered and perforated. According to Brook, "placoderm desmids have two layers internal to the exterior gelatinous sheath". The two inner layers have a slightly different chemical composition. Brook states that the innermost, structureless wall layer was found to be composed of cellulose. The layer external to it, the middle layer, is constructed of cellulose impregnated with pectin. Pectin is better known as the hard, horny substance that is most often found on the external shells of oysters and clams. It is extremely strong and has been reported in the literature as being resistant to decay and degradation, especially by the bacterial action of microbes. This may be one of the reasons why desmids appear to be so well preserved when found in older sediments. In visual kerogen and/or palynological preparations, analysts often make the mistake of thinking that they are looking at the actual algal cyst preserved in the sediment when, in fact, they are only observing the external skeletal material, or sheath. Because the organic sheath is transparent and often difficult to see in brightfield illumination, the best way to look for fossil desmid-like vegetative bodies in the kerogen residue on visual kerogen slides, or in palynological preparations, is by using phase-contrast illumination. They are almost impossible to see in bright field illumination because of their transparency. Their minute size and thin sheath also make them difficult to observe in interference-contrast microscopy.

Many, but not all, desmids have a protective mucilaginous cell envelope, composed of extracellular polysaccharides, surrounding their vegetative cells. Phycologists are not sure what the purpose of the mucilaginous envelope is, but it appears likely that it acts as a protective sheath that prevents the vegetative cells from drying out under adverse conditions and/or keeps the cells from being destroyed when ingested by other microorganisms, such as Daphnia.

The majority of the desmid species have a median constriction that serves to define the two halves of the single cell. In many instances the two halves (referred to as semi-cells) appear identically the same, each a "mirror image" of the other. Because the two semi-cells of desmids are not formed at the same time, there is often a slight difference in the morphology between the two, one part being slightly larger than the other. Reproduction in the desmids, as mentioned earlier, is by cell division, the daughter cells taking on the exact shape of the parent cell. Shortly after the formation of daughter cells, a second wall structure, which is much thicker, is formed. This process is known as semi-cell morphogenesis. Once the process has been completed, the primary cell wall is cast off either as a single piece, or as fragments.

Dr. Professor Jeremy David Picket-Heaps, University of Melbourne, Victoria, Australia, has taken a series of time lapse photographs, which were ultimately made into a video, showing the normal vegetative (i.e., asexual) reproduction of the placoderm desmid *Micrasterias* sp. He has graciously allowed these authors to use his award winning presentation in this manuscript. The video, along with information about the photograph, can be can be accessed at www.olympusbioscapes.com/staticgallery/2009/hm47.html.

How Are Fossil Desmids Identified?

The identification of fossil desmids is based exclusively upon the external morphology of the vegetative cell (sheath). As with other algal groups, the differences in the morphology of desmids, is highly variable According to Gerrath (2003, p. 354) the variations in their morphology are inconceivable. He estimates that there are some 800 or more species just for the genus *Staurastrum*. Approximately 320 of these species are found in North America. [Note: Sometimes various species of the Xanthophytes (e.g., *Pseudostaurastrum lobulatum* and *Isthmochloron trispinatum*), desmid look-alikes, may be confused with true desmids. To our knowledge, we have not encountered any fossils belonging to the Xanthophytes in the outcrop samples from Terrell and Val Verde Counties. Their presence however, is certainly a possibility.]

Because of their minute size, usually 6 μm to 12 μm in diameter in our samples, desmid-like vegetative cells can be, and often are, covered by other larger pieces of extraneous plant fragments and/or finely disseminated amorphous material. The writers found that it is best to look near the outer margins of the cover glass, where the organic debris is not heavily concentrated and where the morphology of the organic constituents can be observed more easily when examining visual kerogen slides. Because of their small size, it is best to search for desmids using a microscope equipped with a 100 X phase-contrast objective.

As stated by Gerrath (2003, p. 361), "The morphological diversity exhibited within the group (referring to the Desmidiales) is remarkable. Because of the peculiar structure and symmetry of the vegetative cell, its form will appear different when viewed from different directions." This problem is exacerbated in fossil material due to the distortion and abrasion of the vegetative cells during sediment burial, compaction, transport, and diagenesis.

Some desmids are biradiate; that is, they are constructed in such a manner that there are three axes, or planes, of symmetry that pass through the center of the desmid. Similarly, some forms can also be triradiate. The center of a desmid is often referred to as the isthmus, or point of medial constriction. It is often found to coincide with the location of the nucleus. The appearance of some desmids will vary depending upon what axis or axial plane the microscopist is viewing. This particular morphology, which is typical of the desmids belonging to the genus *Staurastrum,* is one of the important criteria used to recognize the presence of this unique algal type in our sample material.

Regarding fossil desmid-like microalgae, the writers base their interpretation on from one to four external morphological factors: 1) the bifurcated or trifurcated terminal ends of the processes on the vegetative cell body, 2) the symmetry of the fossil vegetative cell, 3) the presence or indication of an ismuthus or suture line dividing the vegetative body into semicells, and 4) the presence of pores or what appears to be a fine network of fenestrate cells along the processes and on the main body of the cell itself. Not all fossil specimens, or fragments thereof, will exhibit all of these features. Quite often, because of poor preservation (a result of biodegradation, sample processing, deformed specimens, effects of thermal heating, and sediment compaction) the palynologist or visual kerogen analyst may be forced to base an interpretation on only one or two of these morphological features.

Habitat

Brook (1981, p. 211) states that the British algologists W. and G.S. West (1909), as a result of extensive studies of the British freshwater plankton, were the first to recognize that desmids seemed to be associated with particular types of water. These writers concluded that plankton populations containing the greatest diversity in their desmid population correspond geographically with pre-Carboniferous rocks and occur in water that is particularly low in dissolved minerals.

In discussing the relative importance of planktonic desmids compared to other algal groups, Brook (1981, p. 212) found that the ratios between certain algal genera and species can be used to characterize the nutritional state of a given body of water. Coesel (1983) found that the presence of certain desmid types, even in relatively low numbers, often is an indicator of mildly acidic, oligotrophic (i.e., poor feeding), conditions. Brook (1971), in a study of planktonic desmids from Minnesota, observed that a highly diverse assemblage of planktonic desmids and other algae tends to produce a Compound Phytoplankton Quotient number (a number based on a ratio scale devised by Nygaard, 1949) of 2.0 or less. This, as we understand it, is indicative of an oligotrophic environment. Assuming this is true, then one would likely interpret a less diverse assemblage of planktonic desmids and algal cysts, perhaps like what we are seeing in the Eagle Ford Shale, to be more indicative of a eutrophic (i.e., good feeding) environment. We would assume that in this instance, the Compound Planktonic Quotient would have a value of 2.0 or greater. After much research on the subject, Brook (1981, p. 215) makes a point that, "a quotient should be formulated based only on a limited number of planktonic desmids (and other algae) whose status (position relative to that of others) in the plankton and especially whose nutritional requirements have been adequately investigated". When dealing with fossil material this technique may or may not apply depending on how extensive the investigation is. In our particular study, a cursory examination of the visual kerogen slides, it is all but impossible.

Because none of the writers are taxonomists and/or experts in the field of phycology, we are unable to readily identify all the algal types that occur within the organic-rich portion of the lower Eagle Ford Shale. We suspect the variety and types of algae that are present are considerably greater than the few genera and species that we observed in this study. This is especially true when one realizes that we are looking at a representative time span of ~5 million years or more. Furthermore, because of the long geologic time span since the lower Eagle Ford Shale was deposited and accumulated (~95 million years ago), we question if anyone can be absolutely sure as to what the trophic state of the waters were at that point in time. Desmids which may have been able to tolerate a brackish-water environment at that point in time might now be extinct. A more detailed study of the desmid-like population, especially in the lower Eagle Ford Shale, is certainly warranted.

From our examination of the organic debris on visual kerogen slides, the writers interpret the lower Eagle Ford Shale to represent an environment that had a rich floral and faunal assemblage. We suspect that the water column was rich in nutrients and dissolved minerals and therefore would most likely be considered as providing organisms with a food-rich habitat. Based on this interpretation, a large part of the lower Eagle Ford Shale would most likely have been associated with a depositional environment which was eutrophic in nature (i.e., a good feeding environment). Whether our interpretations are correct or not, will remain to be determined by additional studies.

As noted throughout this article, desmids are almost exclusively found in a freshwater habitat although some have been reported from brackish-water environments (Parmentier and Egmond, 2007). Gessner and Simonsen (1967) discuss the presence of freshwater desmids mixed with a more brackish marine microalga in one of the tributaries of the Amazon Delta, namely, the river Guama. They found that the marine microalga, dominated by marine diatoms, is brought into the freshwater environment because of tidal surges. Gessner and Simonsen (1967) state, "It is possible that some of this material is transported upstream with the incoming tide due to the whirling up of the marine bottom sediments." They also state that "outgoing tides will produce a similar process". Their findings indicate that these tidal effects can be seen as far as 700 km from the delta. In another study, the two authors state that Gessner (1962), on a boat trip from the villages of Belem to Manau in 1960, collected water and plankton along the river in order to investigate how far upstream dead shells of marine and brackish water diatoms could be observed. Gessner discovered that even near Breves, a village located 350 km from the mouth of the Amazon, empty frustules of several species of marine and brackish-water diatoms could still be observed.

Gerrath (2003, p. 363) states "the greatest known diversity and numbers of desmids occur in the southeastern coastal plain, the Canadian Shield, and the Pacific Coast." He also states that most desmids, especially within lakes and ponds, occur along the sediment surface in shallow water or among aquatic vascular plants. According to Gerrath most North American desmids are most commonly found in bogs closer to the ocean than those farther inland. Desmids have a greater abundance and are more diverse in habitats that have access to open waters.

Geological Occurrences of Desmids

Very little is known about fossil desmids. The oldest reported desmids known by these writers are from the Devonian of New York (Dana, 1863, p. 271, Text- figure 441 A, figure *e*). The specimen, found and illustrated by Dr. M.C. White of New Haven, Connecticut, appears to be closely related, based on its external morphology, to the extant genus *Cosmarium*. Schwab et al., (2011, p. 13) reported the occurrence of desmid-like algal forms, interpreted as belonging to the genus *Staurastrum*, in association with dwarf bryophytes extracted from core samples taken from the Upper Mississippian Barnett Shale of north-central Texas. Bradley (1946) reported on the occurrence of fossil desmids that he extracted from coprolites found in the upper Cretaceous Bridger Formation of Wyoming. There is also a reported occurrence of a fossil desmid, found in amber, from the Cenomanian of northwestern France (Waggoner, 1994). Waggoner identified his desmid as belonging to the genus *Closterium*.

Interpretation of Outcrop and Well Data

In the lower Eagle Ford Shale, moderate concentrations of freshwater algae, what we interpret to be fossil desmids belonging the genus *Staurastrum sp.*(Plates 1-7), are mixed with an even greater concentration of other freshwater algae (primarily *Botryococcus braunii*) debris, marine calcareous nannofossils and the organic linings of micro-foraminifers. [Note: Where possible, the writers have tried to compare morphologically the fossil desmid-like fragments to well preserved extant desmid genera and species, Plate 8.].

