

# **Mushroom and Broccoli-Head Shaped Algal Fragments from the Eagle Ford Shale of South Texas and Coahuila, Mexico\***

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## **Abstract**

This paper describes and illustrates a group of mushroom- and broccoli-head-shaped algal fragments that have been observed in the Eagle Ford Shale (upper Cenomanian - Turonian) of seven wells that were examined from South Texas and one from Coahuila, Mexico. These vegetative cellular structures are often found as fragments which have been broken and separated from the main algal body. They generally have a well-developed "head" and "stalk" and are in some places found in association with zoospores, foraminifer's linings and other algal constituents. The umbrella-shaped vegetative protuberances, based on what the writers have observed, are interpreted as being developed from specialized cells located along a cellular, threadlike algal filament. They emerge from the algal filaments, and/or colony, as stem-like structures. Although some are found still attached to the host, most have been "torn" away and occur as isolated entities.

These morphologically distinct structures are common constituents in the organic-matter residues extracted from the lower portion of the upper Eagle Ford Shale and throughout the entire lower Eagle Ford Shale. The writers have not observed them, as of this writing, in the Austin Chalk (Coniacian to Campanian), Buda (Cenomanian) and/or Del Rio formations (Cenomanian). Similar looking fossil fragments have been found and illustrated by these authors in core samples that were examined from the Upper Mississippian lower Barnett Shale, also an oil-gas-rich formation, located in north-central Texas.

## **Introduction**

Mushroom and broccoli-head-shaped organic constituents, interpreted by the writers as representing the vegetative development stage of unidentified algal colonies, are common constituents in the Eagle Ford Shale (upper Cenomanian -Turonian) of south Texas and Coahuila, Mexico ([Figure 1](#)). These palynomorphs always appear to occur at approximately the same stratigraphic intervals ([Figure 2](#)) in all eight wells

that were examined. The writers have also observed these peculiar forms in the organic-matter residue extracted from well cuttings that have previously been identified by geologists, based on log correlations, as being representative of the Cenomanian Buda and Del Rio stratigraphic sections. These were from a single well, the Mobil-McElroy No. 1, located in south-central Webb County, Texas. When the sample material from the Mobil-McElroy No. 1 was sampled by the senior authors, it was obvious that others had sampled this portion of the stratigraphic section at an earlier date. Consequently, the authors of this article are not sure whether the stratigraphic section is truly representative of the Buda and/or Del Rio Formation at the depth interval we were given. If cuttings samples from the Buda and Del Rio formations were collected, the next question is, "was the material *in situ*?". If the stratigraphic section we examined is in fact the Buda and/or Del Rio Formation, it is the writers' opinion that the mushroom- and broccoli-head-shaped algal debris are most likely contaminants, a result of up-hole caving. In the Mobil-McElroy No. 1, these algal forms are found in association with other organic-matter types that are more typical of the lower Eagle Ford Shale flora than what we have observed in our studies of the Buda or Del Rio Formation. Because we do not have any pertinent drilling information (i.e., casing points, etc.) on the Mobil-McElroy No. 1, we have no idea as to how much of the well borehole is open-hole and how much is cased. [NOTE: Based on a re-interpretation of the visual kerogen and geochemical analyses performed by Schwab and Bayliss, these two authors now believe that the Buda and/or Del Rio section was not represented in the well-cutting samples collected from the Mobil-McElroy No. 1 well and that the section which was examined is dominantly Eagle Ford Shale. The Buda and Del Rio sections may be present but at a slightly deeper interval than what was collected.]

In our examination of well cuttings and core samples from eight wells scattered across some 3000 square miles of South Texas and adjacent northern Coahuila, Mexico, we have observed these unique forms always occurring at approximately the same stratigraphic level ([Figure 2](#)). Based on our observations, the writers are of the opinion that the localized occurrence of these vegetative cells can provide biostratigraphers with another possible "zone" marker for the upper Cenomanian and lower Turonian, in addition to the nannofossils and foraminifers, for this portion of the stratigraphic section. They may also prove to be important environmental indicators regarding the depositional habitat of the organic detritus that was being supplied to the depositional site during Eagle Ford time. Their occurrence with planktonic foraminifera is given major consideration in the interpretation of environment (please refer to [Figure 3](#) and section on depositional environment). Although the writers do not know what group of algae these fragments belong to, they do appear to have a similar morphology to representatives of the cyanobacteria, red algae, and tribophyte algae. The extremely small size of the fossil fragments makes the recognition of their internal morphological details, i.e., the outlines of a cell wall, chloroplasts, etc., extremely difficult, if not impossible, to ascertain using the light microscope. Examples of these isolated vegetative fragments are illustrated in [Figures 4, 5, 6, and 7](#).

The writers find these particular algal elements in association with what are interpreted to be trichomes of cyanobacteria having a morphology that closely resembles the genus *Anabaena*, as illustrated by Missouri State University in their study of the extant algal content of Lake Houston, Texas ([Figure 8 A](#)). The cyanobacteria *Anabaena* sp. is difficult for these writers to distinguish from *Anabaenopsis* sp. Because of this, the fossil specimens on [Figure 8 B-F](#) could be representative of either genus. (See Komarek et al. (2003, p. 169-172) for more detailed information regarding these two genera.) Other less common algal constituents having a morphology that resembles the red alga *Audouinella* sp. may also be present in our sample material ([Figure 9 C, D](#); [Figure 10 A, B](#)). We base our identification and interpretation of the fossil material on a comparison to extant forms illustrated by Sheath (2003, p. 211).

Yoder, a carbonate petrographer and one of the authors of this article, recently took some photomicrographs of several thin sections he prepared of core and well cuttings samples of the Eagle Ford Shale in some of the wells that were examined in this study. Upon enlarging one of Yoder's photomicrographs and viewing it in more detail, it became obvious to the senior author that much of the debris in this thin section was algal in nature. When the algal colonies that were observed in Yoder's photomicrograph are compared to a photomicrograph of the extant algae *Audouinellai*, the two photomicrographs exhibited a similarly well developed cell structure. The cellular structures, although not interlocking, are reminiscent of the chain-maille armor once used by swordsmen for body protection. Because none of the authors are phycologists or trained botanists, we cannot be absolutely sure that the fossil algal components in Yoder's thin section are related to *Audouinella* or some other genus having a similar external morphology. What can be said with certainty is that approximately 60 percent of the detritus in Yoder's photomicrograph, as illustrated in [Figure 11](#) B appears to be algal in nature. [NOTE: Being that this is only one photomicrograph that covers a very limited portion of the thin section itself, the results may vary considerably from one portion of the thin section to another. Since the senior author has not looked at this particular thin section microscopically, he cannot say with absolute certainty whether the entire thin section contains 60 percent algal material or whether just that photographed portion of the thin section contained 60 percent algal debris.]

In addition to the algae just mentioned, the writers have also observed in their organic-matter kerogen slides minute plant-like structures that resemble stems with leaves. Some even appear as an array of flower petals on a stem-like structure ([Figure 10 C-F](#)). Although these forms are rare, they also are more commonly associated with the lower portions of the upper Eagle Ford and throughout the entire lower Eagle Ford Shale. What group of algae these plant-like forms are related to is uncertain.

### **Purpose of Report**

In our review of the literature the writers found very little information regarding the palynology and flora of the upper and lower Eagle Ford Shale (late Cenomanian to early Turonian in age). Although there are a number of papers that discuss the foraminifera and nannofossil assemblages, almost no information exists regarding organic-matter types especially that which describes and illustrates the organic constituents found in the Eagle Ford Shale.

The primary purpose of this manuscript is to illustrate the various mushroom-shaped and broccoli-head forms of vegetative algal cells that these writers have observed in the Eagle Ford Shale of South Texas and their stratigraphic occurrence within the Eagle Ford Formation. A second reason for presenting these data is to bring attention to the fact that the bulk of the Eagle Ford Shale that the writers examined has a very high freshwater to brackish-water algal and amorphous kerogen content. This observation, based on past experience, is often contradictory to many of the results being presented by those doing Rock-Eval Pyrolysis analyses. Many of the same well samples that the writers examined in this well study for the Lewis Energy Group were also submitted to two other service companies for Rock-Eval Pyrolysis analyses. Each service company came up with similar results. The Rock-Eval pyrolysis data from each company categorized the organic matter as being predominantly a Type 3 terrestrial kerogen mix. Their findings are totally inconsistent with our findings. In all eight wells that these writers analyzed, the kerogen type throughout the lower upper and lower Eagle Ford Shale, based on our visual observations, would have to be categorized as being a combination of a Type 1 and Type 2 kerogen mix. The problem with a machine (i.e., Rock-Eval Pyrolysis) analyzing a miniscule amount of crushed rock sample is that it cannot accurately differentiate between the various types of organic constituents that are

present in a rock. Likewise, the Rock-Eval technique cannot define which floral elements are from a freshwater water source and which are from a dominantly marine environment. This is especially important when trying to establish which floral components are cellulose rich, a possible source for much of the early gas being generated in the Eagle Ford, and which are not.

### **F k e w u l q p "**

To the writers' knowledge, no one has reported the occurrence of these mushroom- and broccoli-head-shaped algal fragments which are a common constituent throughout the lower upper Eagle Ford and lower Eagle Ford Shale of South Texas. One reason for this oversight may be because of their small size, usually less than 20  $\mu\text{m}$  in length. This is exacerbated by the fact that many palynologists have their palynology slides prepared from organic-matter residues where all the organic debris less than 20  $\mu\text{m}$  in diameter has been removed by sieving. While sieving fine debris from the organic residue leaves a fairly clean palynological preparation where most of the trilete spores, pollen and dinoflagellates are concentrated on the cover-glass, it removes a large portion of the minute algal types. Sieving is used by palynologists as a means of improving their opportunity for the recognition and/or identification of trilete spores, pollen and dinoflagellates. In organic-matter analyses sieving is not used because it drastically distorts the true percentages of organic-matter types, especially the concentration of finely disseminated algal-amorphous debris that might be present within the sediment being analyzed.

Although the authors are unsure of which group of algae is represented by these particular fossil fragments, several conclusions can be formulated based on what we have observed so far. Mushroom- and broccoli-head-shaped algal forms, interpreted to be reproductive bodies, have been observed as developing from protuberances that are associated with specialized cells located on rhizoid-like, or mycelium-like, filamentous runners, or strands, of what are interpreted to be larger vegetative fragments of the algal colony.

The writers interpret the vegetative structures to first develop as gelatinous protuberances from the main body of the algal colony. During growth, these protuberances form a vegetative structure composed of a stalk and a head ([Figures 12, 13, 14](#)). Both the stalk and head are seen to be composed of a myriad of cells. The writers have observed that the head of the structure has many more cells than what can be seen on the stalk portion of the protuberance. In many cases these algal fragments appear like miniature pieces of broccoli crowns, hence the name broccoli-head algae.

In its early stages of development, the head of the protuberance appears to be made of just a few cells sitting on a gelatinous stem or stalk ([Figure 15 A, B](#)). During the growth of the vegetative structure, the head size increases, giving rise to an abundance of cells. As the stalk and head become more mature, the mushroom- or broccoli-shaped head enlarges and may split, or be partitioned into, two lobes, both containing large masses of cell structures. The concentration of the cells is noticeably more abundant in the head of the vegetative algal structure than in the stem area. We interpret these cell structures, in the head, to be similar to akinetes. An akinete, according to Wehr and Sheath (2003, p. 835), is a thick-walled cell produced by members of several algal classes. It functions as an asexual resting stage and typically is resistant to harsh conditions, especially low temperatures.

