Elsevier Editorial System(tm) for Palaeogeography, Palaeoclimatology, Palaeoecology
Manuscript Draft

Manuscript Number:

Title: Late Neogene Paleoclimate and Paleoenvironment Reconstructions from Pipe Creek Sinkhole, Indiana, USA

Article Type: Research Paper

Section/Category:

Keywords: Neogene, Pliocene, Karst, Isotope, Lacustrine, Terra rossa

Corresponding Author: Mr. Aaron Jacob Shunk, M.S.

Corresponding Author's Institution: Baylor University

First Author: Aaron Jacob Shunk, M.S.

Order of Authors: Aaron Jacob Shunk, M.S.; Steven G Driese, PhD; James O Farlow, PhD; Michael S Zavada, PhD; Mohammad K Zobaa, M.S.

Manuscript Region of Origin:

Abstract: The Late Neogene represents warm Earth conditions immediately prior to the development of extensive northern hemisphere glaciation, and this period in Earth history may therefore provide the best available analog for the projected outcome of continued global warming. There are few interior continental sites of Late Neogene age from the eastern half of North America and subsequently very little is known about the conditions characterizing climate. The Early Pliocene (~5 Ma) Pipe Creek Sinkhole (PCS) includes the sediment fill of a complex karst environment that developed in north-central Indiana, USA (Lat. 40° 27' 25.4", Long. 85° 47' 37.2"). The site includes more than 3 m of high-chroma, red-colored silty-clay sediment interpreted to be terra rossa. The δ13 C values PCS terra rossa average -20 ±0.7‰ PDB, and are interpreted to represent sediment deposited in a closed cave system under high temperatures and with well-drained soils. An in-situ paleosol at the top of the terra rossa represents a transition from a closed cave to an open environment that eventually flooded, thereby becoming a small pond. δ13 C values from lacustrine

sediments with organic matter derived dominantly from algae average -20.6 ‰ and suggest the pond was stagnant and enriched with bicarbonate from the underlying limestones or via aquifers. Pond sediments include abundant vertebrate fossils, which are broadly consistent with those inhabiting an open ecosystem such as a savannah or parkland. However, the PCS pollen includes low taxonomic diversity that is dominated by pine with some hickory and flowering plants, but no grass pollen. It is likely that the pollen assemblage represents a local pine dominated ecosystem associated with the pond paleoenvironment, such as a riparian community, and that the greater landscape was drier and open. An alternative hypothesis is that the climate became wetter and initiated the formation of the pond, and an early succession forest ecosystem developed.

1. Introduction

1.1 Background

The Pipe Creek Sinkhole (PCS) is located in Grant County, Indiana (Fig. 1) and contains a paleoclimate record that is especially significant because it is Late Miocene or Early Pliocene and represents warm-Earth conditions immediately prior to the development of extensive northern hemisphere glaciation. Understanding paleoclimatic records from this period may provide critical information for predicting the outcome of global warming.

Although during the Early Pliocene (5 to 3 Ma) many of the external factors that determine climate, such as intensity of incident sunlight, global geography, and atmospheric concentration of carbon dioxide were similar to those operating today, the climate was nevertheless greatly different with elevated temperatures at polar regions and continental glaciers absent from the northern hemisphere, which made sea-level much higher than today (Federov et al., 2006). One distinct difference between the Early Pliocene and today was the global ocean circulation pattern. At 4.6 Ma a critical step occurred in the gradual closure of the Central American seaway and, as a consequence, the Atlantic Ocean circulation pattern changed significantly to the modern pattern with the development of strong North Atlantic Deep Waters (NADW) and intensification of the Gulf Stream (Haug and Tiedemann, 1998). Furthermore, there is abundant evidence that the equatorial Pacific Ocean lacked the east-west temperature gradient present today and that oceanic sea surface temperatures (SST) resembled those present during El Niño events before 3 Mya (Wara et al., 2005; Ravelo et al., 2006). This is significant because the PCS is located in a region that is currently sensitive to drought during El Niño events, and it appears that late Miocene to early Pliocene paleoclimates resembled the conditions present during modern El Niño events (Molnar and Cane, 2007). There are few other interior continental sites from the eastern half of North America of late Miocene to early Pliocene age, other than the Gray Fossil Site in eastern Tennessee (Shunk et al., 2006), and subsequently very little is known about conditions characterizing the Late Neogene climate of this region. The PCS therefore provides an extraordinary opportunity to evaluate the hypothesis that El Niño-like conditions affected Mio-Pliocene paleoclimate in eastern North America and to compare proxy data with the results of computer models.

The primary purpose of this paper is to reconstruct aspects of the paleoenvironment and paleoclimate from PCS sediments and organic matter. In order to do this, we use a combination of field relationships, lithostratigraphy, micromorphology, pollen analysis, and bulk elemental and stable isotope geochemistry.

1.2 Site Description

The Pipe Creek Sinkhole (PCS) includes the sediment fill of a complex karst environment located in north-central Indiana, USA (Fig. 1; Lat. 40° 27’ 25.4”, Long. 85° 47’ 37.2”). The PCS developed in dipping limestone flank beds of Silurian reef deposits and contains >5 m of Tertiary sediment overlain by Pleistocene glacial till. The PCS site lies within a 75 m by 50 m (by 11 m deep) sinkhole that probably originated as small cave, the roof of which eventually collapsed, thereby allowing the site to fill with fluvial sediments. During a portion of the depositional history a small pond developed and accumulated sediment containing a diverse fauna and flora (Farlow et al, 2001).

The PCS contains a well-preserved sedimentary record comprising multiple depositional facies that include (from oldest to youngest): 1) >3 m of high-chroma, red-colored sediment (Munsell color 2.5YR 3/6 to 10R 3/6) that is dominantly clay, but intercalated with carbonate roof-fall and other bedrock materials varying in size from silt to boulders (Fig. 2a); and 2) a gleyed, dark brown (7.5YR 4/4 to 10YR 3/6) or black-colored (Munsell color 10YR 7/8 to 2.5Y 6/8) facies that includes abundant allochthonous sand, as well as diverse faunal and floral assemblages (Fig. 2b). Hereafter, the underlying red-colored sediment facies and the overlying dark-colored sediment facies are referred to as the *red facies* and *dark facies*, respectively. A light yellow-brown to brown-red paleosol that formed from pedogenic modification of the *red facies* is present in portions of the site. Farlow et al. (2001) analyzed the fauna and flora from the PCS *dark facies* sediment and discovered that plants are represented by a diversity of extant terrestrial and wetland forms, whereas the vertebrate assemblage includes a combination of extant and extinct frogs, turtles, fish, birds, snakes, and small and large mammals, which collectively indicate a Late Hemphilian age for the deposit. Analysis of rodent fossils from the PCS, in association with the other biota, collectively suggests an early Pliocene age of slightly more than 5 Ma for the site (Martin et al., 2002). The fossil bones are rarely articulated or associated, but are generally well-preserved, usually with little surficial or internal weathering. Features of the PCS bones, along with the abundant aquatic plant fossils, suggest that the pond sediments remained saturated during early diagenesis and did not experience fluctuations in water content; this further indicates that the *dark facies* depositional environment was dominantly a permanent pond rather than an ephemeral one (Farlow and Argast, 2006).

2. Methods

2.1 Field lithostratigraphy

Field lithostratigraphic analysis, sampling, and mapping were conducted as sediment was excavated from the site in various stages. Much of the Tertiary sediment fill of the deposit was disrupted in 1998 when quarrying operations removed the thick layer of glacial till exposing the underlying Late Neogene sediment. Fortunately, relatively intact stratigraphic sections were preserved near very large (4 m diameter) boulders of the local limestone bedrock. In 2003-2005 continued excavations exposed large amounts of sediment, which was photographed and sampled for geochemical and petrographic analysis. Large boulders were removed from the site interior with heavy machinery, thereby exposing additional fresh strata that were available for further analysis. Detailed site maps with surveyed elevations are currently in preparation for publication elsewhere.

2.2 Micromorphology, geochemistry, and palynology

Ten representative samples for thin-section analysis were collected from different stratigraphic levels within the PCS. Samples were dried and then surface-impregnated with resin prior to commercial thin-section preparation. Thirty total bulk sediment samples (with visible fossil wood removed) were collected for δ^{13} C and δ^{15} N, % C, and % N analyses from the PCS sediment. Nineteen samples were collected from the thickest remaining section of the *dark facies* at a 10 cm sampling interval (Fig. 2b), and four samples were collected from various intervals of the paleosol, and three samples were collected at a 1m sampling interval from the top, middle, and bottom of the thickest exposed section of the *red facies*. In addition, more than ten >1cm pieces of well-preserved fossil wood were collected and combined to form a composite sample that represents an "average" isotopic value for fossil tree wood.

