



Paleoproterozoic compression-like structures from the Changzhougou Formation, China: Eukaryotes or clasts?

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Abstract

The Paleoproterozoic Changzhougou Formation (Changcheng Group) of North China contains compression-like structures, millimeters to centimeters in diameter and about a millimeter thick that are circular, elliptical, elongate, and irregular in shape. These structures were interpreted to be carbonaceous compressions of megascopic eukaryotes by Zhu et al. (2000). Some of the compression-like structures were reported to contain masses of cellular material with well-preserved cell walls. Further investigation of these structures, including plane light investigations of thin sections and macerates, petrographic study of thin sections, SEM, EDS, CHN, XRD, and biomarker analyses, indicates that they are pseudo-fossils.

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1. Introduction

The origin, evolution, and distribution of early eukaryotes are topics of great interest in paleobiology. A rich eukaryotic fossil record is now established for late Neoproterozoic time (see Knoll, 2003; Butterfield, 2004; Porter, 2004; Grey, 2005); although less abundant, Mesoproterozoic sediments also have some well-preserved eukaryotic fossils (see Knoll, 1994; Javaux et al., 2004). Well-preserved eukaryotes from the Paleoproterozoic are much less common (see Knoll, 1992; Javaux et al., 2001). Paleoproterozoic eukaryotes are often controversial due to poor preservation, uncertain age control, and/or over-interpretation.

The best, direct evidence for early eukaryotes (Paleoproterozoic and Mesoproterozoic) is body fossils (Javaux et al., 2003). Body fossil evidence is limited to carbonaceous compressions, relatively simple acritarchs, and ‘string of bead’ fossils. While there has been some uncertainty regarding the origin of the ‘string of beads’ bedding plane markings (see Hofmann, 1992a), they are generally considered to be biological in origin and have been variously interpreted as multicellular algae (Grey and Williams, 1990), polyp-like animals (Fedonkin and Yochelson, 2004), and multicellular, tissue-grade, colonial eukaryotes (Fedonkin and Yochelson, 2002). ‘String of beads’ bedding plane markings, generally referred to as *Horodyskia* (Fedonkin and Yochelson, 2004), are diverse geographically and are known from the early to late Mesoproterozoic (Grey et al., 2001). Acritarchs are organic-walled microfossils of uncertain taxonomic affinity, but generally considered to be eukaryotic phytoplankton (see Grey, 2005). The

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oldest acritarchs that are presumably eukaryotic are large (up to 234 μm) sphaeromorphs (simple, unornamented spherical to fusiform in shape) that date back to ~ 1800 Ma (e.g., Yan, 1991; Zhang, 1997). Recently, graphitic disks from Archean amphibolite-facies metasediments have been interpreted as compressed acritarchs, presumably of eukaryotes (Schiffbauer et al., 2005). The oldest acanthomorph acritarch (i.e., large, complex, and process-bearing) is from the ~ 1500 Ma Roper Group, Australia (Javaux et al., 2001). More recent (Neoproterozoic) acanthomorphs have been alternately interpreted as fungi (see Butterfield, 2005a,b); however, these fossils are not represented in Paleoproterozoic sediments. Carbonaceous compressions are macroscopic fossils (visible to the naked eye, >0.2 mm in diameter), which have a diverse range of forms, varying from circular, elongate, filamentous, to complex branching (for a visual key, see Hofmann, 1985a, 1994). These fossils are preserved on bedding plane surfaces; the organic films of the compressions are generally about a few micrometers thick (Hofmann, 1992b). Due to the thin carbonaceous film, colors of the compressions tend to be dark gray to black. The oldest generally acknowledged carbonaceous compression is *Grypania spiralis* from the 1874 ± 9 Ma Negaunee Iron-Formation, Michigan (Han and Runnegar, 1992; see Schneider et al. (2002) for the age). However, the taxonomic affinity of *Grypania* is still in dispute (see Samuelsson and Butterfield, 2001). There are other reports of Paleoproterozoic carbonaceous compressions (e.g., Hofmann and Chen, 1981; Zhu and Chen, 1995; Yan and Liu, 1997; Zhu et al., 2000), and all are from the Jixian region of China.¹

In general, Paleoproterozoic carbonaceous compressions are the simplest in morphology (filamentous, circular, or elongate; *Grypania* is an exception—it has a corkscrew shape). Most forms are without distinctive ornamentation (besides wrinkling) (see Hofmann, 1985a, 1994). Morphology becomes more complex and possible anatomical detail is retained in some Mesoproterozoic examples, such as *Grypania* (see Hofmann, 1994) and *Longfengshania* (see Du et al., 1995). In the Neoproterozoic, even more complex morphology is found, with some unambiguously branching forms in the late Neoproterozoic (Xiao et al., 2002). Not only does complexity tend to increase with time, so

does the number of carbonaceous compressions. They become much more common and diverse in the late Neoproterozoic (Xiao et al., 2002).

Due to the simplicity of Paleoproterozoic compressions, caution must be used when interpreting these structures. By itself, gross morphological resemblance to younger fossils or modern analogues does not constitute a strong argument for a biogenic origin of compression-like structures. Multiple lines of evidence and other origins need to be considered. Various sedimentological processes can produce structures that mimic morphology seen in fossils (Sharma et al., 1992). Superficial similarities in morphology should be weighed against additional paleontological evidence. These general concerns echo the ones given by Cloud (1973) in his plea for caution with regard to the tendency to describe structures of uncertain origin as *bona fide* fossils. Cloud's caveats are as relevant today as they were over 30 years ago.

