slides and Avalanches, 1, B. Voight, Ed. (Elsevier, Amsterdam, 1978), pp. 259–275], and Gros Ventre, WY (B. Voight, *ibid.*, pp. 113–166).
6. C. Culmann, *Die Graphische Statik* (Meyer and Zeller, Zürich, Switzerland, 1875).
7. Studies determining material properties from topographic limits have been applied to clay strata in England [W. Skempton, *Proc. Yorks. Geol. Soc.* **29**, 33 (1953)], to friable loess deposits in Iowa [R. A. Lohnes and R. L. Handy, *J. Geol.* **76**, 247 (1968)], to coastal bluffs composed of glacial deposits [W. S. McGreal, *Z. Geomorphol. Suppl.* **23**, 76 (1979)], and to loess-derived alluvium in Tennessee [A. Simon, in *Applied Quaternary Research*, E. F. J. DeMulder and B. P. Hageman, Eds. (Balkema, Rotterdam, Netherlands, 1989), pp. 129–146; A. Simon and C. R. Hupp, *U.S. Geol. Surv. Open-File Rep. 91-502* (1992)].
8. E. Hoek and J. W. Bray, *Rock Slope Engineering* (Institute of Mining and Metallurgy, London, 1977).
9. K. M. Schmidt, thesis, University of Washington, Seattle (1994).
10. A. J. Fiksdal and M. J. Brunengo, *Forest Slope Stability Project Phase II* (Washington State Department of Ecology, Olympia, WA, 1981).
11. M. J. Selby [*Z. Geomorphol. Suppl.* **24**, 31 (1980)] related finer scale variations in the gradient of bedrock hillslopes to outcrop-scale rock mass strength.
12. S. Y. Johnson, thesis, University of Washington, Seattle (1982); *Can. J. Earth Sci.* **21**, 92 (1984).
13. K. M. Schmidt and D. R. Montgomery, in preparation.
14. A variably loaded sheargraph is a portable instrument used to determine in situ strength properties of earth materials. A cup is seated with a given normal force, and the material is sheared until failure occurs. By variation of the normal force and thus of the associated shear force, a suite of values is produced that, in conjunction with Mohr-Coulomb failure theory, determines friction angle and cohesion.
15. G. Plafker and J. P. Galloway, Eds., *U.S. Geol. Surv. Circ. 1045* (1989); T. E. Spittler, E. L. Harp, D. K. Keefer, R. C. Wilson, R. H. Sydnor, in *The Loma Prieta (Santa Cruz Mountains), California, Earthquake of 17 October 1989*, S. R. McNutt and R. H. Sydnor, Eds. (Department of Conservation, Division of Mines and Geology, Sacramento, CA, 1990), pp. 59–66; T. E. Spittler and E. L. Harp, *U.S. Geol. Surv. Open-File Rep. 90-688* (1990).
16. Landslides triggered by the 1989 Loma Prieta earthquake were mapped in seven geologic units: Butano Sandstone, San Lorenzo Formation, Santa Cruz Mudstone, Vaqueros Sandstone, Santa Margarita Sandstone, Monterey Formation, and Purisima Formation. As the combined thickness of the above listed sequence exceeds the local relief, the sequence was considered as a single material unit in order to examine regional topographic development.
17. Strength properties reported by D. K. Keefer [*U.S. Geol. Surv. Open-File Rep. 91-618* (1991)] were determined from drill core samples (<7.3 cm in diameter) of landslide failure planes.
18. D. K. Keefer, *Geol. Soc. Am. Bull.* **95**, 406 (1984); R. C. Wilson and D. K. Keefer, Eds., *U.S. Geol. Surv. Prof. Pap. 1360* (1985).
19. D. M. Boore, L. Seekins, W. B. Joyner, *Seism. Res. Lett.* **60**, 151 (1989); A. F. Shakal, M. J. DeLisle, M. S. Reichle, R. B. Darragh, in *The Loma Prieta (Santa Cruz Mountains), California, Earthquake of 17 October 1989*, S. R. McNutt and R. H. Sydnor, Eds. (Department of Conservation, Division of Mines and Geology, Sacramento, CA, 1990), pp. 29–46; R. H. Sydnor, G. B. Griggs, G. E. Weber, R. J. McCarthy, N. Plant, *ibid.*, pp. 67–82.
20. R. H. Schmidtke and E. Z. Lajtai, *Int. J. Rock Mech. Min. Sci.* **22**, 461 (1985); E. Z. Lajtai and R. H. Schmidtke, *Rock Mech. Rock Eng.* **19**, 11 (1986).
21. Ascertaining that bedrock landsliding indeed limits relief over geologic time is complicated because only a portion of a landscape displays active landsliding at any one time, and older deposits are often poorly preserved or removed by fluvial or glacial transport. Thus, it may prove difficult to test whether rates of material removal by bedrock landsliding are commensurate with regional erosion rates.
22. P. England and P. Molnar, *Geology* **18**, 1173 (1990); P. Molnar and P. England, *Nature* **346**, 29 (1990).
23. Supported by the Washington State Timber/Fish/Wildlife Agreement (grants FY92-010 and FY94-004) and by gifts from the Washington Forest Protection Association and the Weyerhaeuser Company. Special thanks are extended to T. Dunne; to field assistants Y. Merrand, V. Langenheim, and J. Stock; and to two anonymous reviewers.