Powdered bulk samples for geochemical analysis were treated with 10% HCl for 2 hours to remove the carbonate fraction. The bulk sediment and wood samples were sent for commercial analysis at the University of Arizona and measured on a Finnigan Delta-plus XL, continuous-flow gas-ratio mass spectrometer coupled to a Costech elemental analyzer. Samples were combusted in the elemental analyzer, and standardization is based on acetanilide for elemental concentration, NBS-22 and USGS-24 standards for $\delta^{13}C$, and the IAEA-N-1 and IAEA-N-2 standards for $\delta^{15}N$. Precision is better than 0.09 for $\delta^{13}C$ and 0.2 for $\delta^{15}N$, based on repeated internal standards. Nineteen samples were collected from the PCS *dark facies* for pollen and kerogen analysis and processed in the pollen lab of the Biology Department at East Tennessee State University. Samples for pollen identification were processed using a modified version of Barss and Williams (1973). Samples processed for kerogen used 10-15 grams of each sample which were disaggregated by crushing in a porcelain mortar. To remove the carbonates, concentrated (35 %) HCl was added to the crushed sample and left for about 24 hours to ensure a complete removal of carbonates. Samples were then washed several times with distilled water until being neutral. To remove the silicates, about 100-150 ml of concentrated (45 %) HF was added and left for about five days to dissolve all the silicates and were occasionally stirred. After removing the carbonates and silicates the kerogen residues were separated from the inorganic materials by sieving through a 125 μm brass sieve and collecting the residue in a 10 μm nylon sieve. No further oxidation or staining were applied to the residues. A few drops of polyvinyl alcohol were added to the residue for dispersion on glass slides and Canada Balsam was used as a permanent mounting medium. Each slide was examined using transmitted light microscopy at X 200, X 500 and X 1000 magnification using a Zeiss Axiophot.

3 Results

3.1 Field stratigraphical and micromorphological analysis

PCS deposits are unlithified and lithostratigraphic relationships are extremely complex because multiple sediment sources and sediment reworking are inherent to primary deposition of clastic sediment in karst environments. The lithostratigraphy is further complicated by post-depositional sediment slumping, reworking, and soft sediment deformation associated with post depositional alteration that occurred during additional Pliocene sedimentation as well as during Pleistocene glaciation. For example, a portion of the *dark facies* sediment is injected into underlying *red facies* sediment due to soft sediment deformation (Fig. 2c). There is clear evidence of sediment mixing and reworking within some regions of the site (Fig. 2d). In portions of the site, strata are interlayered at cm to m scaled layers of various sediment types (Fig. 2e). At the top of the Tertiary sediment section, there is intercalation of different sediment facies with the glacial cover mass. However, in other areas the sediment sections are intact, with correct vertical stratigraphic relationships preserved for characterization in the field (Fig. 2f). No speleothems are present within the PCS sediments, but the site does include calcite crystals with complex growth patterns on some of the large boulders. Abundant, angular carbonate material, ranging in size from sand to boulders, is present throughout the deposits, but in general, sediment without the carbonate-derived particles is non-calcareous and does not react with acid.

The *red facies* sediment matrix is comprised dominantly of clastic material (clay) (Fig. 3a, b) intercalated with coarser-grained (sand and pebble to boulder size) carbonate. Portions of the uppermost *red facies* have been pedogenically modified into an immature paleosol (as discussed in subsequent text), and this paleosol and the unaltered lower-portions of the *red facies* will be considered independently, hereafter. The lower portion of the *red facies* (Fig. 2a) does not contain vertebrates, plant fossils, or root trace fossils and includes very little silt- and sand-sized clastic material. Micromorphologic analyses of the *red facies* sediment matrix reveals the texture commonly has a vuggy-cracked microstructure with abundant yellow clay coatings along planar voids. Cracked microstructure portions of the matrix are defined by shrink fractures with FeMn and FeOOH quasi-coatings (Fig. 3a). Along with the fine-grained matrix there are abundant reworked (rounded) sand-size litho-relics of the same composition as the matrix (Fig. 3b), and the sediment includes abundant angular carbonate clasts.

The uppermost portion of the *red facies* is yellow (Munsell color 10YR 7/8 to 2.5Y 6/8) to brown (7.5YR 4/4 to 10YR 3/6)- colored sediment that includes bifurcating and tapered root trace fossils, abundant illuviated clay, and abundant FeMn nodules, which collectively indicate that the site includes a paleosol (Fig 3f-h). Roots regularly cross-cut and overprint the *red facies* fractures, which indicate the rooting occurred after the fractures and their associated quasi-coatings developed. Birefringent clay is common with geopetal orientations that formed in multiple generations (Fig. 3h). However, aside from the color change, presence of illuviated clay and isolated rooting, the paleosol includes no other advanced pedogenic features such as distinct soil horizons or ped structure. The paleosol is often yellow, and below the paleosol yellow illuviated clay coatings commonly line macropores in portions of the underlying *red facies*. Some of the yellow clay appears to represent the alteration of the *red facies* sediment, as evidenced by some of the sediment partially altered from red to yellow (Fig. 3b) and abundant illuviated yellow clay beneath the paleosol. In other situations the yellow sediment appears to represent primary deposition as evidenced by micro-laminated (mm-scale) sediment that alternates between yellow clay and FeMn stained laminae, and in decimeter-scale interlayering between yellow and red sediment types (Fig. 2e). The abundance of yellow pore-filling sediment decreases with depth in the profile, but yellow infilling exists in all *red facies* sediment observed (to a depth of 3m).

A substantial amount of the *dark facies* was removed by quarry operations prior to our analysis. Remaining in situ sediment had a maximum thickness of 1.9 m (Fig. 2b), but typically occurred in thinner (< 0.5m) sheets blanketing most of the site. The *dark facies* lies stratigraphically above the *red facies* and its capping paleosol (Fig. 2f). The *dark* includes all known Tertiary plant and animal fossils discovered from the site. The *dark facies* is similar to the *red facies* because it includes abundant reworked fine sand up to cobble- size litho-relics (Fig. 3c), but the *dark facies* also includes abundant medium-sand-sized quartz grains and quartzite pebbles, which are not present within the underlying *red facies* (Fig. 2b, 3d). The *dark facies* is bedded in places and includes abundant fauna and flora. Fossil wood is generally well-preserved, in some cases retaining visible vascular structure (Fig. 3e), but is commonly impregnated with Fe-Mn giving it a black-color. Micromorphologic analysis reveals that the *black facies* is rich in Fe-Mn nodules (Fig. 3c). Sepic-plasmic clay fabric and isolated FeMn nodules are also abundant within the *dark facies* (Fig. 3c).

3.2 Geochemical analysis

The δ^{13} C values of organic C in bulk sediment samples analyzed from PCS deposits averaged -22.0 ‰ PDB (± 2.3) (Fig. 4). The *dark facies* sediment averaged 0.9 % (± 0.6) organic carbon (OC), with δ^{13} C values averaging -21.9 ‰ (±0.6), δ^{15} N values averaging 4.5 ‰ (±1.0), and C/N ratios averaging 17.5 (±6.4) (Fig. 4). The *red facies* sediment averaged 0.1 % OC with δ^{13} C values averaging -20 ‰ (±0.7) and 0.03 % N with δ^{15} N values averaging 6‰ (±0.4). The paleosol samples averaged 0.1 % OC with δ^{13} C values averaging -23.7 ‰ (±1.1), and 0.1 %N with δ^{15} N values averaging 4.5 ‰ (±1.0). The composite wood sample contained 47% OC with a δ^{13} C value of -25.2 ‰, and 0.7 % N with δ^{15} N value of 5.2 ‰ (Fig. 5). There is a relationship whereby within the interval from 1.5 to 1.7 m depth in the *dark facies* the C/N values decrease to a minimum, δ^{15} N values reach their maximum values, and % OC is at a minimum value averaging 0.25 (Figs. 4, 5).

3.3 Pollen and kerogen analysis

PCS pollen and kerogen are generally well-preserved, and palynomorph distribution is dominated by pollen grains of the family Pinaceae (58% of the total count) (Fig. 6a). Freshwater algae and zooclast (derived from freshwater zooplankton) comprise the second highest percentage at about 27%. Pollen of the Juglandaceae is the only other significantly represented woody taxon and comprises about 10% of the flora. There is a notable absence of the common forest and understory tree pollen, and the other recorded taxa (about 5%) include pollen grains of Asteraceae, Polygalaceae and Chenopodiaceae.

Samples from depths of 0.9, 0.7 and 0.4 m are generally poor in organic matter. Palynomorphs and amorphous organic matter (AOM) are rare. Opaques and phytoclasts are the dominant kerogen components (Tyson, 1995). Samples from depths of -0.1, -0.2, -0.3, -0.5, -1, -1.1, -1.2 and -1.3 m are rich in organic matter. Palynomorphs and AOM are very rare, whereas opaques and phytoclasts are dominant in these samples. Samples from the -1.4, -1.5, -1.6 and -1.7 m depths are very poor in kerogen content. Palynomorphs and AOM are rare, whereas opaques and phytoclasts are dominant. *Chomotriletes* (fresh water algae) are abundant in samples from -1.6 and -1.7 m depths. *Chomotriletes* are also recorded from the other samples, but are not as abundant as in these two samples. The sample from the -1.9 m depth has especially high organic content. Palynomorphs are common in this sample, whereas AOM are still rare; opaques and phytoclasts are dominant.

Pollen of the Pinaceae were investigated using Pearson's (1984) color chart to determine the Thermal Alteration Index (TAI), and the pale yellow to yellow are the dominant exine pointing to a TAI of 1 to 1+, which indicates that the pollen are clearly thermally immature. There is an abundance of equidimensional opaques that are associated with dark brown phytoclasts of total kerogen, which indicates some degree of oxidation in this environment. Overall there is a very high abundance of the small-sized kerogen particles over the large ones (Fig. 6k-l).