Towe (1992) briefly summarized several criteria to evaluate claims of ancient megafossils, which included carbonaceous compressions. These fell into the two general categories of biogenicity and syngeneticity (Schopf and Walter (1983) and Buick (1990) elegantly discussed these categories but with regard to Archean microfossils). To be syngenetic, fossils must have been formed in and be contemporaneous with the sediments that contain them. To add credence to biogenicity, a purported fossil must not be explained by purely inorganic processes or by the processes of sample preparation (i.e., the artifacts and contaminants that could result from preparation) (Towe, 1992).

In 2000, Zhu and others published a paper of potentially great significance. They reported to have found some of the oldest carbonaceous compressions, which also were thought to preserve some of the multicellular remains of the original organisms. These structures came from the Paleoproterozoic (~ 1800 Ma) Changzhougou Formation in the Yanshan of North China. They assigned the structures to three categories (discoïd, ellipsoid, and sausage-like), which they considered to have morphological resemblance to *Chuararia*, *Shouhsienia*, and *Tawuia*. Due to the importance of claims of this magnitude, a collaborative project was initiated and the structures were re-investigated. We examined outcrops, slabs, thin sections, and macerations of original material as well as collecting and preparing new material for analysis. We employed SEM, EDS, XRD, CHN, and biomarker analyses on the new material in order to determine their origin. The results of these studies indicate that these compression-like structures are not fossils but flat clasts of sedimentary material.

¹ Note: when the words “carbonaceous compression” or “compression” are used in this paper, they refer to *bona fide* fossils. When “compression-like structures” is used, it refers to structures that are dubiofossils, i.e., those that require further study to test biogenicity.

2. Stratigraphy and age

The Yanshan of North China contains one of the truly remarkable successions of Proterozoic sedimentary rocks—the so-called Jixian section (see Zhang and Li, 1991). This ~9000 m thick succession is subdivided into three groups (often called “systems” in the Chinese literature): the Changcheng (up to 2762 m thick), the Jixian (up to 6088 m thick), and the Qingbaikou (up to 370 m thick) Groups (Lu et al., 1996), ranging in age from the Paleoproterozoic through the Neoproterozoic.

The Changcheng Group is composed of the Changzhougou, Chuanlinggou, Tuanshanzi, and Dahongyu Formations, in ascending order (see Fig. 1). Another scheme for the Changcheng Group includes the overlying Gaoyuzhuang Formation (see Kusky and Li, 2003).

The four-formation version of the Changcheng Group is used here based on the unconformity between the Dahongyu and Gaoyuzhuang Formations (Lu et al., 1996).

The Changzhougou Formation has a wide distribution in Hebei Province and Tianjin Municipality. In the Jixian region, the Changzhougou Formation is 859 m thick and in the Kuancheng and Xinglong areas (where the compression-like structures were found; Fig. 2) it is ~1300 m thick (Zhu et al., 2000). The Changzhougou Formation rests non-conformably on metamorphic basement. The formation has been defined as the first depositional sequence in the Changcheng Group, with the base of the formation being a type I sequence boundary and the top being a type II boundary (Lu et al., 1996). Lithostratigraphically, the formation is subdivided into

