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ORIGINAL ARTICLE

Fossil charcoal from the Middle Jurassic of the Ordos Basin, China and its paleoatmospheric implications

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Abstract The Yan'an Formation of the Ordos Basin is a sequence of four members, consisting of siliciclastic sediments deposited in alluvial, lacustrine and mire settings during the Middle Jurassic. Samples collected from Members Two and Four contain abundant blackened plant material identified through standard analytical techniques as fusain (fossil charcoal). The occurrence of fusain in fluvial sandstones at multiple horizons in the outcrops, combined with the previously reported high concentration of inertinite in the coals of Member One, indicates that paleowildfire was a common occurrence in the Ordos Basin during Yan'an deposition. Sedimentary evidence from Yan'an outcrops suggests that the paleoclimate was seasonal during deposition of Members Two through Four, which may have contributed to the wildfire frequency. The presence of fusain in the Yan'an Formation indicates that atmospheric oxygen levels were clearly above the minimum required for sustained combustion during the Middle Jurassic. This conclusion contradicts previous geochemical models for paleoatmospheric composition, but supports more recent studies.

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1. Introduction

Charcoal is produced by natural wildfire and results from incomplete combustion of plant matter, woody material in particular. Because it is relatively resistant to oxidation or decomposition, it can be incorporated into sediments in various environments. The coal lithotype fusain has long been attributed to the pyrolysis of plant tissues. Although alternative, non-pyrolytic origins have been suggested (Beck et al., 1982), these suggestions have generally been disregarded, and the current state of understanding, supported by experimental studies, ascribes all fusain occurrences to the burning of plant matter, either by wildfire or by contact with hot volcanic products (Scott, 1989;

Sander and Gee, 1990; Jones and Chaloner, 1991; Jones, 1993). Because coarse, fragmental fusain is formed by the pyrolysis of wood, it can be identified by the recognition of macroscopic and microscopic features that occur in modern charcoal. Criteria for recognition and identification of wood-derived fusain are well documented, including physical (macroscopic) similarities to modern charcoal, such as blocky fracturing, silky luster (in contrast to the conchoidal fracture and vitreous to resinous luster of vitrinitic coal), a high degree of preservation of cellular structure, high reflectivity, homogenized cell walls, and resistance to chemical oxidation (Harris, 1958; Cope and Chaloner, 1980; Chaloner, 1989; Sander and Gee, 1990; Jones and Chaloner, 1991; Scott, 2010). Charcoalified leaf matter is identifiable in the field by its fragile nature, as compared to the more durable character of coalified leaves. In this study, we perform a preliminary examination of the stratigraphic record of charcoal in the Middle Jurassic of North China, document its occurrence in the Yan'an Formation in the Ordos Basin, and consider its implications for paleoatmospheric oxygen levels.

2. Setting and stratigraphy

The Ordos Basin, occupying 370,000 km^2 of Shaanxi Province and adjacent areas of Gansu, Ningxia and Shanxi provinces and the Inner Mongolia Autonomous Region, formed during the Mesozoic as a structural subdivision of the larger Northern China Basin (Deng et al., 2010). Although the depositional extent of the basin decreased through the Mesozoic, the basin remained active through the Cretaceous Period (Johnson et al., 1989; Deng et al., 2010). Except for minor marine deposits in Lower Triassic sections in some locations, Mesozoic deposition in the basin was entirely continental.

The Jurassic System is widespread across the Ordos Basin and comprises the Lower Jurassic Fuxian Formation, the Middle Jurassic Yan'an Formation, the upper Middle Jurassic Zhiluo Formation, and the Anding and Fenfanghe Formations of the Upper Jurassic. The Yan'an Formation rests disconformably on strata of the Fuxian Formation. Significant oil and coal resources occur in Triassic and Jurassic strata in the basin, notably including coals in Member One of the Yan'an Formation (Johnson et al., 1989; Deng et al., 2010).

For this study, we examined occurrences of fusain in the Yan'an Formation in outcrops west of the city of Yan'an (Fig. 1). The formation consists mainly of sandstones, mudstones, shales and coals deposited in fluvial, lacustrine and mire (swamp) environments. The formation varies in thickness from 120 m to about 360 m and is divided into four members (Deng et al., 2010). The flora of the formation is a diverse assemblage that includes various plant groups. Among them Ginkgoales are the dominant group, with frequently seen taxa such as *Ginkgoites*, *Baiera*, *Sphenobaiera*, *Czekanowskia*, and *Phoenicopsis*. They are followed by ferns, with frequently seen taxa such as *Coniopteris* and *Eboracia*. Cycads and Coniferales are minor elements in the flora (Wang, 1995; Deng et al., 2010).

3. Methods

Samples of fluvial sandstone containing fragmental material displaying the macroscopic properties of charcoal were collected from Members Two and Four of the Yan'an Formation. They were cleaned and examined optically with an Olympus SZX12 binocular microscope with DP70 digital image capture head and assessed for potential further study. When necessary, samples of the rock matrix were trimmed with a diamond saw and prepared for scanning electron microscope (SEM) study by washing in acetone and pure alcohol. In preparation for SEM examination, cleaned samples were mounted to aluminum stubs using double sided carbon tape. Some samples were coated with gold in an Ar-enriched atmosphere at 0.04 Torr with an Emscope SC500 sputter coater. Coated samples were imaged with a JEOL JSM-6510LV SEM using a secondary electron detector at high vacuum conditions with an accelerating voltage of 20 kV and a working distance of 10 mm. Uncoated samples were imaged using a back-scattered electron detector under low vacuum (15 Pa) conditions at 15 kV. Total organic carbon (TOC) content was measured on pulverized, acid-treated bulk rock samples by combustion at 950 °C with a Leco TruSpec® CN analyzer. Resistance to chemical oxidation was tested by immersion in Schulze's reagent for 24 h at 20 °C, following which samples were assessed for degree of maceration (Wood et al., 1996).