The mixture of fresh water and marine algal types, odd as it may seem, takes place in the most organic-rich facies of the lower Eagle Ford where total organic carbon values are often in excess of 5.0 percent by weight (Wt. %). The high concentrations of freshwater and marine algal debris mixed together within the same stratigraphic unit, have produced a sharp division among geologists, geochemists, micropaleontologists, sedimentary and carbonate petrologists, and palynologists, regarding their interpretations of the depositional environment. From the writers' geological perspective, there are only two scenarios to choose from regarding the deposition of the lower Eagle Ford Shale, and both represent rapid burial under anoxic conditions.

In scenario one, a view supported by some geologists (e.g., Lock and Peschier, 2006), seismic stratigraphers, and sedimentary petrographers, the freshwater organics were carried into a salt-water body (i.e., ancestral Gulf of Mexico) by streams and the runoff from torrential rains and transported out onto the outer continental shelf (fresh water overriding the salt water in a density-contrast flow regime) where they were ultimately deposited.

In scenario two, an interpretation based largely on the algal flora (desmid-like vegetative cells and *Botryococcus braunii*) incorporated in the sediment and geochemical analyses, the marine waters are interpreted to have periodically invaded coastal basins and wetland areas throughout the history of the deposition of the lower Eagle Ford. Due to subsidence and/or the collapse of the onshore and coastal basins and sub-basins, combined with rising sea level, the entire coastal plain (of the ancestral Gulf of Mexico) was eventually inundated by marine waters during late Eagle Ford time. Deposition is interpreted to have been associated with a lacustrine environment including semi-restricted basins, coastal wetlands, bogs, estuaries, and lagoons that were accessed by open marine waters (much like Galveston Bay, Trinity Bay, Oyster Bay, Sabine Lake, etc.). The depositional system most likely involved a quiet, shallow-water setting with little turbulence. This interpretation is supported by, at least in part, the presence of thin beds or banks of oyster shell fragments found throughout various intervals of the stratigraphic section.

Regardless which scenario one chooses, it can be shown that organic matter, derived from freshwater habitats, continued to supply moderate to large quantities of debris throughout the entire deposition of the Eagle Ford--to compose a significant part of a mixture of freshwater and marine organisms in the Eagle Ford Shale.

During our examination of organic residues recovered from outcrop samples collected in February, 2011, from Terrell and Val Verde counties, Texas, and in earlier examinations of well cuttings and cores conducted for Lewis Energy Group of San Antonio, Texas, the writers found that the lower Eagle Ford Shale (especially the organic-rich facies) contained a well preserved suite of freshwater microalgae. Finite algal strands (threads of cellulose that connect the algal colonies) and detailed cell wall structure can still be seen in many of the algal colonies and vegetative cells. The overall pristine-like preservation and structural integrity of the organic constituents is an indication that the lower Eagle Ford material was not transported over any great distance. Deposition of the algal debris is interpreted to be *in situ*. Accumulation and burial of the organic debris occurred rapidly in a reducing environment. As pointed out by Tschudy, 1969, conditions such as this are more commonly associated with bogs, at the bottoms of lakes and in the depths of closed basins. This is not the norm in a deep-water, open-ocean, outer-shelf type of environment of deposition, where organic debris is kept in suspension and often fed upon by plankton and other marine organisms.

[Note: Algal and other plant debris in the upper Eagle Ford is finer in its overall particle size, badly frayed and exhibits considerable biodegradation, corrosion, and wear. This is an indication that the organic constituents may have been transported a considerable distance, exposed to subaerial oxidation or subjected to high levels of bacterial biodegradation. These same conditions, or set of conditions, regarding the organic matter, are also found in the subsurface well cuttings and core samples that were collected from wells drilled in Webb and La Salle counties, Texas.]

A literature search, regarding scientific papers that discuss the occurrence of freshwater and/or marine dinoflagellates within the lower Eagle Ford Shale, provided us with little to no diagnostic information. Brown and Pierce (1962) and Christopher (1982), studied an almost complete section of the Eagle Ford Group from north Texas. Although Brown and Pierce (1962, Fig. 4, p. 2138) illustrate some of the marine dinoflagellates that they observed, no mention pertaining to the presence of freshwater algae was noted by either of the two authors. To our knowledge this is the first time that desmid-like microalgae, presumably from a freshwater source, has been reported and illustrated from the lower Eagle Ford Shale.

Paleogeography of the Lower Eagle Ford Shale

In reviewing the paleogeographic maps produced by Dr. Ron Blakey, Professor Emeritus, Northern Arizona University, especially the maps depicting his rendition of the south Texas area approximately 100 Ma and 85 Ma (± 5 million years) (http://cpgeosystems.com/namK100.jpg and http://cpgeosystems.com/namK85.jpg) and personal communication with him, it is concluded that sea level rose quickly during this 15 to 20 million year time span (Figure 2A and Figure 2B).

It can also be said, with a high degree of certainty, that the south Texas coast line during the Cenomanian, as depicted by Blakey's paleogeographic map (Figure 4A), was probably very similar to what it is like today. It was undoubtedly traversed with inter-connecting waterways cutting across wetland areas dotted with fens, bogs, marshes, streams, pond, lakes, estuaries, lagoons and embayment's. We envision much of the coastal area, especially that shown within the "boxed" outline on Blakey's map (Figure 4A), to be very much like the area observed in the ACE Basin National Estuarine Research Preserve, located 45 miles south of Charleston, South Carolina (Figure 4B). [NOTE: The photograph of the ACE Basin National Estuarine Research Preserve in South Carolina was supplied to, and authorized for use in this report by, Skip Theberge who is currently with the National Oceanic and Atmospheric Association (NOAA) Central Library.]. The photograph (Figure 4B) can be accessed at: http://www.photolib.noaa.gov/htmls/nerr0021.htm

The entire coastal area, as interpreted by these writers, was an area which had localized areas of subsidence (basins) associated with meandering streams and rivers having numerous oxbow lakes that ultimately became collection basins for high concentrations of organic debris (mainly algae and herbaceous plants). Calm and clear surface waters with little turbidity was probably the norm in the wetlands environment except during storms, just as it is today. This type of an environment, based on our visual kerogen analyses, is interpreted to have occurred throughout most of the lower Eagle Ford Shale depositional cycle. Algal build-up, although dominantly onshore in rivers, lakes, ponds, and bogs, extended into lagoons and bays. Prolific algal blooms, which were seasonal, regularly formed offshore and in the coastal basins, occupying large areas along the vast coastal shoreline. The pattern was undoubtedly very similar to that illustrated in a recent satellite photograph taken of the present-day Louisiana and Texas Gulf Coast (Figure 3A and B).

Some geologists interpret the lower Eagle Ford Shale to represent a sedimentary sequence that was deposited in a marine, deep-water outer-shelf environment (~100 meters or more in water depth). It is likely that this interpretation, in part, stems from the fact that calcareous nannofossils, foraminifers and marine dinoflagellates were, and are, reported to be abundant throughout various portions of the stratigraphic section. Palynologically and geochemically, this type of a depositional environment does not favor the high concentrations of freshwater algae that we find associated with the lower Eagle Ford Shale section in south Texas.

Although much has been written about the marine fauna, essentially nothing has been published on the flora, especially the freshwater algae. This being true, few geologists are aware of the exceedingly large assemblage of freshwater fossils present in the lower Eagle Ford section. Based on our recent findings regarding the high concentration of freshwater alga *Botryococcus braunii*, along with other freshwater palynomorphs (desmid-like microalgae) in the lower Eagle Ford Shale, the analytical data favor a depositional environment associated with a series of shoreline basins, lakes, and embayments whose water depths were highly variable (generally no more than 5 to 30 meters in depth). The heavy algal growth had to have been within the upper portion of the euphotic zone in a system that had open access to invading marine waters.

Figure 3A and Figure 3B, the same photograph shown twice, shows the oceanic, longshore currents in the Gulf of Mexico and the high concentrations of algal blooms (light green) along the coastline. This satellite photograph (http://www.eosnap.com/public/media/2009/02/louisiana/20090207-louisiana-thumb.jpg) is provided here with permission of Chelys (www.chelys.it). The distance of the coastline in this photograph is approximately 200 miles in length.

From the photograph, one can observe that the algal build-up and accumulation is concentrated very close to shoreline, in waters that are no greater than 50 to 60 feet in depth. Algal debris, although it may float out into deeper waters, is generally pushed back towards shoreline by wave action, longshore currents and eddies. It is our opinion that this type of situation must have occurred many times throughout the Cenomanian and gave rise to the high concentrations of oil- and gas-prone organics (algae and herbaceous vegetation) within the lower Eagle Ford Shale.

In our experience of looking at thousands of visual kerogen preparations and performing countless geochemical analyses on well samples from the Gulf of Mexico, massive freshwater algal concentrations do not normally accumulate on the outer continental shelf areas in waters that have depths greater than 25 to 50 meters. The same can be said for major accumulations of total organic carbon whose values are in excess of 3 to 6 percent by weight (Wt%). Our organic-matter studies and analytical geochemical data suggest just the opposite, that these conditions are more often associated with relatively shallow-water conditions with accumulations in semi-restricted basins where accumulation of organic vegetation has a tendency to be high.

Based on our analytical data (visual kerogen and organic geochemistry), it is our opinion that the intermittent and constant rise in sea level, compounded by sporadic periods of subsidence along the existing coastal shoreline, probably occurred many times throughout early Eagle Ford time. The invasion of marine waters undoubtedly brought in an influx of calcareous nannofossils, foraminifers, and other marine constituents that were deposited penecontemporaneously with the freshwater flora (algae and herbaceous plants). It is very likely that the waters in many of these basins, lagoons, and/or embayments may have been stratified, allowing the marine organisms to thrive in more saline waters beneath the overlying fresh water microalgae. This certainly would help to account for any concentration of marine and freshwater organisms being within the same stratigraphic interval.

The basins, sub-basins, and topographic lows that formed on the wetlands and coastal areas along the ancestral Gulf Coast of Mexico are interpreted to have stretched along, and parallel with, the entire Cenomanian coastline from the Del Rio area of south Texas to the northeastern expanse of what is now commonly referred to as East Texas. The coastal margins of the ancestral Gulf of Mexico, as shown on Blakey's Paleogeographic Map of Texas as it may have looked approximately 100 million years ago (±5my.) (Figure 5A), coincides well with the Cenomanian Eagle Ford Shale Trend map (Figure 5B) (Petroleum Management Technology News, p2 Energy Solutions, *Houston Chronicle*, October 6, 2009).