4. Interpretations and Discussion

4.1 PCS paleoenvironment: Red Facies

Figure 7 depicts a summary conceptual model of the geomorphic and stratigraphic development of the PCS. The *red facies* sediment includes no rooting and reduced amounts of yellow clay, and there are no vertebrate fossils present within this sediment. The *red facies* includes abundant angular to sub-rounded limestone clasts that include marine fossils (abundant crinoid stem fossils) and are interpreted to be derived from the local bedrock (Fig. 2a), as well as rounded, coarse sand-sized litho-relics that are comprised of the same *terra rossa* material, which indicate that the *red facies* includes reworked material (Fig. 3b). The reworked sediment source must have been relatively near the PCS deposit because unlithified clay litho-relicts are easily destroyed when transported great distances. The presence of sand-sized litho-relicts, as well as the coarse-sand-sized carbonate particles within the *red facies*, indicates that there was sufficient energy present to entrain and transport any available coarse clastic material into the basin during the time when the *red facies* was deposited. Thus, the absence of coarse-grained exogenic sediment (such as the abundant quartz clasts present within the *dark facies*), in combination with the lack of vertebrate fossils or root trace fossils in the *red facies,* suggests that this sediment was deposited in a closed karst (cave) environment. The lack of bedding in the *red facies* and persistence of the high-chroma color suggest that the sediment was deposited in a subaerial environment above the water table. Thus, it appears the PCS *red facies* represents deposition within a mostly closed, subaerial depositional environment that received inputs of reworked, fine-grained *terra rossa* sediment that was transferred deeply into the closed karst system, and that the environment was largely closed to the landscape above, which restricted coarse sediment inputs. The large boulders (up to 4 m diameter) are likely remnants of roof and wall fall associated with the breakdown of the karst bedrock.

Micromorphological analysis of the PCS *red facies* indicates that the non-carbonate sediment consists of almost exclusively clay-size material (Fig. 3a). The *red facies* fabric is dominantly comprised of a cracked microstructure with abundant vugs that are often lined with Fe-oxide stained clay coatings (Fig. 3a), which is remarkably similar to the micromorphology of other described examples of *terra rossa* (Durn, 2003). The cracked microstructure with abundant Fe-Oxide quasi-coatings suggest that the red facies underwent shrink-swell and redoximorphic processes associated with wet/dry cycles. The conspicuous bright red color (between 5YR and 10R) of *terra rossa* is likely a result of the preferential formation of hematite over goethite (i.e. rubification), which occurs under relatively low water activity, high temperature, good aeration (a result of underlying permeable limestone), and/ or high turnover rate for organic matter (Durn, 2003). Thick accumulations of *terra rossa* commonly fill karst depressions worldwide, including the region where the PCS occurs (Olson et al., 1980).

4.2 Red facies paleoclimate

The PCS *red facies* is dominantly comprised of detrital grains that appear to represent *terra rossa* sediment carried into a closed karst (cave) system by water or air currents from the land surface (Fig. 7). Cave sediments generally reflect and record large-scale trends in climate and other geologic or geomorphic variables (Springer, 2005). The Naracoorte cave deposits seem to provide a reasonable analogy for many of the observed features within the PCS. Moriarty et al. (2000) indicate that the Mid-Pleistocene cave fills in the Naracoorte Cave system represent an open, subaerial environment of deposition in which exogenic sediment entered the cave system by both air-fall and water transport from the land surface. This complex depositional setting created debris cones with sedimentary fans at their bases that develop beneath the doline entry points. Interestingly, in this system climate controlled the type of sedimentation deposited, whereby during wet climate phases carbonate and associated speleothems were common and during drier conditions (with a net water deficit) clastic sediment was transported and deposited during episodic storm events, and clastic and chemical depositional events rarely coincided. Thus, the absence of well-developed speleothems or any carbonate cement supports an interpretation that the PCS *red facies* was deposited in relatively dry climatic conditions with a net water deficit. Also, *terra rossa* sediments are common in Mediterranean climates characterized by cool, wet winters alternating with warm, dry summers that create xeric soils (Durn, 2003).

The origin of *terra rossa* in Indiana and in general has long been under debate. The view that it represents the residue product from solution of limestone has been rejected by Olsen et al. (1980) because insufficient quantities of insoluble residue in the limestone rock require dissolution of thickness greater than the limestone available, and therefore, terra rossa is considered a complex soil with multiple sources of parent material. However, recent field and petrographic evidence presented by Merino and Banerjee (2008) provides evidence that *terra rossa* forms by the replacement of limestone by authigenic clay at a moving metasomatic front with additions of major chemical elements from dissolved eolian dust. Durn (2003) points out that regardless of the source of terra rossa, its formation is dependant on the process of rubification in a specific pedoenvironment associated with hard limestone weathering in a Mediterranean climate.

The δ^{13} C values from cave sediment TOC from Fogelpole Cave and Illinois Caverns in southwestern Illinois demonstrate that paleoclimatic interpretations from cave sediments are typically in good agreement with other proxy records for reconstructing the distribution of C3 and C4 vegetation on the landscape (Panno et al., 2004). The debate about an autochthonous or allochthonous source for terra rossa is significant for understanding PCS *red facies* δ^{13} C values. If the *red facies* is a complex soil from the landscape, then the organic material in these sediments likely represents the vegetation on the landscape, and *red facies* δ^{13}C values average -20.0 ‰, which suggest a mixture of C3 and C4 plant contributions. However, if the *red facies* represents an in-situ residuum from carbonate dissolution, then its organic material would not represent vegetation growing on the landscape. Unfortunately, after an extensive literature review, we were unable to find other reported δ^{13} C values from *terra rossa* for comparison. Thus, paleoclimatic interpretations from the *red facies* δ^{13} C values should be made with caution because: 1) it is possible that the δ^{13} C values may reflect something besides vegetation in the watershed; and 2) the *terra rossa* sediment TOC is very low (averaging 0.1%) and could be modified prior to deposition by microbial processes that can alter the geochemistry of organic matter. δ^{15} N values from the *red facies* average 6, but humification typically increases ^{15}N and the N system is generally poorly understood in soils (Kramer et al., 2003) so the data provides little insight about the source of organic material. However, if the *red facies* δ^{13} C values are representative of the distribution of C3 and C4 vegetation on the landscape, then a mixed C3 and C4 ecosystem is in good agreement with the Mediterranean-like climates required to form *terra rossa*, the habitat reconstructions from the vertebrate fossils, and the relatively dry conditions necessary for the deposition of clastic cave sediment without carbonate cement or speleothems.

4.3 PCS paleosol and interlayered section paleoenvironment and paleoclimate

The pedogenic alteration of the *red facies* to a paleosol represents a major change in the PCS depositional environments. Because vascular plants require sunlight, the presence of root traces indicates that the cavern had opened prior to pedogenic modification of the *red facies*. The PCS paleosol lacks advanced soil features like distinct soil horizons or a well-developed ped structure, which suggests the paleosol is relatively immature and likely represents a paleoEntisol or paleoInceptisol. Root traces cross-cut Fe-oxide lined voids and cracks in the *red facies*, which indicates that the redoximorphic conditions were present prior to the development of the paleosol.

The distinctly yellow color of the uppermost *red facies* and paleosol appears to result from the combination of primary deposition of yellow laminated sediment and/ or the in situ modification of previously deposited *red facies* sediment. The process of yellowing a ferralitic soil likely indicates the transformation of hematite and Al-poor goethite to Al-rich goethite, associated with sediment wetting (Fritsch, et al., 2005). In portions of the site, the top of the *red facies* is inter-layered between red and yellow sediment types (Fig. 2e), which indicates the conditions responsible for deposition of each sediment type alternated through time as sediment was deposited. If yellow sediment represents wetter conditions compared to the red sediment, then the interlaying between sediment types suggests that the PCS paleoenvironement alternated between wet and dry conditions. A possible analogy for the inter-layered sediment within the PCS was described in the Naracoorte Cave (Australia) system by Moriarty et al. (2000). Interestingly, alternating wet- and dry-climate phases controlled the type of sedimentation within the Naracoorte cave deposits and the sedimentation style was inter-layered in a manner similar to that in the PCS. However, it is unclear if the alternation between wet and dry paleoenvironmental conditions relates to an increase of moisture due to the opening to the land surface or to oscillations in paleoclimate.

The paleosol $\delta^{13}C$ values average -23.7 ‰, which are more negative than those of the underlying *red facies* parent material. Because humification during pedogenesis typically increases ^{13}C due to a loss of lighter ^{12}C via microbial respiration (Kramer et al., 2003), the soil $\delta^{13}C$ values likely reflect additional contributions of organic material derived from C3 plants to the sediment during pedogenesis (e.g., from the addition of root remains) rather than humification.

4.2 Dark facies paleoenvironment

The *dark facies* includes abundant sand-sized and coarser clastic sediment as well as fossil wood and bone derived from the land surface. The *dark facies* sediment onlaps the paleosol (Fig. 2f), which indicates that the *dark facies* was deposited after the site opened to the surface. Thus, at some point following the opening of the PCS environment to the land surface, the PCS flooded and it appears that a ponded environment developed. The development of a pond on top of *red facies* sediment that was deposited above the water-table may relate to the opening of the karst environment to the surface, which may have provided additional water to the environment producing a perched pond. Alternatively, the development of the pond may relate to the development of wetter climatic conditions and an increase to the water-table. A similar increase of the water-table and an associated filling of karst environments with water have been documented in Florida and Georgia due to a climate shift to wetter conditions that occurred at ~8,500 ^{14}C yr BP (Filley et al. 2001). Taphonomic features of the PCS vertebrate fossils, in combination with the presence of abundant aquatic flora and fauna, suggest that the pond environment persisted for an extended interval rather than being repeatedly ephemeral (Farlow and Argast, 2006). However, minor amounts of sepic-plasmic (bright clay) fabrics and in situ Fe-Mn nodules within the *dark facies* (Fig. 3d) indicate that the *dark facies* sediments experienced wet and dry periods, but the timing for the establishment of freely drained conditions is unclear.

