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Latest Miocene to earliest Pliocene sedimentation and climate record derived from paleosinkhole fill deposits, Gray Fossil Site, northeastern Tennessee, U.S.A.

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Abstract

Lacustrine sediments deposited within a paleosinkhole at the Gray Fossil Site (GFS) in northeastern Tennessee, USA, provide a latest Miocene and earliest Pliocene (4.5–7 Ma) record of sedimentation and paleoclimate. The basal *graded facies* consists of mm- to cm-thick, normally graded layers of primarily locally derived terrigenous silts and fine sands with low organic content, which record storm flow influxes into a 40 m-deep paleosinkhole lake. The graded facies is overlain by the *laminated facies*, which is characterized by mm thick, non-graded "A–B couplets" of abundant macerated terrestrial organic matter and fine to coarse quartz sand (A), alternating with quartz and carbonate silt (B).

Isotopic evidence for establishment of either C4-dominated or mixed C3/C4 terrestrial ecosystems is not evident at this site; $\delta^{13}C$ values of bulk organic matter from the basal graded facies range from −24‰ to −26‰ PDB, and decrease upsection to −28‰ to −30‰ in the organic-rich laminated facies. Isotope values covary with changes in both total organic content (TOC: 0.25–1 wt.% in graded facies, 2–12 wt.% in laminated facies) and in carbon–nitrogen ratio (C/N: 1–2 in graded facies, 20–50 in laminated facies). These upsection changes in sedimentary facies and organic geochemistry within the GFS are attributed to either: (1) a climate shift characterized by increased precipitation and concomitant increased vegetation within the paleosinkhole watershed over time, or (2) progressive shallowing and eutrophication of the paleosinkhole lake, coupled with organic diagenesis within either the watershed or the paleosinkhole sediments, in which there was isotopic discrimination associated with organic matter decomposition. Subaerial exposure of the paleosinkhole lake is recorded by paleosol development.

Keywords: Paleosinkhole; Paleoclimate; Pliocene; Tennessee; Gray Fossil Site

1. Introduction

The Late Miocene to Early Pliocene was characterized by major climate, faunal, and floral changes. A global increase in C4 grassland ecosystems occurred during the Late Miocene (8 to 6 Ma), which expanded into middle and high latitudes and was accompanied by a significant Cenozoic faunal turnover (Cerling et al., 1997, 1998). Ungulate survivorship patterns from the Late Miocene extinction indicate that North American climate changes involved some combination of cooling, drying, and an increase in the seasonality of temperature and/or precipitation (Janis, 1989). *Gomphotherium*-tusk growth patterns suggest development of a wet season

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and an increase in the seasonality of precipitation, with increased aridity during the Late Miocene (Fox, 2000).

Terrestrial records of climate for the eastern half of North America from this important transitional period in Earth history are currently sparse. Records from the western half of North America generally indicate that the climate there became drier, and that grasslands expanded and replaced the great Miocene savannah during the Late Miocene. The Palmetto Fauna in southern Florida, in contrast, suggests that a wetter climate prevailed in this region into the Early Pliocene (Hulbert, 2001). The Pipe Creek Sinkhole, an Early Pliocene site located in northern Indiana, has been interpreted as dry, open and prairie-like, but with a mix of trees nearby, based upon the fauna and flora preserved within the site (Farlow et al., 2001). The recently discovered Gray Fossil Site (GFS) in northeastern Tennessee, which is the focus of this study, contains an apparently continuous record of lacustrine sedimentation from a portion of the Late Hemphillian (latest Miocene–earliest Pliocene) preserved in sediments filling a paleosinkhole. Previous research (Wallace and Wang, 2004; S.P. Horn, personal communication) suggested that the macroflora, pollen, and fauna are all consistent with existence of a dense, Oak–Hickory forest ecosystem during sinkhole filling at the GFS. However, the depositional patterns and organic geochemical records of the GFS sediment differ significantly from those records previously reported in Indiana and Florida. Pollen records from the stratigraphically lowest (and oldest) GFS sediments are limited due to poor pollen preservation and low total pollen counts, but resemble those sampled from younger deposits at the site in their dominance of oak–hickory forest taxa (S.P. Horn, pers. comm., 2005).

In this paper, our primary objective is to reconstruct the paleoenvironments and paleoclimate history for northeastern Tennessee based upon the latest Miocene to earliest Pliocene sediment record of the GFS, using field stratigraphic relationships, petrographic analysis, stable isotope values (δ^{13}C) of organic matter, total organic carbon (TOC), and carbon–nitrogen ratios (C/N). Analyses of the rich vertebrate fauna and terrestrial flora of the GFS are not included as parts of this study, but updates on such current, ongoing efforts by researchers at East Tennessee State University are available at the following website: http://faculty.etsu.edu/wallaces/gray/.

2. Site description and chronology

The Gray Fossil Site (GFS) is interpreted as the fill of a paleosinkhole, which was exposed during highway construction in May of 2000 in northeastern Tennessee (36.5°N, 82.5°W (Fig. 1). The GFS deposits extend laterally ~2.6 ha (150 m N–S by 175 m E–W) and consist of 40 m of dark colored, unlithified silty-clay sediments of lacustrine origin, buried beneath >5 m of alluvium and colluvium. The paleosinkhole developed on a fold limb within Knox Group (Cambrian–Ordovician) dolostones, and apparently represents an ancient sinkhole lake that plugged and terminally filled (Fig. 2) (Shunk, 2003; Wallace and Wang, 2004; S.P. Horn, personal communication).

A diverse, very well preserved fauna and flora are preserved within the GFS lacustrine sediment. Occurrences of *Tapirus*, cf. *T. polkensis*, *Teleoceras* sp., a small *Megalonyx* sp. or *Plimetanastes* sp., and cf. *Catagonus* sp. within the laminated facies collectively indicate that the mammals can be assigned to the Hemphillian Land Mammal Age and are Late Miocene–Early Pliocene (>4.5 Ma) in age (Parmalee et al., 2002). The recent discovery of *Plionarctos* sp., a short-faced bear, suggests that the site is Late Hemphillian, with a maximum age of 7 Ma (Wallace and Wang, 2004). A Late Hemphillian age (7 to 4.5 Ma) is further supported by the presence of medial projections on the posterior processes of the rhinoceros *Teleoceras* sp. unciforms, because this feature is only common at the end of the *Teleoceras* lineage in the latest Miocene to earliest Pliocene (Harrison and Manning, 1983). Attempts to secure an absolute date for the site have been largely unsuccessful because the upper lacustrine sediments are all palaeomagnetically reversed (G.M. Clark, pers. comm., 2001), which indicates that they are greater than 0.78 Ma in age; unfortunately the reversal cannot be further constrained in time (i.e., it could be one of many possible reversals) (Cande and Kent, 1995). Therefore, the palaeontologically based age constraints (7–4.5 Ma) appear justifiable and are used in this study.

Occurrences of multiple fossil crocodilians (*Alligator* sp.) within the GFS fauna constrain paleoclimate conditions with a Coldest Month Mean Temperature (CMMT) of >5.5 °C, because temperature is the principal influence on the global distribution of crocodilians (Markwick, 1998). The presence of crocodilians within the GFS *laminated facies* therefore suggests that the site did not freeze annually.