The writers postulate that the reproduction of these particular algal types (or of the colony to which these structures belong) is probably by one of two methods. The first method may involve the cell spores (daughter cells) being produced in the broccoli-head structure and then liberated

to become new individuals. The other method may involve reproduction by fragmentation, where the mushroom-shaped and/or broccoli-head forms break away from the parent and are transported to a new location where they become re-attached to a suitable substrate and re-develop into a new colony. Our interpretation is based purely on speculation and the comparison of the fossil material to modern algal forms showing similar morphological features.

Several forms of cyanobacteria have vegetative structures similar to what we have observed in our fossil organic-matter suite, including members belonging to the families Hydrococcaceae and Chamaesiphonaceae; genera *Geitlerbactron* and *Chamaecalyx* and the family Dermocarpellaceae; genera *Cyanocystis* or *Dermocarpella*). According to Komarek (2003, p. 96-102), these genera are represented by both freshwater and coastal marine species.

An example of the cyanobacteria *Geitlerbactron*, based on Komarek's descriptions and photographic examples, is shown in [Figure 9 A](#). The illustration shows what we think to be similar vegetative protuberance-like structures as to what we see in some of our organic matter debris from the Eagle Ford Shale.

In looking at a series of photomicrographs that illustrate extant genera and species of cyanobacteria, published in the Purdue University Cyanobacteria Image Gallery (<http://www-cyanosite.bio.purdue.edu/images/images.html>), the writers did not observe any of the distinctive cell structure that was observed in our fossil material. Cellular structures are also not well defined in any of the photomicrographs presented by Komarek (2003, p. 98). For this reason, the writers have ruled out the cyanobacteria as being a source for the mushroom- and broccoli-head-shaped algal fragments observed in the Eagle Ford Shale.

Of all the groups that these broccoli and umbrella shaped fragments could possibly be associated with, the writers are of the opinion that the fossil material more closely resembles the internal and external morphology observed in the algae. This is especially true when one considers their minute size and the distinct cellular arrangement in, or on, the vegetative protuberances themselves. Of particular interest to us is the similarity in the character of the fossil material to representatives of the Red Algae. This is easily seen when one compares the similarities of our fossil representatives to the photomicrograph of the Red Algae *Chroothoece*, described by Sheath (2003, p. 209) and illustrated by the authors in [Figure 9 B](#).

There are likely many other algae and/or phytoplankton having a similar appearance to what we have observed in our sample material. Likewise, many others could also be considered as a source for these particular morphologically distinct vegetative cells. However, until the writers can find a more complete fossil specimen of the algal colony with these particular structures attached, we can only speculate as to their identification and taxonomic position within the hierarchy of the algae and/or other fungus-like eukaryotic microorganisms (i.e., the Oomycetes).

### **Depositional Environment**

Based on our visual kerogen analyses of the eight wells in this study, the writers find that in the lower upper Eagle Ford the predominant organic-matter types include algal-amorphous kerogen debris and herbaceous plant fragments. In the Eagle Ford Shale sections that we

examined in the eight wells shown in [Figure 1](#), there is a noticeable reduction in the overall amount of herbaceous debris, in comparison to a slight increase in the algal content, as one passes from the upper Eagle Ford Shale into the organic-rich lower Eagle Ford Shale unit. The writers estimate that the overall concentration of herbaceous debris (trilete spores, pollen, plant tissue fragments, cuticle and fungal debris), makes up less than 30 percent of the total organic-matter assemblage in the Eagle Ford Shale. The bulk of the organic detritus, approximately 60 percent of the total organic-matter assemblage, is composed primarily of algae mixed with finely disseminated algal-amorphous debris (the latter may also include some non-descript, finely disseminated herbaceous constituents). Together, vitrinite and inerts are interpreted to make up less than 10 percent of the total organic-matter suite. The authors are of the opinion that the bulk of the organic debris in the upper and lower Eagle Ford is composed almost exclusively of organic matter that is of a freshwater to brackish-water (including marginal marine) origin.

The current view many geologists favor regarding a possible depositional model for the Eagle Ford Shale is that the formation is representative of a deep-water outer-shelf deposit. This particular view is one that is favored by Yoder, a carbonate petrographer and one of the co-authors of this paper. Yoder bases his interpretation on his analyses of thin-section studies. He is of the opinion that because of the large percentages of planktonic foraminifers and calcareous nannofossils that are prevalent in various zones of the Eagle Ford Shale, the sediments had to have been deposited in a deep-water marine environment (i.e., 200 feet or greater). While it is true that planktonic foraminifera do not live in a brackish-water environment, nothing prevents them from becoming trapped in a shallow-marine environment that is suddenly inundated by a freshwater source. This is especially true for a wetlands environment. When this happens, and it has happened on many occasions throughout time, one can and should expect a major "kill" in a significant portion of the planktonic foraminifera population.

Arnold and Parker (2002, p. 109) state that "the depth habitats of individual species (referring to planktonic foraminifera) can seldom be defined within narrow limits because they show diurnal, ontogenetic, seasonal, and long-term variation that is beyond the scope of most studies to fully document." In addition, they state that living planktonic foraminifera have their maximum abundance in the first 50 meters (~164 feet) of the water column in the euphotic zone. Berger's (1971) data also suggest that the greatest concentrations of planktonic foraminifera occurs on the inner continental shelf, not in waters greater than 100 meters deep ([Figure 3](#)). The fact that planktonic foraminifera are present in the shallow-water environments of the Eagle Ford Shale should not be surprising. The planktonic foraminifera, like much of the other plankton, are there because that is where the highest concentration of their food source (i.e., algae), is located.

According to Be (1977), there is an exponential decline in their abundance below this depth. This environmental event can be correlated to, or with, the abundance of nutrients available, prey, and the availability of sunlight (Bijma and Hemleben, 1994). As noted by Arnold and Parker (2002, p. 109), the presence of large numbers of foraminifera (extant genera and species) do not necessarily indicate a deep-water environment. The writers believe that this holds true not only for the extant planktonic foraminifera, but for the fossil genera as well.

The view held by Schwab, Bayliss and Smith regarding the deposition of the Eagle Ford Shale is that much of it, especially the lower organic-rich facies of the Eagle Ford Shale, was deposited in a relatively shallow-water setting. These authors are more inclined towards a depositional environment that was characterized by water depths in the order of 150 feet or less (i.e., an inner shelf environment or possibly within a shallow silled basin). Because of the high organic content, which appears to be similar across a wide area, it is our interpretation that the depositional site was a restricted basin associated with coastal wetlands (i.e., salt marshes, bogs, lakes, ponds, embayments and other coastal marine environments). Marine coastal environments are usually areas that are characterized by having high organic productivity combined with

a diverse environmental variability. This is more consistent with what these writers have observed from their organic-matter (visual kerogen) studies. Furthermore, it correlates well geologically and sedimentologically--when one is trying to explain the high concentrations of freshwater to brackish-water organics mixed with an equally high percentage of organisms which are normally associated with an open marine environment.

What is a coastal salt-marsh environment? In a coastal salt-marsh environment, according to Sen Gupta (2002, p. 143), the inorganic portion of the sediment is interpreted to have been derived from both terrestrial and marine sources. This is what the writers interpret to be the case with a large portion of the Eagle Ford Shale (especially the organic-rich sections). Coastal salt marshes are generally associated with a wetlands and inner shelf type environment. The inner shelf is defined by Sen Gupta (2002, p. 153) as the shallowest part of the continental shelf, and is representative of the area of low tide out to a depth of about 40 meters. Schwab, Bayliss and Smith's reasons for interpreting the Eagle Ford Shale as being a nearshore inner shelf deposit, rather than a deep marine outer shelf type deposit, is based, in part, on the massive amount of organic detritus which is present in the Eagle Ford sediments. This, coupled with the fact that much of the material is relatively coarse in size with many fine structures still intact, is an indication of rapid burial in an anoxic environment. We would not expect this high concentration of organic matter, nor this particle size fraction and preservation, to be associated with an outer shelf environment. If this were truly a deep-water environment, or one that was deposited far from shoreline, we would expect the particle size of the kerogen constituents and the individual preservation of the fine cellular debris to show more evidence of biodegradation and corrosion due to transport and microbial activity.

Sen Gupta (2002, p. 142) states that in a salt-marsh environment, the organic matter being deposited is dependent upon and influenced by the amount of river and stream transport, strength of tidal flow and the effects of wind. He further states that in a typical salt-marsh environment, the organic-matter content of the sediment is highly variable, even in the near-surface part of the substrate, and that one typically encounters anoxic conditions only a few centimeters below the surface except where extensively burrowed.

If this is a salt-marsh environment as we believe it to be (at least in part), such a habitat would be home to a variety of smaller organisms, including foraminifers and possibly calcareous nannofossils if the salinity gradient is great enough. In a salt-marsh setting, the ecosystem contains an abundance of dissolved nutrients, a rich supply of energy-rich reduced compounds and high concentrations of particulate organic debris. Also of importance is the high nitrogen content that is commonly associated with the enormous amount of particulate organic matter being deposited. The latter is perfect for sustaining high concentrations of other phytoplankton, planktonic foraminifers and various sorts of microbial life. The type of organisms that one will encounter in a salt-marsh is dependent upon whether you are in the upper reaches of a salt-marsh environment (near-surface or ground level salt-marsh conditions) or in the deeper areas of a salt marsh environment (submerged lower salt-marsh conditions). In an extant salt-marsh environment, Sen Gupta (2002, p. 142) states that "the bulk of the primary production (or organic detritus) is provided by marsh grasses (i.e., aquatic herbaceous plants), but that a substantial proportion is also derived from intertidal algae".

Some geologists postulate that the precursor for much of the oil and gas in the Eagle Ford Shale is due to the upwelling of rich nutrients from deep oceanic sources. This may be true for other source rocks similar to the Eagle Ford, but we do not think that is the scenario represented by the high organic-matter content found within the Eagle Ford Shale of South Texas. The authors of this paper think the source for much of the hydrocarbon content in the Eagle Ford Shale can be directly attributed to the in situ abnormally high algal-amorphous and aquatic herbaceous

content of the Eagle Ford. Because of the extremely high content of organic detritus throughout the lower portions of the Eagle Ford, the authors have concluded that the oxygen levels in the area of deposition must have been depleted rather quickly. We postulate that this condition led to an environment that was characterized by having a limited variety in its fauna and flora. This condition is certainly a possibility from what the writers have observed during the course of their study.

The presence of calcareous nannofossils and foraminifers, commonly seen in various parts of the Eagle Ford Shale, certainly represent a fauna and flora having marine affinities. These forms occur along with equally high percentages of freshwater and brackish-water organic constituents and are interpreted to have been deposited penecontemporaneously. We interpret much of the planktonic nannofossils and foraminifers to have been brought into the environment and deposited during periodic rises in sea level and/or by strong tides and storm action. With such a high algal content present, it is possible that many foraminifers became entrapped within the algal filaments during feeding. It certainly does not take much of a rise in sea level for planktonic marine phytoplankton to be transported into a freshwater and/or brackish-water environment. Others would argue, just as emphatically, that the freshwater organic detritus was transported to a deeper outer shelf environment, with the fresh water riding on the surface of the more saline waters.

According to Jorissen (2002, p. 163), Reimers et al., (1986) and Carney (1989) are of the opinion that "the flux of organic particles from surface waters to the seafloor is the main source for most deep-oceanic ecosystems. Only a small fraction of the organic matter arriving at the seafloor is directly consumable by the macro- and meiofauna. Most of the labile (unstable) particles are immediately consumed at the sediment-water interface and in the first millimeters of the sediment." Based on the high concentration of organic matter, along with its good preservation characteristics, Schwab, Bayliss and Smith are of the opinion that the majority of organic material was most likely in a labile condition when it was deposited (not significantly biodegraded or greatly chewed upon by other phytoplankton) and therefore was never in suspension for any great length of time. This we think gives credence to an environment of rapid deposition associated with a shallow inner shelf having a high influx of vegetation and algal growth.