The deepest *dark facies* strata were deposited into a sub-basin cut into the underlying *red facies* sediment and located between two large boulders that created a deepened channel. It is possible the opening of the site to the surface introduced higher energy storm-water flows that scoured into, and eroded away, portions of the previously deposited *red facies* sediment. The *dark facies* includes abundant litho-relics, which indicate the sediment has been reworked, and the angular shape of the grains indicates these sediments are derived from a very nearby source (Fig. 3d). Illuviated clay within some of the reworked litho-relics suggests that the sediment was transported from a subaerially exposed environment such as a soil (i.e., they are pedo-relics), which indicates that portions of the pond sediments were exposed at intermittent periods during the history of the pond.

C/N ratios, δ^{13} C, and δ^{15} N values from sediment total organic carbon (TOC) provide a powerful tool for understanding a lacustrine environment and for reconstructing paleoclimate. Meyers (1994) showed that in appropriate lacustrine environments elemental C/N ratios and stable C isotope values appear to retain paleoenvironmental information for multi-Myr periods. This is useful because elemental C/N ratios from TOC preserved in pond sediment can be used to distinguish algae (endogenetic) and land plant sources (dominantly exogenetic) of organic material, because land plants include abundant support tissue that results in land plant C/N ratios > 20, whereas algae C/N values range between 4 and 10. Carbon isotopic ratios are useful to distinguish between plants using the C3 (Calvin-Benson) and C4 (Hatch-Slack) pathways because C3 plants have δ^{13} C values averaging -27 ‰ (PDB) and C4 plant values average -14 ‰ (PDB). Freshwater algae use C3 plants use pathways and typically utilize dissolved CO_2 in the aquifer, which is usually in isotopic equilibrium with atmospheric CO_2. Therefore, under normal circumstances algal δ^{13} C values are the same as land plant values, whereas the source of inorganic C for marine algae is dissolved bicarbonate, which creates organic matter with δ^{13} C values between -22 and -20‰ (Meyers, 1994). However, Brenner et al. (1999) indicate that the δ^{13} C geochemical system can be complex in some lacustrine settings such as a small, shallow, and potentially stagnant karst environment, as suggested here for the PCS. There are multiple factors that influence the δ^{13} C of autochthonous sedimented organic matter including: (1) the rate of atmospheric CO_2 exchange, (2) carbonate weathering, (3) the source of C used for primary production, and (4) in-lake rates of photosynthesis. For example, many algae and aquatic vascular plants are capable of utilizing CO_2 from bicarbonate ions when free CO_2 is in very low supply and $HCO3^-$ is abundant, which generally occurs in stagnant environments or during periods of rapid primary production. Also, during periods of high primary productivity, algae discriminate against ^{13}C and preferentially utilize ^{12}C, which can deplete the light isotope (^{12}C) in the photic zone and produce algae with increased δ^{13} C values. Furthermore, some rooted submersed aquatic vegetation have higher δ^{13} C values than other C3 plants (-12.8 to 15.9 ‰) because C assimilation is more difficult in water without access to atmospheric CO_2 (Brenner et al. 2006). Under such conditions, it is possible for δ^{13} C values of lacustrine algae to resemble typical marine algae values of -22 to -20 ‰. Thus, if the PCS pond was stagnant, maintained high rates of primary productivity, or included abundant submersed aquatic vegetation, then organic matter from autochthonous sources may have included greater δ^{13}C values that can resemble a C4 plant influence.

The δ^{15}N values appear to maintain their primary values in well-preserved lacustrine sediments, and N-isotopes offer a rough estimate for the source of organic material into a lacustrine basin because δ^{15}N values of algae average 8 ‰, whereas land plants average 1 ‰ (Meyers and Ishiwatari, 1993). However, it has been shown that some individual autochthonous vegetation types (such as rooted and submersed aquatic vegetation) do not display distinct δ^{15}N values, which makes N-isotopes less useful for distinguishing sources of organic material in environments that potentially include these plants (Brenner et al. 2006).

The presence of abundant charophyte cysts and fossil wood within the PCS deposits are clear indicators that the PCS received organic matter from both autochthonous and allochthonous sources. C/N values of *dark facies* sediment (from which visible fossil wood was removed) average 17.5 ‰ and generally indicate the sediment TOC includes a mixture of algal and vascular land plant contributions (Fig. 5), which is consistent with the δ^{15}N values that average 4.5 (Fig. 4). However, samples between 1.5 and 1.7m depth that maintain C/N values averaging 6.1, δ^{15}N values that average 6.4 ‰, and therefore, have C/N ratios and δ^{15}N values that are consistent with organic matter derived dominantly from algae (Fig. 5). Furthermore, this zone includes abundant *Chomotriletes* (fresh water algae) grains and very low total kerogen. Thus, collectively these proxy data strongly suggest that this depth interval received dominantly algal contributions to the sediment TOC record. Interestingly, the δ^{13}C values from these depths average -20.6 ‰, and in figure 5 these samples plot as marine algae, which strongly suggest that PCS autochthonous algae maintained increased δ^{13}C values. The low %TOC (averaging 0.25%) from the 1.5 to 1.7 m depth interval suggests that productivity was not great during the deposition of these sediments. Thus, the geochemical data and presence of abundant algal cell counts from these depths are consistent with the presence of algae (and possible other macrophytes) that utilized bicarbonate for photosynthesis (Fig. 5), and this interval provides strong evidence that the PCS pond sediment includes considerable contributions of organic material derived from algae with high δ^{13}C values that arose from their use of $HCO3^{-}$ for photosynthesis. A similar modern environment is described for Mud Lake (located in Florida, USA), which shifted from a dominant organic matter source of grasses and surrounding emergent vegetation that utilized atmospheric CO_2 to submerged and floating macrophytes as well as phytoplankton using dissolved CO_2 or bicoarbonate for photosynthesis (Filley et al., 2001).

The remainder of the PCS *dark facies* has higher C/N ratios, lower δ^{15}N values, and abundant kerogen relative to the 1.5 to 1.7 m depth interval, which indicates that TOC likely represents a mixture of vascular land plant and algal contributions. The δ^{13}C values from the remainder of the deposits average -22 ‰, and are consistent with dominantly algae mixed with small amounts of organic material derived from C3 vascular plants characterized by relatively high δ^{13}C values (averaging -25.2 ‰) and C/N ratios (averaging 67.6). Additionally, the apparent shift from sediments with organic mater derived dominantly from algae between depths of 1.5 to 1.7 m to a mixed source of algae and vascular wood organic material up-section suggests that the *dark facies* stratigraphy is not mixed or time averaged and therefore represents a time series. This observation is further supported by the presence of cm-scale laminations within the same portion of the *dark facies*.

4.4 PCS dark facies paleoclimate

The PCS *dark facies* includes a well-preserved vertebrate fauna and a flora that includes abundant fossil wood and pollen, which provide multiple proxies for paleoclimate reconstruction. Farlow et al. (2001) indicated that the vertebrate fossil assemblage and floral assemblage includes a mixture of aquatic and terrestrial forms that likely represent a mixture of the local inhabitants of the PCS pond as well as plants and animal derived from an open savannah-like ecosystem with trees nearby. The composite sample of fossil wood indicates that the vascular C3 wood had an average δ^{13}C value of -25.2 ‰. Cerling et al. (1997) indicated that terrestrial C3 land plants can have a considerable range of δ^{13} C values because in water-stressed ecosystems plants are enriched in ^{13}C and can maintain δ^{13} C values as high as -22 ‰, whereas in forest ecosystems with closed canopies plants can have values as low as -35 ‰ due to the recycling and depletion of ^{13}C in the air beneath the tree canopy. Also, potential differences in the carbon isotopic composition of the atmosphere influence terrestrial plant δ^{13} C values as variations in the isotopic composition of atmospheric CO_2 mirror changes in global C-cycling (Arens et al. 2000). Thus, a value of -25.2‰ for C3 plant fossil wood suggests that the trees likely grew under slightly water-stressed conditions or that the carbon isotopic composition of the atmosphere was slightly heavier during the Early Pliocene (Fig. 5).

Pollen counts from the PCS *dark facies* indicates that pollen from the family Pinaceae (Pine) (58%) represent the major palynomorph element followed by algal remains and zooclasts (27%). The only other dominate woody species is Juglandaceae (Hickory) (10%). Pollen from an array of associated forest trees and understory plants are absent from the PCS and would be expected if this represented a closed canopy forest. The occurrence of pollen of the Asteraceae (Daisy), and Chenopodiaceae (Goosefoot) (5%) (Fig. 6) suggest a disturbed habitat. The occurrence of the Polygalaceae (Milkwort) is often associated with wetland habitats and reinforces the occurrence of permanent standing water. This coupled with the abundance of algal remains, and zooclasts further supports the presence of a small, stagnant pond that formed in collapsed karst environment with limited clastic input. The pollen assemblage is low in taxonomic diversity, and probably represents input from a very local environment. The presence of a pine – hickory woodland or savanna (compared to a stratified forest) suggests that disturbance was important part of the local ecosystem (Platt, 1999 and references therein). Thermal Alteration Index (TAI) of the pollen of the Pinaceae indicate that the organic matter is thermally immature. The occurrence of charred phytoclast and amorphous organic material are probably a result of oxidation by fire. This coupled with the abundance of large herbivores may have maintained this habitat as a Pine-Hickory woodland / savanna with an understory of Asteraceae and Chenopodiaceae, both indicative of disturbed habitats.