3. Methods

3.1. Sampling and laboratory methods

Samples for petrographic, isotopic, TOC, and C/N analysis were collected from both outcrop exposures

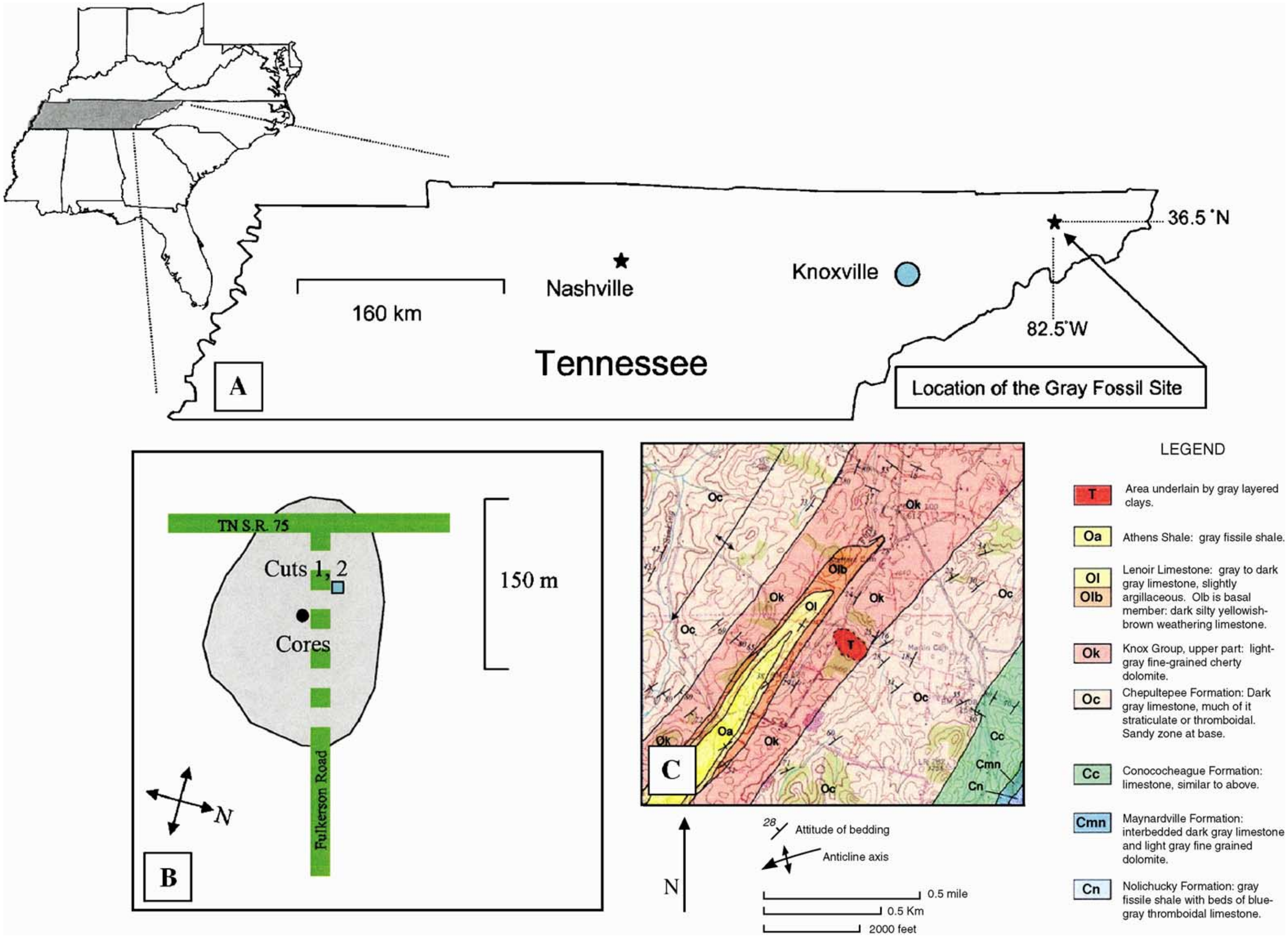

Fig. 1. Map showing location of the Gray Fossil Site (GFS). (A) Inset map of northeastern Tennessee, USA. (B) Site map showing locations of highwall bench cuts 1 and 2, and of cores, relative to Tennessee State Route 75 (TN S.R. 75) and Fulkerson Road. (C) Geologic map of area around GFS (labeled T for Tertiary on map), modified from Kohl (2003); Cambrian bedrock units include Nolichucky, Maynardville, and Conococheague Formations, whereas Ordovician bedrock units include Knox Group, Lenoir Limestone and Athens Shale.

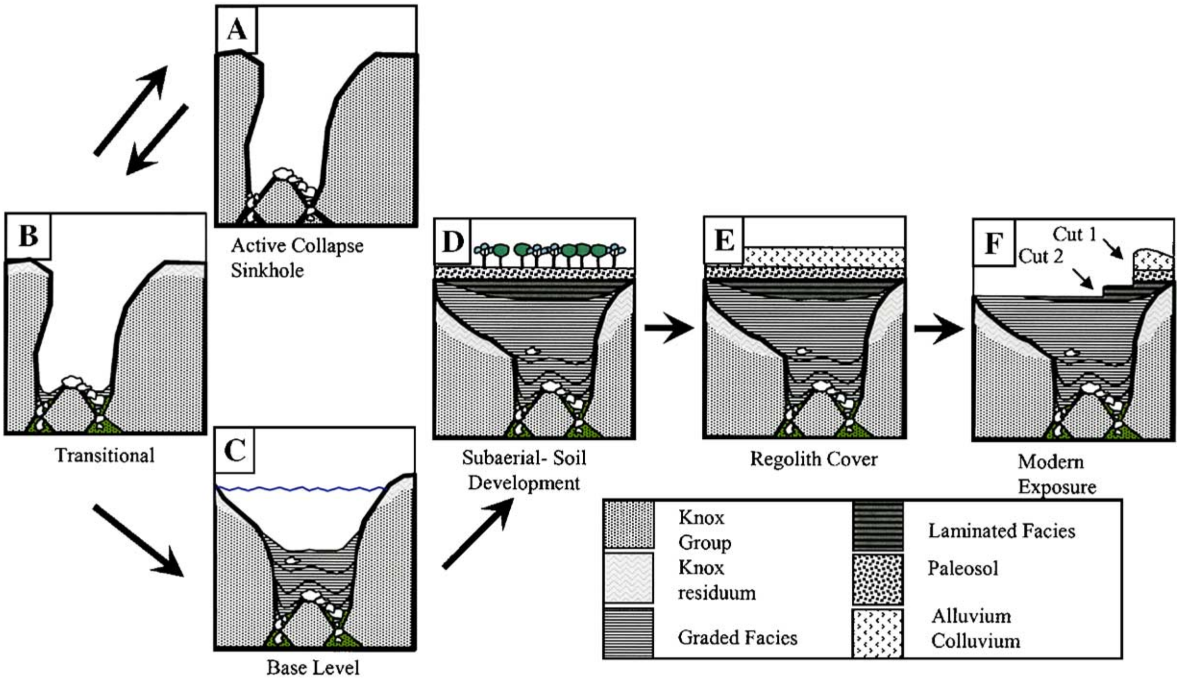

Fig. 2. Diagram showing conceptual model for geomorphic and stratigraphic development of the Gray Fossil Site (GFS), based upon the geomorphic development of sinkhole lakes in north-central Florida (Kidinger et al., 1996). (A) *Active collapse sinkhole phase* — initial stage of sinkhole development in which surface water is transferred into underlying aquifer. GFS formed on a fold limb within Cambrian–Ordovician age Knox Group dolostones. (B) *Transitional phase* — partially sediment-filled, but sediment may be periodically flushed down sinkhole collapse, thus causing reactivation of sinkhole Active Phase (may happen numerous times). As lake develops, Knox residuum forms at surface of site. (C) *Base level phase* — GFS now plugged with sediment and is sinkhole lacustrine environment. (D) *Subaerial phase* — GFS is subaerially exposed and soil development begins. Water table fluctuations may reactivate Base Level Phase and additional lacustrine sediment may be deposited during periods of high water levels. (E) *Regolith cover phase* — a combination of chert-rich alluvium and colluvium are deposited and armor the site. (F) *Erosion and modern exposure* — site is discovered when sediments are exposed during road construction (showing highwall cuts 1 and 2; coring was located in center of deposit where maximum stratigraphic thickness occurs (see Fig. 1B).

and approximately 15 m of core samples, which were obtained using a hydraulically driven, direct-push technology (DPT) rig mounted on a truck that provided continuous 3 cm-diameter cores encased in 1.2 m-long acetate liners. Two overlapping road cuts trend northwest–southeast through the upper, central portion of the GFS sediments (Figs. 1B and 2F). Sediments from highwall cut 1 extend from about 505 to 504 m above sea level (asl) and include the transition from the *subaerial facies* to the underlying *laminated facies*. Highwall cut 2 is ~6 m southwest of cut 1, contains sediments extending from about 503.7 to 495m asl, and includes the transition from the *laminated facies* to the underlying *graded facies*. Core 1 was sampled about 25 m southeast of cut 2. The nearly continuous core was stored in a freezer at -5 °C until processed, and half of the core remains archived at the University of Tennessee, Knoxville. Samples for thin-section analysis were collected at 16 representative elevations within the GFS stratigraphy from both highwall surface exposures and core samples. Samples were completely dried and then coated with resin prior to commercial thin-section preparation.