We contend this trend map of the Eagle Ford Shale, in conjunction with Blakey's Paleogeographic Maps, plus the data generated by our visual kerogen analyses, support our hypothesis that the lower Eagle Ford shale can just as easily be interpreted as a shallow water, inner-shelf deposit as one that was associated with a deep-marine, outer-shelf environment. The fact that nannofossils are present in the stratigraphic section does not necessarily indicate that the whole lower Eagle Ford Shale section was deposited within a deepwater, outer-shelf environment.

Conclusions

1. Organic residue from The lower Eagle Ford Shale is exceptionally rich in its content of colonial algae (*Botryococcus braunii*) and desmids-like microalgae similar to desmid-like vegetative cells belonging to the genus *Staurastrum*.
2. Extant desmids, are found almost exclusively in a freshwater habitat. None are known to occur in marine waters.
3. Most desmids are found along the surface sediment in shallow waters among aquatic vascular plants and algae, not in a deepwater, outer-shelf-marine environment.
4. Extant desmids are a very important indicator of the eutrophication level of large bodies of water.
5. Calcareous nannofossils and micro-plankton are present in various abundances throughout the Eagle Ford. This is important in that it indicates the presence of a significant marine environment being present during lower Eagle Ford deposition.
6. Deposition of the freshwater vascular plant material and algal debris in the lower Eagle Ford Shale and their occurrence with marine calcareous nannofossils was penecontemporaneous.
7. The lower Eagle Ford Shale in Terrell, Val Verde, Webb, and La Salle Counties of south Texas is interpreted as exhibiting both freshwater-brackish and brackish-marine environmental conditions, depending upon the location at any given point during Cenomanian

time. The geographical area was probably similar (environmentally and topographically) to the current conditions found along the Texas and Louisiana Gulf Coast.

8. The occurrence of desmid-like vegetative bodies is most abundant in the organic-rich facies of the lower Eagle Ford Shale (Cenomanian in age) and may be significant (as a marker) in helping to identify this particular zone (facies) when analyzing visual kerogen and/or palynological slides.

9. The repetitious nature of the sediments and floral suite in the lower Eagle Ford Shale suggests that the climate and environment of deposition was fairly uniform during this period of 5 to 6 million years.

10. The algae *Botryococcus braunii* is better observed with the a microscope using a 40X objective in brightfield illumination while the desmid-like vegetative bodies are better observed using a 100X objective in phase-contrast illumination.

Acknowledgements

The writers thank Dr. Brian Brister of Gunn Oil Company, Wichita Falls, Texas for all of his helpful suggestions that were made during the preparation of this manuscript. We also express our appreciation to Professor Drs. Peter Coesel, John Kinross, and Alfred van Geest for their help in obtaining extant desmid photographs. Our appreciation is also to M.C. van Westen, and William Bourland, for use of their photographs in this manuscript. The outstanding video showing the reproduction process in the desmid *Micrasterias* by Dr. Jeremy David Pickett-Heaps is also gratefully acknowledged. The authors also thank Rod Lewis, President and CEO, Lewis Energy Group, San Antonio, Texas, and Stan Jumper, Vice President, Exploration and Development, Lewis Energy Company, Dallas, Texas, for allowing this material to be published. To Art Donovan and Scott Staerker, BP, Houston, we deeply appreciate their kindness in allowing us to be included as participants in the Field Trip Group, sponsored by BP, that examined various outcrop locations of the Eagle Ford Shale along U. S. Highway 90 in February 2011.

References

Bradley, W.H., 1946, Coprolites from the Bridger Formation of Wyoming, their composition and microorganisms: American Journal of Science, v. 244, p. 215-339.

Brook, A.J., 1971, The Phytoplankton of Minnesota Lakes - a preliminary survey: Water Resources Research Center, University of Minnesota, Bulletin, v. 36, p. 1-12.

Brook, A.J., 1981, The Biology Of Desmids: Botanical Monographs, v. 16, University of California Press, Blackwell Scientific, Oxford, United Kingdom, 276 p.

Brown, C.W., and R.W. Pierce, 1962, Palynologic correlations in Cretaceous Eagle Ford Group, Northeast Texas: Bulletin of the American

Association of Petroleum Geologists, v. 46/12, p. 2133-2147.

Christopher, R.A., 1982, The Occurrence of the *Complexiopollis-Atlanopollis* Zone (Palynomorphs) in the Eagle Ford Group (Upper Cretaceous) of Texas: Journal of Paleontology, v. 56/2, p. 525-541.

Coesel, P.F.M., 1983, The significance of desmids as indicators of the trophic status of freshwaters: Schweizerische Zeitschrift fur Hydrologie, v. 45, p. 388-394.

Dana, J.D., 1863, Manual of Geology: Treating of the principals of the science with special reference to American Geological History, for the use of Colleges, Academics, and School of Science: Theodore Bliss and Company, Philadelphia, USA and Trubner and Company, London, United Kingdom, 798 p.

Donovan, A.D., W. Li, A. Pramudito, and T.S. Staerker, 2011, Sequence stratigraphy of the Eagle Ford Boquillas formation in the outcrops of West Texas and subsurface of South Texas: Houston Geological Society Bulletin, v. 54/2, p. 39, 41.

Gerrath, J.F., 2003, Conjugating green algae and Desmids, *in* J.D. Wehr, and R.G. Sheath, Freshwater Algae of North America: Ecology and Classification: p. 353-383.

Gessner, F., 1962, Der Elektrolytgehalt des Amazonas: Archiv für Hydrobiologie. v. 58, p. 490-499.

Gessner, F., and Simonsen, R., 1967, Marine Diatoms In The Amazon?, *in* Limnology and Oceanography, v. 12/4, October 1967.

Houston Chronicle, The Eagle Ford Play, October 6, 2009, v. 108/358, p. 1, Houston, Texas, USA.

Lock, B.E., and L. Peschier, 2006, Boquillas (Eagle Ford) upper slope sediments, west Texas: Outcrop analogs for potential shale reservoirs: Gulf Coast Association of Geological Societies Transactions, v. 58, p. 491-508.

Nygaard, G., 1949, Hydrobiological studies on some Danish ponds and lakes, Part 2: The quotient hypothesis and some new or little known phytoplankton organisms: Det Kongekuge Danske Videnskabemes Selskab, Biologiske Skrifter, v. 7/1, p. 1-293

Schwab, K.W., G.S. Bayliss, M.A. Smith, and N.B. Yoder, 2011, Dwarf Hepatic Floral Fragments (Possibly Liverworts) from the Upper Mississippian Barnett Shale in the Fort Worth Basin of North Central Texas: AAPG Search and Discovery, Article #70091. Web accessed 25 October 2011, http://www.searchanddiscovery.com/documents/2011/70091schwab/ndx_schwab.pdf

Tschudy, R.H., 1969, Relationship of palynomorphs to sedimentation, *in* R.H. Tschudy, and R.A. Scott, (Eds.) Aspects of Palynology, John Wiley and Sons, Inc., New York, USA, p. 79-96.

Waggoner, B.M., 1994, An aquatic microfossil assemblage from Cenomanian amber of France: Lethaia: An International Journal of Paleontology and Stratigraphy, v. 27/1, p. 77-84. DOI;10.1111/j.1502-3931.1994.tb01559.x

Wehr, J.D., and R.G. Sheath, 2003, Freshwater Algae of North America, Ecology and Classification: A Volume in the Aquatic Ecology Series, Academic Press, and Imprint of Elsevier, 918 p.

West, W., and G.S. West, 1909, The British freshwater phytoplankton with special reference to the desmid plankton and the distribution of British desmids: Proceedings of The Royal Society B-Biological Sciences, v. 81, p. 165-206.

Websites

Blakey, R., 2011, Paleogeography and geologic evolution of North America, *in* Colorado Plateau Geosystems, Inc., Reconstructing the Ancient Earth: Web accessed 28 November 2011 (http://cpgeosystems.com/paleomaps.html).

Bourland, W., 2011, Micro*Scope: Web accessed 28 November 2011, http://starcentral.mbl.edu/microscope

Chelys, 2011, Internet resource: Web accessed 28 November 2011, www.chelys.it.

Eomap GmbH & Co. KG, 2009, EOMap: February 13, 2009, Web accessed 28 November 2011, http://.eomap.com/

Kinross, J., 2011, The Algal Web: Web accessed 28 November 2011, http://www.algalweb.net/algweb2.htm

Parmentier, J., and W. van Egmond, 2007, Gallery of Desmids: Microscopy-U.K. Host of Micscape Magazine: Web accessed 28 November 2011, http://www.microscopy-uk.org.uk/mag/artjan01/des2.html

NOAA, 2011, NOAA Photo Library: Web accessed 28 November 2011, http://www.photolib.noaa.gov/htmls/nerr0021.htm

van Geest, A., 2011, Digital Image Collection of Desmids: Web accessed 28 November 2011, http://www.digicodes.info/index.html

van Westen, M., 2011, Desmids of Drenthe: Web accessed 28 November 2011, http://desmids.science4all.nl/?Desmid_Pictures

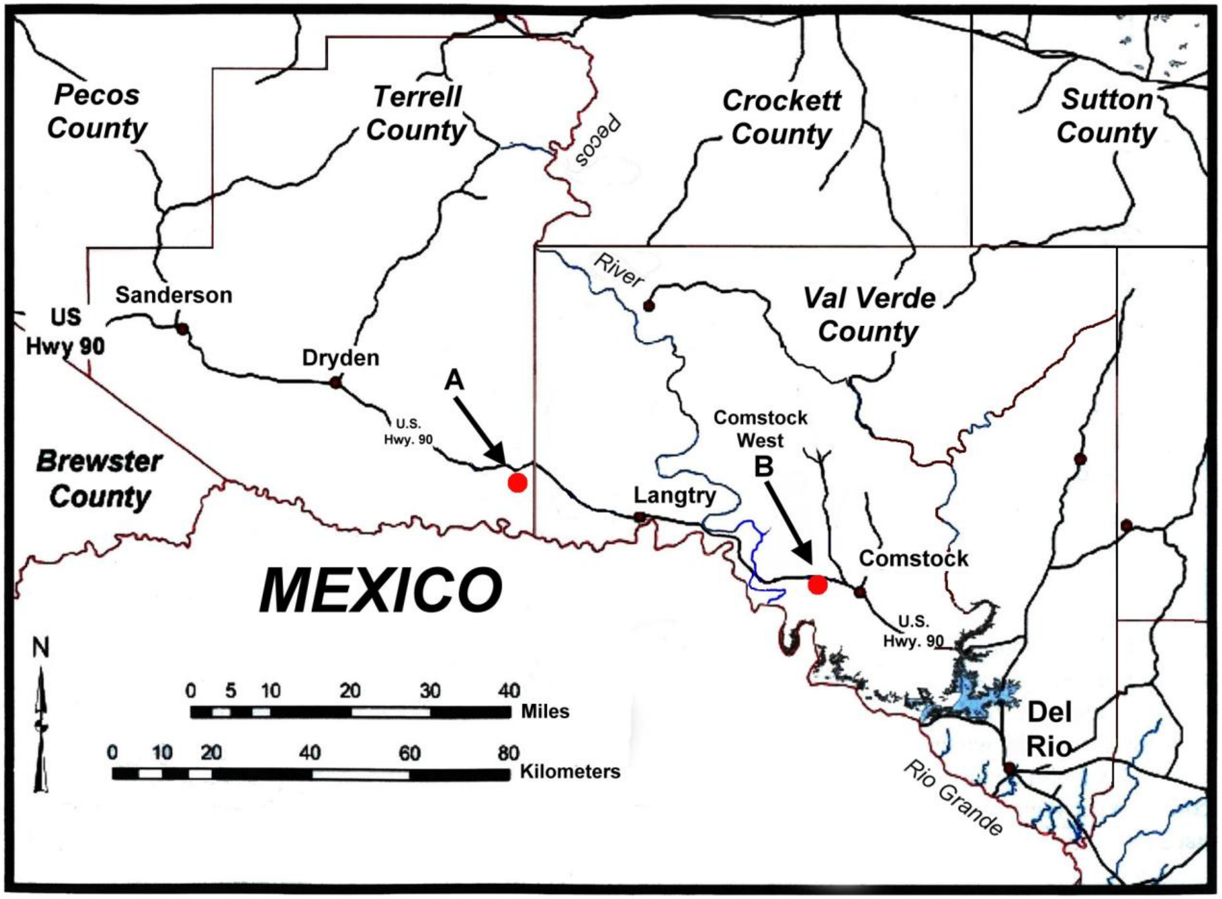

Figure 1. Map of south Texas showing outcrop locations, areas A and B, which were examined in this study.