An example of what the writers postulate may be seen in [Figures 16, 17, and 18](#). During the summer of 2011, Texas and many other states were plagued with extremely hot weather conditions coupled with very little rainfall. Forest fires across South Texas were common, as was the massive algal bloom that formed on the inner shelf areas along the Texas Gulf Coast. Aerial photos taken of the southern Gulf Coast of Texas shows that the bulk of the algae and other phytoplankton was heavily concentrated within the coastal lagoons, bays and inner shelf along the Texas shoreline. Only minor percentages of the algal constituents appear to be associated with the outer continental shelf. When compared to a map showing the water depth of the shelf area ([Figure 18](#)); most of the algal and phytoplankton appear to be concentrated within brackish to marine waters that are less than 130 to 135 feet in depth, (The photos used in this article are from Scientific American, 2011, which were taken from NASA/GSFC Rapid Response-Lance-Subsets (2011)).

If one migrates the present shoreline back to where it approximately was during late Cenomanian - Turonian, it is easy to see how the same depositional pattern shown in [Figures 16, 17, and 18](#) could be applied to the depositional framework that prevailed during the deposition of the Eagle Ford Shale. Had deposition really occurred in a deep-water setting, 250 feet or greater, one would not expect to find anywhere near the high concentration of moderately coarse-grained organic-matter constituents that we see. In addition most of the detritus in a deep-water setting tends to have a higher concentration of finely disseminated organic matter with the larger plant fragments showing a high degree of biodegradation due to microbial activity (i.e., the organic matter was suspended in the water column for a greater period of time). This is not what the writers

concluded after observation and analyses of the organic matter which was extracted from the various core and cuttings samples in the eight wells they examined from the Eagle Ford Shale of South Texas and adjacent Mexico.

After much thought and discussion it would appear that no one scenario, based on a single group of microfossils or set of paleontological data, can adequately define the environmental conditions under which all of the Eagle Ford Shale was deposited. Based on the presence of foraminifera and calcareous nannofossils, there is no way one can deny the presence of marine waters. Likewise, the high content of freshwater and brackish-coastal marine types of plant material is indicative of a terrestrial, nearshore or shoreline depositional environment which is most often associated with a shallow or surface water habitat. Undoubtedly the micro-environments changed on a seasonal basis, just like they do today. The regional landscape probably remained much the same over tens of thousands of years, the topographic expression and environment of deposition changing as a result of tectonic events and/or eustatics.

Perhaps the best way to look at the depositional environment for the Eagle Ford Shale is by viewing it as a series of environments, not just one. The lower Eagle Ford organic-rich facies and part of the lower upper Eagle Ford could have been associated with more of a shallow-water restricted basin, or series of basins, which was plagued with limited water circulation and, because of the large accumulation and growth of organic matter, had a low oxygen content. A stratified water column, associated with a shallow to moderately deep-water silled basin, or series of silled basins, or perhaps even a failed rift system as some geologists have suggested, would certainly support the data that we have obtained from our examination of the Eagle Ford Shale in the eight wells that were examined in this study.

### **Stratigraphic Significance**

The eight wells examined in this study cover are scattered over an area approximately 75 miles wide (east-west) by 40 miles in length (north-south). The organic-matter suite representative of this particular 3000 square-mile area is essentially the same everywhere we look. The stratigraphic section is dominated by high concentrations of algal debris and finely disseminated amorphous constituents (much of which is interpreted to be algal-herbaceous fragments), and moderate concentrations of herbaceous plant material. Fungal debris, foraminiferal linings, vitrinite and inerts make up a very small percentage of the total organic-matter suite.

The stratigraphic occurrence of these peculiar algal constituents observed in the wells in Dimmit, Webb and La Salle counties of South Texas and in cuttings samples from a well drilled in Coahuila, Mexico are important indicators for the recognition of the lower portion of the lower upper Eagle Ford and lower Eagle Ford Shale. The writers have not observed these distinctive algal fragments in the overlying Austin Chalk. Likewise, because of possible contamination problems in the Buda and Del Rio sections of the Mobil-McElroy No. 1 well (if this is really Buda and Del Rio), we cannot rule out their occurrence in this underlying part of the stratigraphic section. From what we have observed in our analyses, these mushroom- and/or broccoli-head-shaped vegetative algal structures are generally confined to the lower portion of the upper Eagle Ford Shale and throughout the entire section of the lower Eagle Ford Shale.

Most of the mushroom-shaped and broccoli-head-shaped algal fragments are approximately 8 to 15 micrometers in length, but the senior author has observed some that are more than 70 micrometers in length. Similar vegetative structures found in the lower Barnett Shale (Upper Mississippian) of north-central Texas, also an oil- and gas-rich shale play, were photographed and illustrated by Schwab et al. (2011).

Although the authors of this article cannot be completely sure which genera of algae the vegetative bodies are associated with, they do think some interesting comparisons to living algal colonies, based on their external morphology, can be made. If the algae represented by these fossil forms is typical of what we see in the algae of today, much of it was probably epiphytic on other plant life while others formed algal mat-like structures in littoral areas close to shoreline. Much of the algal debris is interpreted to have been associated with the surrounding wetlands, growing in marshes, bogs and other standing bodies of water. The writers believe this is where most of the vegetative organic matter most was deposited and accumulated under anoxic conditions throughout much of early Eagle Ford time.

### **Conclusions**

In our study of seven wells from South Texas and one from Coahuila, Mexico, mushroom-shaped and/or broccoli-head-shaped algal fragments were found to be very common in the lower portions of the upper Eagle Ford Shale and throughout the entire lower Eagle Ford Shale. They can be used with a high degree of success to recognize the presence of the Eagle Ford Shale in well cuttings samples that have been processed for visual kerogen analyses. Their limited occurrence and apparently short stratigraphic range in time, makes them a good "zonal" marker for the lower upper Eagle Ford and lower Eagle Ford Shale across the South Texas area. Because the fauna and flora that we observed appear to have a low diversity in genera and species, the writers think that the greater portion of the depositional area (i.e., habitat) may have suffered from poor water circulation and may have had low oxygen content. Acidic waters could also be a possibility and help explain the reduced size of the planktonic forams which are found.

Most photosynthetic algae living within the upper 15 to 20 meters of the water column accumulate in wetland environments associated with shallow-water shoreline habitats where water salinities can be highly variable. They serve as a food source for much of the planktonic foraminifera and other phytoplankton that migrate in from a more open marine habitat. The bulk of the organic debris in all of the lower upper and lower Eagle Ford Shale samples that were examined in this study should be categorized as a Type 1 and Type 2 freshwater to brackish-water kerogen concentrate. Organic matter similar to what was observed in the lower upper and lower Eagle Ford Shale most commonly accumulates in bogs, ponds, lakes, estuaries and embayments associated with a coastal or inner shelf environment. The writers think that only a small fraction of the total organic-matter concentrate was transported out onto the outer shelf. We view the high concentration of organic matter as clearly being an onshore or shoreline accumulation of debris.

The writers also contend that the high cellulose content of the algal and herbaceous debris are most likely the source for the large accumulations of methane and wet gas condensates that are currently being produced from this particular portion of the Eagle Ford Shale.

### **Acknowledgements**

This paper is dedicated to the memory of Dr. William C. Elsik (formerly with EXXON Production and Research Company, Houston, Texas) and Dr. John A. Clendening (formerly with AMOCO Inc., also in Houston, Texas). These two outstanding palynologists contributed much to

the education of the senior author and to the scientific community in general. Their talent, friendship and scientific contributions will be missed by many in the field of palynology.

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Rapid Response-Lance-Subsets (NASA/GSFC ) <[http://lance-modis.eosdis.nasa.gov/imagery/subsets/?subset=AERONET\\_Univ\\_of\\_Houston.2011248.terra.1km](http://lance-modis.eosdis.nasa.gov/imagery/subsets/?subset=AERONET_Univ_of_Houston.2011248.terra.1km)> Select: AERONET\_Univ\_of\_Houston Subset - Terra 1km True Color 2011/248 (09/05).

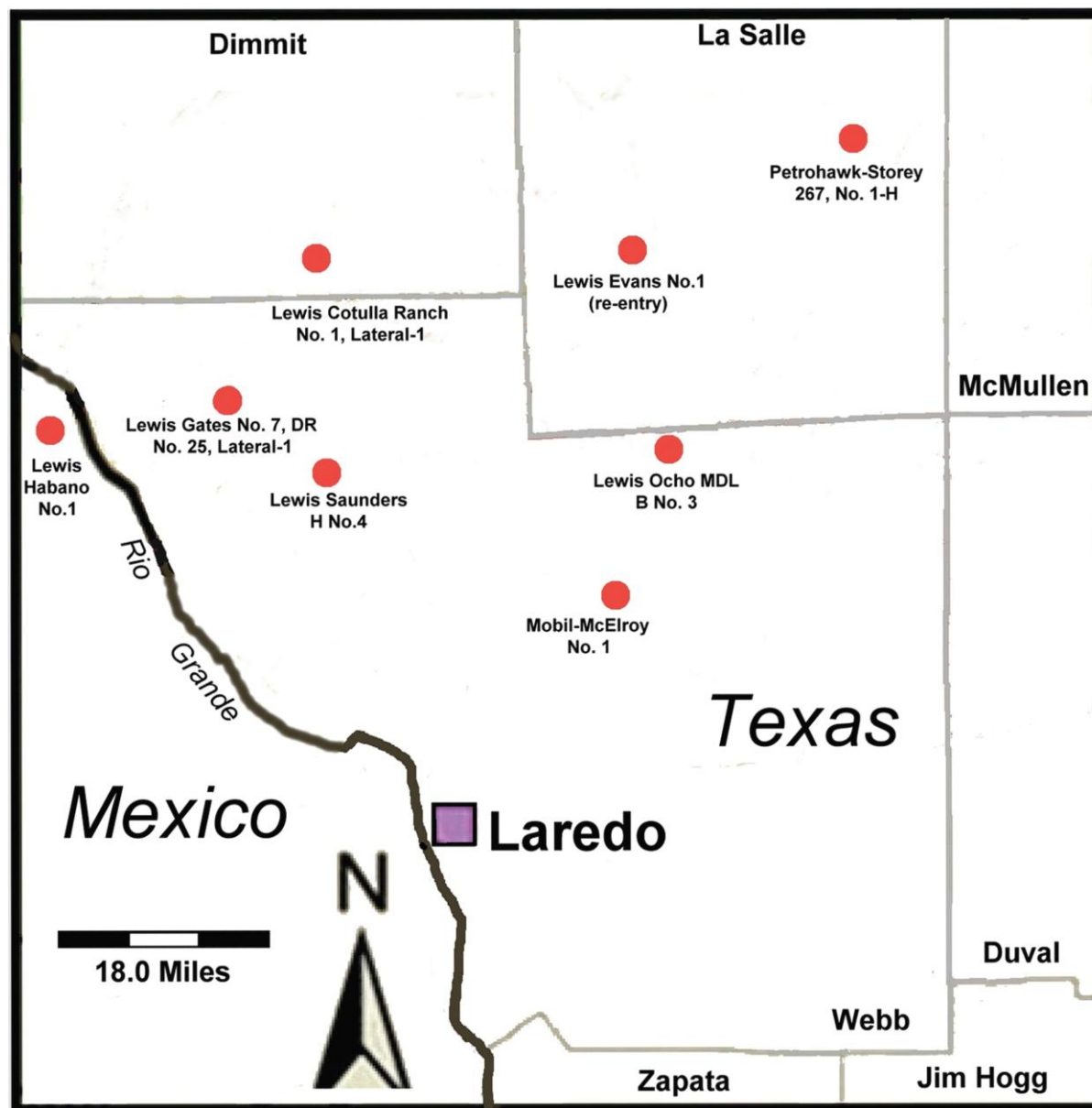
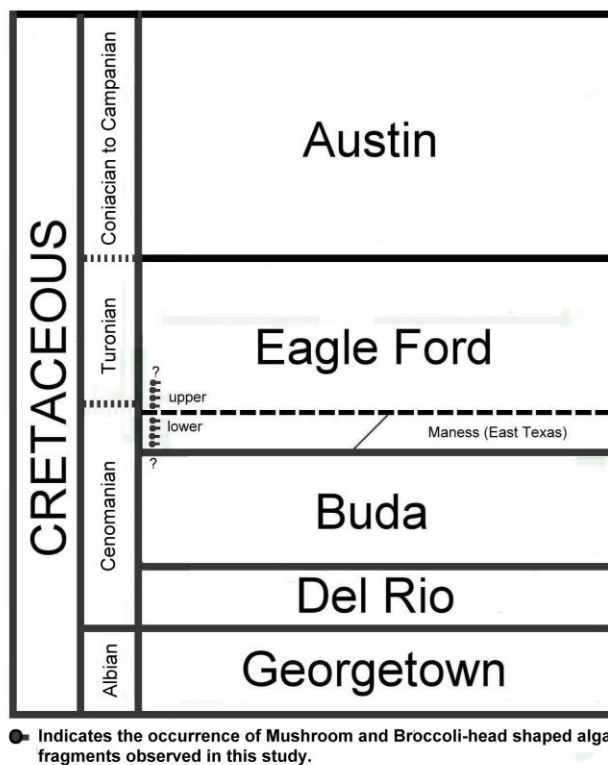