Fifty-four samples were collected for measurements of δ^{13}C and % total organic carbon (TOC). Six organic (A) laminae and six silty-clay (B) laminae samples were physically separated and collected from the *laminated facies* sediments. Representative samples were collected from the *subaerial facies*, the *laminated facies*, and the *graded facies*. Isotope ratios were measured using a Finnegan MAT Delta ^{plus} mass spectrometer at the University of Tennessee, Knoxville. Samples were prepared by treating powdered bulk sediment with 10% HCl for 1.5 h to remove the carbonate portion of the samples, and ~0.1g of sample were loaded into a sealed glass tube with 0.5 g Cu, 0.5 g CuO, and a small piece of Pt wire and combusted at 1000 °C for four hours. CO_2 was collected on a vacuum line, cryogenically purified, and analyzed isotopically. δ^{13}C values are reported in the standard per mil (‰) notation relative to the V-PDB standard. The value of the USGS-24 standard was -15.918 ± 0.011‰ ($n=4$).

Estimated % TOC values were obtained during the CO_2 collection process for isotopic analysis using a manometer on the vacuum line, which quantifies the amount of CO_2 produced by sample combustion. This value is subject to modest errors introduced during the weighing and loading of samples, and therefore has an analytical precision of $\pm 0.1\%$. Thirteen samples were additionally analyzed for C/N at the University of Georgia Lab for Environmental Analysis using a Carbon, Sulfur, Nitrogen analyzer (CNS 2000) manufactured by LECO corporation. Samples were ignited at 1350 °C; under these conditions C is converted into CO_2 and N is converted to N_2. CO_2 was quantified by an IR cell while N_2 was quantified using a thermal conductivity cell. The analytical precision of this procedure was ± 0.039 ($n = 8$).

One deep core sample from an elevation of 486 m within the graded facies (Fig. 5) was processed for pollen at the University of Tennessee, Department of Geography, using standard pollen preparation techniques (Faegri and Iversen, 1989).

4. Results

4.1. Stratigraphy and petrography

A total of 21 m of stratigraphic section was examined at the GFS by combining data obtained from

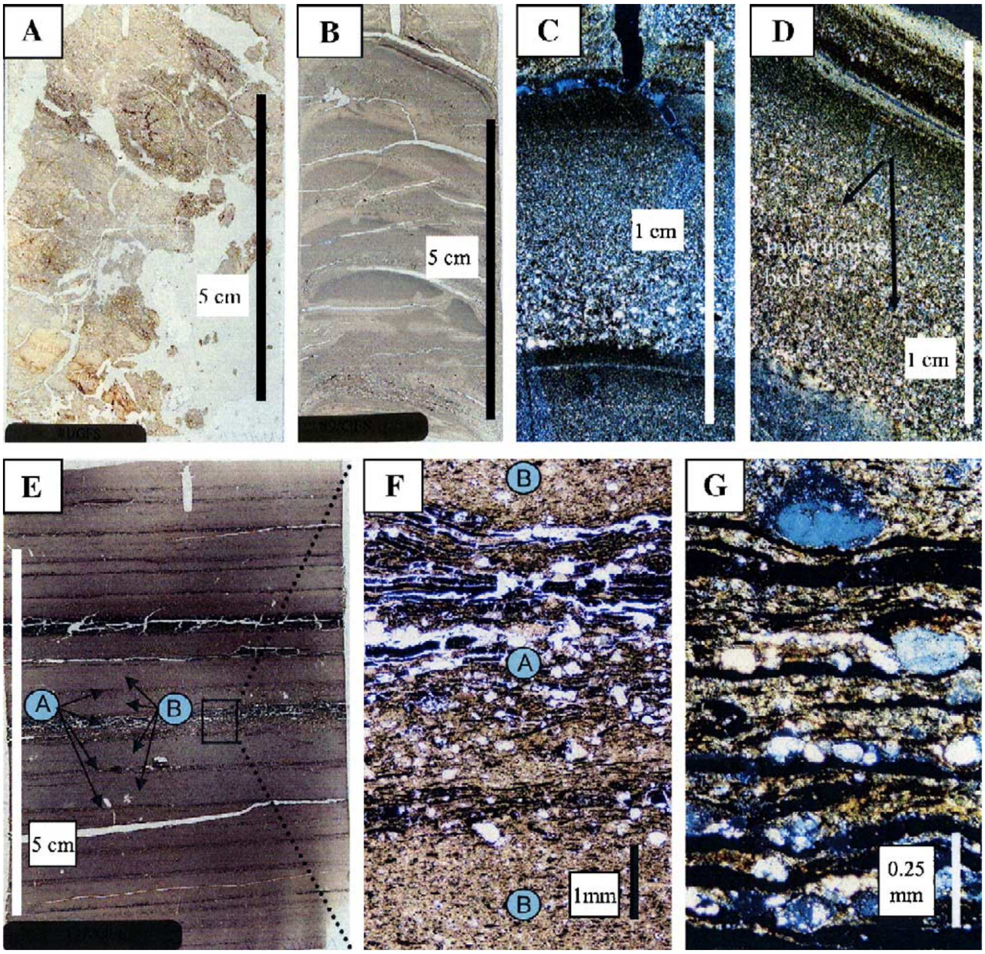

Fig. 3. Examples of lithofacies and depositional patterns of Gray Fossil Site (GFS) sediments. (A) Paleosol developed on lacustrine sediments at elevation of ~504.8 m showing well-developed angular to subangular blocky peds in ordinary light. (B) Example of graded facies depositional pattern characterized by sharp boundaries between graded beds that represent unconformities. (C) Thick, individual graded bed typical of the *graded facies*. (D) "Interrupted" graded bed; black arrows indicate micro-unconformities defined by interruptive coarse layers. (E) Example of GFS *laminated facies*, in which laminations are composed of alternating high-energy, black, organic-rich A laminae with lower-energy silty-clay B laminae. These laminae AB "couplets" are interpreted as lacustrine rhythmites. (F, G) Examples of A laminae, which consist of coarser-grained quartz and chert sand grains, eroded paleosol clasts, and organic matter (plant) fragments, and B laminae composed of more uniform silt and clay. Note that A laminae are not graded and are poorly sorted.

highwall surface exposures and subsurface drillcores (Figs. 3–5). The GFS stratigraphy studied below 496 m elevation consists of a 15 m-thick section of lacustrine sediments characterized by nearly continuous successions of individual graded beds that average 0.8 cm in thickness. Henceforth, these sediments will be referred to as the *graded facies*. The graded beds are normally size-graded, and fine upward from fine- to medium-sand to clay (Fig. 3B–D). These sediments have a light gray, low-chroma color (2.5Y 5/1 to 2.5Y 4/2) and low amounts of visible organic matter. Detrital grains consist of subrounded to rounded quartz and dolostone rock fragments, which typically grade into finer particle sizes with the same mineralogy. Rare quartz grains with resorption rims and embayments occurring within the graded beds are present and resemble those described by Smith (2003) in the stratigraphically highest subaerial cover sediments. The contacts between adjacent beds are generally sharp, but some graded layers are truncated by additional coarse material (Fig. 3D). Siderite and pyrite are present throughout the *graded facies* and occur as graded clasts or as individual layers between graded beds.

Between 501.5 and 504.8 m elevation a distinct new sediment type is apparent within the GFS strata (Figs. 3–5). These deposits consist of ~5 m of organic-rich lacustrine sediment characterized by couplets consisting of dark brown to black (A) laminae that alternate with silty-clay, gray to light-brown (B) laminae (Fig. 3E–G). Henceforth, these sediments are referred to as the *laminated facies*. This portion of GFS stratigraphy includes abundant macroscopic terrestrial plant material, which is generally highly macerated (Fig. 3G), but whole plant fossils are preserved in some cases (Fig. 4A). Detrital grains consist mainly of sub-rounded to rounded quartz and dolostone clasts with similar size distribution and mineralogy as the underlying *graded facies* sediments (Fig. 4B–D). Angular soil aggregates (pedorelicts) are present (Fig. 4C). Additional grain types include polycrystalline and monocrystalline quartz with resorption rims and embayments (Fig. 4D) resembling those described by Smith (2003) in the stratigraphically higher subaerial cover sediments. Gypsum rosettes, pyrite, Fe and Mn oxides, and siderite also occur within the *laminated facies*, but these chemical precipitates are minor compared to the terrigenous clastic grains and detrital plant fragments (Fig. 4E).