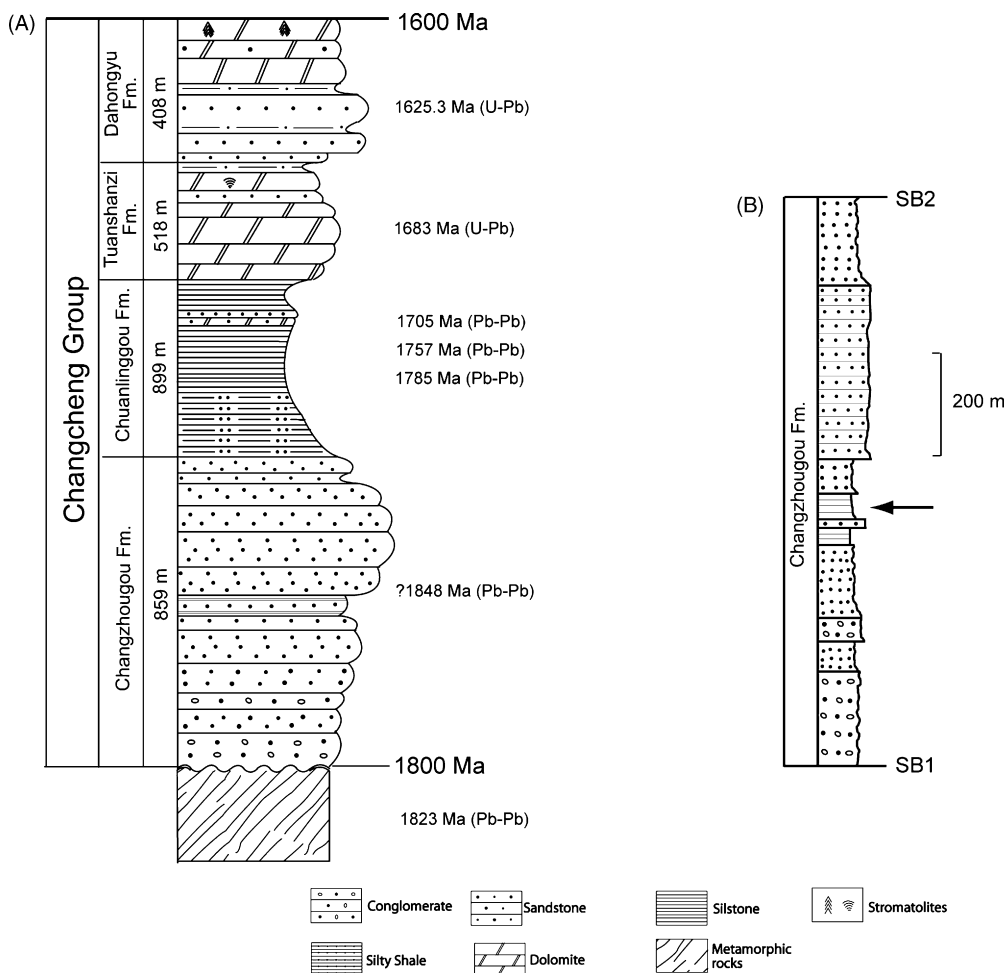


Fig. 1. (A) Generalized stratigraphic section of the Changcheng Group from the Yanshan Range, North China. Formation thicknesses are for the Jixian area. (B) Measured section of the Changzhougou Formation at the Kuancheng locality. Samples were collected at the level indicated by the arrow. SB1 = sequence boundary 1, SB2 = sequences boundary 2. Profile modified slightly from Zhu et al. (2000).

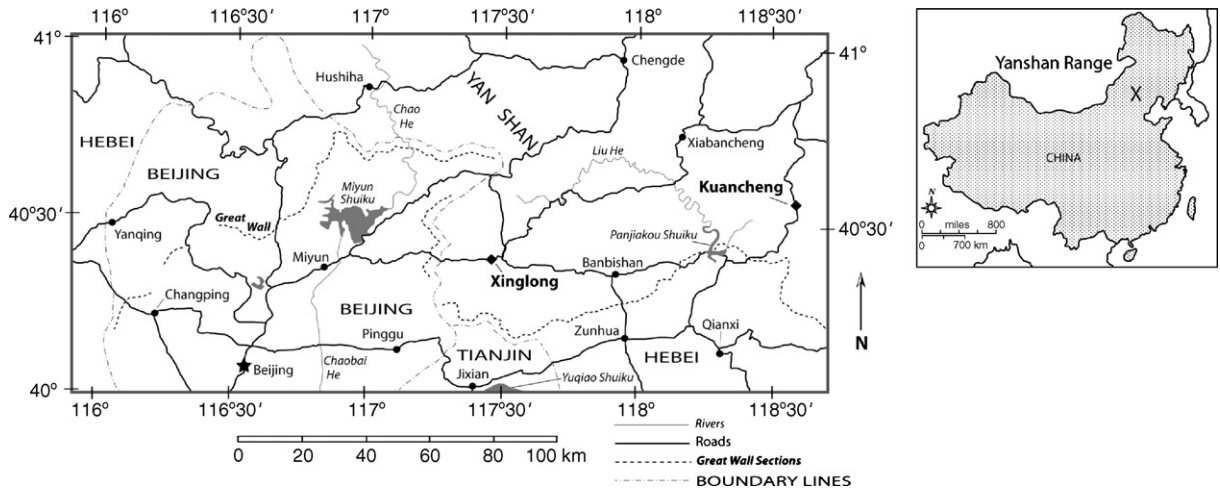


Fig. 2. Map with major roads showing the Xinglong and Kuancheng localities, Yanshan Range, North China.

lower, middle, and upper members (Zhu et al., 2000; Zhang and Chen, 2000); although, in some schemes, it is divided only into lower and upper members (see Zang, 1997). The three-member division is used here. The lower member of the Changzhougou Formation consists of a basal, thick-bedded conglomerate and a coarse, pebbly sandstone; the middle member consists of medium to thick-bedded quartzite and feldspathic sandstone with some shaley interbeds; the upper member consists of interbedded, platy, quartz sandstone and thin beds of sandy-shale (Lu et al., 1996; Zhang and Chen, 2000; Zhu et al., 2000).

There is some uncertainty with regard to the age of the Changzhougou Formation. A Pb–Pb age of 1823 ± 68 Ma was obtained on zircons from the metamorphic basement (Lu et al., 1996). Clay minerals from within the formation yielded a Pb–Pb age of 1848 ± 39 Ma (Kusky and Li, 2003). Pb–Pb isochron studies of whole rock (shale) samples yielded an 1848 ± 58 Ma age (Li et al., 1984). Ages for other formations in the Changcheng Group are as follows: Pb–Pb ages for the Chuanlinggou Formation range from 1705 ± 42 Ma (illite, Zhang, 2000) to 1757 ± 113 Ma (shale; Li et al., 1984) to 1785 ± 19 Ma (illite; see Kusky and Li, 2003). A U–Pb age of 1683 ± 67 Ma was obtained from zircons in the Tuanshanzi Formation (Lu et al., 1996), and a U–Pb age of 1625.3 ± 6.2 was obtained from zircons in the Dahongyu Formation (Lu and Li, 1991). Unfortunately, reports do not indicate the member and other stratigraphic details with regard to the dating. The Changzhougou Formation is generally considered to be ~ 1800 Ma by Chinese researchers (see Lu et al., 1996; Wan et al., 2003) and this seems reasonable at this time.