Figure 1. Location map showing the wells that were examined in this study.

## Stratigraphic Column (South Texas)



**A portion of the geologic section showing the stratigraphic units of south Texas in the area of study. Note: the boundaries of the upper and lower Eagle Ford Shale are interpreted to be transitional (based on organic matter analyses).**

Figure 2. Portion of the Cretaceous section in south Texas in the area of study, showing the occurrence of the diagnostic microfossils identified and interpreted by the authors. Boundaries of the upper and lower Eagle Ford Shale are interpreted to be transitional.

## Concentration of Planktonic Foraminifera versus Water Depth\*

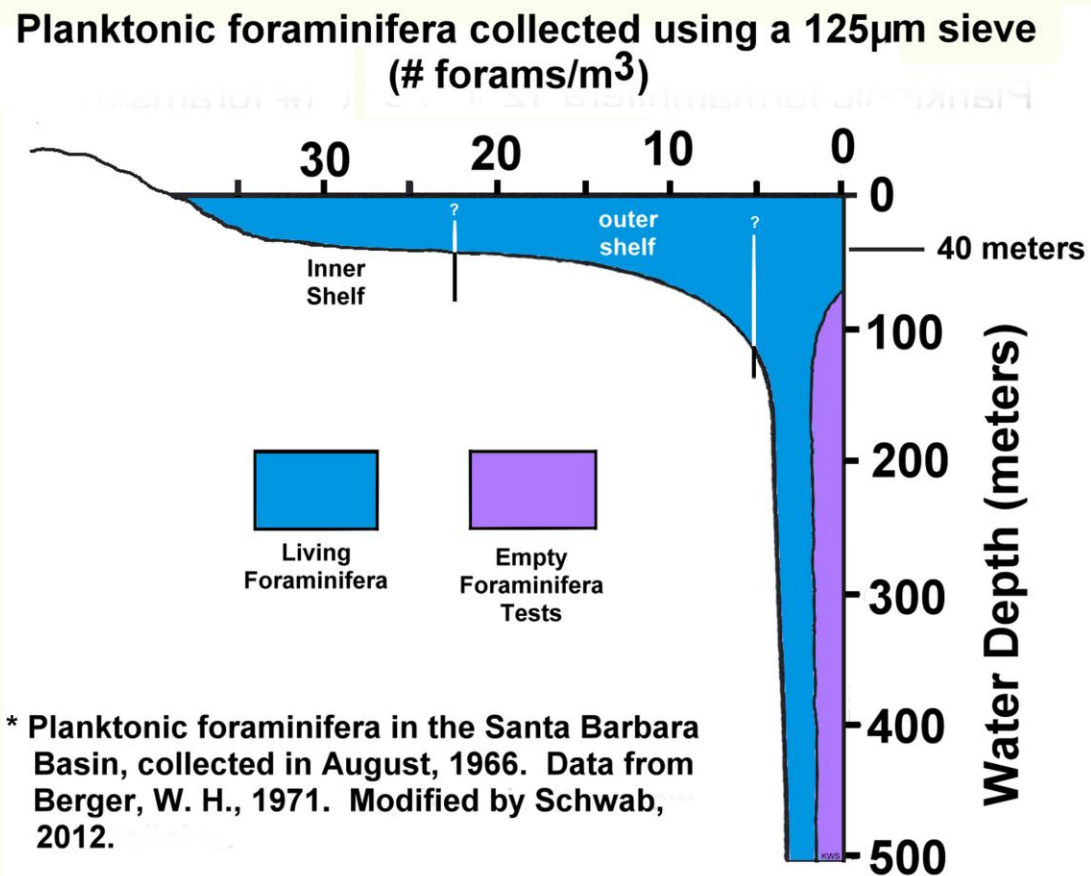


Figure 3. Concentration of planktonic foraminifera versus water depth. Data from Berger (1971).

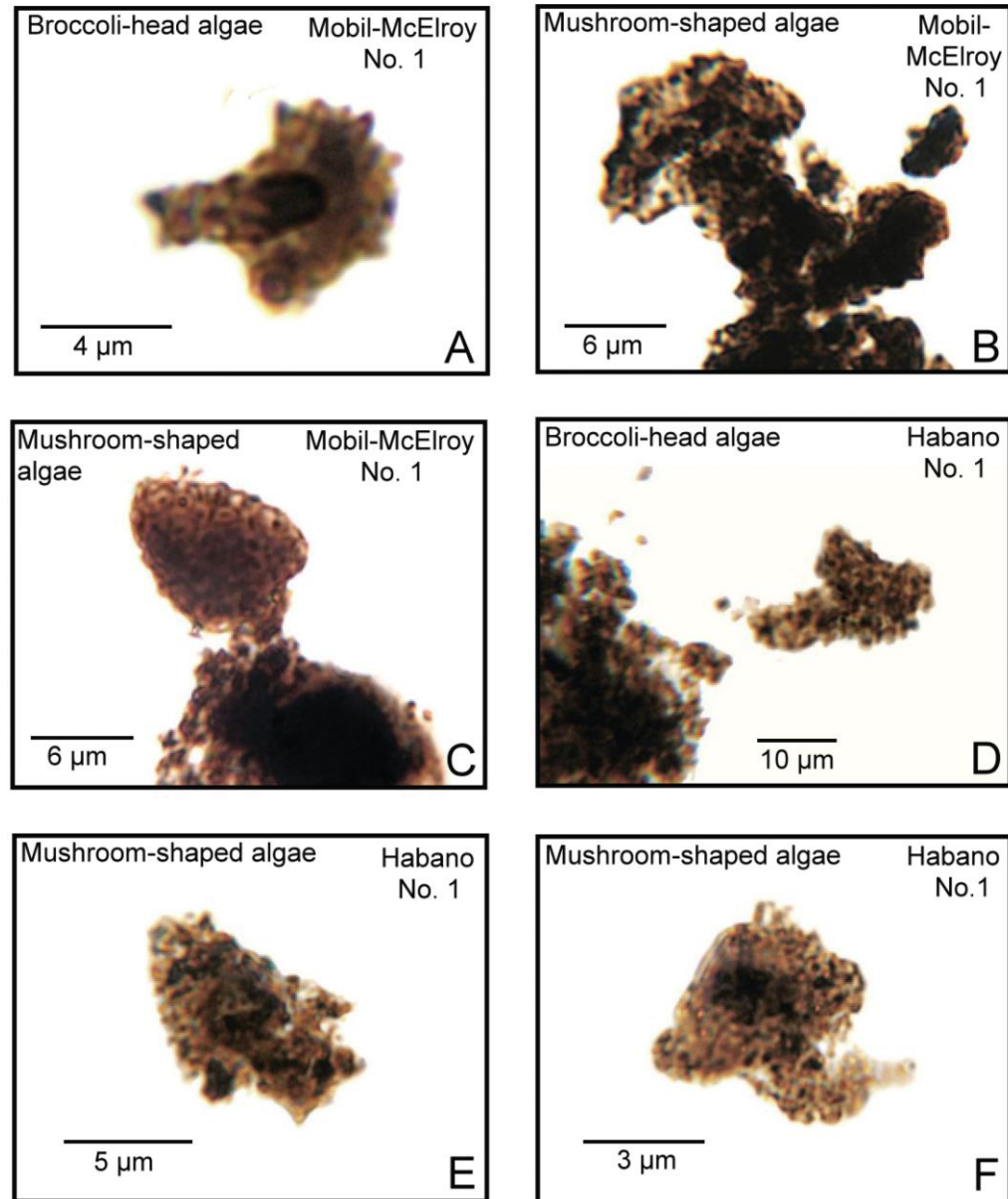


Figure 4 A-F. Minute fragments of mushroom-shaped and/or broccoli-head-shaped vegetative structures from an unknown algal source. All photomicrographs shown in brightfield illumination.