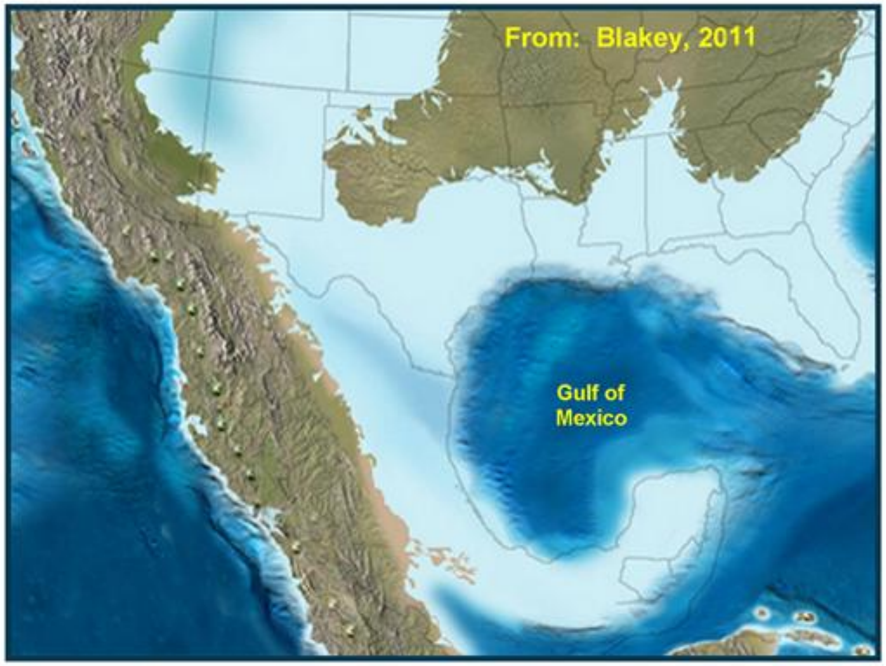

Figure 2A. Paleogeographic map of North America, 85 Ma (Blakey, 2011).

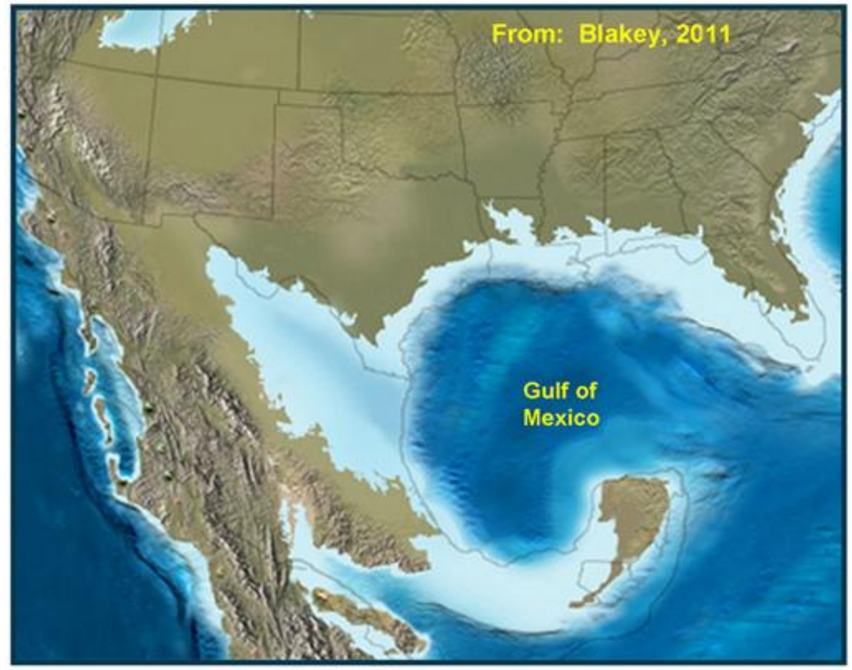

Figure 2B. Paleogeography of North America, 100 Ma (Blakey, 2011).

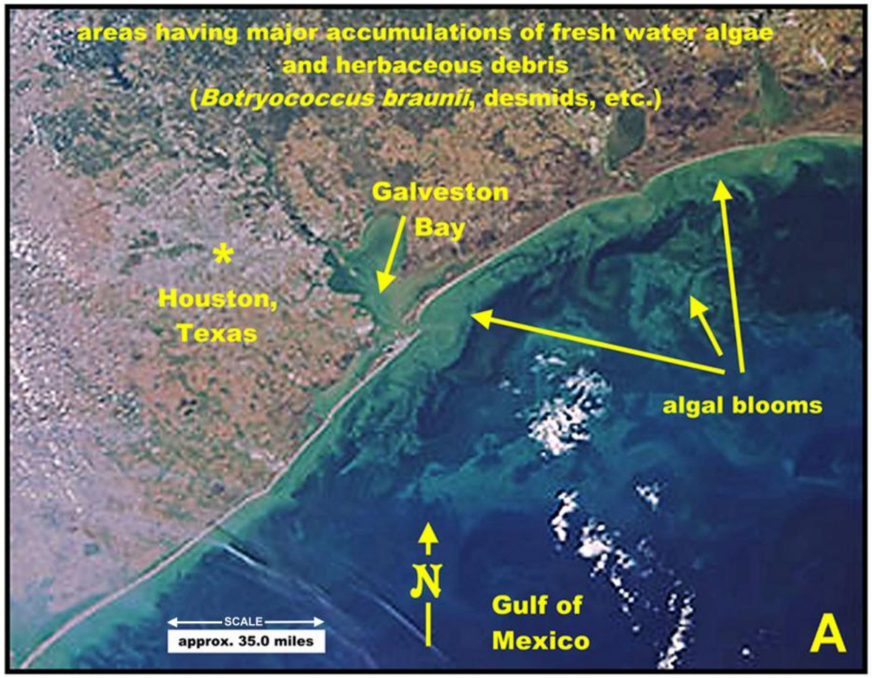

Figure 3A. Photograph of upper Texas coast and western Louisiana, showing algal blooms (Chelys [www.chelys.it]).

Figure 3B. Same photograph as in Figure 3A, without text. (Chelys [www.chelys.it]).

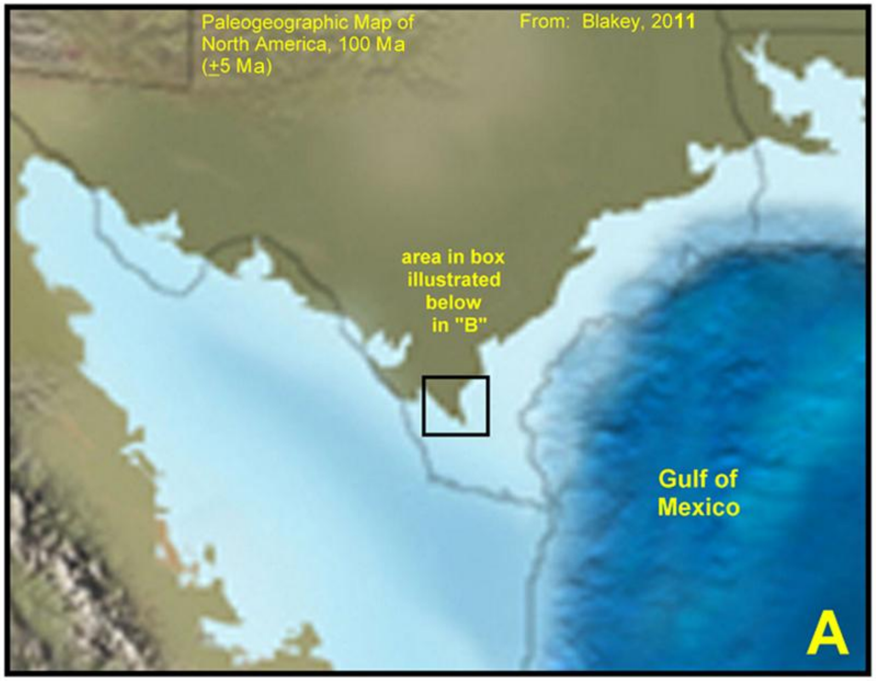

Figure 4A. Paleogeographic map of Texas, 100Ma (Blakey, 2011).

Figure 4B. Modern estuarine environment (NOAA, 2011).

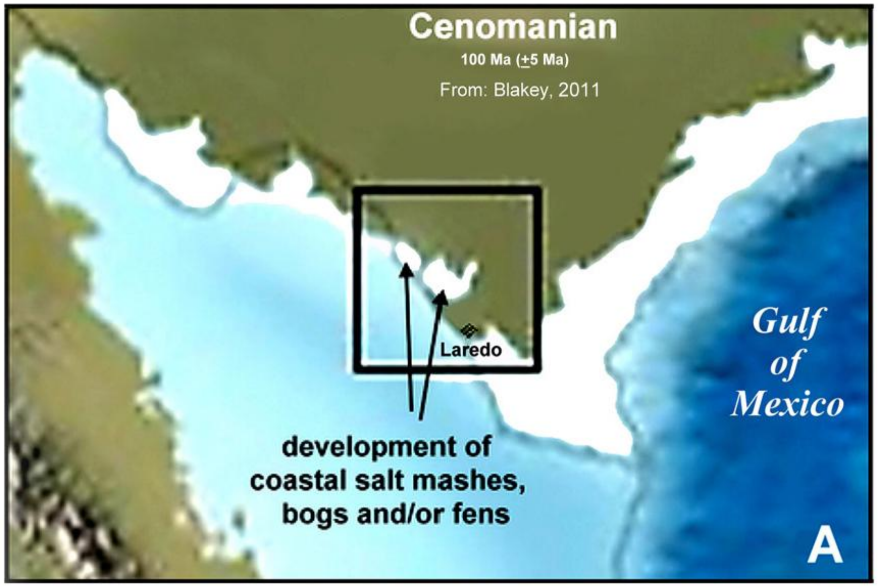

Figure 5A. Paleogeographic map of Texas, 100 Ma (Blakey, 2011).