3. Localities and depositional environment

Two localities are known to contain the “carbonaceous compressions” reported in Zhu et al. (2000). The Xinglong locality is about 70 km northeast of Beijing at $\sim 40^{\circ}22'05''N$, $117^{\circ}16'26''E$; the Kuancheng locality is located 180 km northeast of Beijing at $\sim 40^{\circ}34'54''N$, $118^{\circ}34'40''E$ (Fig. 2). The Changzhougou Formation at both localities is about 1300 m thick and consists of a succession of siliclastics (siltstone and shale) (Zhu et al., 2000). At the Xinglong locality the formation is dominated by thick-bedded siltstone. One of the most prominent features at the Kuancheng locality is the interbedded laminated siltstone and shale. The siltstone-shale interbeds are overlain by thick siltstone beds (similar to those seen at the Xinglong locality). Synclinal cracks, often ptlygmatically folded, were observed at both localities.

The general lack of key sedimentological features at the Xinglong and Kuancheng localities make a depositional environment interpretation difficult. Zhu et al. (2000) favor a marginal tidal paleoenvironment. Song and Gao (1985) found the following sedimentary structures in the middle member of the Changzhougou Formation in the Ming Tombs District, Beijing (about 90 km from Xinglong): flaser and lenticular bedding, herringbone cross-stratification, ripple marks, mud cracks, water escape structures, and raindrop impressions. The siltstone-shale interbedding at the Kuancheng locality is consistent with this intertidal interpretation. Although a more detailed facies analysis is needed at the Kuancheng and Xinglong localities, an intertidal paleoenvironment seems reasonable. The thick-bedded siltstone at both localities may represent ‘sand’ flats that

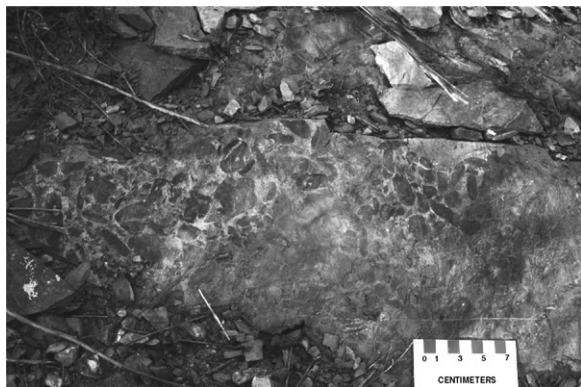


Fig. 3. Bedding plane surface of a siltstone block showing the compression-like structures; Xinglong locality.

often occur in a tidal flat environment. Also common in ancient tidal flats are mud chips and mud-chip conglomerates (McLane, 1995). These chips (i.e., ripped up clasts) can form when energetic storms erode loosely consolidated clays and clay-rich silts.

4. The compression-like structures

The compression-like structures are chip-shaped without curled margins and range in size, a few millimeters to a few centimeters in diameter and a few to several millimeters in thickness. Unlike many carbonaceous compressions, these structures can have a significant third dimension (z axis). No walls or carbonaceous envelopes are apparent when viewed in thin section or in the SEM. The two longer axes (x and y) are parallel to bedding. Elongate forms do not exhibit a preferred orientation on bedding plane surfaces and no imbrication has been observed. The outlines of the shapes are quite variable; most are irregular (with angular outlines), while some are circular to elongate (with smooth outlines) (Fig. 3). No distinguishing markings or other features are found on their surfaces. Unlike the compression-like structures shown individually in Fig. 2 of Zhu et al. (2000), there does not appear to be consistency in

shape of populations on the observed bedding planes. These structures are abundant on bedding plane surfaces in the middle member of the Changzhougou Formation at both the Kuancheng and Xinglong localities.

5. Methods

Semi-polished thin sections of samples with compression-like structures were made perpendicular to bedding for petrographic study. Two of these are illustrated in Fig. 4A and B. Thin sections were examined with plane transmitted light and polarized light. Other samples were prepared for the SEM, environmental SEM, EDS (X-ray energy dispersive spectrometry) analyses, and the XRD and CHN analyses described below. The three samples chosen for the analyses (Fig. 5A–C) were all found in siltstone blocks; the compression-like structures were cleaved nearly in half across the bedding plane surface, but one side was a slightly more convex and the other a slightly more concave. Both sides had darker material, which *prima facie*, appeared to be carbonaceous (see Fig. 5A–C). One side of each sample was used for XRD and CHN analyses (described below). The other side was used for the SEM and EDS analysis by the following methods: compression-like structures on bedding planes were ground with a 600 carborundum grit to produce a flat surface, cleaned with petroleum ether to remove excess oils, and then coated with carbon. *Note:* although the material was coated with carbon for SEM preparation, the coating was only 50–100 Å thick, which is below the detection limits of the EDS (penetration of the X-ray beam is about 4 μm, well-beyond the coating; therefore, this would not affect the values obtained for the carbon concentration of the samples). An examination of the surface features of one sample from Kuancheng was conducted with an SEM (JEOL, Model JSM 6300v). A Princeton Gamma Tech EDS onboard an environmental SEM (FEI Co. XL30 ESEM) was used to map the elemental composition of the compression-like structures and their surrounding matrices in three differ-