6 June 1995; accepted 25 August 1995

Megascopic Multicellular Organisms from the 1700-Million-Year-Old Tuanshanzi Formation in the Jixian Area, North China

Zhu Shixing and Chen Huineng

Hundreds of specimens of megascopic carbonaceous fossils shaped like leaves have been found at the ~1700-million-year-old Tuanshanzi Formation of the uppermost Paleoproterozoic Changcheng Group (1600 to 1850 million years old) in the Jixian area, north China. These leaflike fossils mostly resemble the *Longfengshania*; each consists of a blade (with spoonlike, lanceolate, or ribbonlike shapes) with a single stipe, a holdfast, or both. On the basis of their megascopic dimensions, preliminary differentiation of organs or tissues, and possible remains of multicellular structures, they are benthic, multicellular algal fossils similar to the longfengshanids. These fossils indicate that multicellular organisms originated at least 1700 million years ago.

The emergence of multicellular organisms (metaphytes and metazoans) is an important event in the evolutionary history of Precambrian life since the emergence of unicellular eukaryotes. The oldest remains of multicellular organisms are therefore one of the keys to the early evolution of life on Earth. A few megascopic carbonaceous films of *Tyrasotaenia* from the 1700-million-year-old Tuanshanzi Formation of the Changcheng Group in the Jixian area, north China, have been reported (*1*) but have not been widely accepted as multicellular organisms (*2*, *3*).

In addition to a few samples of ribbonlike and sausagelike megafossils resembling the vendotaenids and tawuids, respectively, we have recently found more than 300 specimens of megascopic carbonaceous fossils shaped like leaves from the locality and horizon close to that described in (*1*). These leaflike megafossils have obvious characteristics of multicellular algae. The megascopic carbonaceous remains were found near Tuanshanzi Village and its adjacent area (40°10′N, 117°27′E), about 20 km northeast of Jixian Town (Fig. 1). The best-preserved specimens came from the lower part (first member) of the Tuanshanzi Formation, ~44 to 47 m above its base (Fig. 2). The Tuanshanzi Formation belongs to the Paleoproterozoic Changcheng Group. The group includes the Changzhougou (conglomerate, sandstone), Chuanlinggou (silty and illitic shale), Tuanshanzi (muddy and silty dolomicrite), and Dahongyu (sandstone, volcanic rocks, cherty dolomicrite) formations in ascending order, and has a total thickness of

Tianjin Institute of Geology and Mineral Resources, Chinese Academy of Geological Sciences, 4 Eighth Road, Dazhigu, Tianjin 300170, People's Republic of China.