The $\delta^{13}C$ values from the pond sediments average -22 ‰ (PDB), with C/N values averaging 17.5, and under normal circumstances these values would suggest that the organic matter is composed of a mixture of algae and terrestrially derived vascular land plants and includes a significant contribution of C4 grasses (Fig. 5). However as discussed previously, it appears that the organic material in PCS has less negative δ^{13} C values possibly derived from the algae or freshwater zooplankton that utilized abundant bicarbonate as a carbon source. Thus, the δ^{13} C values from the *dark facies* do not provide evidence for C4 grasses, which is consistent with the absence of grass pollen throughout the stratigraphy.

5. Conclusions

The simplest hypothesis for a conceptual model of the geomorphic and stratigraphic development of the PCS is presented in Figure 7. It is consistent with the following basic information: 1) there is an abrupt facies shift from the non-fossiliferous, finer-grained, high-chroma *red facies* sediment to the fossiliferous, gleyed *dark facies* sediment that includes abundant sand; 2) there was development of a paleosol from underlying *red facies* sediment prior to, or concurrent with, the deposition of *dark facies* sediment; and 3) eventually a pond developed and sediment derived from the land surface was subsequently deposited in an open, sub-aqueous environment. Within the PCS there are abundant reworked litho-relics and interlayered sediment layers, which are consistent with sediment that was reworked from a nearby source such as a debris cone. The pond was likely stagnant with algae utilizing bicarbonate for photosysnthesis, which is consistent with a small body of water situated in a karst depression in such a way that mixing of atmospheric CO_2 and water was restricted.

The PCS includes a >3 m succession of *terra rossa* with δ^{13} C values that average -20 ±0.7‰ PDB, and PCS clastic cave deposits lack carbonate cement, which also suggest the environment was dry with a net water deficit. *Terra rossa* typically forms in well-drained soils with high temperatures (Mediterranean-like) that produce xeric soils (Durn, 2003). PCS vertebrate fossils are consistent with a mixture of local pond inhabitants and animals from an open savannah-like ecosystem but with trees nearby (Farlow et al., 2001). The mean $\delta^{13}C$ value of PCS tree fossil wood is -25.2‰ PDB, which suggests that trees did not grow in a closed canopy. Charcoal within the *dark facies* suggests that fire was a disturbance factor in this ecosystem. Pollen records from the PCS are dominated by pollen from pine (primarily an early succession plant in the deciduous forest) with contributions from hickory and plants that are indicative of disturbed habitats (Asteraceae and Chenopodiaceae). The pollen record includes low taxonomic diversity and may represent a woodland / savanna habit proximal to the PCS pond itself.

An alternative hypothesis to explain the PCS stratigraphy is that the climate became wetter, which initiated the development of the pond itself due to an increase to the water-table. The presence of interlayering sediment types that suggest alternating wet and dry paleoenvironmental conditions are consistent with alternating wet and dry climate conditions prior to the facies shift. If the climate went from relatively dry (*red facies*) to wetter conditions (*dark facies*), then this transition may have promoted the development of an early succession pine-dominated forest.

Acknowledgments

This research was supported by NSF grant EAR-0207182 and American Association of Petroleum Geologists Foundation: R.E. McAdams Memorial Grant, 2007.

References Cited

Arens N.C., Jahren, H., Amundson, R., 2000. Can C3 plants faithfully record the carbon isotopic composition of atmospheric carbon dioxide? Paleobiology, 26, 137-164.

Barss, M.S. and G.L. Williams.,1973. Palynology and nannofossil processing techniques. Geological Survey of Canada, 73-26, 26 pgs.

Brenner, M., Whitmore, T.J., Curtis, J.H., Hodell, Schelske, C.L., 1999. Stable isotope (δ^{13} C and δ^{15} N) signatures of sedimented organic matter as indicators of historic lake trophic state. Journal of Paleolimnology 22, 205-221.

Brenner, M., Hodell, D.A., Leyden, B.W., Curtis, J.H., Kenney, W.F., Gu, B., Newman, J.M., 2006. Mechanisms for organic matter and phosphorus burial in sediments of a shallow, subtropical, macrophyte-dominated lake. Journal of Paleolimnology 35, 129-148.

Cerling, T.E., Harris, J.M., MacFadden, B.J., Leakey, M.G., Quade, J., Elsenmann, V., Ehleringer, J.R., 1997. Global vegetation change through the Miocene/Pliocene boundary. Nature 389, 153-158.

Durn, G., 2003. *Terra rossa* in the Mediterranean region: parent materials, composition and origin. Geologia Croatica, 56, 83-100.

Fedorov, A.V., Dekens, P.S., McCarthy, M. Ravelo, A.C., deMenocal, P.B., Barreiro, M., Pacanowski, R.C., Philander, S.G., 2006. The Pliocene Paradox (Mechanisms for a Permanent El Niño): Science 312, 1485-1489.

Farlow, J.O., Sunderman, J.A., Havens, J.J., Swinehart, A.L., Holman, J.A., Richards, R.L., Miller, N.G., Martin, R.A., Hunt, R.M., Storrs, G.W., Curry, B.B., Fluegeman, R.H., Dawson, R.R., Flint, M.T., 2001. The Pipe Creek Sinkhole biota, a diverse Late

Neogene continental fossil assemblage from Grant County, Indiana. American Midland Naturalist 145, 367-378.

Farlow, J.O., Argast, A., 2006. Preservation of Fossil Bone from the Pipe Creek Sinkhole (Late Neogene, Grant County, Indiana, U.S.A.). Journal of Paleonological Society of Korea. 22, 51-75.

Filley, T.R., Freeman, K.H., Bianchi, T.S., Baskaran, M., Colarusso, L.A., Hatcher, P.G., 2001. An isotopic biogeochemical assessment of shifts in organic matter input to Holocene sediments from Mud Lake, Florida. Organic Geochemistry 32, 1153-1167.

Fritsch, E., Morin, G., Bedidi, A., Bonnin, D., Balan, E., Caquineau, S., Calas, G., 2005. Transformation of haematite and Al-poor goethite to Al-rich goethite and associated yellowing in a ferralitic clay soil profile of the middle Amazon Basin (Manaus, Brazil). European Journal of Soil Science 56, 575-588.

Haug, G.H., Tiedemann, R., 1988. Effect of the formation of the Isthmus of Panama on Atlantic Ocean thermohaline circulation. Nature 393, 673-676.

Kramer, M.G., Sollins, P., Sletten, R.S., Swart, P.K. 2003. N isotope fractionation and measures of organic matter alteration during decomposition. Ecology 84, 2021-2025.

Martin, R.A., Goodwin, H.T., Farlow, J.O., 2002. Late Neogene (Late Hemphillian) rodents from the Pipe Creek Sinkhole, Grant County, Indiana. Journal of Vertebrate Paleontology 22, 137-151

Merino, E., Banerjee, A., 2008. Terra rossa genesis, implications for karst, and eolian dust; a geodynamic thread. Journal of Geology 116, 62-75.

Meyers, P.A., 1994. Preservation of elemental and isotopic source identification of sedimentary organic matter. Chemical Geology 114, 289-302.

Meyers, P.A., Ishiwatari, R., 1993. Lacustrine organic geochemistry-an overview of indicators of organic matter sources and diagenesis in lake sediments

Molnar P., Cane, M.A., 2007. Early Pliocene (pre-Ice Age) El Niño-like global climate: Which El Niño? Geosphere 3, 337-365.

Moriarty, K.C., McCullock, M.T., Wells, R.T., McDowell, M.C., 2000, Mid-Pleistocene cave fills, megafaunal remains and climate change at Maracoorte, South Australia: towards a predictive model using U-Th dating of speleothems: Palaeogeography, Palaeoclimatology, Palaeoecology 159, 113-143.

Olson, C.G., Ruhe, R.V., Mausbach, M.J., 1980. The *terra rossa* limestone contact phenomena in karst, southern Indiana. Journal of Soil Science of America 44, 1075-1079.

Panno, S.V., Curry, B.B., Wang, H., Hackley, K.C., Liu, C.-L., Lundstrom, C., Zhou, J. 2004. Climate change in southern Illinois, USA, based on the age and $\delta^{13}C$ of organic matter in cave sediments. Quaternary Research 61, 301-313.

Platt, W.J. 1999. Southeastern Pine Savannas. In: Anderson, R.C., Fralish, J.S. and J. M. Baskin (Eds.), Savannas, Barrens, and Outcrop plant Communities of North America, Cambridge University Press. pgs. 23-51.

Ravelo, A.C. Dekens, P.S., McCarthy, M., 2006, Evidence for El Niño-like conditions during the Pliocene: GSA Today 16, 4-11

Shunk, A.J., Driese, S.G., Clark, G.M., 2006. Latest Miocene to earliest Pliocene sedimentation and climate record derived from paleosinkhole fill deposits, Gray Fossil Site, northeastern Tennessee, U.S.A. Palaeogeography, Palaeoclimatology, Palaeoecology 231, 265-278.