The transition from the underlying *graded facies* to the overlying *laminated facies* is expressed as a complex depositional pattern between 496.5–501.5 m elev. (Figs. 5, 6). At the base of this 5 m thick transitional interval, the continuous intervals of individual graded beds characterizing the *graded facies* are succeeded by a new depositional pattern that is characterized by very thinly graded beds and mixed non-graded sediment (Fig. 6). By the top of the transitional interval this new depositional pattern is dominated by the *laminated*

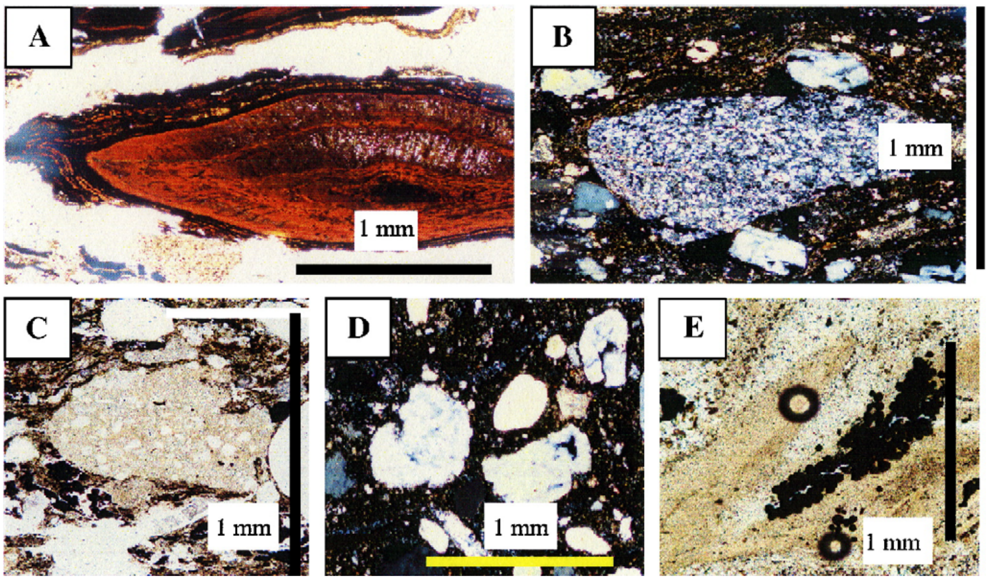

Fig. 4. Examples of sediment types present within the Gray Fossil Site (GFS) sediments. (A) Large GFS plant fragment showing superb preservation of vascular structure. Plane-polarized light (PPL). (B) Chert sand grain derived from the local Knox Group dolostone bedrock. Cross-polarized light (XPL). (C) Reworked sand-sized soil aggregate, PPL. (D) Monocrystalline quartz grains, XPL. Some of the quartz grains at the center are pitted, with resorption rims, suggesting extrabasinal sources for some grains. (E) Pyrite framboids associated with organic matter, PPL.

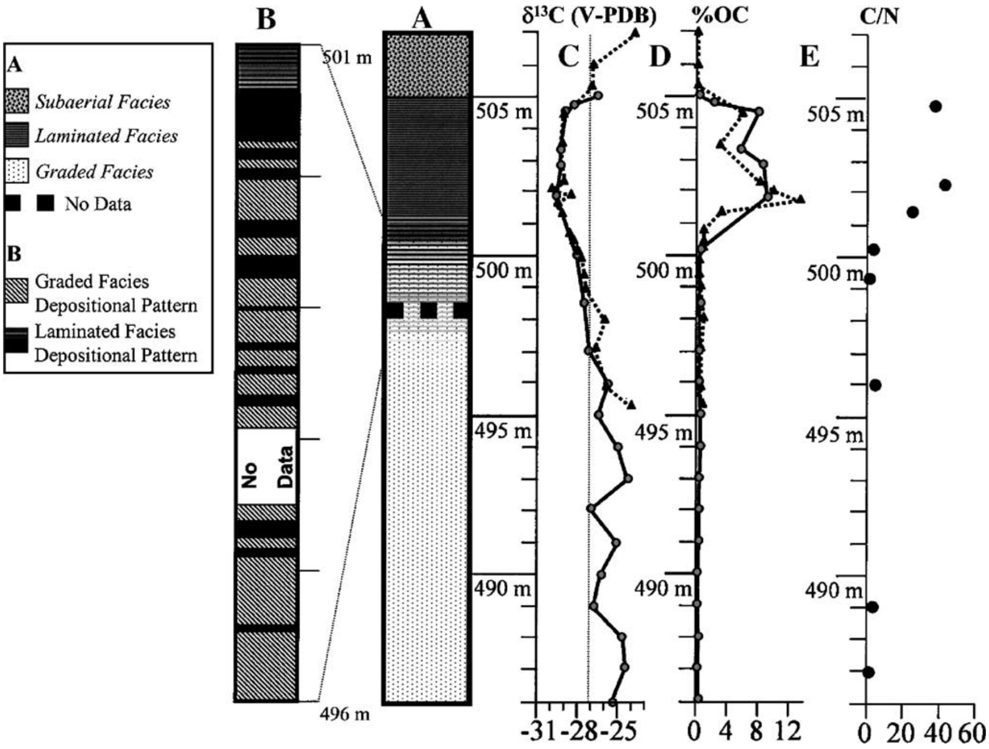

Fig. 5. Diagram showing stratigraphy and geochemistry of the Gray Fossil Site (GFS). (A) Stratigraphic column showing distributions of three distinct facies within upper 20 m of lacustrine GFS sediments. Note *graded facies* at 486–497 m, *laminated facies* at 501–504.8 m, and *subaerial facies* from 504.8 m to top of deposit. (B) Details of transition from *graded facies* to *laminated facies* occurring between 497 to 501 m elevation, which is marked by quasi-rhythmic alternation between laminated and graded facies depositional patterns (see also Fig. 6). (C–E) $\delta^{13}C$ (V-PDB), % TOC, and C/N values of organic matter. Triangles in (C) and (D) indicate data obtained from outcrop (highwall) samples, whereas circles indicate data obtained from cores. Isotopic compositions range from −23.7‰ to −29.6‰ throughout GFS and become more negative up-section within *graded* and *laminated facies*. *Graded facies* contains less than 1% TOC, with C/N values that are low, whereas *laminated facies* averages 8% TOC, with higher C/N values. See text for interpretations.

facies, and within this transitional interval the *laminated* and *graded facies* depositional patterns as they episodically alternate back-and-forth more than a dozen times (Fig. 5). Highly-oxidized, terrestrially-derived plant fragments are first observed at 499 m elevation, and large amounts of finely comminuted organic matter occur by 501 m elevation.

A/B couplets developed at the top of the transitional interval are characterized by variable thicknesses that can exceed 3 cm, but average 0.71 cm, and by poorly defined laminae consisting of mixed coarse and fine grained sediment (Fig. 6). Upsection at the base of the *laminated facies* the laminations are more regular and couplet thicknesses decrease to 0.5 cm. The thinnest and most distinctly laminated sediments observed in the GFS occur within the uppermost, central portion of the site, which was destroyed by excavation for road construction. These couplets average 0.41 cm and consist of distinct dark brown to black (A) laminae averaging ~1 mm thick, which alternate with light brown (B) laminae averaging ~3 mm thick (Fig. 3E–G).