4. Observations

Outcrops of all four members of the Yan'an Formation were examined for this study. Member One was examined in Yan'an City at outcrops of the basal Baotashan Sandstones, but no fusain was observed, although coals of Member One were reported to have a high inertinite content (discussed below; Yang et al., 1996; Yao et al., 1999; Glasspool and Scott, 2010). Similarly, outcrops of Member Three were studied approximately 10 km west of Yan'an City, but these also lacked obvious macroscopic fusain. Only Members Two and Four were found to contain abundant material with sufficient similarity to modern charcoal to justify tentative field identification as fusain. Samples were collected at two sites, one in Member Two and one in Member Four. Descriptions and locations of the two sites are provided below and in Deng et al. (2010).

4.1. Field sites

Site One is in the upper part of Member Two of the Yan'an Formation, which is well exposed in a rock quarry about 8 km west of Yan'an city, west of the village of Zaoyuan, along provincial road 303. The exposure here consists of a cliff of approximately 20 m height, dominated by beds of fine to medium-grained sandstone (Figs. 2, 3A). The lower 12 m of the section consists of horizontally laminated sandstone and tabular sets of planar cross-bedded sandstone in beds 0.3–1.2 m thick. The overlying 8 m is a coarsening-up sequence of shale, mudstone, thinly bedded siltstone and fine-grained sandstone.

Plant remains are abundant in the sandstone at Site One, and are conspicuously concentrated as large fragments at the bases of beds at six horizons within the sandstone-dominated portions of the section (Figs. 2, 3B–D), with the greatest concentration in coarse-grained sandstone near the base of the outcrop.

The plant material occurs in several different forms: (1) large sandstone endocasts (internal molds) of woody material with stems or trunks up to 9 cm in diameter were observed in blocks at the base of the cliff (Fig. 4A), but were not found *in situ* in the outcrop. These largest fragments lack evidence of charring of the outer surface and presumably were deposited as a lag deposit at the base of a channel; (2) more common in the channel sandstones

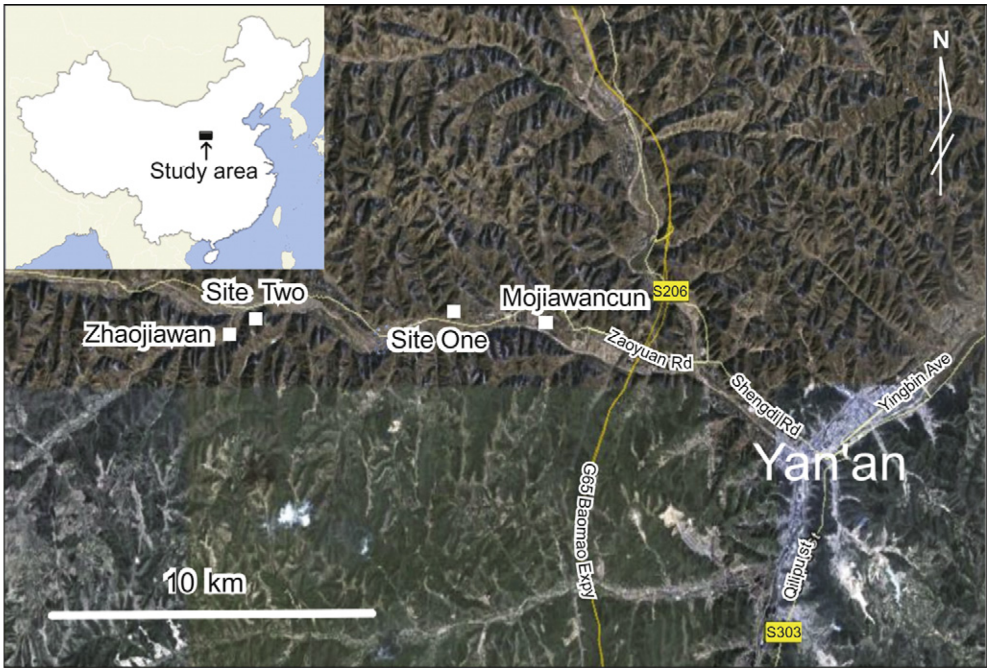

Figure 1 Map of region adjacent to Yan'an in North China illustrating the locations of the sites that were sampled for this study (adapted from Google Earth).

are blackened fragments of plant material (Fig. 4B–D). Some of these are blocky pieces up to 3 cm long that display a silky luster, one of the macroscopic characteristics of fusain (Fig. 4B–C); (3) many of these occur in beds with carbonized material that appears to be leaf impressions that are up to 5 cm long; these are not conclusively identified as fusain (Fig. 4B). In the same beds, there occur larger fragments of material that exhibits shiny fracture surfaces, and therefore are likely coalified wood (Fig. 4C; Scott, 2010). The material most resembling charcoal, i.e., with silky luster, has a black color and black streak, while material resembling coal, i.e., with shiny fractures, has a partially oxidized, brown tint and does not readily form a streak.

The plant remains are mainly concentrated on bedding-planes, but occur also dispersed through the sandstone rock matrix (Figs. 4D, 5A, B). The individual horizons vary in thickness from 2 cm to 25 cm. In many beds, the plant material (both fusain and non-fusain) is concentrated on bedding-planes, and therefore appears in plan-view to constitute a substantial portion of the rock volume, estimated visually as up to 50% (see Fig. 4C). In cross-sectional view, however, the proportion of material in these beds appears negligible. By contrast, in several beds, fusain is distributed evenly throughout the rock matrix, constituting up to 12% of the visible rock volume (Fig. 4D). Analysis of 10 samples of fusain-bearing sandstone beds confirms that the TOC of the sandstones varies greatly, from 0.2% (by weight) in most beds where the material is concentrated on the bedding-planes, to as much as 6% in beds where the fusain is dispersed throughout the rock matrix.