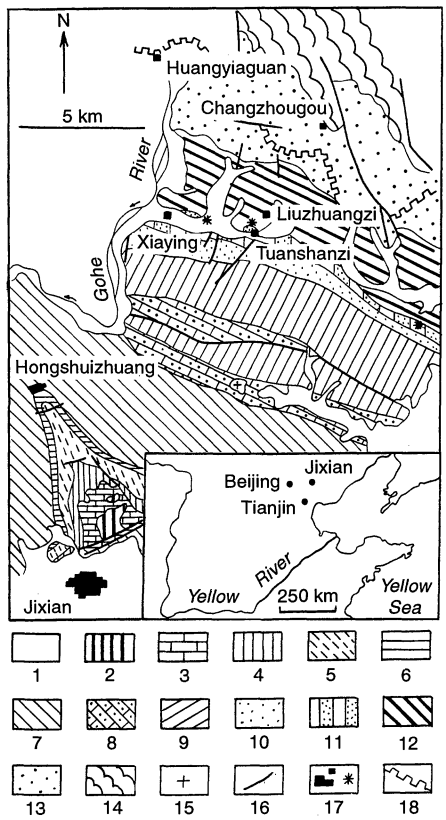

Fig. 1. Location map and geological map of the Jixian area (1, Quaternary; 2, Cambrian; 3, Changlongshan-Jing'eryu Formation; 4, Xiamaling Formation; 5, Tieling Formation; 6, Hongshuizhuang Formation; 7, Wumishan Formation; 8, Yangzhuang Formation; 9, Gaoyuzhuang Formation; 10, Dahongyu Formation; 11, Tuanshanzi Formation; 12, Chuanlinggou Formation; 13, Changzhougou Formation; 14, Archean; 15, Mesozoic granite; 16, fault; 17, town, village, and new fossil occurrences; and 18, Great Wall).

2629 m. These rocks were deposited from ~1850 to 1600 million years ago (Ma) (*4*). The type section of this group is at Tuanshanzi Village and surroundings.

The Tuanshanzi Formation is mainly composed of muddy and silty dolomicrite with a total thickness of 518 m (*5*). The lower member of this formation is rich in muddy, silty, and carbonaceous lithologies, and has pyrite impregnations and black carbonaceous films on the bedding planes. In the upper member, the content of clastics increases markedly upward and dolomitic sandstone, sandy dolostone, thin-bedded sandstone, and small stromatolite bioherms are common. The lower member of the Tuanshanzi Formation is characterized by even bedding with local slumps. In the upper member, flute casts, furrow casts, ripple marks, mud cracks, and salt pseudomorphs are common. The Tuanshanzi Formation represents an upward shallowing sequence; its lower part was mainly formed in a relatively quiet, weakly reducing, subtidal environment (lagoonal facies), whereas its upper part formed in an unstable environment from the intertidal zone to the supratidal zone.

A whole-rock U-Pb isochron age of ~1776 Ma was obtained on a dolostone from the upper part of this formation in the Jixian area (*6*). More recently, a U-Pb isochron age of 1683 ± 67 Ma was obtained on a single zircon from volcanic rocks (lava) of the middle part of this formation in an area closely adjacent to Jixian (*7*). In addition, a U-Pb isochron age of 1625.3 ± 6.2 Ma was obtained on a single zircon from volcanic rocks (lava) of the overlying Dahongyu Formation in the Jixian area (*8*). The age of the lower part of the Tuanshanzi Formation, therefore, is ~1700 Ma.

The leaflike megafossils from the Tuanshanzi Formation all were found in dark gray to black muddy dolostones of the lower part of the formation and are distributed as black carbonaceous films (or, in some cases, brown casting molds), dispersed or in clusters on the bedding planes. They are abundant and most of them are well preserved. The carbonaceous films constituting megafossils are shaped like unbranched leaves or typical thallophytes; each typically consists of a sheetlike blade that has a single ribbonlike stipe, a rhizoidal holdfast consisting of many hairlike haptera, or both. The blades of the leaves have different shapes and sizes, although each kind of blade is roughly uniform. The spoonlike (type 1), lanceolate (type 2), and ribbonlike (type 3) shapes are most common (Fig. 3). The carbonaceous blades have different dimensions; most are 0.5 to 3.5 mm in width and 5 to 10 mm in length, whereas a few of the larger blades are >10 mm wide and some tens of millimeters long (Table 1). In addition, some smaller blades have also been seen in the fossiliferous horizons; the width of these smaller blades is 0.05 to 0.3 mm.

Although the interior and fine detailed structure have not been preserved in most of the carbonaceous leaves, some specimens show fine longitudinal striations on their surfaces as well as palisadelike structures. The palisadelike structures occur at the margins of specimens and may be paraphyses or sporangia (Fig. 4, A through C). In addition, some remains of interior multicellular structure, such as a mucilage canal and the multicellular structure surrounding it (Fig. 4, D and E) and other degraded multicellular structure (Fig. 4F), can be found in a few portions of specimens by scanning electron microscopy.