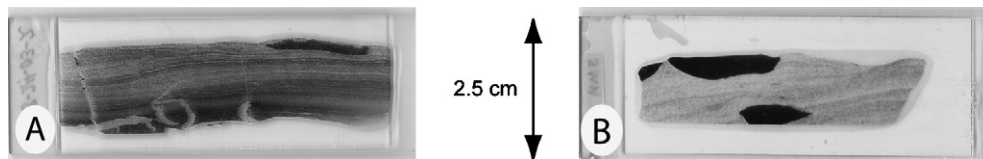


Fig. 4. Scanned images of thin sections (cut perpendicular to bedding) of compression-like structures. (A) Thin section 3 of 8/24/03-2; Xinglong locality. Compression-like structure appears on upper right of thin section. The matrix is fine-grained silt with some finely laminated opaque material. The structure is composed primarily of clay and opaque materials. There is no envelope or membrane surrounding the structures. Bottom of cross-section shows syneresis cracks. (B) Thin section SBO 455; Kuancheng locality. The darker compression-like structures are clearly seen in a lighter silty matrix. Structures are composed primarily of dark clay minerals. There is no envelope or membrane surrounding the structures. Thin section for (A) was made from a block shown in Fig. 5D.

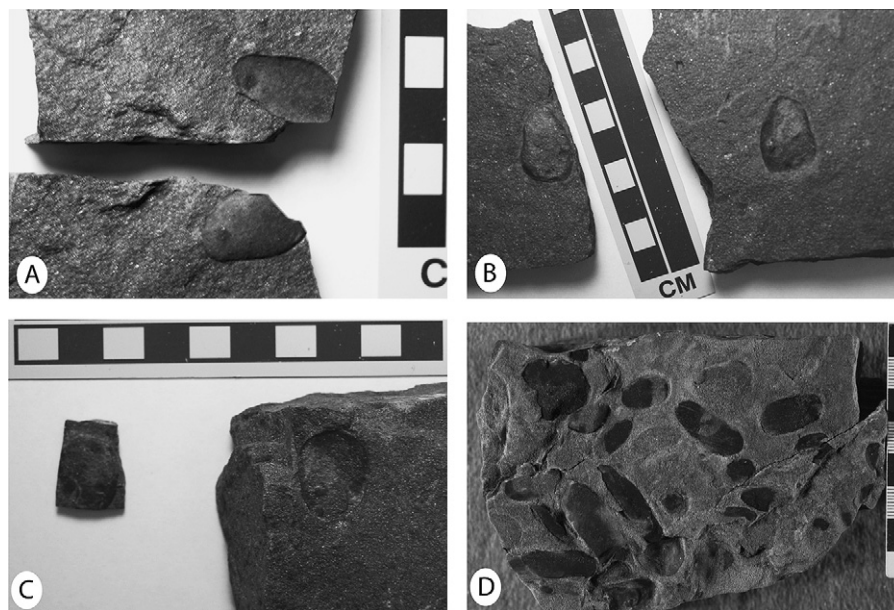


Fig. 5. Samples (A–C) used for XRD and CHN analyses and used to generate the chemical maps shown in Fig. 6. (A) Sample 1 of 7/4/04; (B) Sample 1 of 7/3/04b; (C) Sample 1 of 7/4/04b. All three samples are from the Kuancheng locality. Compression-like structures from (B and C) were shown to be primarily composed of clay minerals. The compression-like structure in (A) is composed mainly of apatite. (D) Bedding plane surface of block used to make thin section shown in Fig. 4B. Both the matrix and the compression-like structure have more clay than specimens shown in (A–C). The silty matrix is gray in color and has much less mica than the other specimens.

ent samples (Fig. 5A–C; maps are shown Fig. 6A–C) from Kuancheng. The EDS was used to make a qualitative assessment of carbon concentration. SEM coupled with energy dispersive spectrometry was also employed in a manner similar to that described in Zhang et al. (2006) to assess microstructure and elemental abundances.

Since the Princeton Gamma Tech EDS has limitations in mapping at lower atomic numbers, XRD (Phillips X-pert MPD) and CHN (Exeter Analytical, Model CEC 440HA) analyses were used to analyze further for carbon. To prepare the other sides of the compression-like structures described above for XRD and CHN analysis, the samples were washed thoroughly with tap water, dried, and the darker material on the surfaces of the split structures was physically liberated from the matrices with an exacto knife. The liberated material was powdered and XRD analysis was carried out at 40 kV and 30 mA. Finally, CHN analysis was run on the powdered materials left over from XRD analysis. Preliminary biomarker analyses on a compression-like structure from the Kuancheng locality were performed by Jacob Waldbauer (MIT) following procedures discussed in Brocks et al. (2003).

Macerates were prepared by Corelab (formerly Laola) of Western Australia, in accordance with techniques presented in Grey (2005, pp. 32–33). Maceration refers to an

acid dissolution technique used to isolate organic-walled microfossils and kerogen.