Springer, G.S. 2005. Clastic Sediment in Caves. in Encyclopedia of Caves. Edited by Cluver, D.C. and White, W.B. Elsevier Inc., p. 102-108.

Tyson, R.V. Sedimentary Organic Matter: Organic facies and palynofacies. Chapman and Hall, 615 pgs.

Wara, M.W., Ravelo, A.C., Delaney, M.L., 2005, Permanent El Niño-Like Conditions During the Pliocene Warm Period: Science 309, 758- 761.

Figure 1. Map showing the location of the Pipe Creek Sinkhole (PCS). The PCS provides a rare opportunity to study the paleoclimate from the Early Pliocene in a region that lacks extensive late Neogene records.

Figure 2. Field pictures from the PCS. A) A >1 m thick exposure of silty-clay *red facies*. B) The 1.9 m thick succession of dark facies; notice the white pins that represent locations for sampling at a 10 cm sampling interval. C) Example of soft sediment deformation whereby *dark facies* material (inside stippled lines) was injected into the *red facies*. D) Example of sediment mixing of PCS *red facies* and *dark facies* material. E) Interlayering of yellow and red sediment present at the uppermost portion of the *red facies* associated with the paleosol and apparent opening of the PCS to the land surface. F) Example of intact stratigraphy showing the underlying *red facies*, the rooted, yellow-colored paleosol, and the *dark facies* sediment.

Figure 3. Examples of PCS micromorphology. Micrographs C and F-H are in cross-polarized light. A) *Red facies* sediment showing the fine-grained, red-colored matrix with a vuggy-cracked microstructure with Fe-Oxide hypocoatings. Note the infilling of a large void with yellow sediment. B) *Red facies* with reworked litho-relicts. Note the partial yellowing of previously deposited *red facies* sediment that is associated with pedogenic alteration of the red sediment color. C) *Dark facies* sediment showing the abundant exogenic sand grains that are not present in the underlying *red facies*. Note the presence of sepic-plasmic clay fabric and in situ FeMn nodules that indicate the sediment underwent wet-dry conditions. D) *Dark facies* sediment rewoked litho-relicts. Note the

angular litho-relicts comprised of the same material indicating that these clasts are reworked from a nearby source. E) An example of well-preserved PCS fossil wood. F) A portion of the PCS paleosol showing illuviated clay and abundant FeMn staining and nodules. G) Paleosol showing a bifurcating and tapered root trace fossil backfilled with illuviated clay. H) Illuviated clay with geopetal pendant structure that backfills a macropore.

Figure 4. Geochemical, kerogen, and pollen distributions within PCS sediments. The dashed vertical line represents the average δ^{13} C value of PCS fossil wood. Paleosol samples are collected from multiple areas within the PCS; samples a-c are yellow/ red-colored samples and sample d is a brown/ red colored sample. The sample at -1.3 m was processed an analyzed twice yielding δ^{13} C values of -14.7 and -15.9 ‰, respectively. The meaning of these values is unclear because sediment from -1.3 m does not include grass pollen.

Figure 5. Composite figure of organic matter source identification (Meyers 1994, Brenner, 1999) and variations in isotopic composition of TOC considering both growing conditions and the differences between C3 and C4 photosynthetic pathways (Cerling et al. 1998). Note that the samples from 1.5 to 1.7 m depths plot as derived from algae utilizing bicarbonate for photosynthesis.

Figure 6. Histogram of percent distribution of PCS pollen and algal cells. Note the abundant pine pollen (Pinaceae) but low amounts of deciduous tree pollen (Juglandaceae)

and absence of grass pollen. B- Pinaceae; C,D- Freshwater algae ?; E- Juglandaceae; F,G- Asteraceae; H- Polygalaceae; I, J- Chenopodiaceae; K,L- Phytoclast and Opaque samples.

Figure 7. A conceptual model of the geomorphic and stratigraphic development of the PCS. A) PCS sedimentation likely initiated in closed (cave) subaerial depositional environment that accumulated >3m of clayey *terra rossa* sediment. B) The presence of a debris cone similar to those described in the Naracoorte cave system (Moriarty et al. 2000) provides a plausible working model to explain the interlayering of different sediment types (Fig 2E), the presence of abundant reworked litho-relicts (Fig. 3B,E), and the high abundance of unassociated and disarticulated but well-preserved large-vertebrate fossils. C) The PCS has evidence for pedogenesis and deep scouring of portions of the *red facies* sediment, which likely occurred when the environment opened to the land surface, thus allowing sediment and water from the surface to enter into the site. D) At some point after the initiation of pedogenesis, the PCS flooded and a stagnant pond developed accumulating at least 1.9 m of *dark facies* sediment that is rich in fossils and pollen. E) Prior to discovery the PCS was buried beneath a thick blanket of Pleistocene glacial till.

Historically the PCS region was characterized by broad leaf forest (E), but it appears that during the Late Neogene the greater landscape was characterized by more open conditions, but with abundant pine trees associated with the pond itself. The formation of *terra rossa* suggest that temperatures were elevated and soils were freely drained during the late Neogene.