On the basis of these characteristics, we can draw the following conclusions about the biological affinity of the Tuanshanzi leaflike carbonaceous films. Although the carbonaceous films have different shapes, each of them can be found repeatedly, and collectively they show obvious stability in morphology. In addition, the spectral analysis shows that some large organic molecules (aggregated by aromatic hydrocarbon, ester, CH_2, or CH_3 groups) are present. Therefore, the films constitute fossils of old organisms and are not general carbonaceous fragments. Because these fossils are shaped like leaves and exhibit structural features of leaves, they are compressions of primitive plants and not primitive animals. The fossils not only have megascopic size and show preliminary differentiation of organs (into a blade and a single stipe or a holdfast), but also show some evidence of multicellular structures, including possible

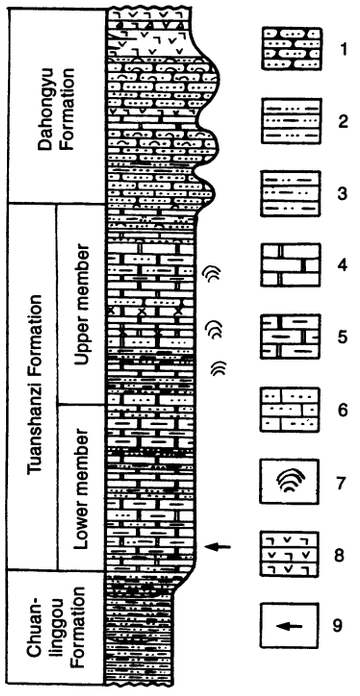

Fig. 2. Generalized lithostratigraphic column of the Tuanshanzi Formation in the Jixian area (1, sandstone; 2, argillaceous siltstone; 3, silty shale; 4, dolostone; 5, muddy dolostone; 6, silty dolostone; 7, stromatolites; 8, volcanic rocks; 9, fossiliferous horizon).

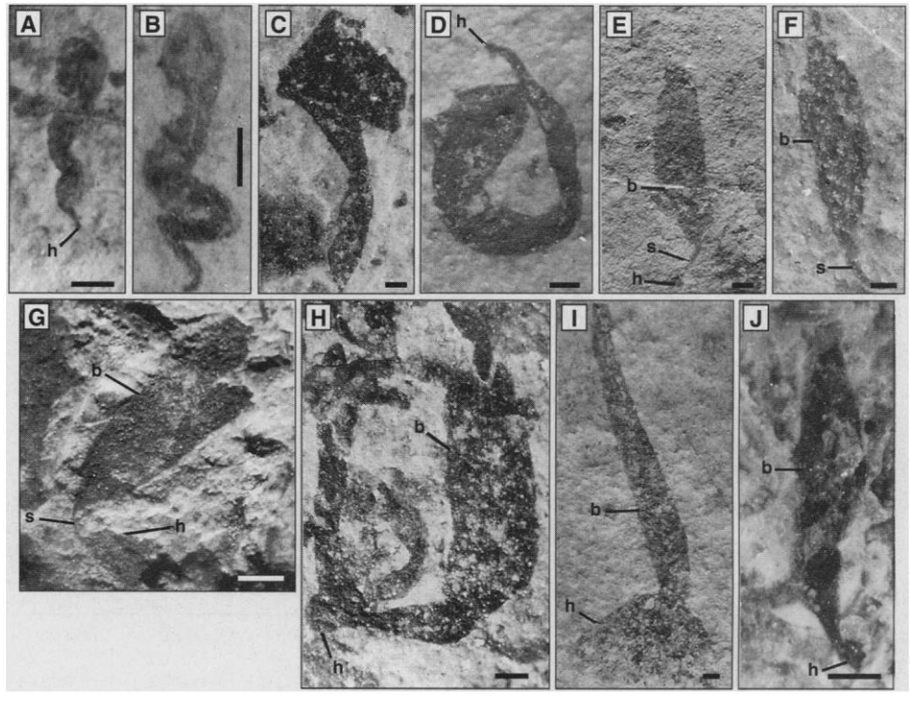

Fig. 3. Leaflike megafossils from the Tuanshanzi Formation of the Paleoproterozoic Changcheng Group (b, blade; s, stipe; and h, holdfast). (**A** through **D**) Spoonlike type (type 1); (**E** through **G**) lanceolate type (type 2); (**H** through **J**) ribbonlike type (type 3). Scale bars, 1 mm.