6. Results

Petrographic studies indicate that the structures are composed primarily of clay minerals (XRD analysis showed that the type of clay was illite) with lesser amount of quartz. In some cases, there is also darker, finely layered, opaque material. Some of the opaques occur with the clay minerals, making the clays hard to distinguish. The matrix surrounding the structures is a siltstone with poor to moderately well-rounded, silt-size (0.04–0.07 mm) quartz grains, varying amounts and local concentrations of sub-rounded feldspar (both plagioclase and orthoclase), clay minerals, biotite, muscovite, and a small component of opaque and accessory minerals. Similar appearing clays are found in both the compression-like structures and in the surrounding matrices, but the compression-like structures have higher local concentrations of clays. Although there is variability in the samples examined, the matrices generally have different grain sizes and textures than the compression-like structures, indicating that the structures are likely foreign objects.

XRD results vary among the samples (Fig. 5A–C), all of which are from Kuancheng. XRD was run only

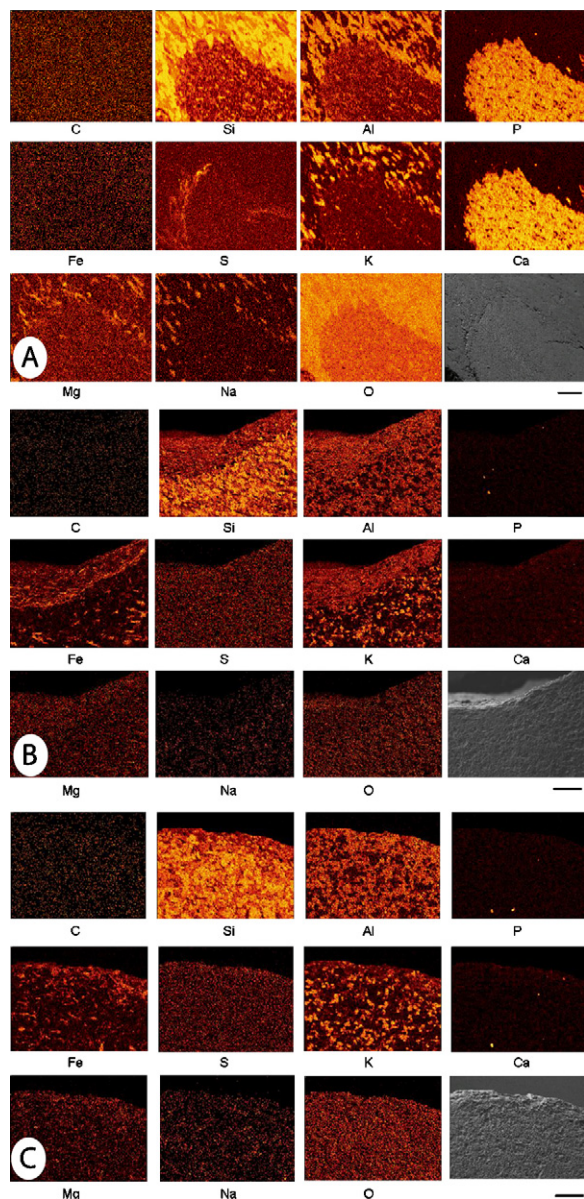


Fig. 6. Chemical maps generated by EDS analysis of cross-sections of specimens shown in Fig. 5. The original SEM images are shown in the lower right of each set of figures. (A) Chemical map showing a cross-section of the compression-like structure in Fig. 5A. The lightest colors represent the highest concentrations of an element. The compression-like structure is clearly delineated from the matrix in the Ca and P maps. No significant amounts of carbon were noted in the compression-like structure or the matrix (lighter color in C and Fe maps are “background noise” from the EDS). Scale bar is 200 μm . (B) Chemical map showing a cross-section of the compression in Fig. 5B. The compression-like structure is outlined by the lighter, yellow color in the Fe map. No significant amounts of carbon were noted in the compression-like structure or the matrix. Scale bar is 500 μm . (C) Chemical showing a cross-section of the compression-like structure in Fig. 5C. The compression-like structure (not visible in lower right) is the thin layer at the top roughly outlined in concentration of lighter,

on the compression-like structures and not the surrounding matrices. The compression-like structure in Fig. 5A has an XRD spectrum that indicates it is composed partially of phosphates with no detectable clay minerals. The analysis of the other two (Fig. 5B–C) generated spectral patterns whose best match is illite and muscovite. Quartz is present as a major constituent in all three samples.

Neither SEM nor petrographic analysis revealed any microbial fossils or cellular preservation, tissue, or other clearly biogenic morphology in the compression-like structures collected in 2003, 2004, and 2005 as part of this collaborative investigation. No film or kerogenous envelope (a feature found in some younger compressions; see Ford and Breed, 1973; Hofmann, 1985b) is associated with any of the compression-like structures.

Macerations of more recently collected Changzhougou Formation shale from the Kuancheng locality (prepared by Corelab) yielded poorly to moderately well-preserved sphaeromorph acritarchs, some up to $\sim 50 \mu\text{m}$ in diameter. These remains are dark brown in color.

Microscopic investigations of thin sections and macerates prepared in Tianjin, which were the basis of the original report (Zhu et al., 2000), reveal the following: (1) the cellular structure reported from macerations of the compression-like structures is yellow to amber in color with some portions colorless and translucent; (2) the cells walls are well preserved and exhibit high relief under white-light microscopy; (3) margins of multicellular masses contain well-developed pseudo-filaments with incomplete partitions; (4) sphaeromorph acritarchs are found in macerates were dark brown in color.