A subaerial suite of sediment caps the *laminated facies* and consists of >5 m of dominantly gravelly colluvium and alluvium, within which multiple paleosols are developed; these deposits were interpreted to represent a post-lacustrine period of geomorphic instability by Smith (2003). The base of the subaerial sediments includes a paleosol developed from the *laminated facies* sediment. This contact abruptly grades from the distinctly laminated lacustrine sediment to oxidized, and pedogenically modified paleosol B-horizon material (Fig. 3A). This transition is differentiated by a distinct color change in which the typical 2.5Y 5/1 to 2.5Y 6/1 (low-chroma) colors of the *laminated facies* sediments are succeeded by the 10YR 6/8 to 10YR 4/6 (high-chroma) colors of the B-horizon, over an interval <3 cm thick. The paleosol has a medium subangular blocky ped structure and other pedogenic features, including a reoriented clay matrix, secondary Fe and Mn oxides, and root traces with illuviated clay coatings. The lower paleosol occurs from 505.2–504.7 m elev. and is overlain by a second paleosol that is characterized by mot-

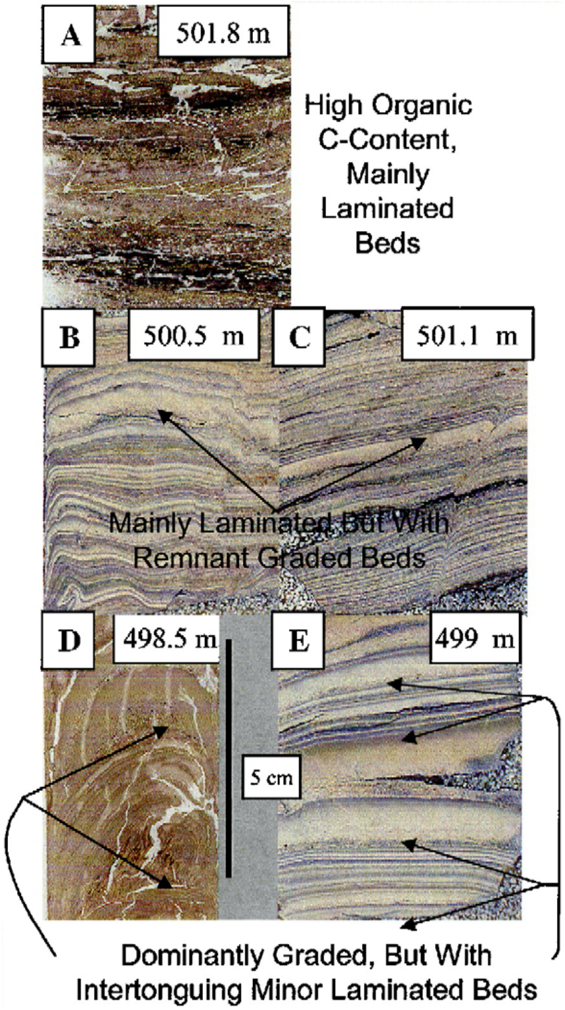

Fig. 6. Details of *graded to laminated facies* transition (cf. Fig. 5B). (A) Base of *laminated facies* (501.8 m elevation) showing development of organic-rich and organic-poor "couplets" that characterizes *laminated facies* sediments. (B, C) Samples from 500.5 and 501.1 m elevation showing thin-mixed depositional pattern of mainly *laminated*, but with remnant *graded facies* beds. (D, E) Samples from 498.5 and 499 m elevation, illustrating dominance of *graded facies*, but with intercalated *laminated facies* depositional pattern.

tled gray and red-orange colors (10YR 5/8 and various low-chroma, "gley" colors). The mottled paleosol has pedogenic slickensides and sepic–plasmic (bright-clay) fabrics, occurs between 505.2–506 m elev., and is overlain by a chert-rich Knox dolostone residuum "cover mass", which persists to the top of the GFS deposit and consists of colluvium and alluvium (Smith, 2003).

4.2. Organic geochemistry

The $\delta^{13}C$ values of bulk samples analyzed from the upper 20 m of the GFS lacustrine sediments range from −23.7‰ to −30.0‰ PDB (Fig. 5C). The *laminated facies* sediments (501.0–504.8 m elev.) have the most negative $\delta^{13}C$ values, which averaged -29.2 ± 0.50‰. Values of $\delta^{13}C$ from the underlying *graded facies* sediments (486.0–500.2 m elev.) were less negative and averaged -26.0 ± 1.3‰. Separates of organic (A) and silty-clay (B) laminae from the *laminated facies* varied insignificantly between laminae, with the average organic layer value of -29.1 ± 0.23‰, as compared with -29.5 ± 0.32‰ for the silty-clay layers. The $\delta^{13}C$ values measured from the paleosols comprising the *subaerial facies* averaged -26 ± 1.5‰.

Estimated percent total organic carbon values (% TOC) varied considerably within the GFS sediments (Fig. 5D). The *laminated facies* averaged 8% TOC, with a standard deviation of ±3.7%. For physical separates of (A) and (B) laminae, the organic (A) laminae averaged 16.4% TOC ±1.7%, whereas the silty-clay (B) laminae averaged 6.5% TOC ±2.1%. The *graded facies* averaged 0.5% TOC ±0.15%. The subaerial facies was lower than either of the lacustrine facies and averaged 0.2% TOC ±0.1%.

The C/N ratios of bulk samples analyzed from the GFS lacustrine sediments clustered into two distinct suites (Figs. 5E and 7). Samples derived from the *graded facies* (below 500.2 m elev.) had an average C/N of 2.0 ± 0.84. Samples analyzed from the *laminated facies* (above 501 m elev.) had an average C/N of 34.6 ± 9.9.

5. Interpretations and discussion

5.1. GFS paleoenvironment and sediment provenance

The physical dimensions, sediment types, and geologic setting (i.e., developed on a fold limb within a thick carbonate bedrock unit) all point to the GFS as representing a paleosinkhole lake and associated sediment fill (Figs. 1 and 2). The presence of articulated terrestrial vertebrate fossils (e.g., tapirs, rhinos, elephants), and teeth (short-faced bear, red panda, and badger), and abundant aquatic vertebrate fossils such as fish, turtles, and crocodilians, within the *laminated* and uppermost *graded facies,* strongly suggest that the GFS was an open lacustrine environment that terminally filled with sediment (Wallace and Wang, 2004). The preservation of the original graded or laminated depositional fabric, without evidence of bioturbation (Figs. 3B–G and 6B–E), in conjunction with the occurrences of precipitated pyrite (Fig. 4E) throughout the uppermost 20 m of the GFS lacustrine stratigraphy, strongly suggests that the basin had

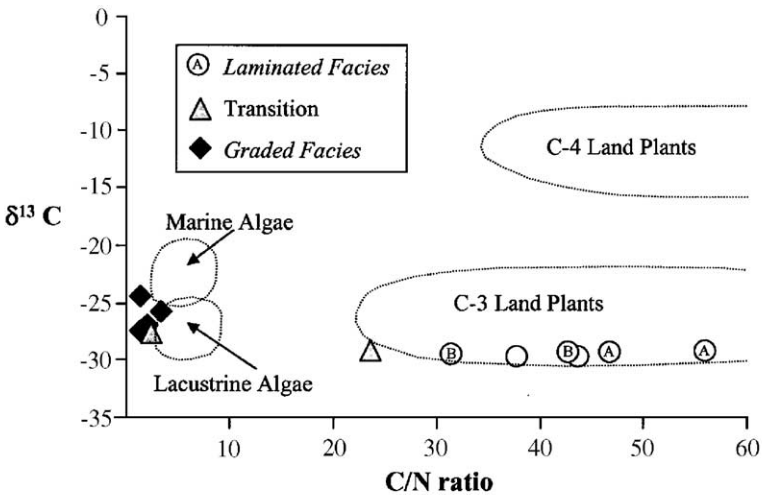

Fig. 7. Cross-plot showing sources of organic matter in the Gray Fossil Site (GFS). Elemental (atomic C/N ratio) and isotopic (δ^{13}C, ‰ V-PDB) source identifiers of bulk organic matter present in GFS sediments. Dotted lines represent suites produced by marine algae, lacustrine algae, C3 land plants, and C4 land plants from Meyers (1994). Organic matter derived from bulk sediment and mechanically separated A and B laminae of *laminated facies* (cf. Fig. 3E–G) appear to be derived from dominantly C3 land plants, whereas organic matter derived from the *graded facies* has C/N values closest to lacustrine algae.

poorly oxygenated bottom waters. The excellent preservation states of organic matter and vertebrate fossils within the *laminated facies* indicate that little destructive diagenesis occurred throughout the post-depositional history of the site (Fig. 4A).

The generally uniform sediment composition (with the exception of greater amounts of organic matter in the *laminated facies*) and grain size (Fig. 3B–G) for both the *graded* and *laminated facies* suggests that the sources of sediment did not change significantly through time. Chert and dolostone rock fragments are both indicative of local derivation from the Cambrian–Ordovician Knox Group dolostones, which are the principal local bedrock sources of sediment (Figs. 1C and 4B), with lesser contributions of locally-derived, reworked soil material (pedorelicts, Fig. 4C). The presence of monocrystalline quartz grains with resorption rims and metamorphic polycrystalline quartz grains indicate that the GFS received sediment from crystalline basement bedrock sources >50 km to the east in southwestern Virginia or northwestern North Carolina (Fig. 4D) (Smith, 2003). The detrital grains present in the GFS are therefore significant because they indicate that the provenance for GFS sediment was both intra- and extrabasinal.