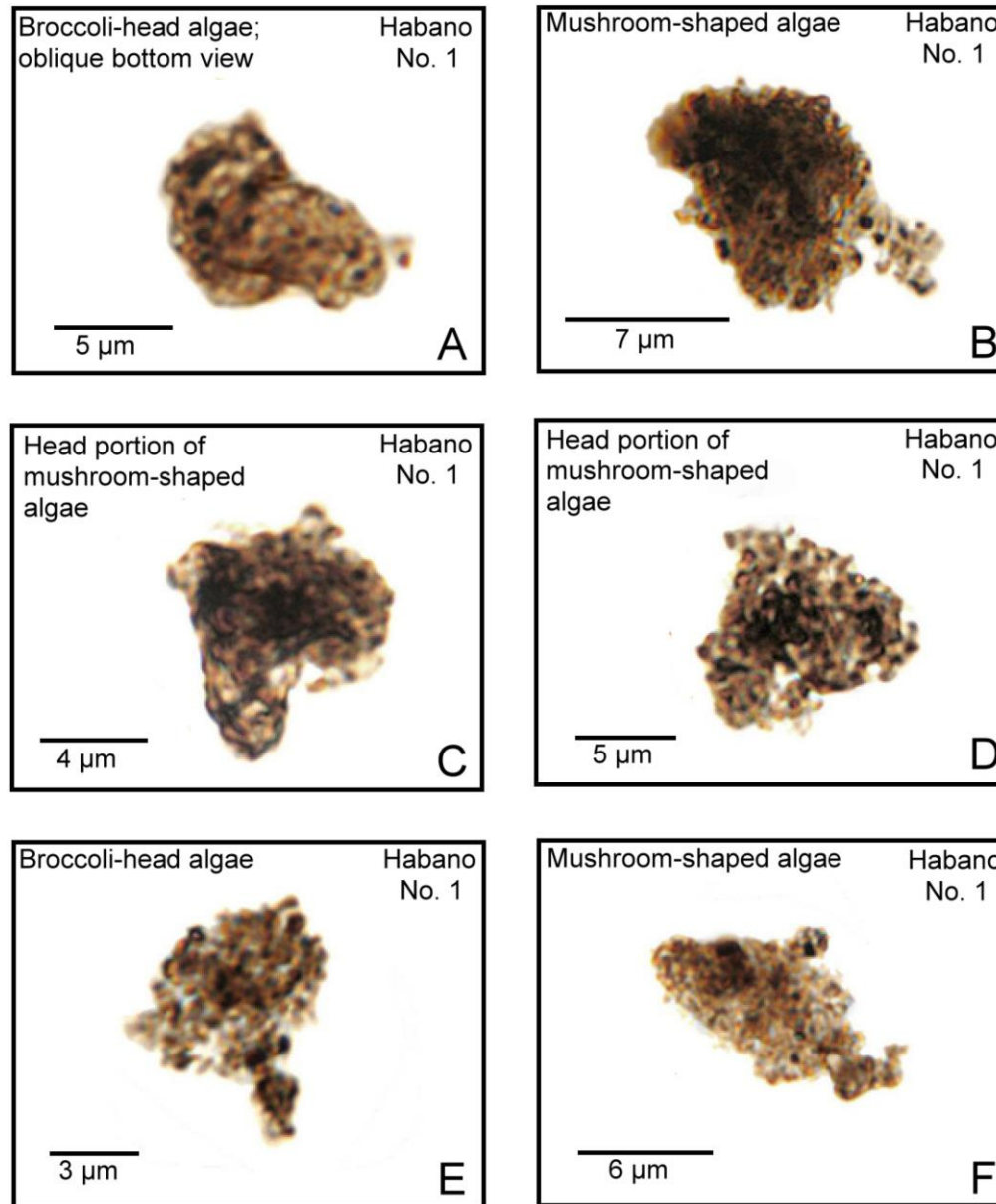


Figure 5 A-F. Fragments of mushroom-shaped and/or broccoli-head-shaped vegetative structures from an unknown algal source, shown in brightfield illumination.

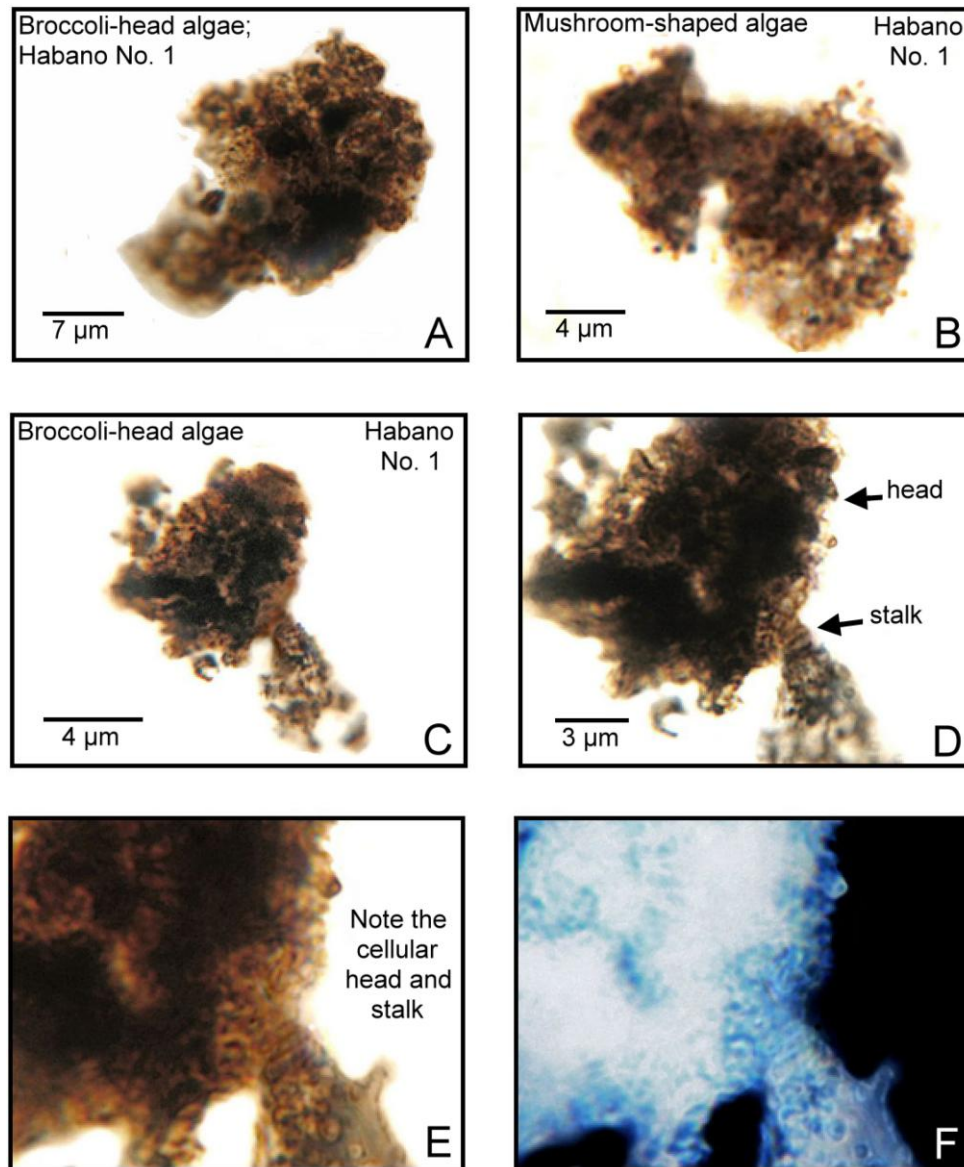


Figure 6. A-C. Fragments of mushroom-shaped and broccoli-head-shaped vegetative structures from an unknown algal source. D-F. enlarged view of the algal fragment shown in C. Note the cellular structure of the "stalk" and at the base of the "head" shown in E and F. All the specimens were photographed in brightfield illumination. F is the same photograph as E. except for alteration of color in order to bring out more detail, using the Invert function available on our Adobe Photoshop Elements 7 Program.

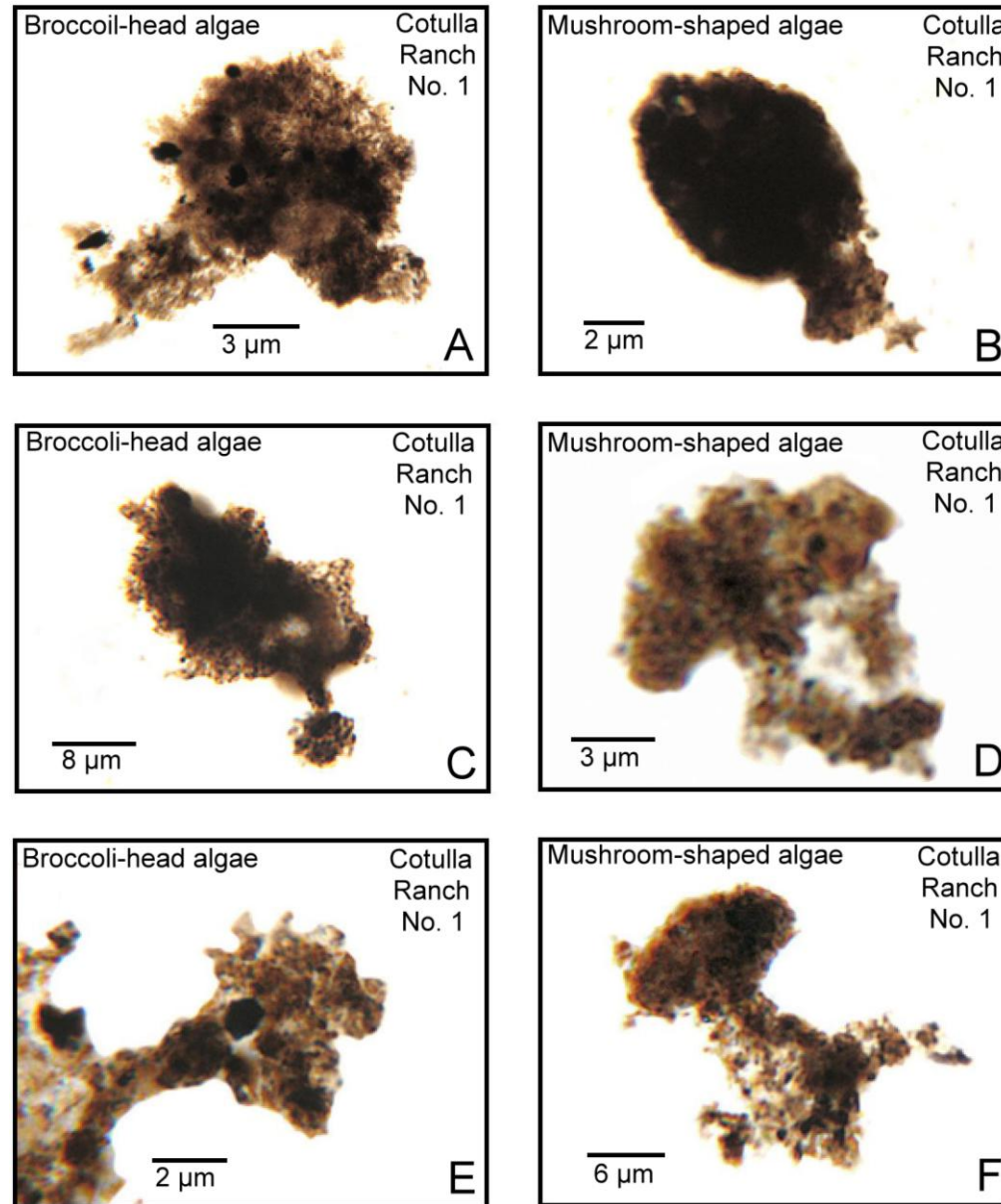


Figure 7 A-F. Various examples of mushroom-shaped and/or broccoli-head-shaped algal fragments. E shows a broccoli-head structure still attached to the main body of the algal colony. Photographed in brightfield illumination.