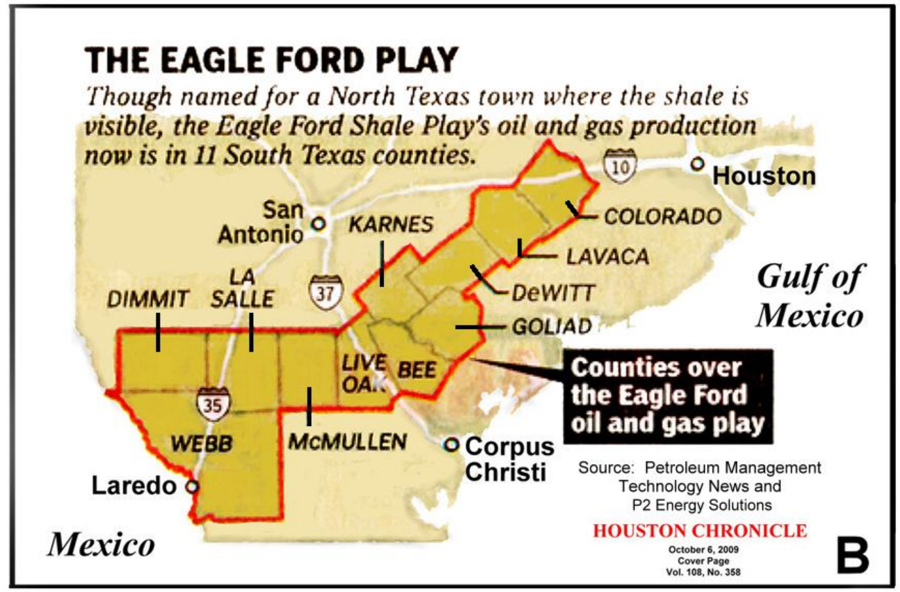

Figure 5B. Map showing the current Eagle Ford Shale "Trend" paralleling the Cenomanian coastline (Houston Chronicle, October 6, 2009).

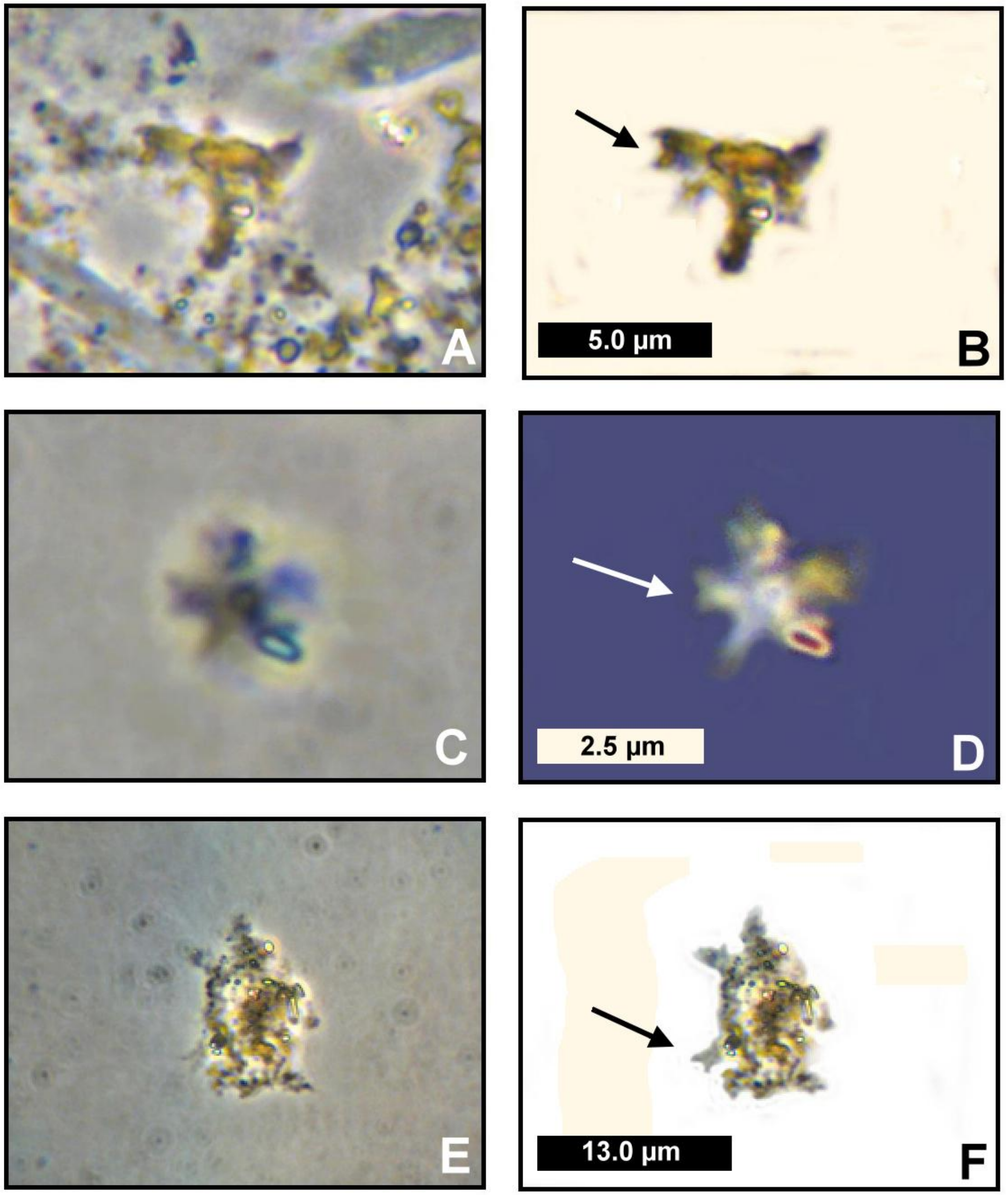

Plate 1. Photomicrographs from Comstock west (1), Val Verde County.

Figures A-B. Apical view of a desmid-like vegetative algal body, probably *Staurastrum* sp**.** Arrow points to well developed bifurcated tip of vegetative process. Photographed in phase-contrast illumination. Figure B shows the desmid-like vegetative body with the finely disseminated organic matter removed. Lower Eagle Ford Shale, Val Verde, County, Texas.

Figures C-D. Photomicrograph of a 5- to 6-rayed desmid-like fossil, probably a specimen belonging to the genus *Staurastrum*. One of the processes is covered, in-part, by a mineral fragment. One can clearly see the 5-rayed pattern. A possible 6th ray is in the center of the specimen perpendicular to eyesight (it appears as a small dot). Of importance is the bifurcated terminal process of the ray that is center left (arrow). This is one of the distinguishing features of the desmids. Both photomicrographs were taken in phase-contrast illumination. The lighting in Figure D was modified with Adobe Photoshop Element in order to help bring out some of the detail of the desmid. Lower Eagle Ford Shale, Val Verde Co., Texas.

Figure E-F. Photomicrograph illustrates a six-rayed desmid-like fossil, probably belonging to the genus *Staurastrum*. Note the well developed bifurcated process in the lower left portion of the vegetative cell (arrow). The dark colored (black) pustules (spots) that cover the body of the vegetative cell are interpreted to be pores or fine hairs. The illustrated specimen is shown in phase-contrast illumination. The background debris has been removed in Figure F. Lower Eagle Ford Shale, Val Verde County, Texas.

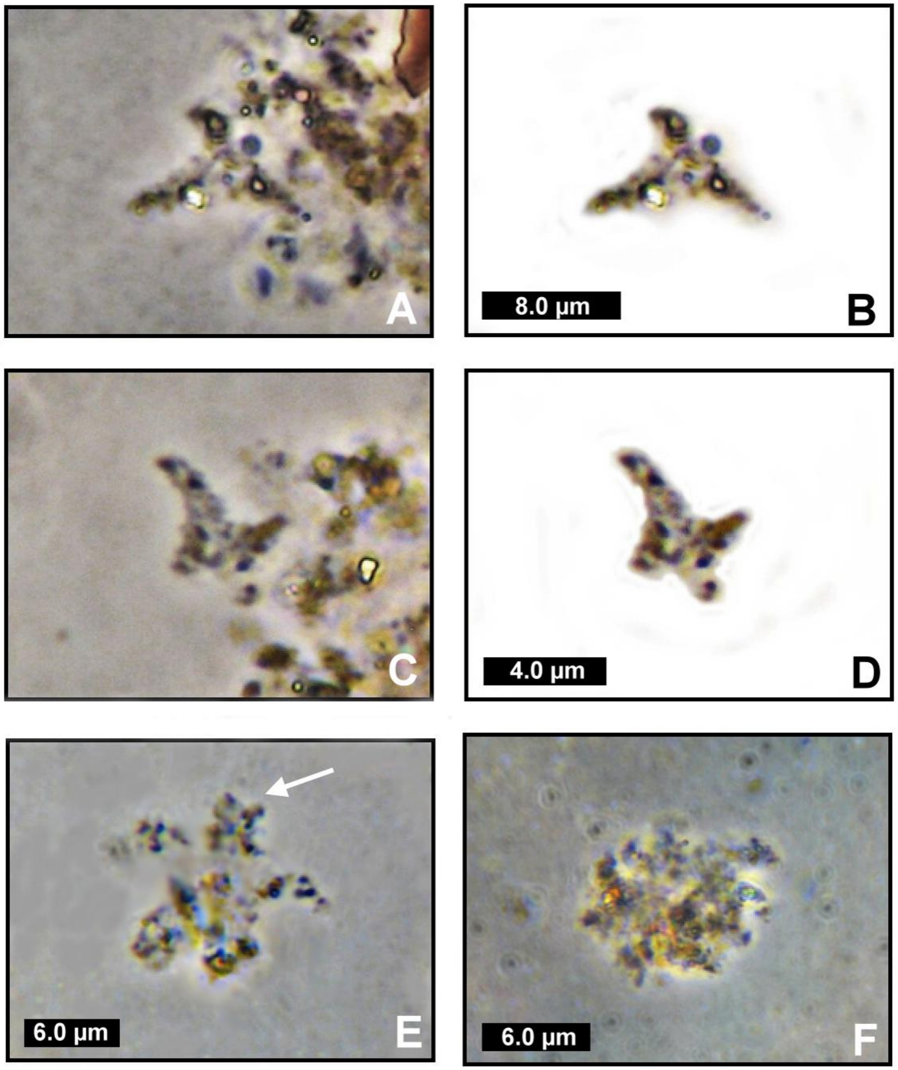

Plate 2. Photomicrographs from Comstock West (2), Val Verde County.