5.2. GFS stratigraphy

5.2.1. Subaerial sediment suite

As discussed previously, two primary suites of sediment occur within the uppermost 30 m of GFS stratigraphy. The subaerial suite consists of greater than 5 m of alluvium and colluvium overlying the lacustrine suite of sediment. The subaerial suite is comprised of a succession of paleosols in which each paleosol represents a period of geomorphic stability following periods of instability recorded by fluvial gravel deposition (Smith, 2003). The paleosol at the base of the subaerial suite of sediment at 504.8 m elev. has relict laminations at the base of this paleosol, which indicate that lacustrine sediments served as the parent material for soil development. This contact suggests that a terrestrial (subaerial) landscape developed after the GFS paleosinkhole had filled, and that the previously deposited lacustrine sediments were subaerially exposed (Fig. 2). The δ^{13}C values of soil organic matter (SOM) in GFS paleosols probably reflect CO_2 derived from decomposed plant debris over time, and are therefore potential indicators of the average C3/C4 plant mix within the GFS ecosystem (Boutton, 1996; Wang et al., 2000). Two δ^{13}C values measured from the paleosols discussed previously average −26.8‰ and suggest contribution from exclusively C3 plants (Fig. 5C) (Cerling et al., 1997). However, a second stratigraphically higher paleosol overlying the basal paleosol at 507.9 m elev. (Fig. 5C) has a less negative δ^{13}C value of −23.7‰, which indicates that the initial dominantly C3 forest ecosystem vegetation present after the paleosinkhole was buried was succeeded by some combination of mixed C3 and C4 plants, CAM plants, or water-stressed C3 plants, during this later episode of soil development.

5.2.2. Lacustrine graded facies

The *graded facies* is characterized by long, continuous intervals of individual graded beds (Fig. 3B, C). Graded beds in sedimentary successions have typically been attributed to "event" deposition caused by storm-generated clouds of suspended sediment or to turbidity currents (Pedersen, 1985; O'Brien, 1996). Anderson and Dean (1988) described a depositional pattern from Coldwater Creek near Mount St. Helens, WA that resembles the pattern of the GFS *graded facies*. In May, 1980 the eruption of Mount St. Helens removed vegetative cover surrounding Coldwater Lake, thus leaving the drainage basin mantled with easily eroded materials. The combination of abundant and seasonally distributed precipitation, and steep slopes out of equilibrium with soil development and vegetative cover, resulted in very high sediment yields and seasonally deposited "turbidites". Sediment-trap studies revealed that the first heavy storms at the onset of the wetter season mobilized most of the annual load of sediment in a "first flush" that produced silty turbidites. During the remainder of the wetter season a mixture of silt and clay was deposited, and during the drier season a layer of clay was deposited. If this temporary depositional pattern had continued indefinitely the resulting annual increments of sediments would have had a graded structure similar to glacio-lacustrine varves (c.f. Anderson and Dean, 1988; Anderson, 1996; Dean, 1993).

The individual graded beds characterizing the *graded facies* depositional pattern are similarly interpreted to represent deposition by isolated 'flushes' of sediment into the GFS paleosinkhole, whereby sediment was rapidly washed into the site from the surrounding watershed and graded as it settled though the static water column. Although the number of graded beds representing one year of deposition cannot be reliably determined, the *graded facies* depositional pattern is consistent with the "first flush" pattern described previously for a drainage basin with easily eroded materials and a seasonal precipitation pattern.

Differences in the biochemical composition and amounts of lacustrine organic matter can indicate shifts in biota inhabiting a lake and its watershed, as well as changes in the lacustrine environment, which alter the organic matter throughout the paleolimnological record (e.g., Valero-Garcés et al., 1997; Dean et al., 2002; Smith et al., 2002). The particulate detritus of plants living in lakes and in areas surrounding lakes are the primary sources of organic matter within lacustrine sediments (Meyers and Ishiwatari, 1993). But many taphonomic, microbial, and diagenetic processes can affect terrestrial organic matter prior to its preservation within the geologic record (e.g., Boutton, 1996; Accoe et al., 2002). In a lacustrine setting, organic matter degradation occurs during sinking and may continue once it reaches the bottom as the organic matter is resuspended and continually oxidized, or becomes subjected to bioturbation. Fortunately, C/N and $\delta^{13}C$ values are robust and primary values are retained in sediments deposited in subaqueous environments (Meyers, 1994). In a small, relatively shallow lake with a poorly oxygenated bottom, like that inferred for the GFS, the amount of degradation occurring as organic matter sinks through the water column is reduced because exposure to oxidation is minimized. It is therefore unlikely that organic matter was altered greatly within the GFS water column, which is supported by the remarkable preservation state of both the plant-derived organic matter and the vertebrate fossils, and we therefore infer that changes in the C/N and $\delta^{13}C$ values from the GFS organic matter probably reflect shifts in the biota living within the lake and neighboring watershed (Fig. 5C–E). However, in a later section we will present an alternative hypothesis that considers the possibility that the observed vertical trends in $\delta^{13}C$ and TOC values with depth and facies do reflect isotopic discrimination against ^{13}C during organic matter decomposition, combined with increasing degree of transformation of organic matter with depth in the sediment column (cf. Boutton, 1996; Accoe et al., 2002).

The *graded facies* sediment contains low amounts of organic carbon averaging 0.5% TOC, which is much lower than the 8% average TOC for the overlying *laminated facies*. The low % TOC recorded within the *graded facies* could be explained in several ways. It could reflect: (1) low production of organic matter prior to deposition within the basin itself, (2) a "dilution effect" caused by increased detrital siliciclastic sediment influx over biogenically derived grains (cf. Dean, 1987; Dean et al., 2002), or (3) the reworking of littoral sediments containing organic matter that had already experienced some prior diagenetic alteration. The $\delta^{13}C$ values of GFS *graded facies* sediments average −26‰ and are consistent with dominantly C3 plant inputs (Fig. 5C and 7). C/N ratios are used to distinguish between algal and land–plant origins of sedimentary organic matter, because algae typically have C/N ratios between 4 and 10, whereas vascular land plants have C/N ratios of >20 (Meyers, 1994). C/N values derived from total organic carbon below 500.2 m elev. within the GFS average 2 and are lower than the typical range for either algae or vascular land plants, but are closer to freshwater algae (Fig. 7). These low C/N ratios are anomalous for organic matter associated with vascular plants and could indicate that the *graded facies* consists of reworked littoral sediments containing lake organic matter that had already experienced some diagenetic alteration during a dry, but occasionally stormy climate. Highly oxidized clasts of organic matter are present within the transition from the *graded facies* to the *laminated facies* at 500.1 m elev., which supports the interpretation that organic matter was at least partially oxidized prior to deposition within the lacustrine basin. The $\delta^{13}C$ values within the *graded facies* oscillate between $-24‰$ and $-27‰$ (Fig. 5C), but this isotopic shift is difficult to interpret without knowing precisely all of the sources of organic matter within the *graded facies* sediment.

5.2.3. Lacustrine laminated facies

The *laminated facies* depositional pattern at the GFS is characterized by sediment that was continuously deposited as couplets that consist of rhythmically alternating darker colored (A) laminae that are coarser-grained (clay to sand) and lighter colored (B) laminae that are finer-grained (silty-clay) (Figs. 3d–g, and 6A). The rhythmic alternations between the (A) and (B) laminae indicate that there were two distinct processes contributing to the *laminated facies* depositional pattern. The GFS sediment is dominantly composed of clastic sedimentary particles, and forces that move clastic particles at rest must first overcome resistance to movement by friction, adhesion, and cohesion (Anderson, 1996). Therefore, the consistent increase in particle size within the (A) laminae indicates that a higher-energy depositional mechanism produced these laminae. Reworked soil aggregates occur exclusively within the (A) laminae and were derived from the local soils, which support this interpretation (Fig. 4C). Reworked soil grains are easily destroyed during transportation and therefore their presence indicates both a local origin and substantial energy to erode and entrain them. The high-energy (A) laminae are typically thinner than the silty-clay (B) laminae, which indicate that the high-energy depositional mechanism producing them was of shorter duration relative to the lower-energy depositional mechanism producing the silty-clay (B) laminae. The *laminated facies* sediment is consistent with relatively long time intervals of low-energy deposition produced from continuous inflow into the paleosinkhole lake, and during periods of higher discharge soil clasts and organic debris were entrained and deposited into the GFS basin as (A) laminae that characterize the GFS rhythmites.