Figure 1

Click here to download high resolution image

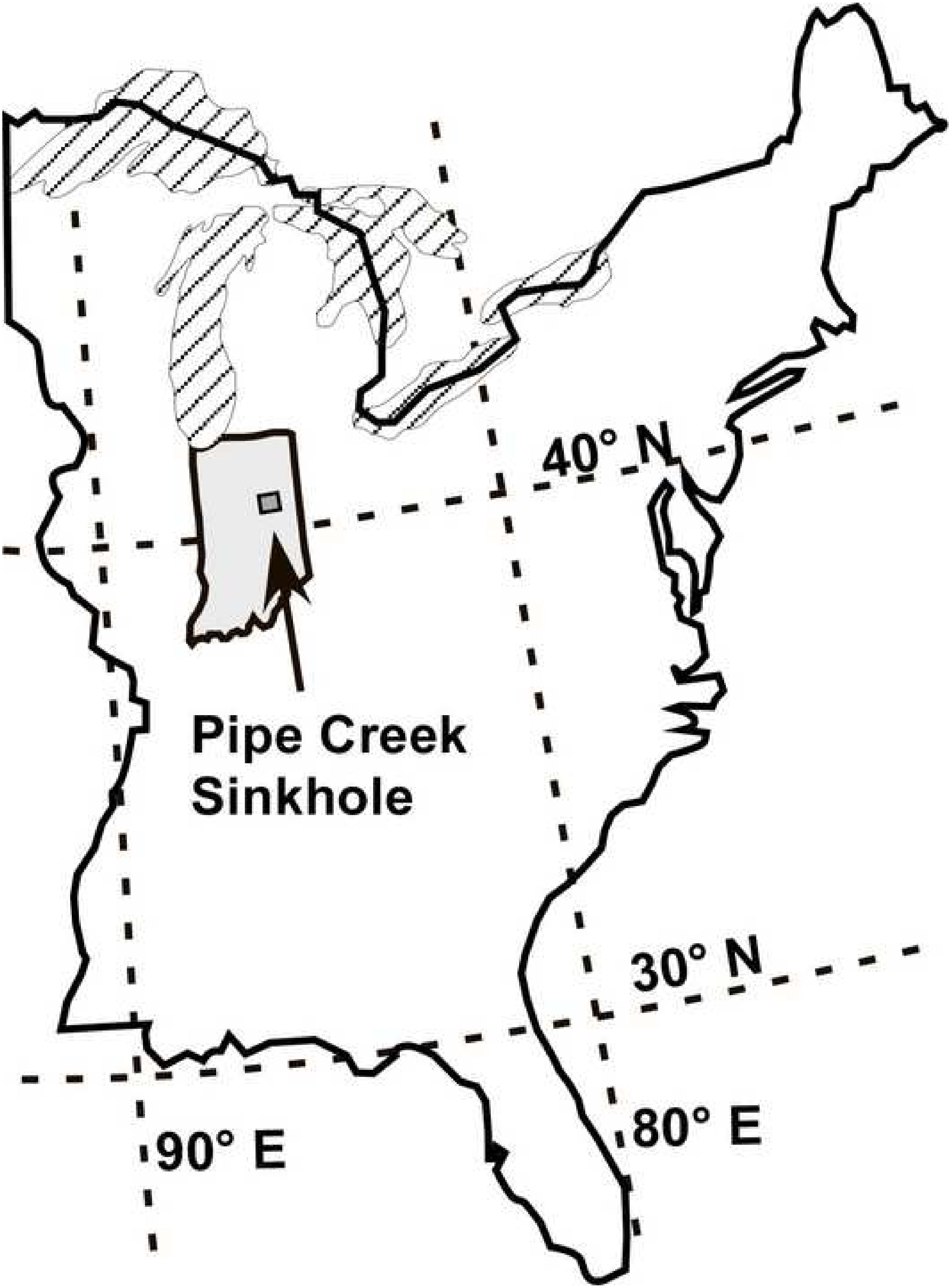

Figure 2
Click here to download high resolution image

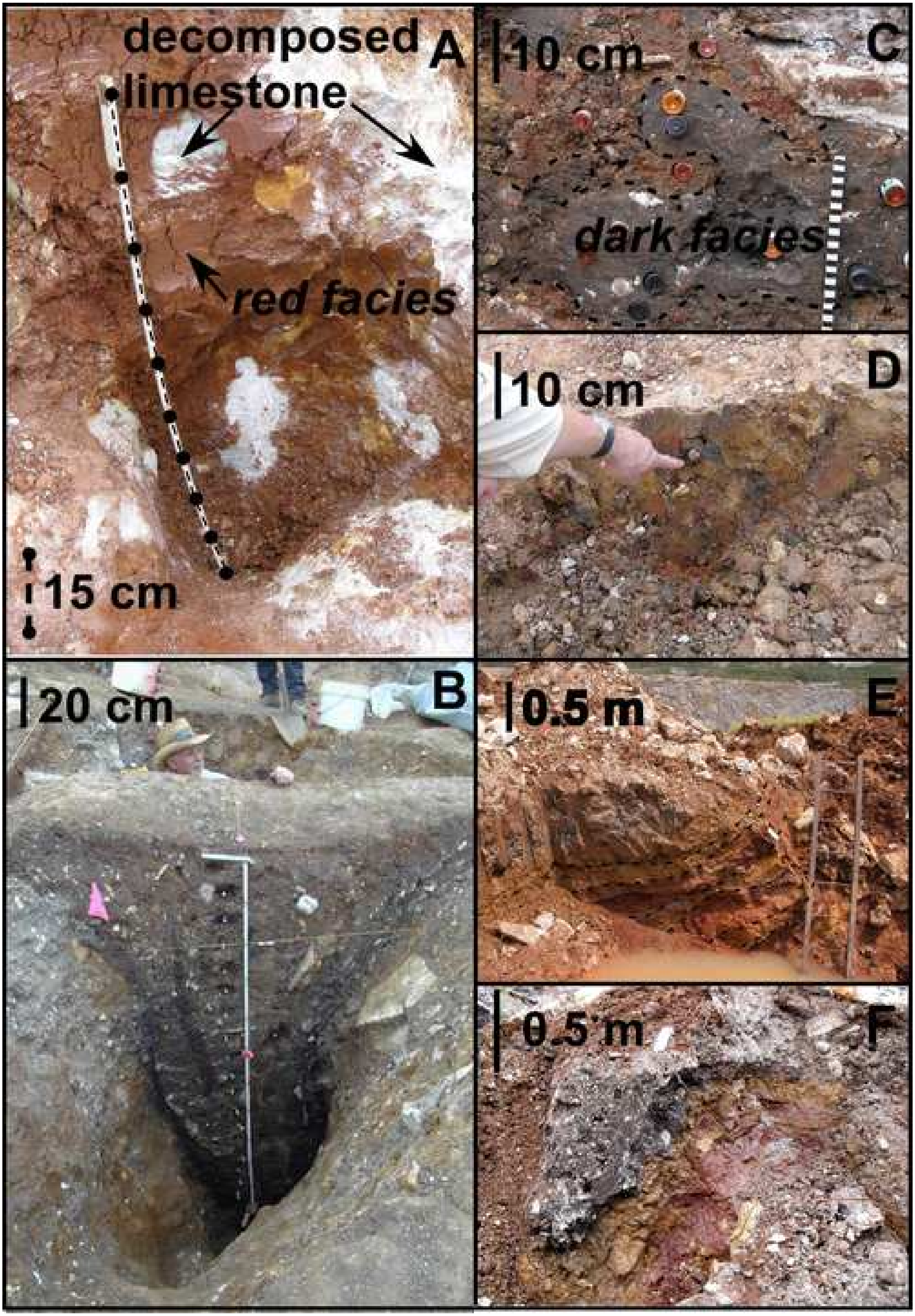

Figure 3

Click here to download high resolution image

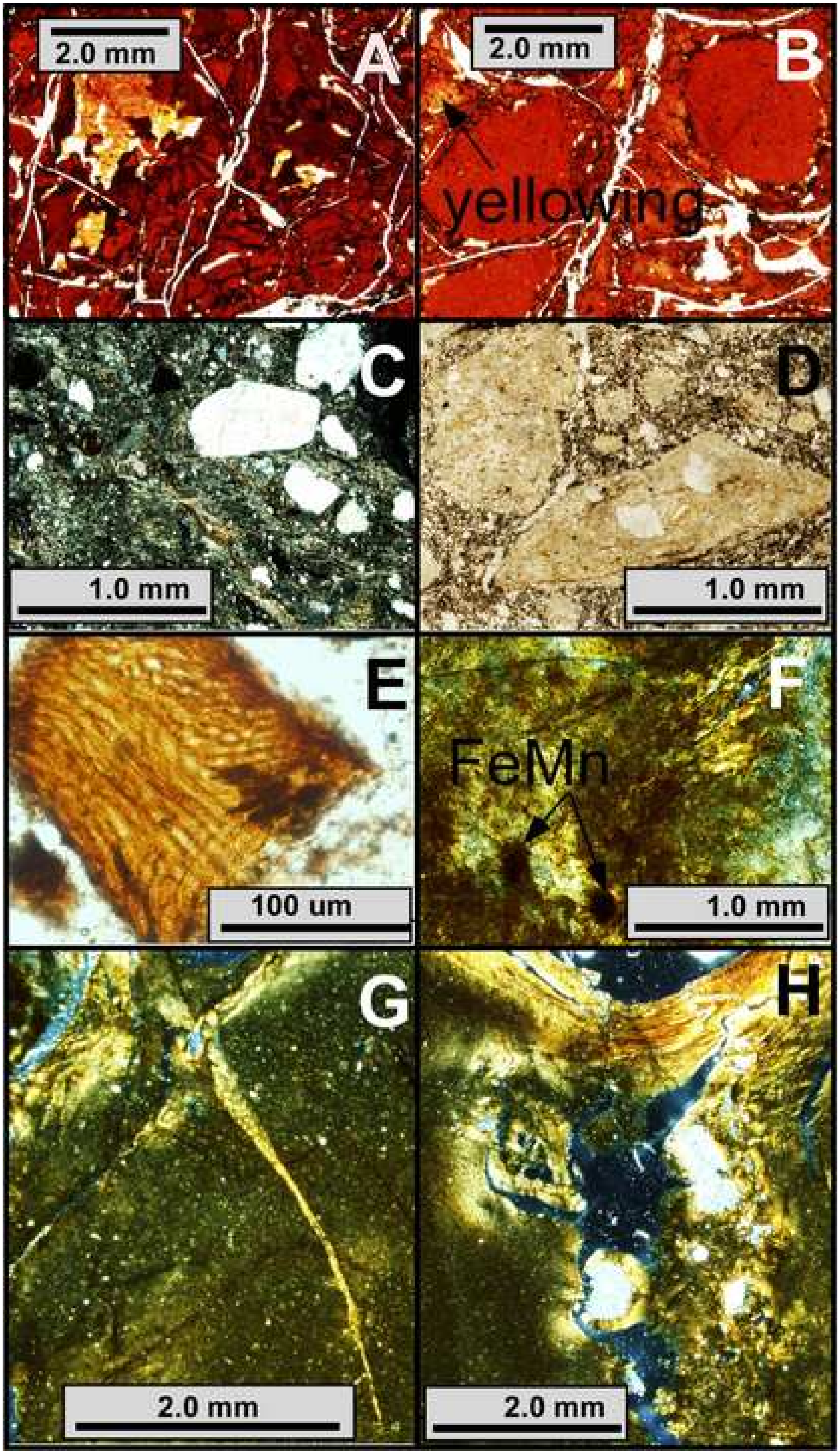

Figure 4