The results of the EDS analysis are presented in Fig. 6. The compositions are represented by color contrasts (lighter colors, such as yellow, represent the highest concentrations of an element). The compression-like structures are distinguished from their enclosing rock by higher or lower abundances of various elements. Although there is variation in elemental abundances in the matrices of the three samples, the chemical maps show that the matrices are enriched in Si, K, and Al. The compression-like structures have a different composition. One structure is enriched in P and Ca (Fig. 6A) indicating apatite; the other two are enriched in Fe. In

orange colors in the Fe map. No significant amounts of carbon were noted in the compression-like structure or the matrix. Scale bar is 500 μm . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 1
Results from the CHN analysis showing very low composition percentages for carbon

Sample (ID)	Weight (μg)	Weight percent			C/N ratio
		C	H	N	
Blanks (μV)	0	34	295	40	0
Calibration	1322	−0.04	−0.06	−0.07	0.58
Control ($\mu\text{V}/\mu\text{g}$)	1254	71.06	6.80	10.35	6.86
Sample 1 of 7/4/04 ($\mu\text{V}/\mu\text{g}$)	2551	0.57	0.21	0.01	56.62
Sample 1 of 7/3/04b ($\mu\text{V}/\mu\text{g}$)	2314	1.12	0.46	0.07	15.43
Sample 1 of 7/4/04b ($\mu\text{V}/\mu\text{g}$)	2229	1.64	0.50	0.02	76.07

Table 2
CHN results from three different studies (see text) used for comparison. Note the much higher elemental abundances for the elements typically ascribed to biological materials

Location	Type	Age	Source	Weight percent			C/N ratio
				C	H	N	
Little Dal Group	<i>Tawuia</i>	Neoproterozoic	Hofmann (1992b)	80.56	13.05	2.26	35.71
Hongshuizhuang Fm.	Kerogens from various compressions	Mesoproterozoic	Liu et al. (1992)	57.04	3.3	0.83	68.72
E. European Platform	Vendotaenids	Late Proterozoic	Gnilovskaya (1983)	41.3	5.1	0.5	82.6

all cases, there is an apparent lack of carbon enrichment in the compression-like structures or the surrounding matrices. The results indicate that the compression-like structures are not carbonaceous; i.e., they are not carbon-rich.

To confirm further the EDS carbon results of the compression-like structures, CHN analysis was used. CHN analysis was restricted to the compressions-like structures. The results show that carbon levels are very low, $\sim 1\%$ (between 0.57 and 1.64%; Table 1). In contrast, Liu et al. (1992) reported a 57.04% carbon composition from materials interpreted to be kerogen in compressions from the Mesoproterozoic Hongshuizhuang Formation. Gnilovskaya (1983) noted a 41.3% carbon composition in vendotaenids (ribbon-like compressions) from late Proterozoic sediments on the East European Platform. Hofmann (1992b) reported a carbon composition of 80.56% in an elemental analysis of a *Tawuia* compression wall from the Neoproterozoic Little Dal Group (Table 2).

Preliminary biomarker analysis on a Kuancheng compression-like structure found extractable hydrocarbons, including both sterane (C_{26-29}) and hopane biomarkers. This analysis also indicates that the sample had a low thermal maturity.

Materials studied (and additional samples) in the analyses described above are housed at the Preston Cloud Research Lab at the University of California, Santa Barbara.

7. Discussion

Zhu et al. (2000, p. 845) claimed that the Changzhougou Formation compression-like structures were the “oldest representative of the multicellular organisms...” Their evidence for a biogenic origin of the compression-like structures relied heavily on gross morphology of selected samples, purported “multicellular remains,” and comparisons with younger compressions whose biogenicity has not been questioned. Although some of the selected compression-like structures reported in Zhu et al. (2000) have a superficial morphological resemblance to younger, more confidently established compressions, they do not have other characteristics that would support the conclusion that they are fossils. Zhu et al. (2000) found masses of cellular material in the compression-like structures; however, reexamination determined that these masses are contaminants (as discussed below).

The compression-like structures have very diverse (and often irregular) morphology and no key features such as wrinkles. Surface wrinkling frequently is found in *bona fide* carbonaceous compressions due to the flexibility and compressibility of the body fossil and the compaction of kerogens from the overlying sediment (see Hofmann, 1985a). The morphological variability and lack of wrinkles can be more satisfactorily explained if the structures are clasts. Ripped-up, partially eroded, and redeposited clasts would have variable size and

shape depending on the energy of the environment and the original nature of the clasts (i.e., soft, hard, pliable, etc.). Pebble-sized clasts can be rounded and platy, and they can have a relatively flat shape that is either primary (derived from laminated mud) or secondary (from compaction) (Ricci Lucchi, 1995). Carbonaceous compressions of confident biologic origin, such as the Neoproterozoic Little Dal macrobiota, show a limited range in size and shape for specimens proximal to one another on bedding planes (see Plate 35 (5), in Hofmann, 1985b). This is not the case with the Changzhougou Formation structures (see Fig. 3).