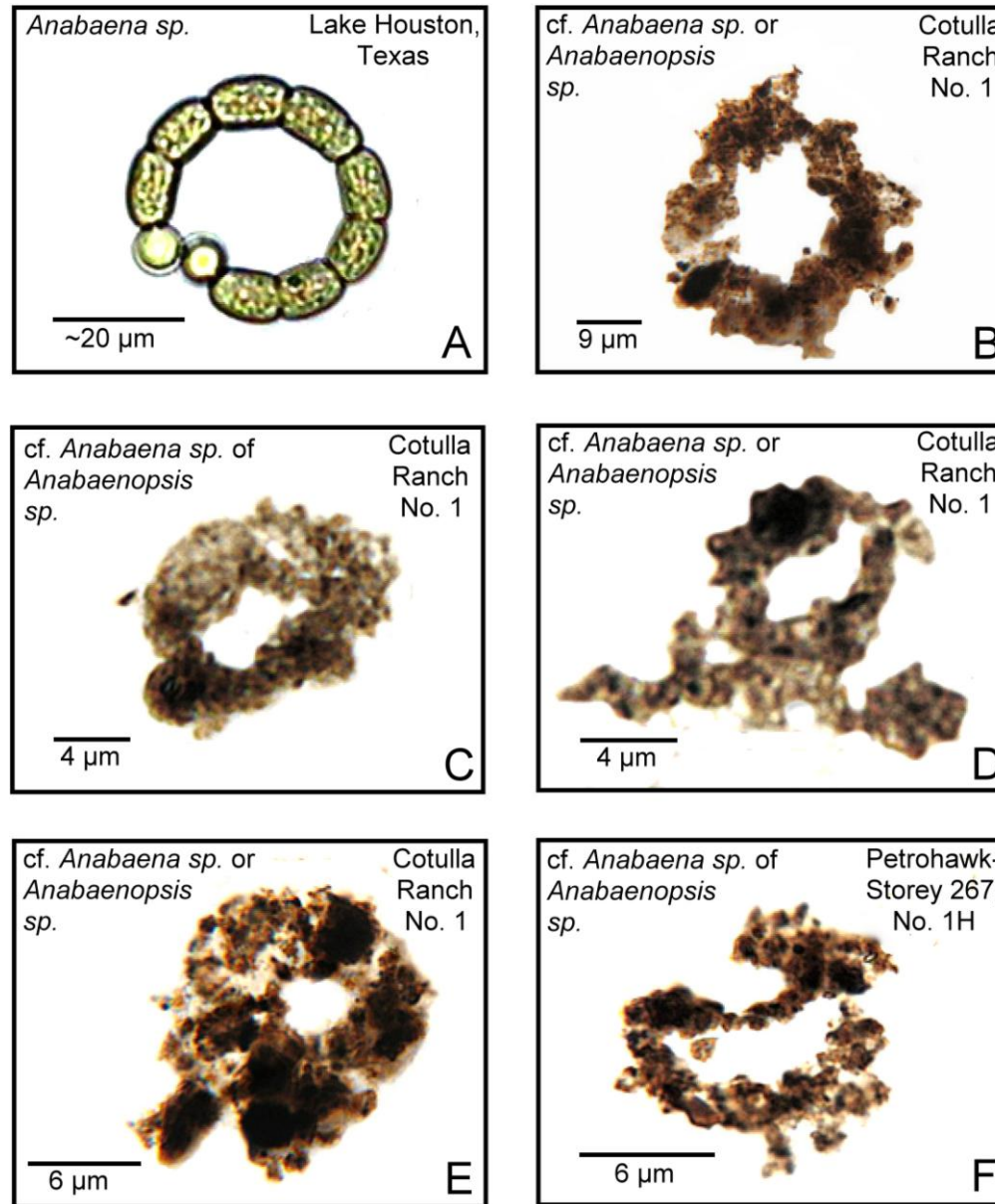


Figure 8. A. Trichome of the extant cyanobacteria *Anabaena* sp. from Lake Houston, Texas, illustrated by The Missouri State University Department of Biology-Phycology, shown here with their permission. B-F show what the writers interpret as being fossil trichomes of the cyanobacteria *Anabaena* sp. and/or *Anabaenopsis* sp. All specimens are photographed in brightfield illumination.

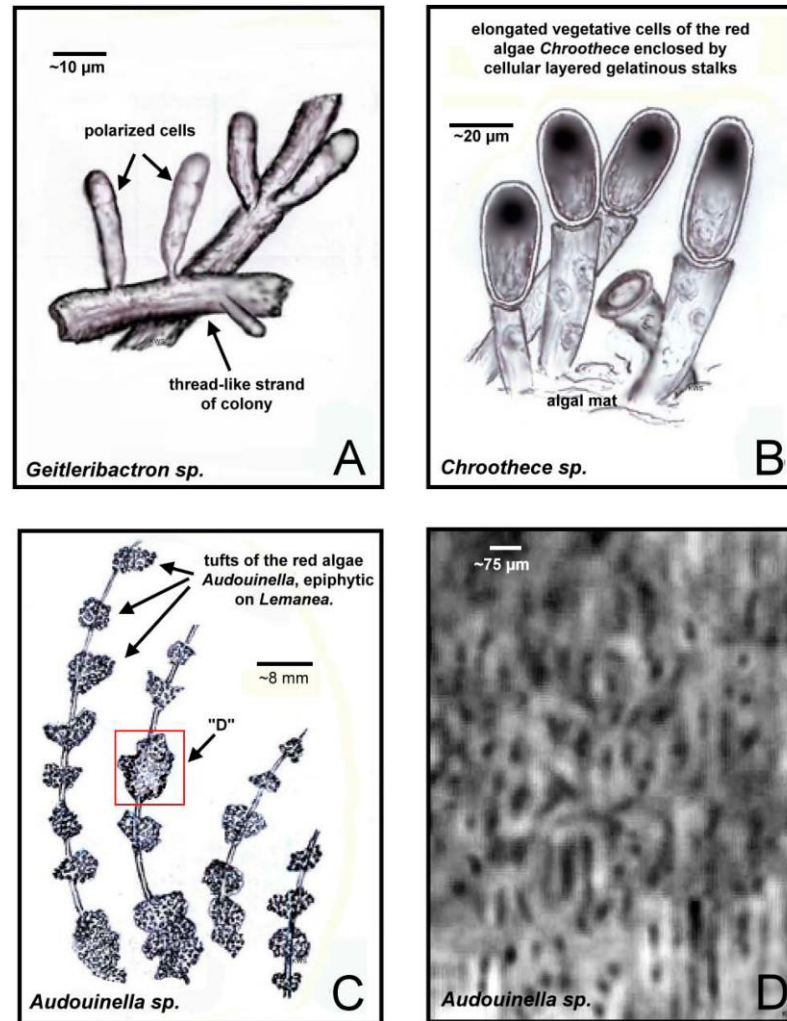


Figure 9. A. Diagrammatic illustration of the cyanobacteria *Geitleribactron* based on the descriptions and photomicrographs presented by Komarek (2003, p. 98, 101-102). [NOTE: *Geitleribactron* is not as yet accepted as a valid extant genus (Mark Schneegurt, Wichita State University (Kansas), personal communication, December 6, 2012)]. B. Diagrammatic illustration of the red algae *Chroothoece* based on the descriptions and photomicrographs presented by Sheath (2003, p. 208-210). Both the head to the algae and the gelatinous stalks are covered, in part, by minute cellular structures which are approximately 8 to 10 µm in size. C-D. Diagrammatic illustration and enlarged photomicrograph of the ephytic red algae *Audouinella*, based on description by Sheath (2003, p. 211-212). D illustrates the external morphology of specimen of *Audouinella*, showing the cellular, chain-like, external morphology of the algal itself, in bright field illumination.

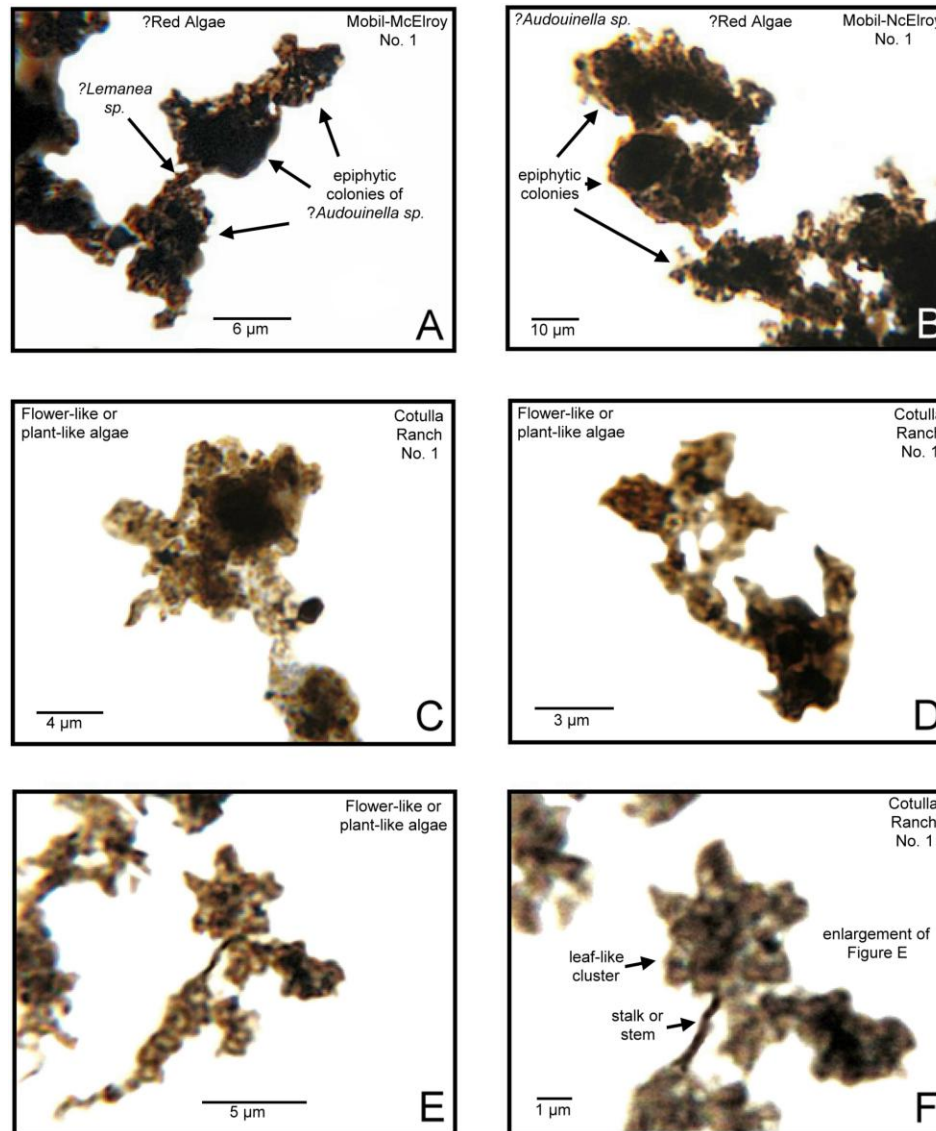


Figure 10. A and B. Possible fragments of the Red Algae *Lemanea* and *Audouinella*; the latter is an epiphyte that commonly forms "tufts" on filamentous algae like *Lemanea*. Both are freshwater forms. They are common in fast-moving streams and rivers. Specimens photographed in brightfield illumination. C-F. Flower-like or plant-like algal fragments that are common organic constituents in the lower portions of the upper Eagle Ford Shale and through the entire lower portions of the Eagle Ford Shale of south Texas. Interpreted to be related to, or members of, the plant-like Green Algae. Illustrated in brightfield illumination.

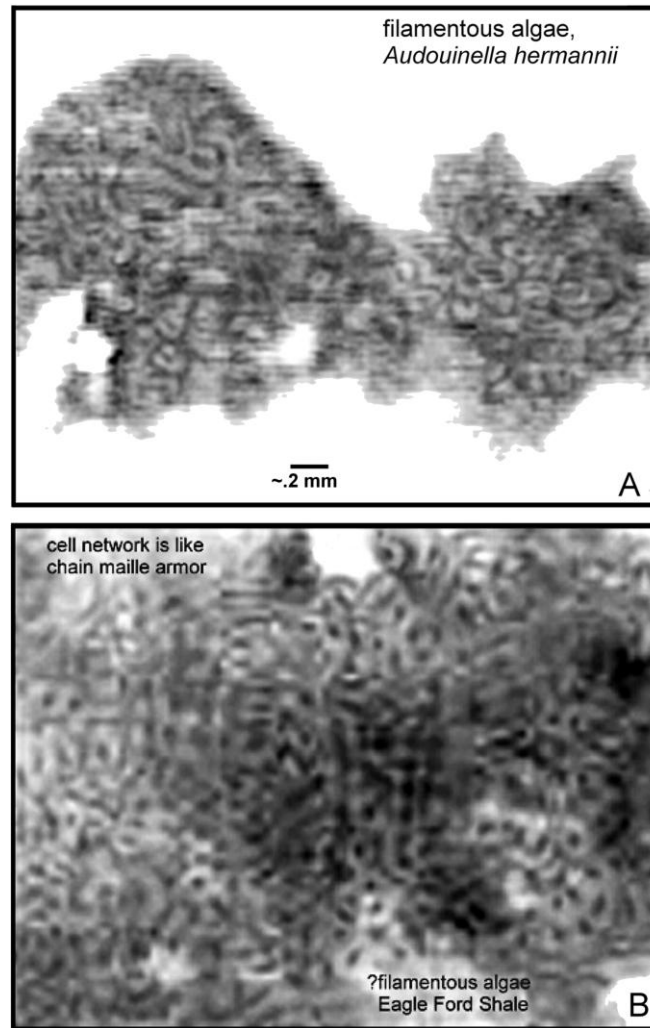


Figure 11. A is an enlarged view of the algae *Audouinella* of [Figure 9 D](#). Of interest is the network of cells; the cell structure, typical of the filamentous algae, commonly has an outside appearance of chain-maille armor, even though the cells of *Audouinella* are not interlocking. The cell size shown is an estimate, not actual measurement, based on specimen size in Sheath (2002, p. 211, Figure 2F). A is shown as being photographed in brightfield illumination. B. Enlarged view of a photomicrograph of a thin section of the Eagle Ford Shale that was prepared by Nelson Yoder and chosen by him to show the presence of planktonic foraminiferal tests (not shown herein). Enlarging the photomicrograph showed foraminiferal tests surrounded by an exceptionally large percentage of algal debris; of particular interest is the cellular structure similar to that of *Audouinella* in A—and, therefore, probably representing a colony of filamentous algae. The thin section appears to be dominated by an overwhelming percentage of algal debris. Yoder's thin section was photographed in brightfield illumination.