Figures A-B. The photomicrograph shows an apical view of a 3- to 4-rayed desmid-like vegetative cell. We interpret this specimen to be somewhat similar to the extant desmid *Staurastrum micron* illustrated in Figure C, Plate 8. Both photomicrographs are illustrated in phase-contrast illumination. In Figure B the background material was removed in order to present a clearer picture of the fossil. Lower Eagle Ford Shale, Val Verde County, Texas.

Figures C-D. These photomicrographs illustrate what the authors interpret to be a desmid-like fossil belonging to genus *Staurastrum.* The fossil specimen is shown in phase-contrast illumination. In Figure D, the background material was removed in order to present a clearer picture of the fossil. Note what we believe to be cellular structures covering the vegetative cell (they appear as dark colored nodes or pustules). Lower Eagle Ford Shale, Val Verde County, Texas.

Figure E. The fossil in the photomicrograph is interpreted to be a 5- to 6-rayed desmid-like algal cyst belonging to the genus *Staurastrum*. Five of the six rays can clearly be seen forming a radial pattern. The top-most process (ray) appears to be bifurcated (arrow). The sixth ray is perpendicular to the camera in the center of the specimen and is out of focus. It is represented by a small knob-like structure. If one looks closely, it appears that one of the terminal ends of a process is open and star-shaped (arrow).The illustrated specimen is shown in phase-contrast illumination. Lower Eagle Ford Shale, Val Verde County, Texas.

Figure F. The photomicrograph shows what the writers interpret to be a multi-rayed desmid-like algal cyst, *Staurastrum sp.* or *Micrasterias sp.,* having 10 processes (rays) or more. One can clearly see a line of demarcation in a southeast-northwest direction. Whether this is due to preservation or is an indication of the presence of an ismuthus is not known. The fossil, shown in this photomicrograph, is illustrated in phase-contrast illumination. Lower Eagle Ford Shale, Val Verde County, Texas.

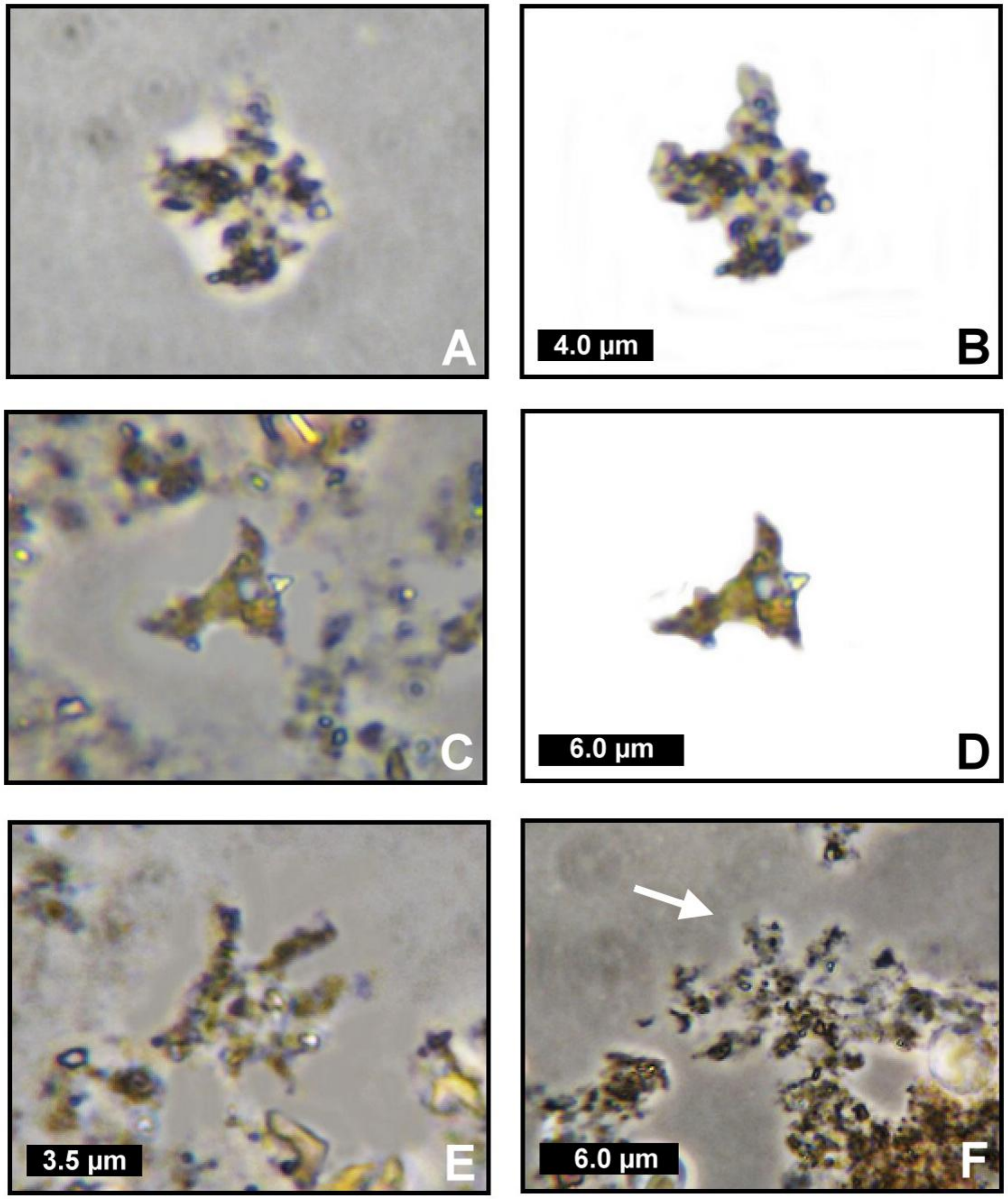

Plate 3. Photomicrographs from Comstock West (3), Val Verde County.

Figures A-B. Fossil specimen of a 4- to 6-rayed desmid-like form interpreted to belong to the genus *Staurastrum*. Note the thickened areas on the surface of the vegetative cell. These features (?pustules) may indicate the presence of cells or pores on the vegetative cell body of the alga itself. They could also represent thickened areas of mucilage formation. Photomicrograph of fossil shown in phase-contrast illumination. Figure B is the same photomicrograph as Figure A except the background area has been lightened to enhance the detail of the morphology of the fossil specimen. Lower Eagle Ford Shale, Val Verde County, Texas.

Figures C-D. An apical view of a poorly preserved desmid-like vegetative cell, possibly a fragment of *Staurastrum* sp. Though not shown clearly, the terminal end of the process (ray) to the left shows it to be bifurcated. The center of the desmid is marked by a highlighted spot, possibly marking the location of a fourth ray. The illustrated fossil specimen is shown in phase-contrast illumination. Figure D is the same photomicrograph as Figure C except the background area has been cleared of all the extraneous debris and lightened to show the fossil more clearly. Lower Eagle Ford Shale, Val Verde County, Texas.

Figures E-F. Photomicrographs of two different multi-rayed desmid-like algal forms interpreted as belonging to the genus *Staurastrum*. Both specimens were photographed in phase-contrast illumination. Lower Eagle Ford Shale, Val Verde County, Texas.

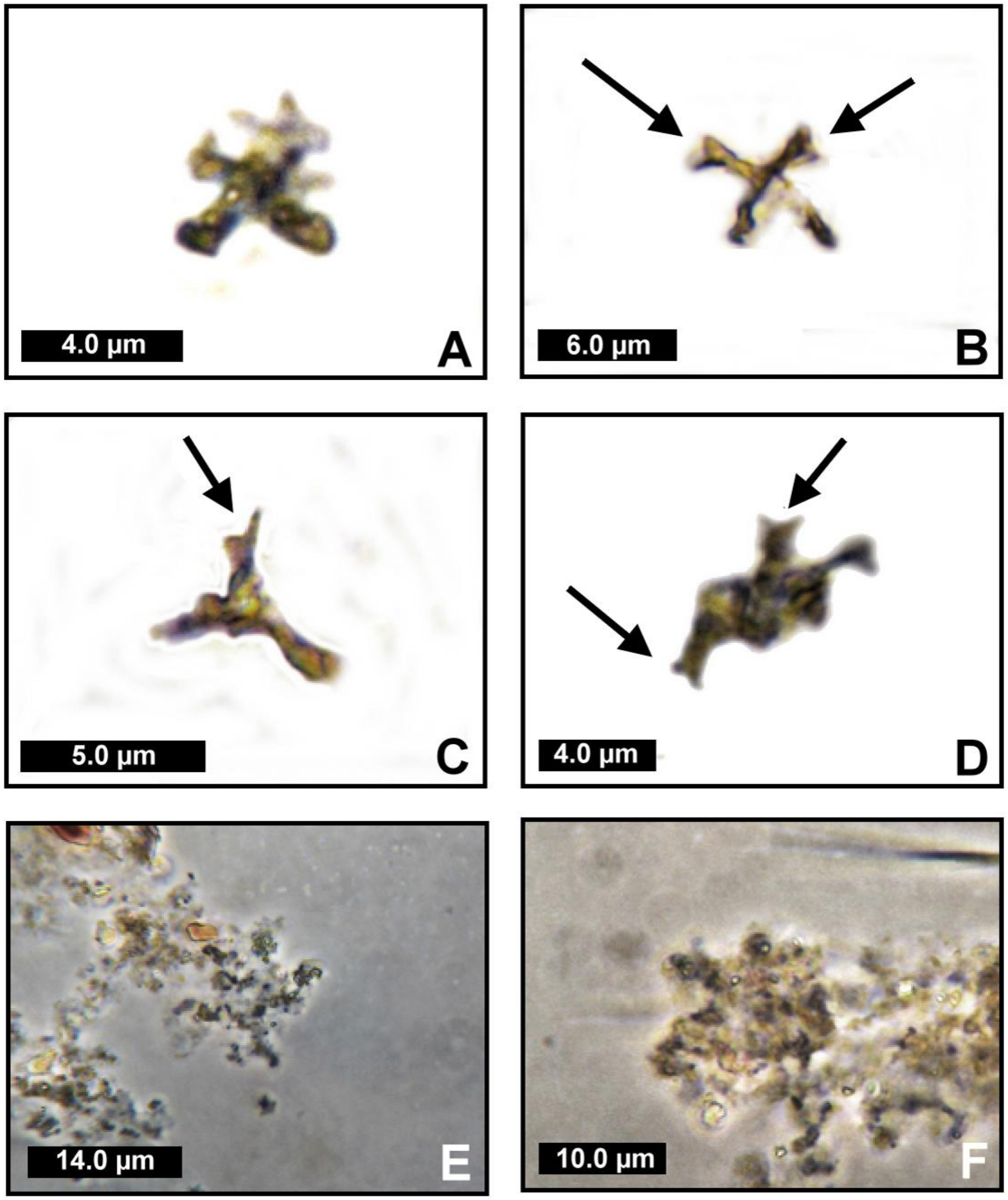

Plate 4. Photomicrographs from Comstock West (4), Val Verde County.