By itself, the presence of clay minerals in the Changzhougou Formation compression-like structures is neither consistent with nor against an interpretation that these are pseudo-fossils. Previous studies have noted that clay minerals are associated with the preservation of carbonaceous compressions (e.g., in Burgess Shale-type preservation; Orr et al., 1998; Xiao et al., 2002). The role of the clays in taphonomic processes is not well understood. Other evidence, such as the presence of carbonaceous envelope or membrane surrounding the structure, would support a biogenic origin. This carbonaceous envelope has been reported in some examples of younger, carbonaceous compressions. Ford and Breed (1972; see Plate 2, Fig. 2) noted that cross sections of *Chuarina* “*wimani*” from the Neoproterozoic Visingsö Group show two simple walls with thicknesses of 5–7 μm . Zang and Walter (1992) reported 0.8–1 μm thick walls in *Chuarina circularis* from the Neoproterozoic Huainan Group of central eastern China. In addition, Hofmann (1985b) noted 1 μm -thick kerogenous walls with specimens of *Chuarina* and *Tawuia* from the Neoproterozoic Little Dal Group. The compression-like structures from the Changzhougou Formation have a more uniform composition throughout the individual structures, although mineralogy can differ from sample to sample. They do not have a thin carbonaceous layer, film, or even significant concentrations of carbon.

Zhu et al. (2000, p. 843) included Laser Raman Spectroscopy analysis of their specimens and cited the composition to be analogous to “blind coal,” which means “anthracite or other coal that burns without a flame” (Jackson, 1997, p. 72). This is inconsistent with the small amount of organic material ($\sim 1\%$, measured in CHN analysis) having a relatively high C:H (see Table 1). The masses of cellular material were found in macerates and illustrated on the cover of the May 2000 issue (vol. 45) of *Chinese Science Bulletin* (Zhu et al., 2000). The yellow to amber color of the multicellular masses is inconsistent with the dark brown color of acritarchs found in shale from the Kuancheng locality and the ther-

mal maturity determined from the preliminary biomarker study. The well-developed pseudo-filaments with incomplete partitions found within the margins of these masses resemble fungi with pseudo-filaments and incomplete septae. These cellular remains are interpreted as contaminants.

8. Conclusions

The Changzhougou Formation compression-like structures lack features usually found in younger, convincing carbonaceous compressions (see Hofmann and Aitken, 1979; Duan, 1982; Hofmann, 1985b; Vidal et al., 1993; Talyzina, 2000). For example, the Changzhougou Formation structures (1) lack a consistent, well-defined morphology, (2) have no distinguishing features such as walls, wrinkles, or other ornamentation, (3) lack internal structure, (4) lack cellular or tissue preservation, (5) have very little carbon, and (6) they have compositions and morphologies consistent with clay-rich clasts. Examination of bedding plane surfaces, hand sample examination, petrographic, microscopic, SEM, and chemical analyses of the structures indicate that they are clasts composed of clays or phosphates with little carbon. These structures probably resulted from thin layers of material ripped up and redeposited in or near what might have been an intertidal environment. Original or host layers of the source for the clasts have not been located in outcrop. The Changzhougou Formation compression-like structures are not body fossils of Paleoproterozoic eukaryotes; they are pseudo-fossils. These structures are dark-colored, ripped-up and re-deposited mud clasts.

Despite these findings, the Changcheng Group still has great potential to extend and expand knowledge of Paleoproterozoic eukaryotes. The pseudo-fossils do not rule out the possibility that carbonaceous compressions may be found in the Changzhougou Formation. Hofmann and Chen (1981) found carbonaceous compressions assignable to *Tyrasotaenia* and *Chuarina* in the uppermost Chuanlinggou Formation and in the 1st member of the Tuanshanzi Formation. Higher upsection in the Tuanshanzi Formation, a diverse assemblage of morphologically complex compression fossils were discovered that resembled *Longfengshania* (Zhu and Chen, 1995; Yan, 1995a; Yan and Liu, 1997). Abundant acritarchs have been found in the Changzhougou Formation (Luo et al., 1985; Yan, 1991; Yan, 1995b; Zang, 1997; Sun and Zhu, 2000; Sun et al., 2002), the Chuanlinggou Formation (Yan, 1982; Luo et al., 1985; Zhang, 1986; Yan, 1995b; Sun and Zhu, 2000), and are also known from the Dahongyu Formation (Yin, 1985). Large ($\sim 200 \mu\text{m}$ in diameter) spheroidal

to somewhat irregularly shaped microfossils of possible eukaryotic origin have been found in chert of the Dahongyu Formation (Zhu and Awramik, in preparation). Preliminary biomarker research in the Changcheng Group has yielded encouraging results. Gammacerane, a biomarker found in some modern ciliates (Porter, 2004), was reported from the Tuanshanzi Formation by Peng et al. (1998) and in the Chuanlinggou, Tuanshanzi, and Dahongyu Formations by Li et al. (2003); gammacerane has also been reported in the Neoproterozoic Chuar Group (Summons et al., 1988). Li et al. (2003) also found abundant steranes in Chuanlinggou, Tuanshanzi, and Dahongyu Formations, likely indicating the presence of eukaryotes. The preliminary biomarker study by Waldbauer (MIT) described above also detected sterane biomarkers in the Changzhougou Formation. These studies demonstrate the great potential of the Changcheng Group to contribute to establishing a rich Paleoproterozoic record of eukaryotic life.

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