Site Two is a cliff exposure of Member Four of the Yan'an Formation, overlain disconformably at the top of the cliff by the Zhiluo Formation (Figs. 2, 6A). The exposure of Member Four comprises about 30 m of sandstone, siltstone, mudstone and shale recording alternating alluvial plain/stream channel and lacustrine deposition (Deng et al., 2010). The sandstones vary from channel bars 2 m thick displaying lateral accretion surfaces (Fig. 6A) to sheet-like floodplain sandstone beds, 0.2–1.0 m thick, interbedded with gray to brown mudstones. The lower channel sandstone displays prominent lateral accretion surfaces, suggesting that the stream channel had a highly sinuous shape. Gray mudstones underlying the thick channel at the base of the cliff in Fig. 6A contain well-developed vertic fractures with pedogenic slickensides, suggesting that the overbank muds were deposited in a seasonal climate.

Plant material was not observed *in situ* at Site Two, but abundant black material is present in blocks of fine-grained sandstone at the base of the cliff (Fig. 6B) that can be correlated by color to a sandstone ledge about 10 m above the base of the outcrop. The material consists of irregularly-shaped fragments up to 2.5 cm long, and appears similar to modern charcoal; i.e., it has black color with a fibrous texture and silky luster, and leaves a black streak. At both sites, the fusain is fragile and powders easily, which is a qualitative indication of a high combustion temperature (Scott, 2010). Unlike Site One, no sandstone casts of large woody stems occur here, but carbonized (i.e., non-fusain) leaf fragments are common on bedding-planes of very-fine grained, micaceous sandstones. In addition, the fusain at Site Two occurs only on bedding-planes, and so constitutes a smaller proportion of the rock volume than in the sandstones at Site One.

4.2. Microscopic features

Fifty samples from Site One and 10 from Site Two were examined using electron microscopy. Samples were prepared as described above in Methods. Field identification of the blackened plant material as fusain, based primarily on the silky, fibrous luster, was confirmed by scanning electron microscopy. The wood shows no evidence of permineralization and displays, in most samples with the macroscopic characteristics of charcoal, the characteristic

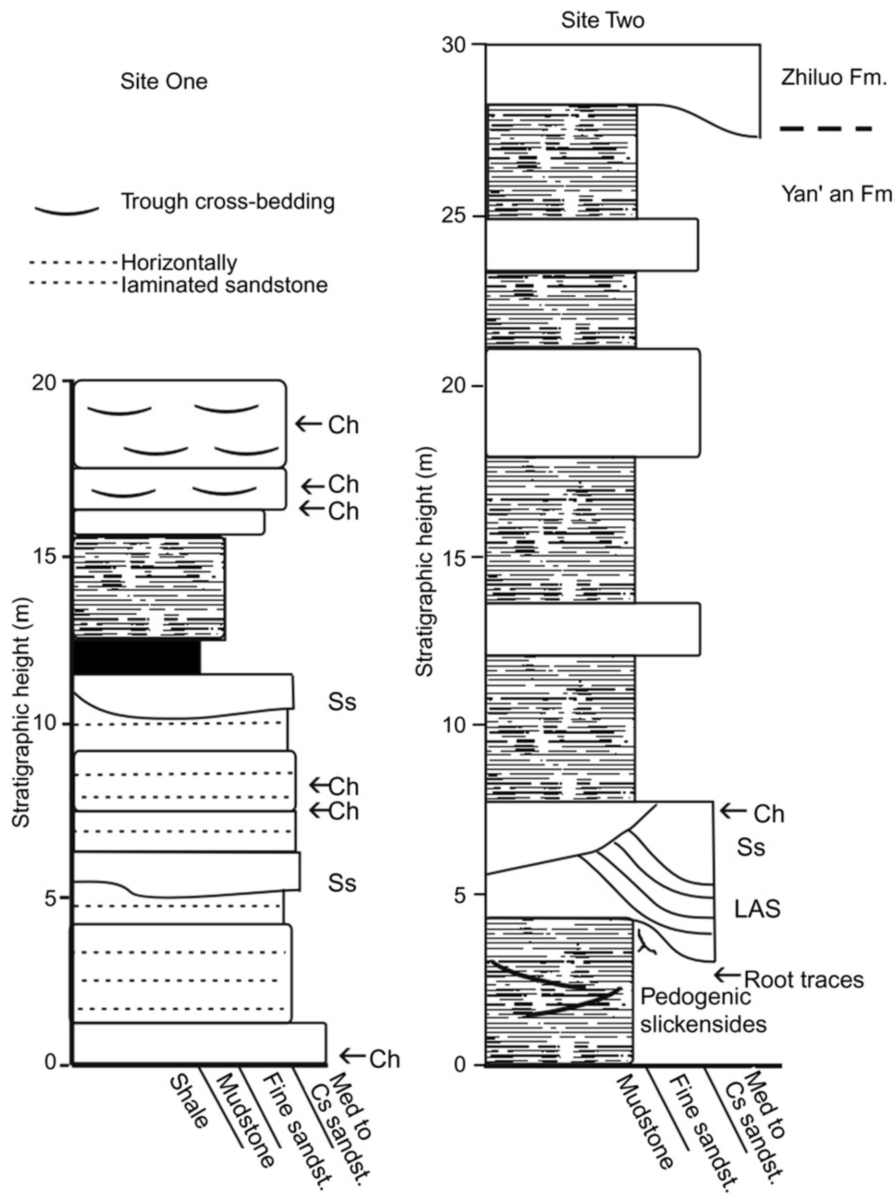

Figure 2 Stratigraphic sections measured at Site One (Member Two) and Site Two (Member Four and its contact with the Zhiluo Formation). Occurrences of fusain (Ch) are indicated for each section. Sandstone scour surfaces (Ss) are notable in the section at Site One, and lateral accretion surfaces (LAS) occur in the outcrop at Site Two.