Figures A-D. Photomicrographs show the apical view of 3-rayed and/or 4-rayed desmid-like algal fossil, possibly belonging to the genus *Staurastrum*. With the exception of Figure A, the other illustrated specimens have what appear to be well developed bifurcated tips (arrows) at the terminal ends of their processes (legs). All four specimens were photographed using phase-contrast illumination. The background of each photomicrograph has been whitened to help enhance the detail of the individual fossils. Eagle Ford Shale, Val Verde County, Texas.

Figure E. Photomicrograph illustrates a 5-rayed (possibly 6-rayed) desmid-like vegetative cell interpreted to belong to the genus *Staurastrum*. The fossil, as shown, is photographed in phase-contrast illumination. Eagle Ford Shale, Val Verde County, Texas.

Figure F. Photomicrograph illustrates what is interpreted to be a 5-rayed or 6-rayed fossil desmid-like fossil belonging to the genus *Staurastrum*. The process of the vegetative cell are thicker than those illustrated in the specimen in Figure E. Note what appears to be a "node" in the center of the fossil desmid. This may be either a piece of debris or an indication of a 6th ray. The fossil was photographed in phase-contrast illumination. Eagle Ford Shale, Val Verde County, Texas.

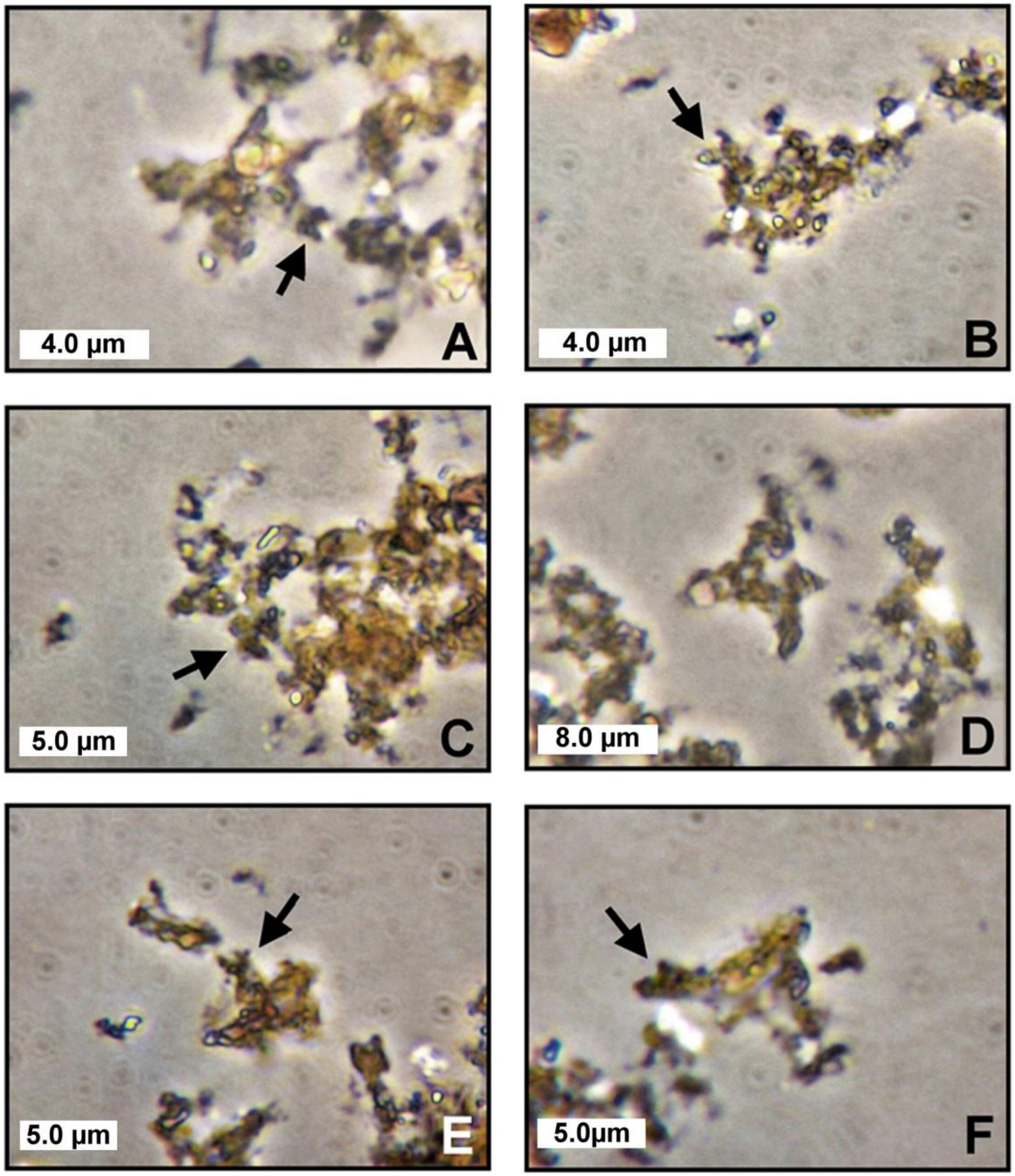

Plate 5. Photomicrographs of desmids (1), Terrell County.

Figures A-B. Possible *Staurastrum* sp. 5- or 6 rayed. Arrow points to a well developed bifurcated and/or trifurcated tip on the appendage (leg) or process. The large and well defined bifurcating tips suggest that this form may be related to the plasmodium desmid *Staurastrum brachiatum*. Photographed using phase-contrast illumination. Lower Eagle Ford Shale, Terrell Co., Texas.

Figures C-E. Specimens of what appears to be a 4- to 6-rayed *Staurastrum* sp. The arrows point to what may be the bifurcated tips at the end of the processes. This is one of the distinctive features of some of the planktonic desmids. Photographed using phase-contrast illumination. Lower Eagle Ford Shale, Terrell Co., Texas.

Figure F. An apical view of a desmid-like 3- to 4-rayed vegetative algal cell interpreted as belonging to the genus *Staurastrum.* Because vegetative cells can often appear as a "chain-like" structure, there is always the possibility that some of the vegetative cells are stacked on top of one another, producing what appears to be 8- to 10-rayed forms. Note the similarities between this form and the desmid *Staurastrum micron* shown in Figure C, Plate 8. The arrow points towards what once was the bifurcated tip of one of the vegetative cell processes (legs). Photographed using phase-contrast illumination. Lower Eagle Ford Shale, Terrell Co., Texas.

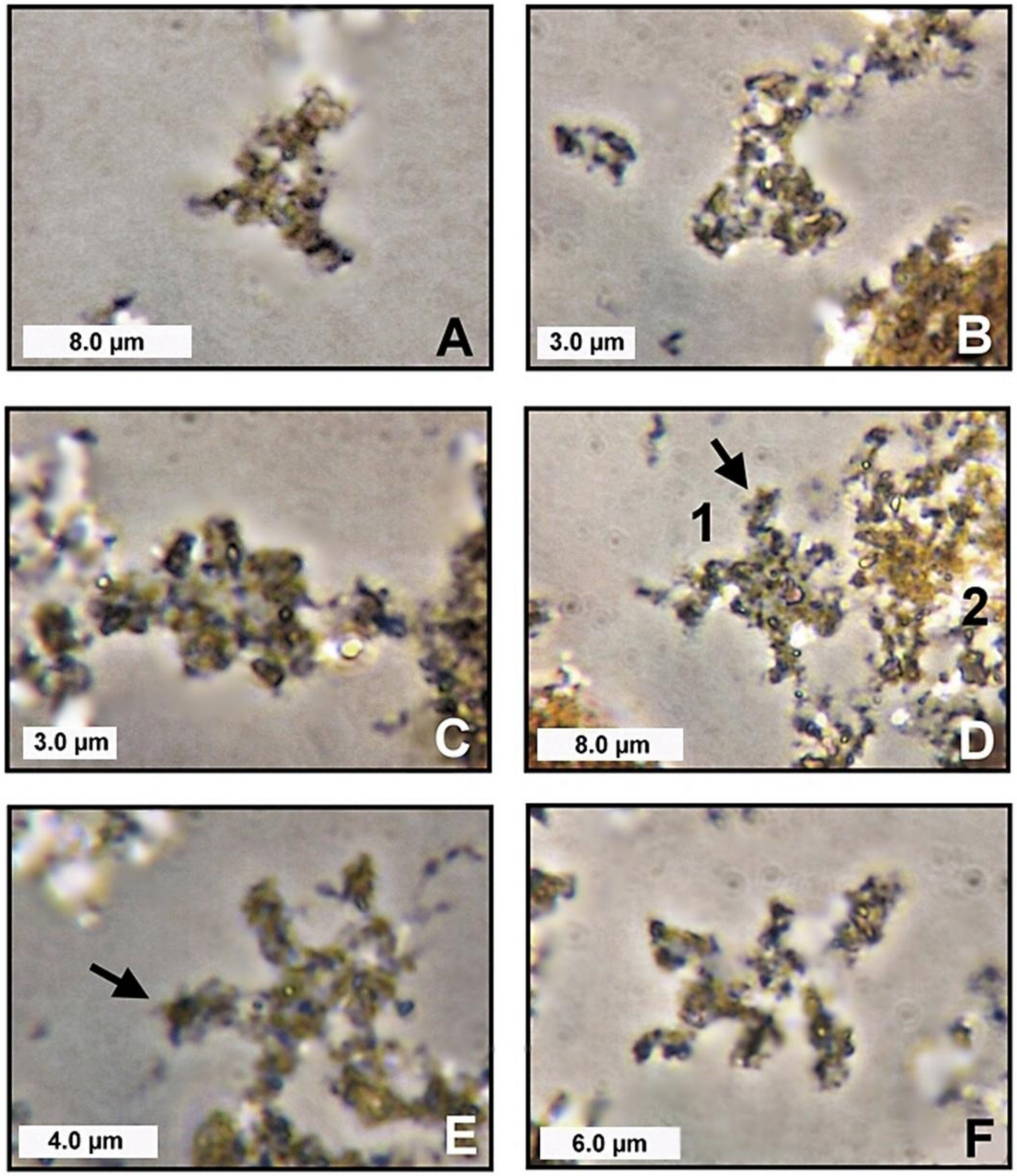

Plate 6. Photomicrographs of desmids (2), Terrell County.

Figures A-B. An apical view of a desmid-like vegetative cell that is interpreted to belong to the genus *Staurastrum*. These specimens have similar morphology, in part, to *Staurastrum micron* shown in Figure C, Plate 8. Photographed using phase-contrast illumination. Lower Eagle Ford Shale, Terrell Co., Texas.

Figure C. The figure shows what appears to be a 5- or 6-rayed form of *Staurastrum* sp. There may be another ray, or process, folded below the surface of the desmid. It appears similar to the extant genus *Staurastrum dilatatum* illustrated in Figure F, Plate 8. Photographed using phase-contrast illumination. Lower Eagle Ford Shale, Terrell Co., Texas.