It is not possible to show that the GFS rhythmically deposited couplets, or rhythmites, were annually generated due to the lack of high-resolution age control in the sediments, however, there are some features that suggest the rhythmites may represent annual varves. Because the laminae within the GFS are laterally continuous and regularly alternate between high-energy coarse laminae and finer grained laminae, without the presence of graded sediment, it difficult to develop a model for the origins of the lamination not involving a strong periodic (seasonal) signal, which is the dominant factor for developing laminated sequences within lakes (Kemp, 1996). In addition, (Shunk, 2003) evaluated 100 successive GFS rhythmites using spectral analysis in the SAS-ETS program, which revealed a statistically significant ~5 couplet periodicity (i.e., the couplets tended to group in sets of five). In a small lake setting like the GFS, it is difficult to envision any other mechanism that could have produced true periodicity, except for annual climate cycles. However, other features of the GFS rhythmites, such as the substantial grain-size variation between the (A) and (B) components and their 3–5 mm average thickness (both greater than typical lacustrine varves), cast considerable doubt on a varve (seasonal) origin of the laminated sediment. We have been unsuccessful in identifying a modern or ancient analog for the GFS laminated facies depositional pattern.

However, if one did assume that the rhythmites within the GFS represent annual varves, then the recurrent association of the high-energy coarse grained (A) laminae and fine grained (B) laminae would indicate that a seasonally variable climate existed during the deposition of the sediments, which is consistent with the previously interpreted seasonal "first flush" depositional pattern within the GFS *graded facies*. The depositional pattern for the *laminated facies* is therefore consistent with a depositional model in which the (B) laminae represent relatively long intervals of low-energy deposition produced from continuous inflow into the paleosinkhole lake, whereas during periods of higher discharge soil clasts and organic debris were entrained and deposited into the GFS basin as (A) laminae. The (A) laminae might represent influx from a relatively short wet-season that added additional coarse sediment to the silty-clay background deposition.

The % TOC within the GFS sediments increases abruptly between 500–501.5 m elev., and the *laminated facies* sediments average 8% TOC. This additional organic matter has $\delta^{13}C$ values averaging $-29.2 \pm 0.50‰$ and C/N values averaging 34.6 ± 9.9, which indicate that the organic matter was derived from primarily C3 vascular land plant inputs into the basin (Fig.

7) (Meyers, 1994; Boutton, 1996). The large amounts of organic matter and $\delta^{13}C$ values within the *laminated facies* are consistent with previous interpretations, based on pollen and macrofloral remains, that the GFS was surrounded by dense forest (Wallace and Wang, 2004; S.P. Horn, personal communication), but the laminated facies paleoenvironment was significantly different from that depositing the underlying *graded facies* sediments, which contain low amounts of organic matter and an entirely different 'flush-type' depositional pattern of the sediment fabric.

5.3. The lacustrine facies shift

We previously established that two discrete facies occur within the GFS lacustrine stratigraphic record (Table 1), and that the transition from the *graded facies* to the overlying *laminated facies* occurs between the elevations of 496.5–501.0 m (Fig. 5). The two most likely explanations for the changing depositional patterns and the shift in the % TOC, stable C isotopic values, and C/N ratios of the sediment characterizing the GFS facies shift are: (1) that the GFS basin became shallower and progressively eutrophied as it filled with sediment, or (2) that the regional climate changed, which affected organic matter and terrigenous clastic sediment inputs.

As the GFS basin matured and filled with sediment, it is possible that factors such as the decrease in water depth, changes in paleo-relief around the basin, and an increase in trophic state could account for the shift in organic matter composition and change in the depositional pattern of the sediment fabric within the *laminated facies* (Fig. 5). Possible mechanisms explaining the observed upward increase in the % TOC from 0.5–8 wt.%, in conjunction with a shift in average C/N values from 2.0 to 34.6, and 4‰ shift towards more negative $\delta^{13}C$ values (Fig. 5), are increased organic loading combined with isotopic discrimination against ^{13}C during organic matter decomposition, either within the watershed or within the GFS paleosinkhole lake, with a concomitant increasing degree of transformation of organic matter with depth in the stratigraphic section (c.f. Accoe et al., 2002). In a study of the evolution of organic C content and $\delta^{13}C$ values of soil organic matter, Accoe et al. (2002) demonstrated that decomposing organisms prefer ^{13}C-depleted molecules for respiration, while the remaining ^{13}C-enriched molecules are used in the production of biomass and the end products of metabolism, resulting in a 4‰ shift from the soil surface (−30‰) to −26‰ at a depth of 30 cm, with a corresponding change in organic matter content, from 3.5% at the surface to 0.5% at a depth of 35 cm. The very low C/N ratios in the graded facies at the GFS, which are well below ratios for C3 land plants and even below low values associated with lacustrine algae, are further evidence that the much of the carbon in organic matter in the graded facies was metabolized by decomposing organisms (Figs. 5 and 7).

The shift in depositional pattern from the individual graded beds to rhythmites could also possibly relate to changes in a complex fluvial–karst depositional system. One possibility is that sediment was flushed indirectly into the basin during isolated events after accumulating in a sub-basin or karst compartment. If the sediment was oxidized during the envisioned storage period, then it is possible the organic geochemical record within the *graded facies* was diagenetically altered and does not accurately represent the regional vegetation within the watershed. Such a scenario was documented by Panno et al. (2004) in a Late Pleistocene karst system in southern Illinois, USA, in which organic-rich and organic-poor laminated cave sediments were related to periodic flooding and slackwater conditions, and in which slumping and sinkhole formation contributed to variable transport conditions. However, details of the transitional interval (Fig. 5b) are inconsistent with this sort of model. The episodic alternation between two distinctly different depositional patterns (graded vs. laminated) seems inconsistent with catastrophic mechanisms such as sinkhole collapse, stream avulsion, or changes from karst to fluvial drainage, which would have immediately affected the sedimentation style and facies in one single event (Figs. 5 and 6). Rather, the GFS basin apparently remained an open lacustrine environment that accumulated a nearly continuous record of sedimentation, until it filled with sediment and became subaerially exposed (Fig. 2).

Table 1
Summary of Gray Fossil Site (GFS) lacustrine facies and their characteristics

Lacustrine facies	Elevation (m)	Average $\delta^{13}C$ (‰ PDB)	Average wt.% TOC	Average C/N	Depositional pattern of sediment fabric
Graded facies	486.0–497 m elevation	−26.0‰	0.5%	2.0	Individual graded beds
Laminated facies	501.5–504.8 m elevation	−29.2‰	8%	34.6	A/B rhythmites (organic-rich and inorganic, alternating)

A climatic explanation could also explain the facies shift within the GFS. In this scenario as envisioned, the *graded facies* sediments represent a drier climatic phase that is replaced by the *laminated facies* sediments. The record of organic matter within the GFS is therefore interpreted to record an increase in the production and/or preservation of organic matter within the GFS watershed, which might reflect an increase in mean annual precipitation and corresponding increase in vegetative cover. The episodic alternation between two sediment types characterizing the transition between facies (Fig. 5b) is consistent with changing precipitation patterns, whereby periods of more continuous precipitation are represented by the very thinly graded beds and mixed non-graded sediment type (Fig. 6), and drier periods correspond with the thick graded beds and resulted from the "first flush" depositional pattern. As regional precipitation increased the rhythmic deposition of couplets that characterize the *laminated facies* were produced from continuous inflow into the paleosinkhole lake corresponding with seasonal periods of higher discharge that entrained and deposited the coarser-grained (A) laminae. This increase in precipitation may have resulted in an increase in vegetation within the watershed, preceded by the development of dense forest, thereby producing the organic debris present within the *laminated facies* sediment. Thus, it is possible the GFS stratigraphy was a sensitive indicator for the dynamic transition from relatively drier to wetter climatic conditions. In addition, the less negative δ^{13}C value of -23.7‰, derived from an overlying paleosol at 507.9 m elev. suggests that the vegetation eventually returned to some combination of waterstressed C-3 plants, CAM plants, or a mix of C3 and C4 vegetation, and would therefore indicate that the wetter conditions were temporary. If this hypothesis is correct, then a possible explanation for this latest Miocene–earliest Pliocene wet phase in northeastern Tennessee is that the wetter climate characterizing the Palmetto fauna of southern Florida (Hulbert, 2001) episodically expanded northward into northeastern Tennessee.