well-preserved cellular structure. Most of the fragments are transverse to longitudinal sections exposing broken, rounded to nearly square tracheids and uniseriate xylem rays (Fig. 7A–E). Many transverse sections expose open lumina (Fig. 7B). Growth rings can be seen in some specimens, as suggested by significant variations in the diameter of lumina and the thickness of cell walls in some samples (Fig. 7B). However, this characteristic is not very prominent in most samples. In general, lumen diameter varies from 5 μm to 12 μm (Fig. 7C–D), a range of variation reflecting the difference between latewood (small lumen) and earlywood (large lumen) in the samples. Walls between adjacent cells are clearly homogenized and vary in width from 2 μm to 3 μm in earlywood to 5 μm to 10 μm in latewood (Fig. 7C–D). Other characteristics include uniseriate circular bordered pits, 5 μm in diameter, on tracheid walls (Fig. 7E) and flaky material covering the xylem that probably represents the outer surface (epidermis) of the plant (Fig. 7F).

5. Interpretation

5.1. Origin of the charcoal

At least some of the blackened plant material incorporated within the stream deposits of the Yan'an Formation can be identified confidently as fusain. The morphology of the charcoal fossils demonstrate that they are clearly derived from gymnosperms, but more precise determination is difficult due to the fragmental nature of the material. Material from Member Two (Site One) is well-preserved, and the characteristics (e.g., uniseriate rays,

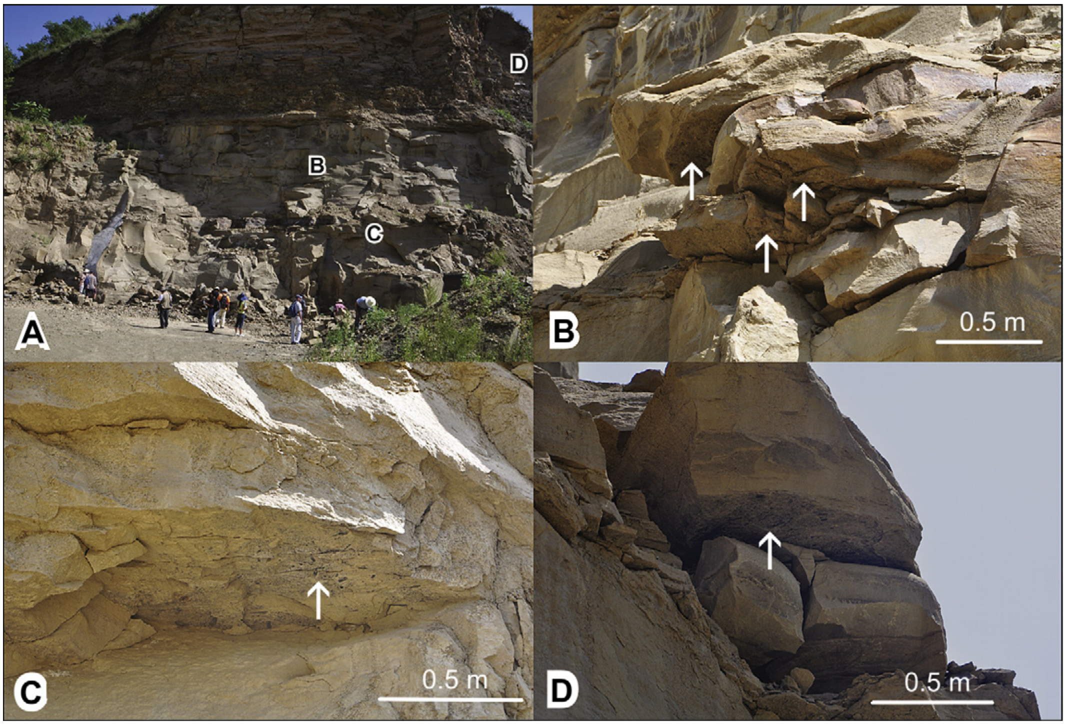

Figure 3 Outcrop of Member Two of the Yan'an Formation at Site One. A: the lower portion of the section is mostly horizontally laminated to planar cross-bedded sandstone. The locations of photos B–D are indicated on the photo; B–D: fusain is visible in outcrop on the undersides of beds (arrows). B and C are from the lower 12 m in the outcrop. D is from the upper 4 m (see Fig. 2).

circular bordered pits) suggest a provenance from Coniferales and Ginkgoales (Falcon-Lang et al., 2001; Jones et al., 2002; Scott, 2010; Yans et al., 2010). The charcoal from Member Four (Site Two) is not as well-preserved as that from Member Two, and we consider its affinity indeterminate. This does not contradict the megafossil-based conclusion that *Ginkgo* and *Ginkgoites* are more prevalent in the flora of the Yan'an Formation (Wang, 1995; Deng et al., 2010).