Click here to download high resolution image

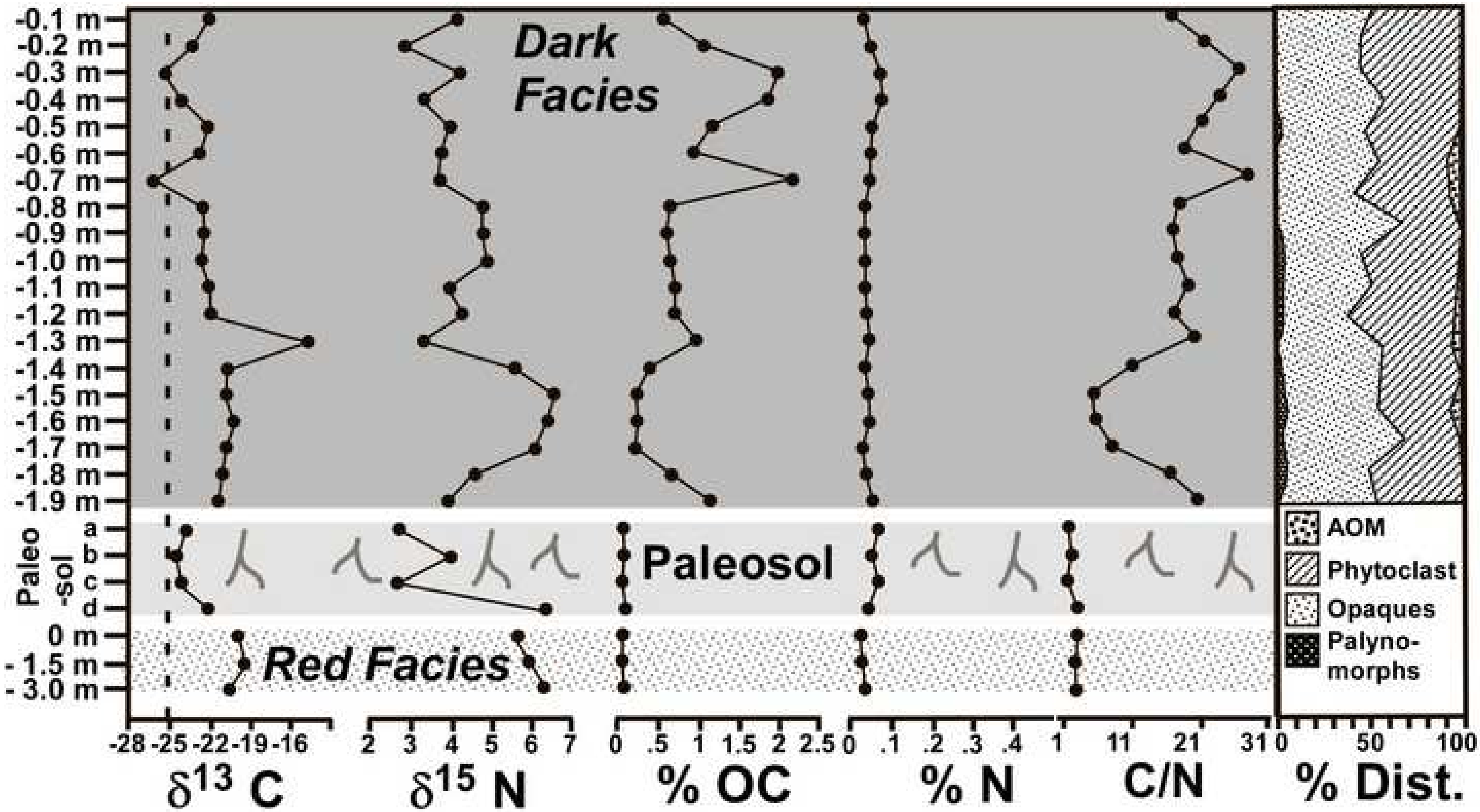

Figure 5
Click here to download high resolution image

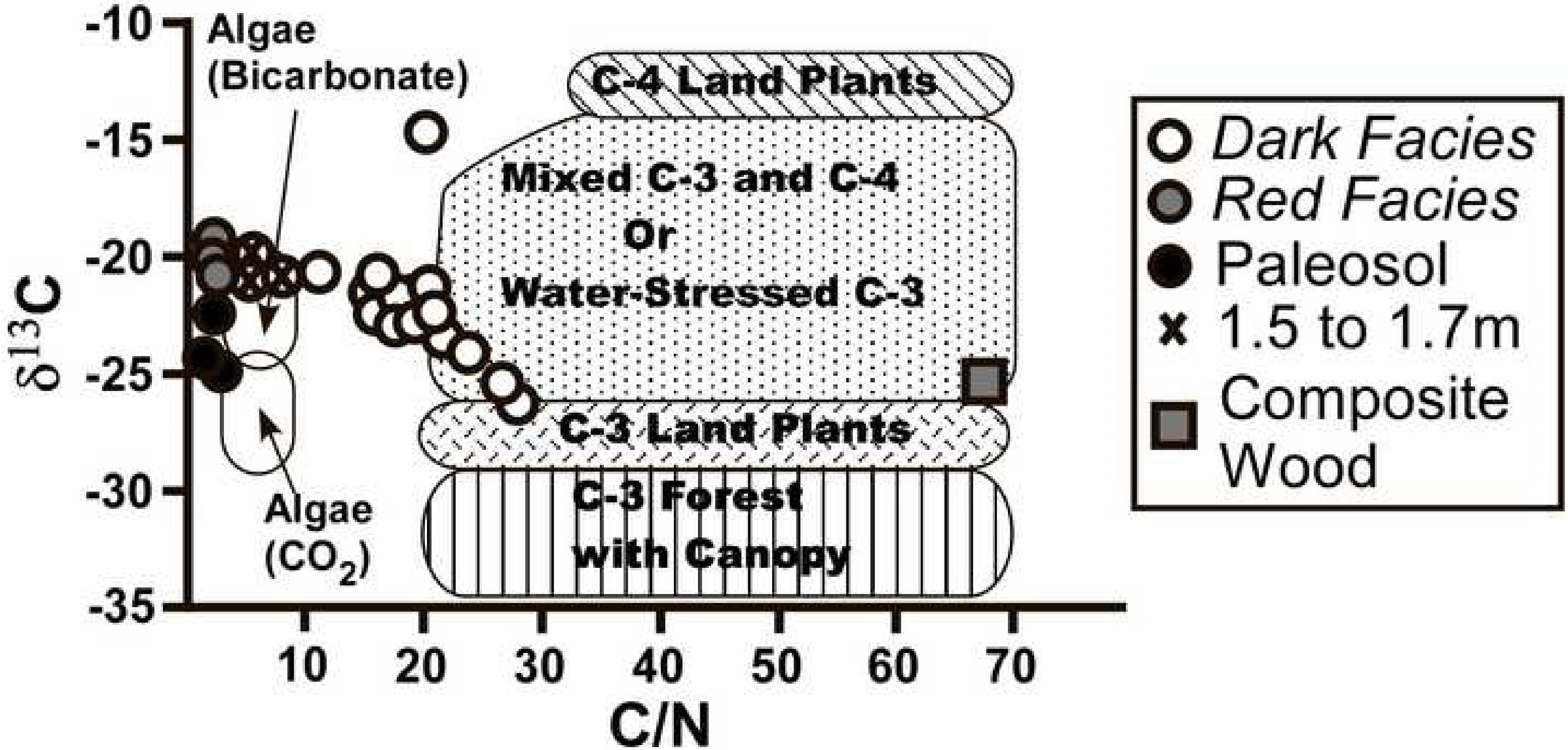

Figure 6
Click here to download high resolution image

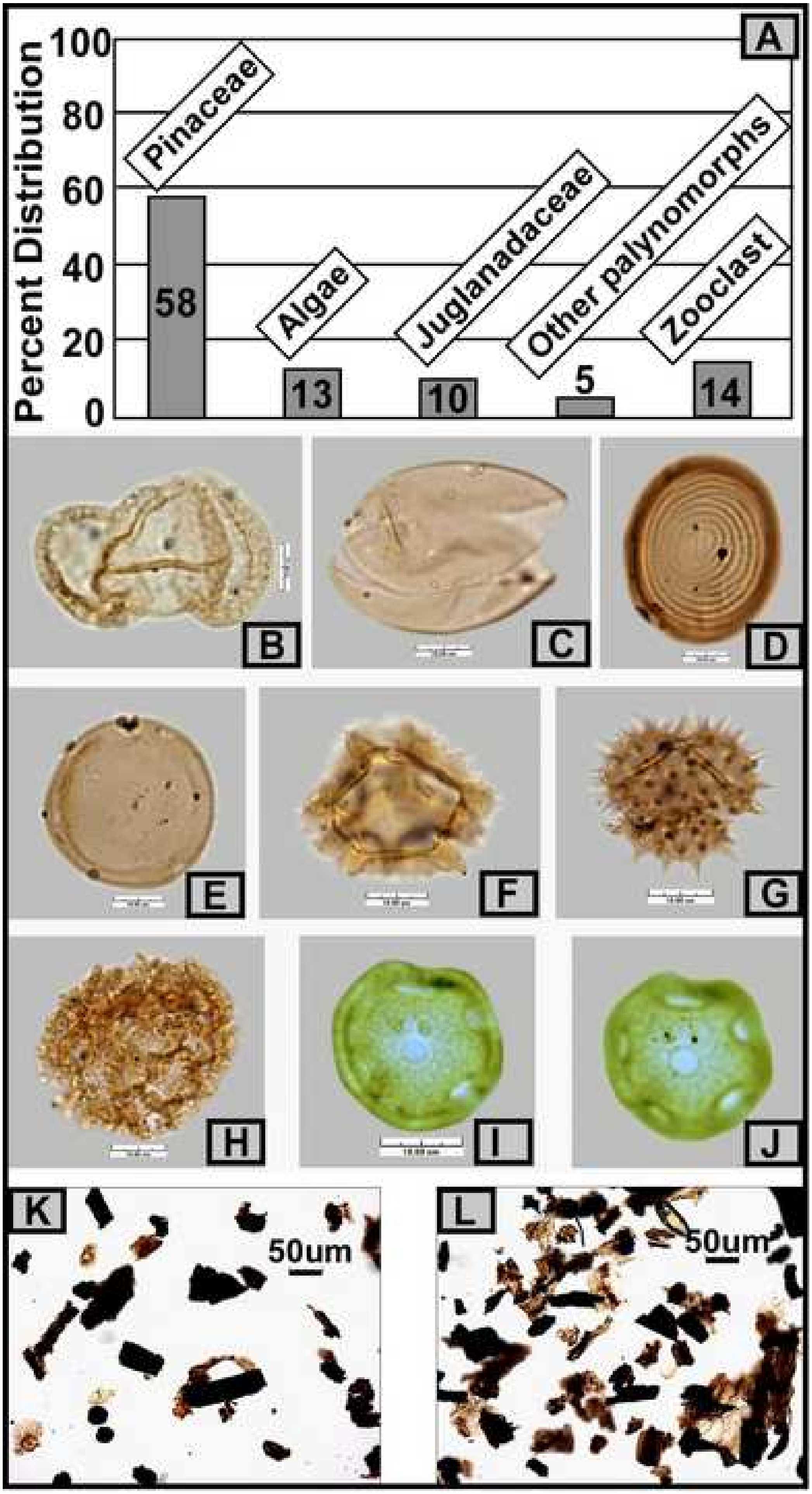

Figure 7

Click here to download high resolution image