Figure D. The photograph shows what appears to be two 5- to 6- rayed specimens of *Staurastrum*sp. The writers interpret these microalgae as belonging to the genus *Staurastrum,* possibly related to *S. brachiatum,* which is shown in Figure E, Plate 8. Photographed using phase-contrast illumination. Lower Eagle Ford Shale, Terrell Co., Texas.

Figures E-F. 6-rayed forms of a desmid-like form interpreted to belong to the genus *Staurastrum.* Please notice the well defined trifurcated tip on one of the appendages of the illustrated specimen in photograph E. These two forms have a similar morphology, to the specimens of *Staurastrum sp*., illustrated in Figure D. Photographed using phase-contrast illumination. Lower Eagle Ford Shale, Terrell Co., Texas.

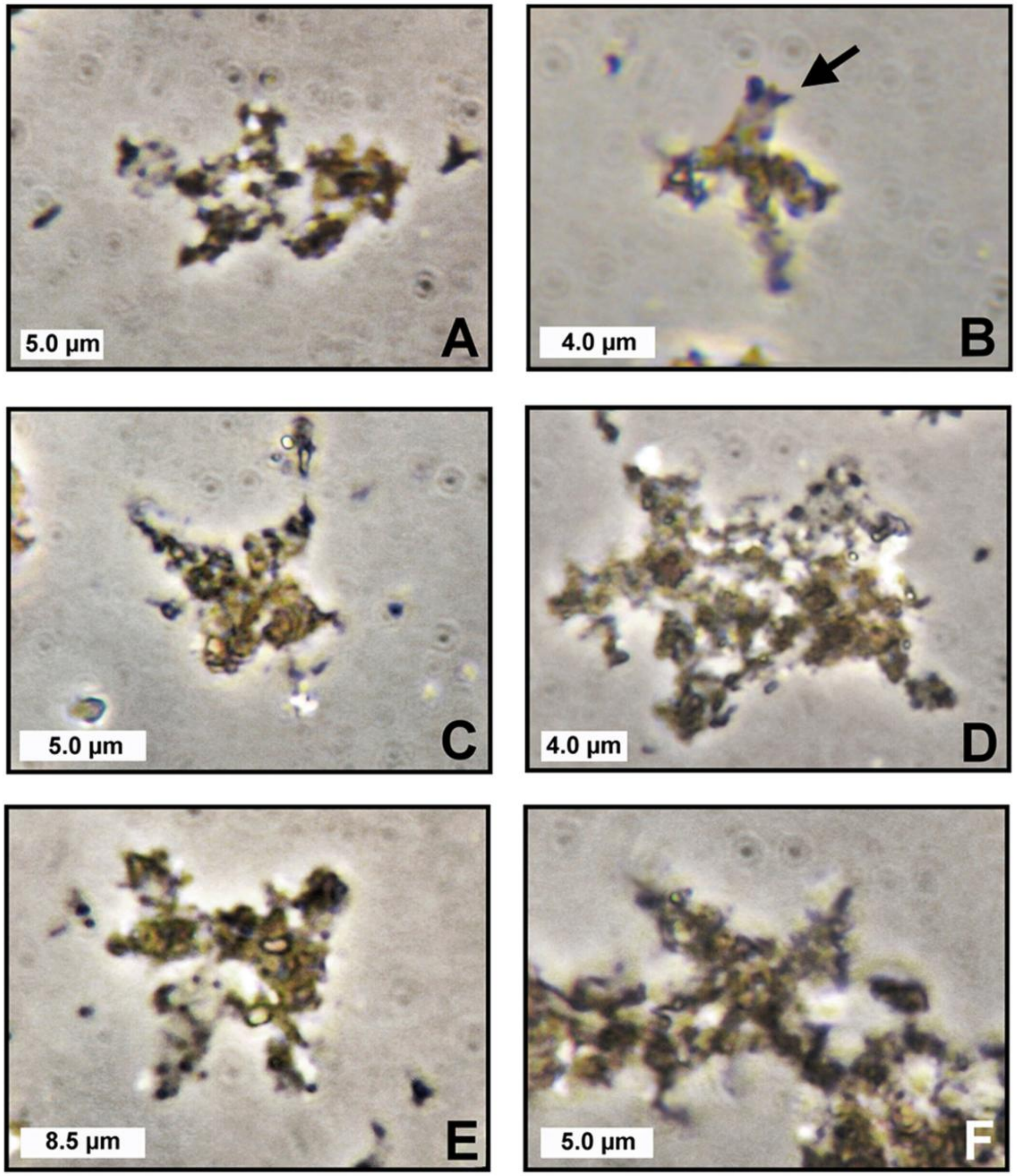

Plate 7. Photomicrographs of Desmids (3), Terrell County.

Figures A-B. Photomicrographs of a 5- or 6-rayed desmid-like fossil that is interpreted to belong to the genus *Staurastrum*. Photographed using phase-contrast illumination. Lower Eagle Ford Shale, Terrell Co., Texas.

Figures C, E-F. This peculiar form of what is interpreted to be *Staurastrum* sp. has a rather unique shape. It usually has a distinctive "bow-tie" or "butter-fly" shape to it. Note the ornamentation on the vegetative cells of the specimen in Figure C. The writers interpret these to be related to pore-openings on vegetative cell itself and/or possible remnants of spine-like structures. We think that it has a similar appearance to the desmids species *Staurastrum lunatum* (not shown) and/or *Staurastrum avicula,* shown in Figures A and B, Plate 8. Photographed using phase-contrast illumination. Lower Eagle Ford Shale, Terrell Co., Texas.

Figure D. Unidentified desmid-like specimen interpreted to belong to desmid genus *Staurastrum.* The authors believe that this form may initially have been similar to the extant desmid *Staurastrum brachiatum*. Photographed using phase-contrast illumination. Lower Eagle Ford Shale, Terrell Co., Texas.

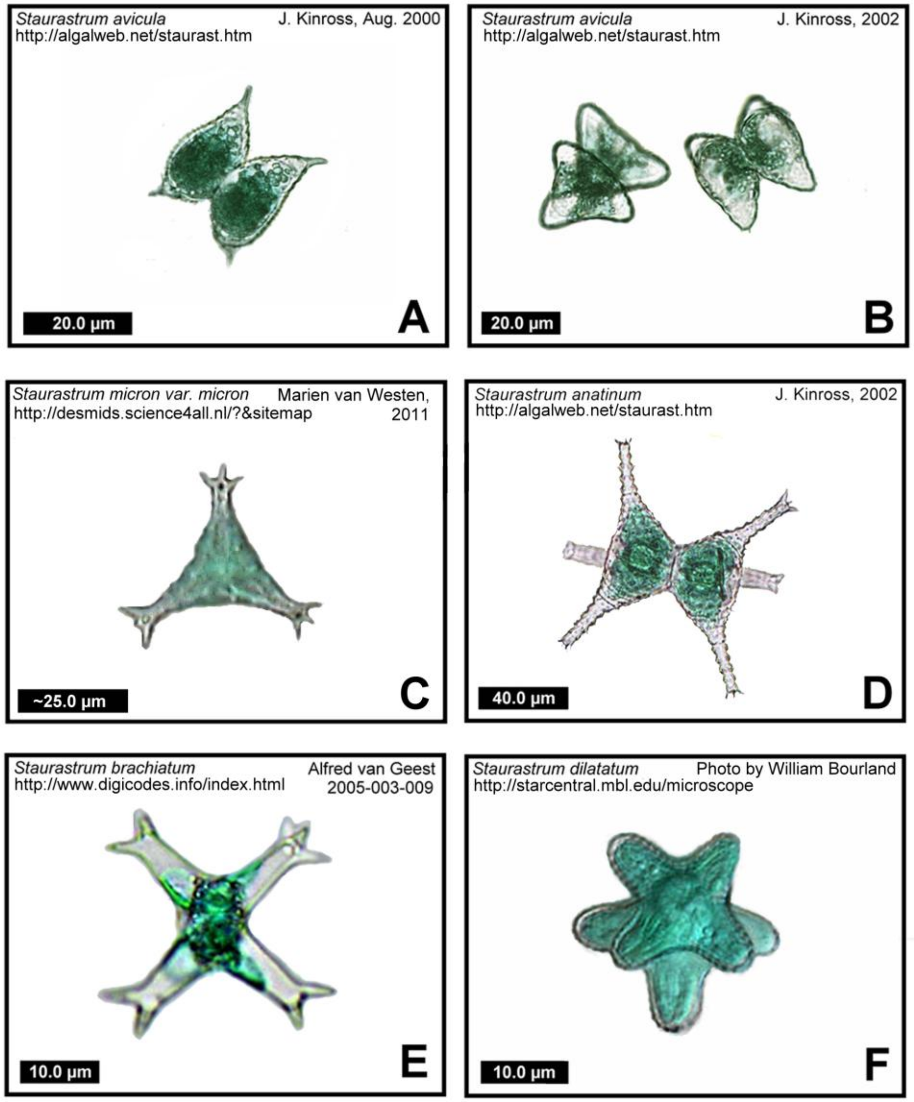

Plate 8. Photomicrographs of extant desmids.

Figures A-B. Photomicrographs of the extant desmid *Staurastrum avicula* as illustrated by Dr. John Kinross (http://algalweb.net/staurast.htm). Photographed using brightfield illumination.

Figure C. Photomicrograph of the extant desmid *Staurastrum micron* var. *micron*. This image, an apical view of *S. micron*, was taken by, and is property of, Marien van Westen, who granted permission for it to be used only for comparative purposes. Specimen was photographed using brightfield illumination. Access at: Desmids of Drenthe: http://desmids.science4all.nl/?Desmid_Pictures and http://desmids.science4all.nl/?Desmid_Pictures::Staurastrum&pic=45&page=0.

Figure D. Photomicrograph of *Staurastrum anatinum* as illustrated by Dr. John Kinross (http://algalweb.net/staurast.htm). Typically this form has 6 well defined processes which have bifurcated or trifurcated tips. Photographed using brightfield illumination.

Figure E. Photomicrograph of *Staurastrum brachiatum* (with permission of Dr. Alfred van Geest, June 2011) (http://www.digicodes.info/index.html) Photographed using brightfield illumination. Original photograph may be viewed at: http://www.digicodes.info/fig/2005003009F1A0500_01.jpg.

Figure F. Photomicrograph of *Staurastrum dilatatum*. Note the rounded terminal ends of the processes. A similar looking desmid-like fossil was found by the authors and is illustrated in Figure C, Plate 6. Note: This image is used with permission of micro*scope, a communal web site that promotes information on the biodiversity of microbes (http://starcentral.mbl.edu/microscope). The original photograph, property of William Bourland, was taken using an interference-contrast microscopy. The photograph, accessed October 2011, may be viewed at: http://starcentral.mbl.edu/microscope/portal.php?pagetitle=assetfactsheet&imageid=22290.