5.2. Taphonomy of the charcoal

Scott (2010) ascribes most macroscopic charcoal to surface fires burning ground litter, rather than crown fires (see also Scott, 2000; Marynowski and Simoneit, 2009). Following the Yan'an wildfires, charcoal and associated plant debris were washed from the overbank environment into stream channels after rain events and transported as part of the bed load in the stream sediments. Large wildfires are well known as triggers for high-sediment-load depositional processes due to the removal of vegetative cover from large areas, thereby releasing sediment for transport during subsequent precipitation events (Meyer and Wood, 1999; Tanner et al., 2003). The abundance and concentration of fusain in fluvial sediments at multiple horizons at Site One suggests that wildfire was relatively common during deposition of Member Two of the Yan'an Formation although we note that each horizon does not necessarily represent a unique fire event; charcoal can be reworked downstream when charcoal stored in bar sediments is released by shifting channel patterns. However, the consistent angularity of the fusain clasts at Site One suggests that the distance of transport was not great, thereby reducing the likelihood of reworking since charcoal fragments are easily and quickly abraded during transport (Marynowski and Simoneit, 2009). Strong flow velocity for some of the streams in Member Two of the Yan'an Formation is implied by the predominance of horizontal lamination, a sedimentary structure formed by upper flow-regime transport conditions. Therefore, the fluvial system that deposited the sediments containing charcoal at Site One was a broad, high-sediment-load stream, in which sand-sheet deposits, comprising low-relief bedforms of horizontally laminated and/or low-angle cross-bedded sandstone (Miall, 1996; Reid and Frostick, 1997; Tooth, 2000), were laterally equivalent to weakly defined channels containing small-scale dunes. Sediment transport and deposition in these types of stream systems are episodically energetic. The coarsest material, comprising unburned larger limbs, accumulated as lag deposits on the floors of the channels, but subsequently decomposed, leaving only sandstone endocasts. Although the coaly material that occurs with some of the charcoal might have originated by reworking of a mire deposit, or potentially, from erosion of the coal-bearing lithofacies of the underlying Member One of the Yan'an Formation, the lack of intraformational clasts (e.g., mudstone rip-up clasts) associated with the coal fragments largely precludes the possibility of erosional reworking of underlying sedimentary formations.

The stream systems at Site Two, where samples were collected from Member Four, do not display similar evidence of high energy transport conditions. Rather, the prominent lateral accretion surfaces in a single-story channel system, with interbedded floodplain mudstone and sheet-like sandstones (Fig. 6A), demonstrates that deposition occurred on a low-gradient surface by a high-sinuosity stream, although the stream was subject to frequent high-discharge flood events that deposited sand across the mud-dominated floodplain.

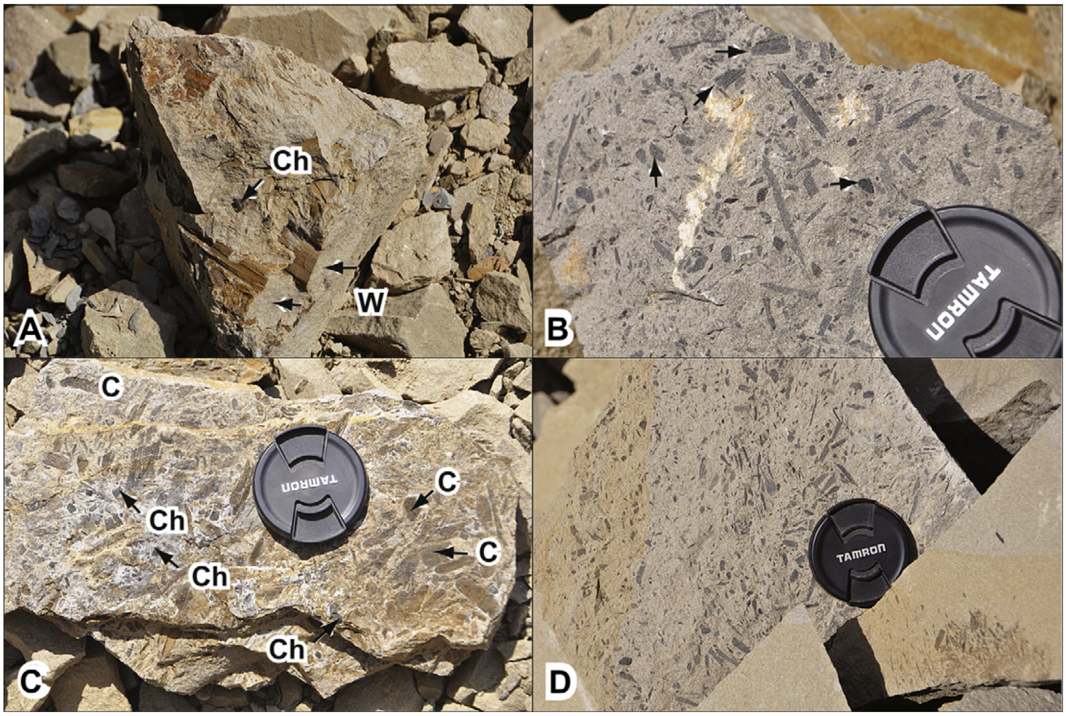

Figure 4 Plant fossils at Site One. A: casts of sandstone replacing woody stems or limbs (W). Fossil charcoal (Ch) occurs in the same block; B: black fragments with fibrous texture and silky texture (arrows) are fossil charcoal (fusain). Elongated fragments are carbonized leaf material. Diameter of the lens cap is 70 mm; C: abundant small blocks of fossil charcoal (Ch) occur with coaly material (C), which has vitreous luster on fracture surfaces; D: transverse section through a sandstone block, showing black plant material distributed throughout the sandstone matrix and not limited to bedding-planes.

Although flashy stream systems, as in Member Two, are often associated with semi-arid, or even desert systems (cf. Sneh, 1983), a strongly arid climate is contra-indicated by a lack of Aridisol features or highly desiccated vegetation. No paleosols were evident in the outcrop at Site One (Member Two), but well-developed vertic features are present in mudstones at Site Two (Member Four). The paleosols here, which thus can be assigned to the order Vertisol, also contain drab root traces and modest gley features, but are completely lacking in calcrete nodules. These pedogenic features, in concert with the presence of lacustrine and coal-mire lithofacies in the formation (particularly in Member One), suggest that the paleoclimate of the Ordos Basin during deposition of the Yan'an Formation was undoubtedly moist, but with pronounced seasonality in the distribution of precipitation. This paleoclimate interpretation is consistent with the interpretation of growth rings in the fusain samples. Wildfires were likely more common during the dry season in such a climate, but the resulting charcoal may have remained on the alluvial plain and was not transported until the following wet season.