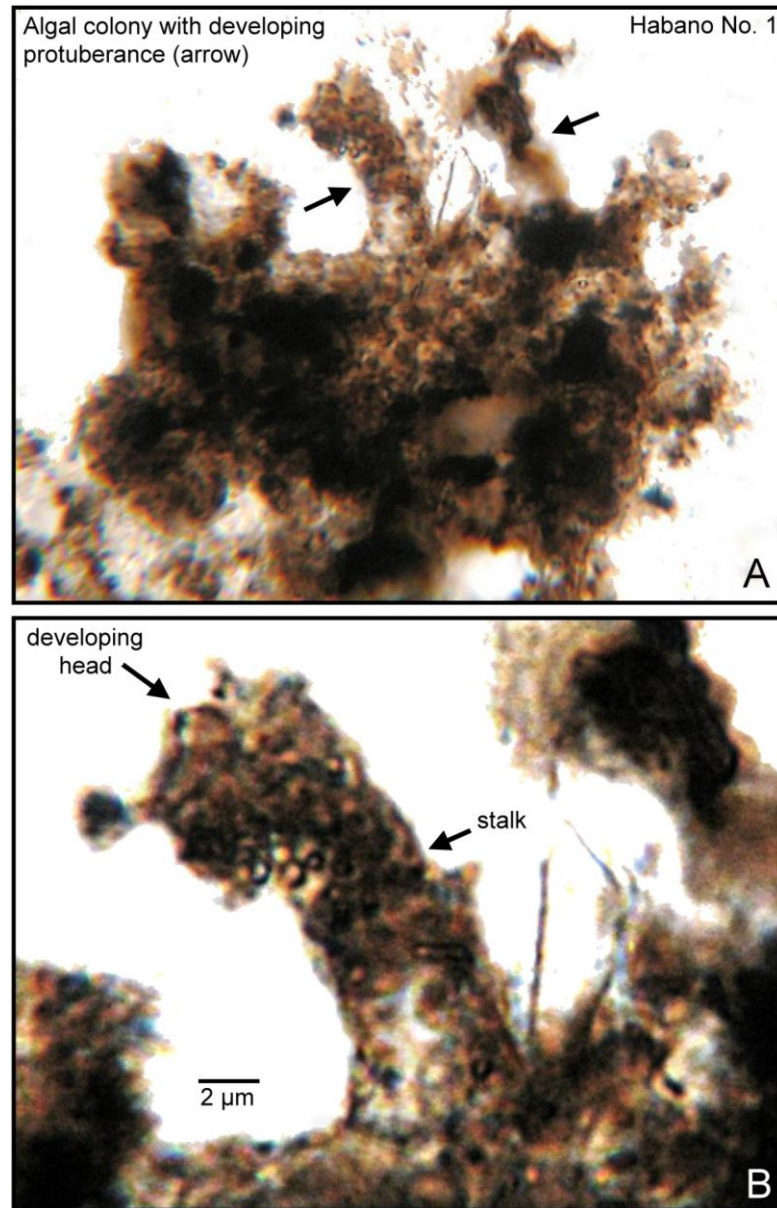


Figure 12. A. Moderate-size fragment interpreted to be part of an algal colony (i.e., an algal strand or rhizoid-like filament) with the development of broccoli-head or mushroom-shaped protuberances erupting from its surface. B. Enlarged portion of the specimen in A illustrating the cellular stalk and head of the vegetative structure. Shown in brightfield illumination.

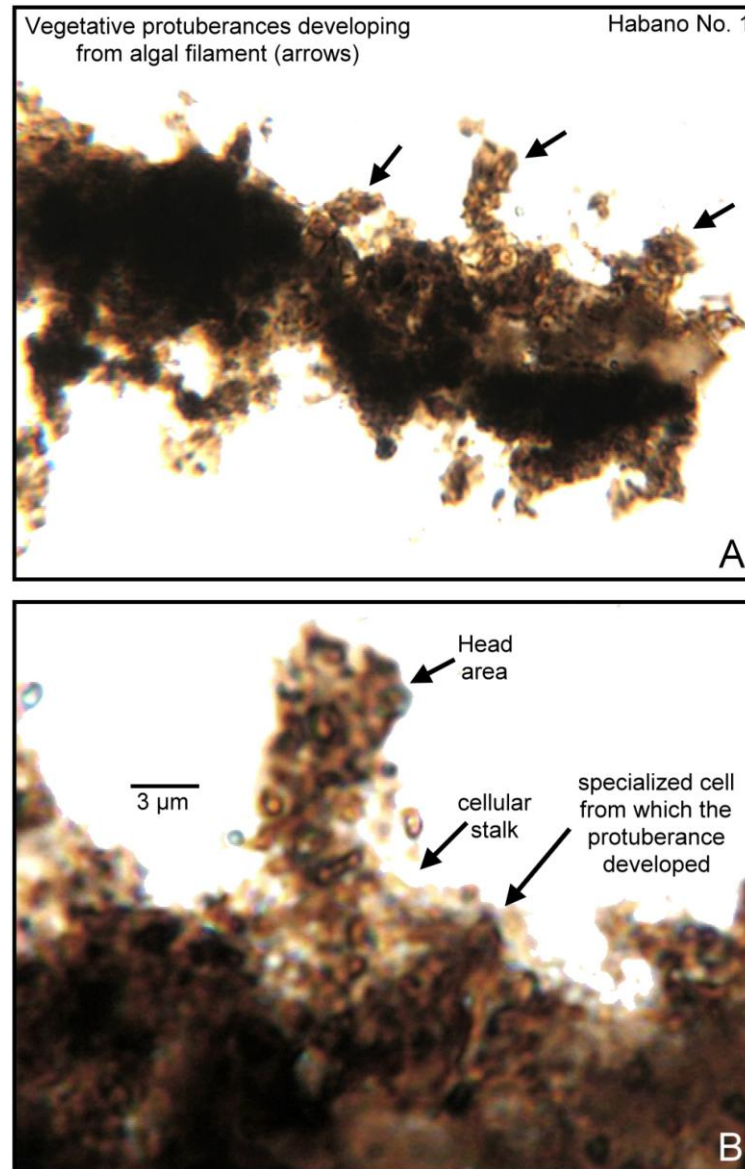


Figure 13. A and B. Vegetative protuberances erupting from the surface of an algal filament or rhizoid-like structure belonging to a larger filamentous algal colony. B. Enlargement of one of the vegetative protuberances shown in A, depicting the eruption of the vegetative cell from what is interpreted to be a specialized cell, or series of cells, on the surface of the main algal body. Photographed in brightfield illumination.

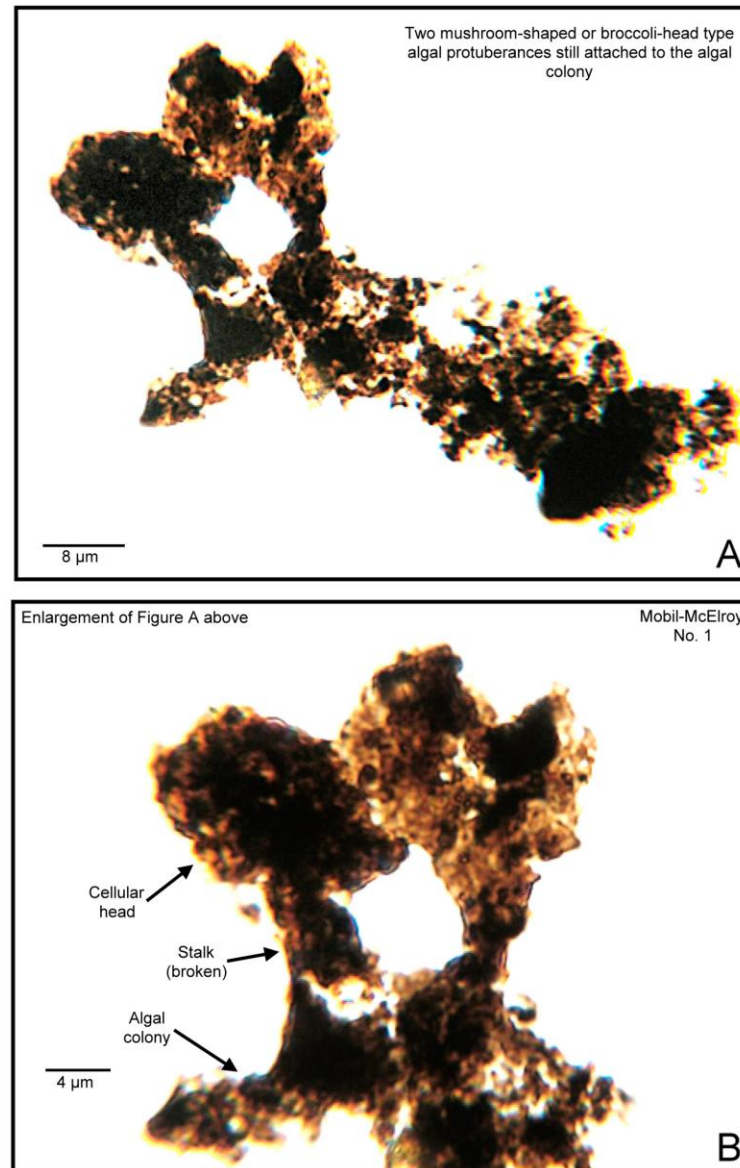


Figure 14. Figures A and B. Two broccoli-head and/or mushroom-shaped algal fragments, which are thought to have been attached to a much larger algal mass, a portion of which is shown in A. B is enlarged part of A. Note the cellular composition of the broccoli-head and/or mushroom-shaped protuberance and how, when broken, they can easily become dislodged and torn from the main portion algal body. Photographed in brightfield illumination.