6. Conclusions

Sediments at the Gray Fossil Site (GFS), northeastern Tennessee, were deposited in a paleosinkhole lake during the latest Miocene–earliest Pliocene (Fig. 2). Paleolacustrine deposits are overlain by >5 m of alluvium and colluvium deposited during one or more episodes of subaerial exposure (Smith, 2003). Two distinct lacustrine facies (*graded* and *laminated*) are preserved within the GFS and appear to record a change in sedimentation "style" at the GFS (Figs. 3, 4 and 6) that occurs in conjunction with upward increases in % TOC, C/N ratios, and a 4‰ shift to more negative δ^{13}C values (Figs 5 and 7). The change in sedimentation pattern could be explained by an abrupt climate shift from relatively drier conditions characterized by a seasonal 'first flush' depositional pattern and minimal amounts of vegetation within the watershed (*graded facies*), to a wetter time interval characterized by more continuous deposition with an alternating high- and low-energy pattern, with large amounts of dominantly C3 land plants (*laminated facies*). Under this first hypothesis, the proposed wetter climatic phase would have been temporary and was replaced by drier conditions recorded in overlying subaerially exposed sediments and paleosols. Alternatively, the geochemical changes could largely be the product of isotopic discrimination by microorganisms associated with organic matter decomposition, either within the watershed or in the paleosinkhole fill during early burial diagenesis; the change in sedimentation style attributable to progressive infilling, shallowing, and eutrophication of the GFS paleosinkhole lake over time. There is no stable carbon isotope evidence for significant present of C4 floral communities at the GFS, in accordance with previous studies of pollen and macrofloral remains, which indicated persistence of a C3 hardwood forest ecosystem throughout the history of the GFS (Wallace and Wang, 2004; S.P. Horn, personal communication).

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References

Accoe, F., Boeckx, P., Van Cleemput, O., Hofman, G., Zhang, Y., Li, R.-H., Guanxiong, C., 2002. Evolution of the $\delta^{13}C$ signature related to total carbon contents and carbon decomposition rate constants in a soil profile under grassland. Rapid Communications in Mass Spectrometry 16, 2184–2189.

Anderson, R.Y., 1996. Seasonal sedimentation: a framework for reconstructing climatic and environmental change. In: Kemp, A.E.S. (Ed.), Laminated Sediments as Palaeo-indicators, Geological Society Special Publication, 116, pp. 1–15.

Anderson, R.Y., Dean, W.E., 1988. Lacustrine varve formation though time. Palaeogeography, Palaeoclimatology, Palaeoecology 62, 215–235.

Boutton, T.W., 1996. Stable carbon isotope ratios of soil organic matter and their use as indicators of vegetation and climate change. In: Boutton, T.W., Yamasaki, S. (Eds.), Mass Spectrometry of Soils. Dekker, New York, pp. 47–82.

Cande, S.C., Kent, D.V., 1995. Revised calibration of the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. Journal of Geophysical Research 100, 6093–6095.

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

Cerling, T.E., Ehleringer, J.R., Harris, J.M., 1998. Carbon dioxide starvation, the development of C4 ecosystems, and mammalian evolution. Philosophical Transactions, Royal Society of London Bulletin 353, 159–171.

Dean, W.E., 1987. Rates, timing, and cyclicity of Holocene eolian activity in north-central United States: evidence from varved lake sediments. Geology 25, 331–334.

Dean, W.E., 1993. Physical properties, mineralogy and geochemistry of Holocene varved sediments from Elk Lake, Minnesota. In: Bradbury, J.P., Dean, W.E. (Eds.), Elk Lake, Minnesota: Evidence for Rapid Climate Change in the North-Central United States. Geological Society of America, Special Paper, 276, pp. 135–158.

Dean, W.E., Forester, R.M., Bradbury, J.P., 2002. Early Holocene change in atmospheric circulation in the Northern Great Plains: an upstream view of the 8.2 ka cold event. Quaternary Science Reviews 21, 1763–1775.

Faegri, K., Iversen, J., 1989. Textbook of Pollen Analysis. John Wiley and Sons, New York.

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, M.R., Flint, M.E.T., 2001. The Pipe Creek Sinkhole biota, a diverse Late Tertiary continental fossil assemblage from Grant County, Indiana. American Midland Naturalist 145, 367–378.

Fox, D.L., 2000. Growth increments in *Gomphotherium* tusks and implications for Late Miocene climate change in North America. Palaeogeography, Palaeoclimatology, Palaeoecology 156, 327–348.

Harrison, J.A., Manning, E.M., 1983. Extreme carpal variability in *Teleoceras* (Rhinocerotidae, Mammalia). Journal of Vertebrate Paleontology 3, 58–64.

Hulbert, R.C., 2001. Florida's fossil vertebrates—an overview. In: Hulbert, R.C. (Ed.), The Fossil Vertebrates of Florida. University Press of Florida, Gainesville, pp. 29–30.

Janis, C.M., 1989. A climatic explanation for patterns of evolutionary diversity in ungulate mammals. Journal of Paleontology 32, 463–481.

Kemp, A.E.S., 1996. Palaeoclimatology and palaeoceanography from laminated sediments. In: Kemp, A.E.S. (Ed.), Laminated Sediments as Palaeo-Indicators, Geological Society Special Publication, 116, pp. vii–xii.

Kidinger, J.L., Davis, J.B., Flocks, J.G., 1996. Geologic controls on the formation of lakes in north-central Florida. In: Pitman, J.K., Carroll, A.R. (Eds.), Modern and Ancient Lake Systems. Utah Geological Association Guidebook, 26, pp. 9–30.

Kohl, M., 2003. Geologic map of Gray Site and vicinity. Tennessee Division of Geology, Nashville, 1:24,000 scale.

Markwick, P.J., 1998. Fossil crocodilians as indicators of Late Cretaceous and Cenozoic climates: implication for using palaeontological data in reconstructing palaeoclimate. Palaeogeography, Palaeoclimatology, Palaeoecology 137, 205–271.

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. Organic Geochemistry 20, 867–900.

O'Brien, R.R., 1996. Shale lamination and sedimentary processes. In: Kemp, A.E.S. (Ed.), Palaeoclimatology and Palaeoceanography from Laminated Sediments. The Geological Society, London, pp. vii–xii.

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.

Parmalee, P.W., Klippel, W.E., Meylan, P.A., Holman, J.A., 2002. A Late Miocene–Early Pliocene population of *Trachemys* (Testundines: Emydidae) from east Tennessee. Annals of Carnegie Museum 71, 233–239.

Pedersen, G.K., 1985. Thin, fine-grained storm layers in a muddy shelf sequence: an example from the Lower Jurassic in the Stenlille 1 well, Denmark. Journal of the Geological Society, London 142, 357–374.

Shunk, A.J., 2003. Evidence for an abrupt latest Miocene–earliest Pliocene climate shift preserved in a sinkhole paleolake at the Gray Fossil Site, northeastern Tennessee. University of Tennessee, Knoxville, unpublished M.S. Thesis, 79 pp.

Smith, S.A., 2003. Sedimentation, pedogenesis, and paleodrainage straddling the Neogene–Quaternary boundary: a perspective from an infilled sinkhole lake: The Gray Fossil Site, northeastern TN. University of Tennessee, Knoxville, unpublished M.S. Thesis, 66 pp.

Smith, A.J., Donovan, J.J., Ito, E., Engstrom, D.R., Panek, V.A., 2002. Climate-driven hydrologic transients in lake sediment records: multiproxy record of Mid-Holocene drought. Quaternary Science Reviews 21, 625–646.

Valero-Garcés, B.L., Laird, K.R., Fritz, S.C., Kelts, K., Ito, E., Grimm, E.C., 1997. Holocene climate in the northern Great Plains inferred from sediment stratigraphy, stable isotopes, carbonate geochemistry, diatoms, and pollen at Moon Lake, North Dakota. Quaternary Research 48, 359–369.

Wallace, S.C., Wang, X., 2004. Two new carnivores from an unusual Late Tertiary forest biota in eastern North America. Nature 431, 556–559.

Wang, Y., Amundson, R., Niu, X., 2000. Seasonal and altitudinal variation in decomposition of soil organic matter inferred from radiocarbon measurements of soil CO_2 flux. Global Biogeochemical Cycles 14, 199–211.