6. Discussion

The record of fusain in Phanerozoic sediments of Silurian age (Glasspool et al., 2004) and younger has been taken as an indicator that paleoatmospheric oxygen levels have not fallen below the minimum for sustained burning of biomass (e.g., forest fires) under natural conditions (Cope and Chaloner, 1980; Chaloner, 1989).

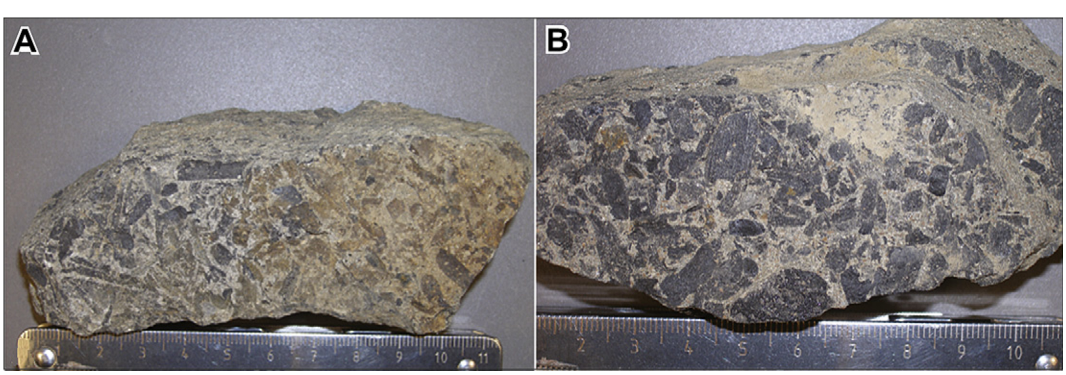

Figure 5 Samples collected from Site One for laboratory analysis. A and B: black plant material is mostly flattened and arranged parallel to bedding.

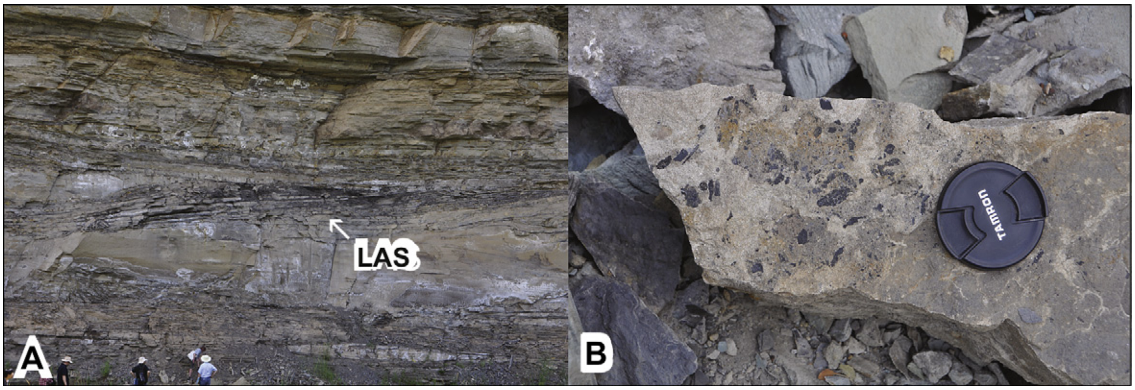

Figure 6 Features of Site Two. A: Member Four of the Yan'an Formation consists of interbedded sandstones and mudstones. The thicker sandstone bed contains lateral accretion surfaces (LAS) and is interpreted as a single-story high-sinuosity stream deposit. B: blocks of fusain occur on bedding-planes of the fine-grained sandstones in the outcrop.