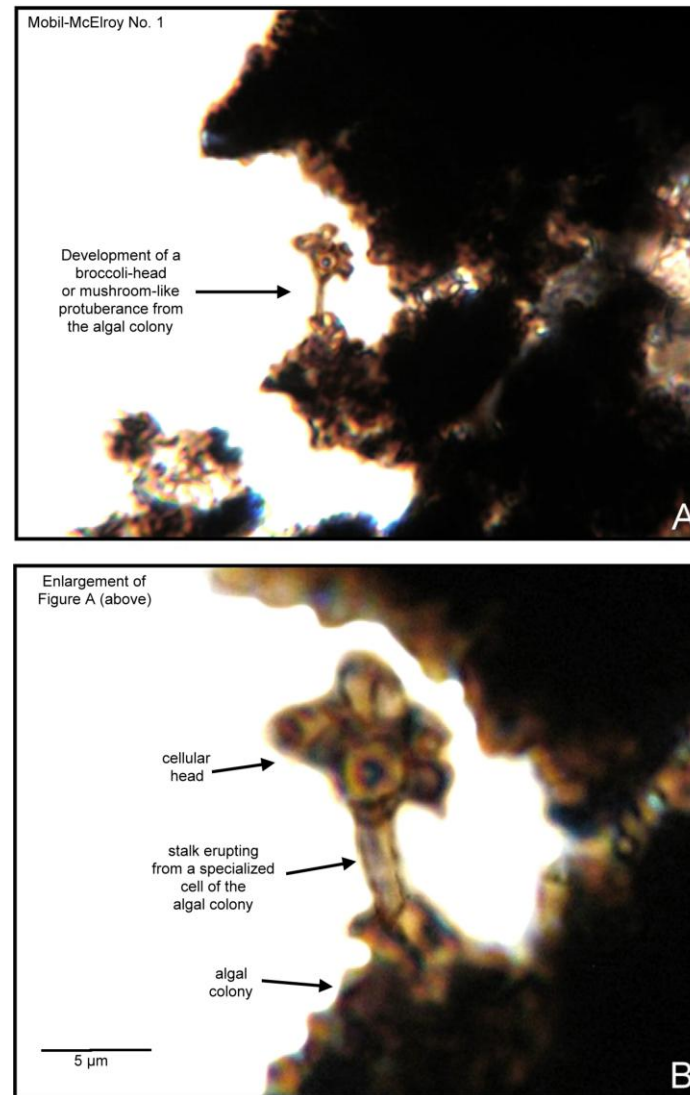


Figure 15. A and B. Broccoli-head and/or mushroom-shaped vegetative algal structure. B. Enlargement of part of A illustrating the development of the algal structure and how it forms from a specialized cell, or cells, on the main algal body. The stalk erupted from the algal colony, giving rise to a cluster of cells at the head vegetative protuberance. As development of the broccoli-head or mushroom-shaped structure continues, it is assumed more and more cells are formed. In B there are approximately 8 to 12 cells making up the head portion of the vegetative stalk. The writers think that more cells are added rapidly to the structure until it is similar to that shown in [Figure 12](#). Photographed in brightfield illumination.



Figure 16. South and east Texas, along with Louisiana and northwestern Gulf of Mexico, showing wildfires that raged across the Texas area during the late summer and early fall of 2011. [Note: The light blue-green color shown in the embayments and in the waters along the Texas Gulf Coast represent large areas of algal blooms.] From Rapid Response-Lance-Subsets:

[http://lance-modis.eosdis.nasa.gov/imagery/subsets/?subset=AERONET\\_Univ\\_of\\_Houston.2011248.terra.1km](http://lance-modis.eosdis.nasa.gov/imagery/subsets/?subset=AERONET_Univ_of_Houston.2011248.terra.1km) Select: AERONET\_Univ\_of\_Houston Subset - Terra 1km True Color 2011/248 (09/05).

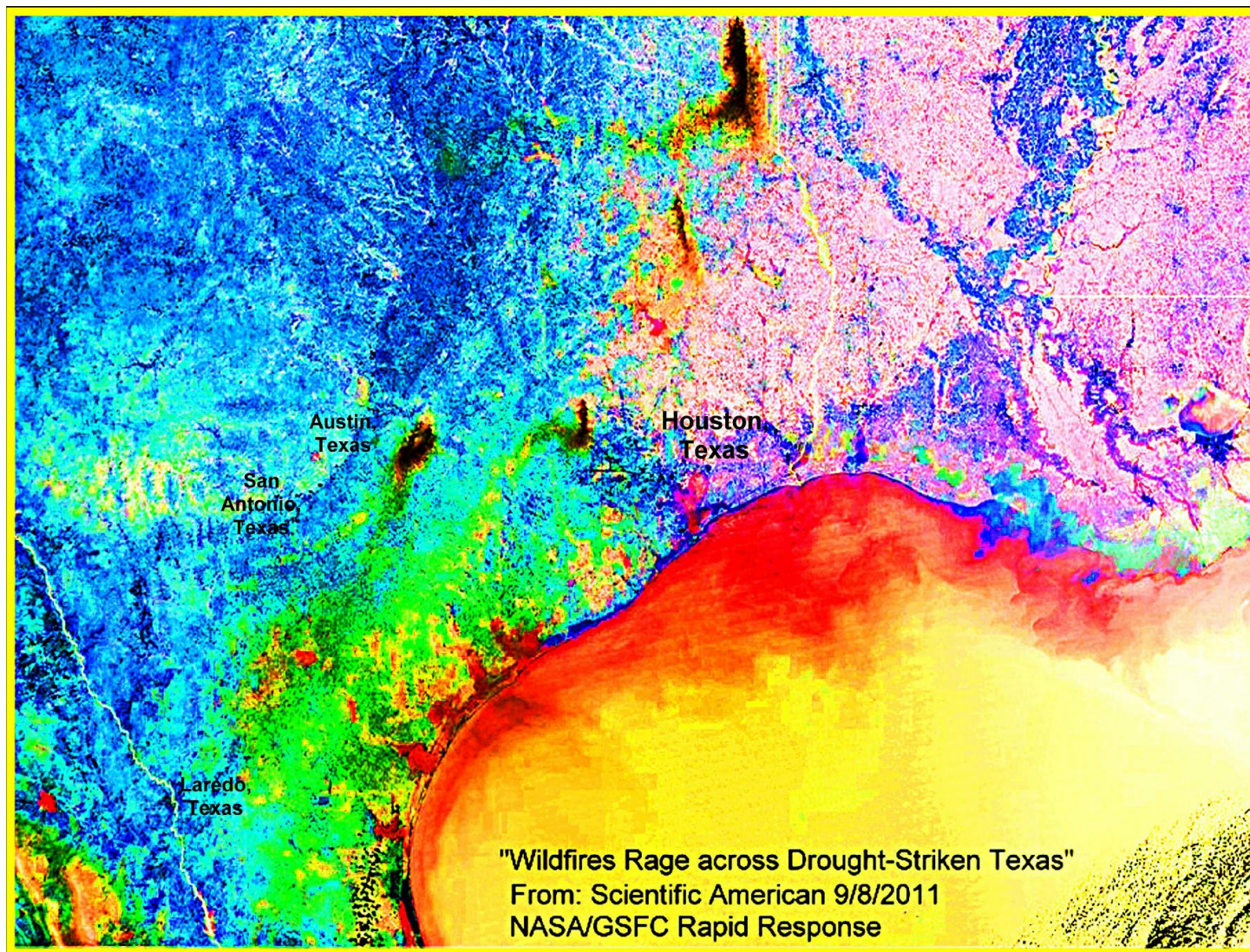


Figure 17. The same photograph shown in [Figure 16](#); original color has been altered by using the invert function (under filter, then adjustments) of Adobe Photoshop Elements 7. The hue and intensity of the colors have been made more vivid to show the concentrations of algae and other microplankton (which appear red in color) that occur within the inland lakes, reservoirs, coastal embayments and inner shelf areas. From Rapid Response-Lance-Subsets:

[http://lance-modis.eosdis.nasa.gov/imagery/subsets/?subset=AERONET\\_Univ\\_of\\_Houston.2011248.terra.1km](http://lance-modis.eosdis.nasa.gov/imagery/subsets/?subset=AERONET_Univ_of_Houston.2011248.terra.1km) Select: AERONET\_Univ\_of\_Houston Subset - Terra 1km True Color 2011/248 (09/05).

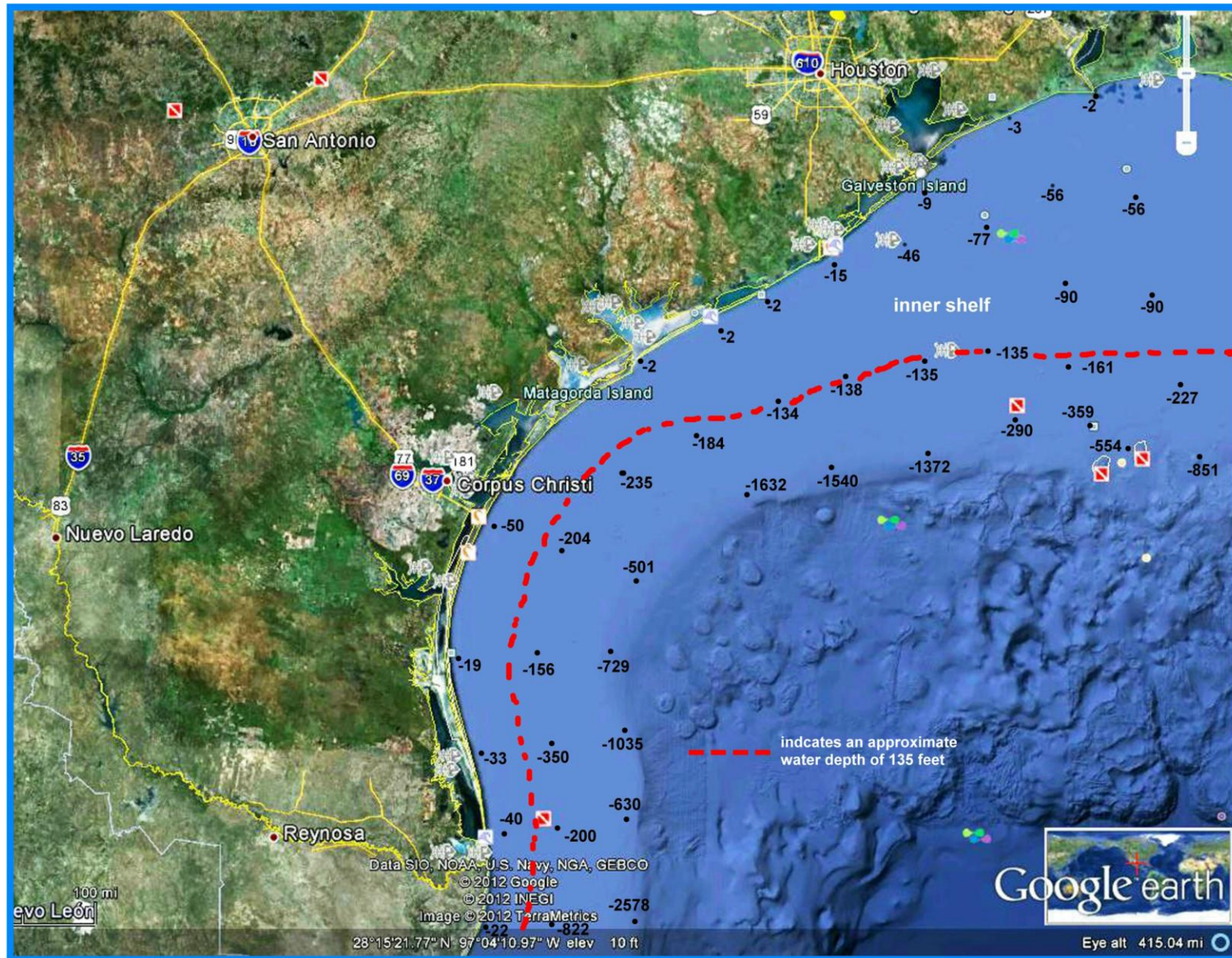


Figure 18. Google Earth view of most of the same area shown in [Figures 16](#) and [17](#). The water depths shown are approximate and are based on the water depths taken from the Google Earth Program for the general area; they are given to show the approximate boundary between the inner shelf (less than 150 feet in depth) and the outer shelf.