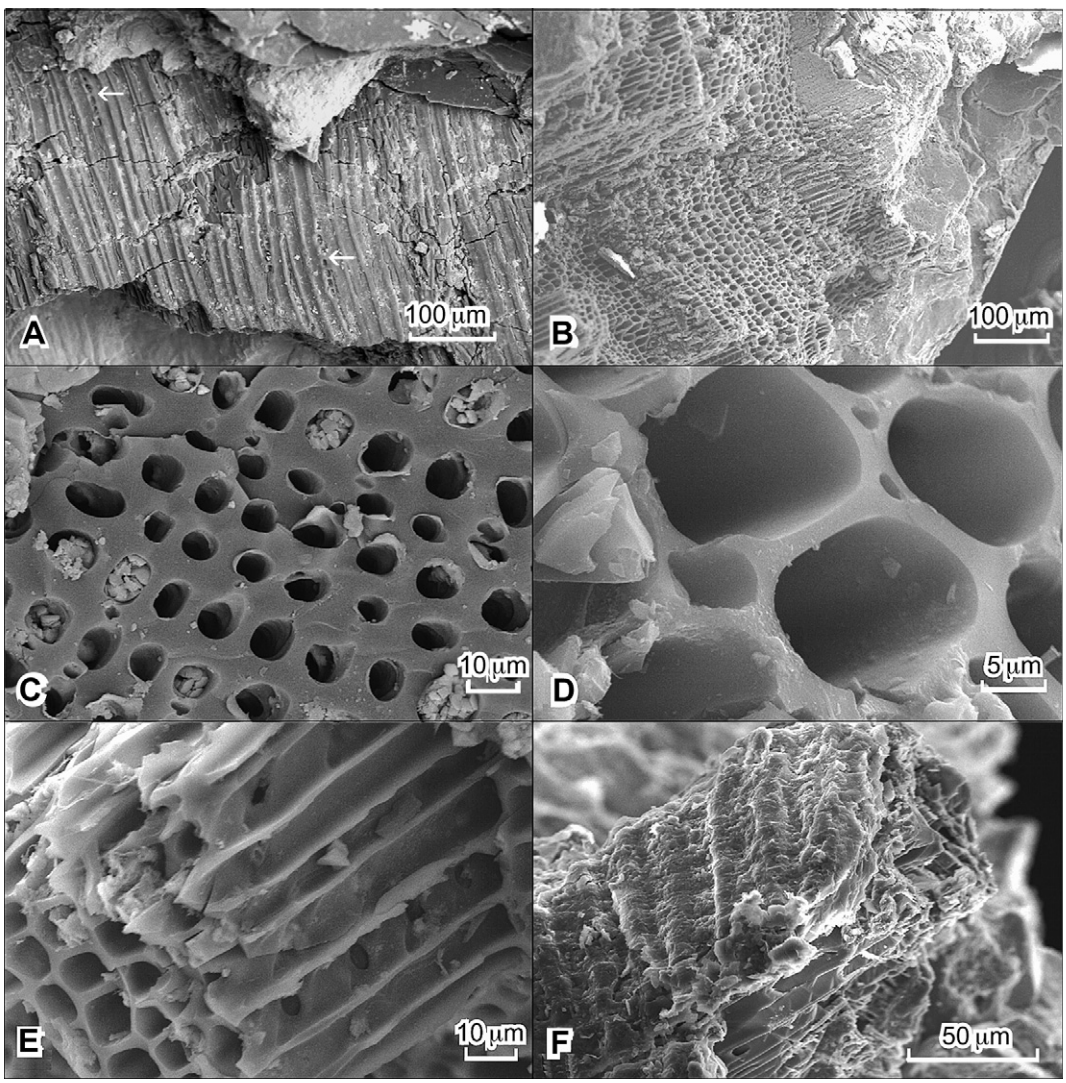

Figure 7 SEM analysis. Scale bars as shown on individual images. A: overview at low magnification of wood fragment showing uniseriate xylem rays; B: view of transverse section illustrates open lumina. Variation of lumen size between rows may reflect seasonal changes in growth rate; C: walls between adjacent cells are fully homogenized, indicating pyrolysis at temperatures higher than 300 °C. Note the thickened walls and smaller lumina of latewood; D: thinner cell walls and larger lumina in earlywood; E: uniseriate circular bordered pits on tracheid wall; F: the layer covering tracheids is possibly the original epidermis.

However, the absolute value of this minimum level has been a source of controversy. The lower limit for sustained combustion of biomass has been suggested as 13% (Chaloner, 1989), although experiments have indicated that dry crumpled paper does not sustain combustion below an oxygen level of 16% (Watson et al., 1978). Other recent work has suggested that wood will sustain combustion at 12% $p(O_2)$, but only at very low moisture content (2%; Wildman et al., 2004). At higher moisture content (12%), wood will not burn below 16% $p(O_2)$. Belcher and McElwain (2008) more recently determined experimentally that the moisture content of most plant matter requires a minimum $p(O_2)$ of 15% for sustained combustion to occur, but also suggested that under the natural conditions of fires ignited by lightning strikes accompanied by rain, 17% is a more reasonable minimum.

The distribution of fusain is uneven throughout the Phanerozoic. Its abundance in Carboniferous strata, particularly in coal measures, has long been noted and interpreted as evidence of atmospheric oxygen levels significantly higher than present atmospheric levels (PAL), possibly as high as 35% (Berner and Canfield, 1989; Scott, 2000; Jones et al., 2002). Conversely, an apparent paucity of fusain in Triassic strata (Scott, 2000; Jones et al., 2002) has been cited as evidence corroborating some geochemical models of relatively low atmospheric oxygen throughout this period (Falkowski et al., 2005; Berner, 2006). Tanner et al. (2006) reviewed the record of fusain in Upper Triassic strata and found the extensive record of Upper Triassic fusain incompatible with models suggesting O_2 levels as low as 10% (Falkowski et al., 2005). Consequently, these authors rejected the early Mesozoic $p(O_2)$ minimums predicted by these geochemical models, but noted that alternative models that incorporate fire-feedback and phosphorous cycling mechanisms predict more robust $p(O_2)$ levels (20%–25%) for the entire Mesozoic (Bergman et al., 2004).

Falkowski et al. (2005) suggested a correlation between atmospheric oxygen levels and the evolution of placental mammals, based on theoretical projections of atmospheric composition from geochemical models (Berner et al., 2000, 2003). Their results indicated variations in oxygen levels during the Middle Jurassic below 15% and thus are incompatible with the abundance of fusain found within the Yan'an Formation (Fig. 8). Specifically, Falkowski et al. (2005) wrote that ambient oxygen levels were around 10% at the start of the Jurassic Period, rising to a maximum of 17% during the Early Jurassic (Sinemurian), but falling to as low as 12% by the start of the Middle Jurassic, before rising gradually to 16% to the end of the Middle Jurassic (end of the Callovian). The experimental work by Belcher and McElwain (2008), establishing 15% $p(O_2)$ as the minimum for sustained biomass burning, demonstrates that the models utilized by Falkowski et al. (2005) are incompatible with the geological record. Significantly, Belcher and McElwain (2008) examined published records of charcoal occurrence from the Mesozoic, including several reports from the Middle Jurassic (Fig. 8). In addition to these reports, mostly published more than 50 years ago, more recent work unequivocally demonstrates the occurrence of wildfire during the Middle Jurassic (cf. Morgans et al., 1999; Marynowski et al., 2011).

Newer work by Glasspool and Scott (2010) reconstructs the history of changes in atmospheric oxygen across most of the Phanerozoic on the basis of variations in coal macerals (i.e., inertinite content). These authors conclude that $p(O_2)$ has been

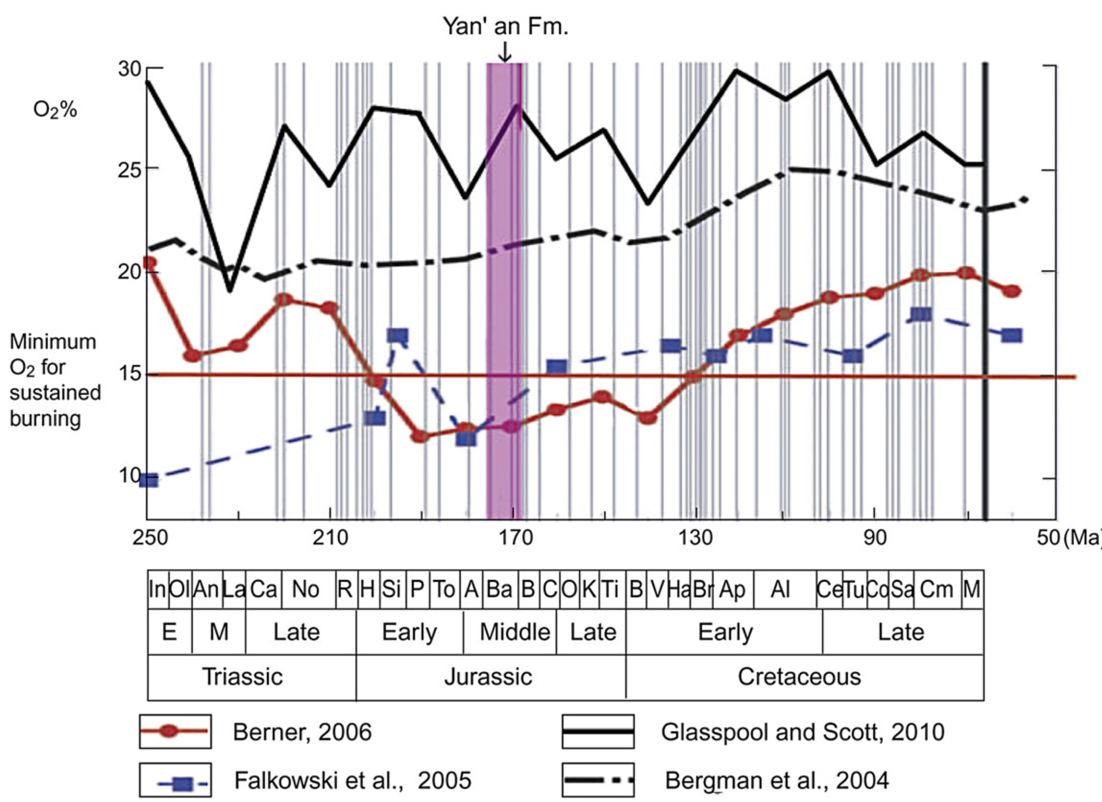

Figure 8 Comparison of models for variations in paleoatmospheric $p(O_2)$ for the Mesozoic Era (adapted from Belcher and McElwain, 2008). Vertical bars represent documented occurrences of fusain (from Belcher and McElwain, 2008). The approximate age of the Yan'an Formation is represented by the shaded vertical bar.

higher than PAL almost continuously since the Middle Paleozoic, including most of the Mesozoic Era. In particular, Glasspool and Scott (2010) cite data from Yang et al., (1996) for inertinite values in the Yan'an coals ranging from 39% to 54%, against a global mean of 32.9%, and calculate a best estimate $p(O_2)$ of 28.3% for the interval of Yan'an deposition (Aalenian-Bajocian). This followed a Toarcian "inertinite low," when the global mean inertinite was 5.6% and the calculated $p(O_2)$ fell to 22.6%. Thus, the presence of abundant fusain in the Yan'an Formation, while not by itself indicative of elevated $p(O_2)$, supports the model of Glasspool and Scott (2010) and the earlier model of Bergman et al. (2004) for Middle Jurassic oxygen substantially higher than the minimum required for sustained combustion.

7. Conclusions

Through a combination of field (i.e., macroscopic) and laboratory methods, electron microscopy in particular, we document that fusain (fossil charcoal) is abundant in sediments of the Middle Jurassic Yan'an Formation. In Member Two, in particular, fusain occurs in stream channel sediments at six distinct horizons within a 20 m outcrop section dominated by fluvial sandstone. Fusain occurs also in Member Four, but does not appear to be as abundant as in Member Two. Cursory examination of Members One and Three of the Yan'an Formation did not reveal any obvious fusain in stream deposits, although inertinite occurs in high concentrations in the coals of Member One. Additional research is required to document the stratigraphic record of fusain in the Ordos Basin more thoroughly.

We conclude that an adequate record of fusain suggests that paleowildfire was not a rare event during the Middle Jurassic. When combined with data on the inertinite content of coals (Yang et al., 1996; Glasspool and Scott, 2010), the evidence for wildfire in the Yan'an Formation indicates that atmospheric oxygen levels during the Middle Jurassic were well above those suggested by most previous geochemical models (Berner et al., 2000, 2003; Berner, 2005, 2006; Falkowski et al., 2005), but consistent with those that incorporate fire-feedback and phosphorous cycling (Bergman et al., 2004). This interpretation is consistent with experimental studies of $p(O_2)$ requirements for wildfire and of the Phanerozoic history of $p(O_2)$ based on inertinite abundance (Belcher and McElwain, 2008; Glasspool and Scott, 2010).

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