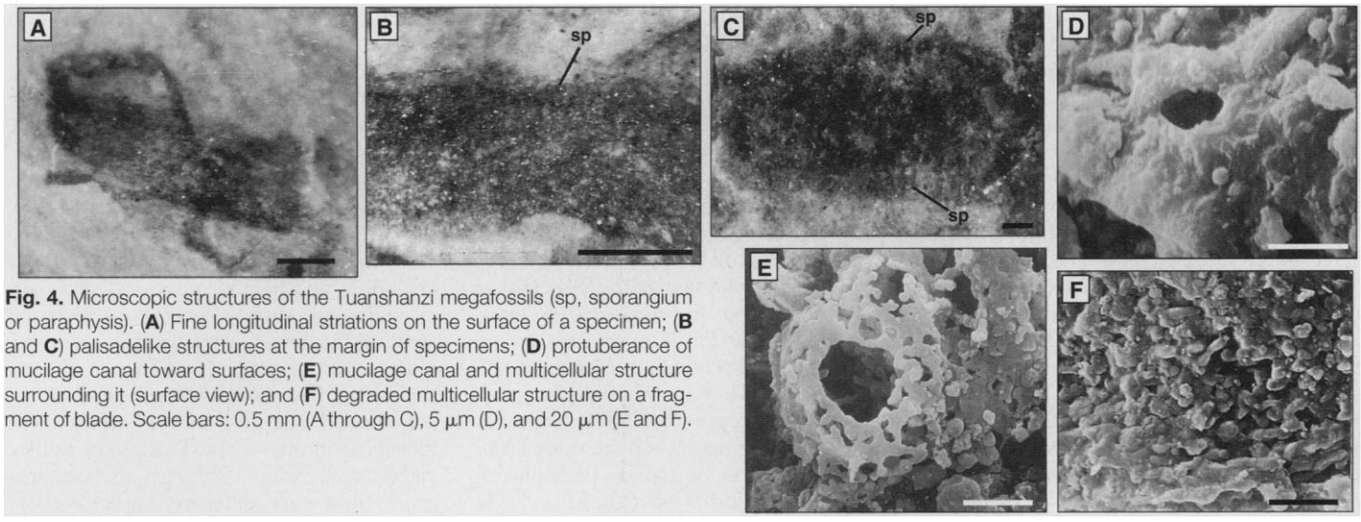

Fig. 4. Microscopic structures of the Tuanshanzi megafossils (sp, sporangium or paraphysis). (**A**) Fine longitudinal striations on the surface of a specimen; (**B** and **C**) palisadelike structures at the margin of specimens; (**D**) protuberance of mucilage canal toward surfaces; (**E**) mucilage canal and multicellular structure surrounding it (surface view); and (**F**) degraded multicellular structure on a fragment of blade. Scale bars: 0.5 mm (A through C), 5 μm (D), and 20 μm (E and F).

sporangia. Thus, these fossils can be excluded from the prokaryotes and their aggregates (*2*) as well as from the protists generally, and they should possess the affinity of benthic, multicellular organisms, that is, metaphytes.

Except for the spoonlike type, the blades of most of the fossil leaves vary between lanceolate and ribbonlike in morphology and resemble a large category of longfengshanid remains represented by *Longfengshania* (*2*, *9*). With respect to modern multicellular lower plants, the fossils are most similar to (but smaller than) the Laminariales, especially the Laminariaceae of brown algae (Phaeophycophyte), whose sporophytes not only have typical multicellular structures (with mucilage canals, hyphae filamentous structure, and a palisadelike structure consisting of unilocular sporangium and paraphyses) but are usually differentiated into a cylindrical stalk or stipe and one or many lanceolate to ribbonlike blades or laminae (*10*). Thus, the most leaflike fossils from the Tuanshanzi Formation are possibly fossils of brown algae closely related to the order Laminariales. The relation of the spoonlike fossils to modern algae is not yet clear. Although they resemble certain green algae such as *Ulvaria* in outline, they more likely are related to the brown algae (Scytosiphonales) on the basis of their palisadelike structure composed of sporangium and multicellular (?) filaments at the margins of the specimen (Fig. 4C).

These fossils are preliminarily defined as benthic, eukaryotic, multicellular metaphytes, possibly dominated by ancient brown algae. The oldest reported megascopic carbonaceous fossil, *Grypania spiralis* (Walter), was a corkscrew-shaped, spaghettilike organism from the 2100-million-year-old Negaunee Iron Formation, Michigan (*11*); however, although a eukaryote interpretation of *Grypania* seems most likely, a prokaryotic origin cannot be excluded (*12*). Most Precambrian carbonaceous megafossils are not confidently interpreted as multicellular algae, except for the longfengshanid films (*2*, *9*) and a number of branched fossils recently reported from the Upper Sinian (Vendian) of China (*13*). Because the longfengshanids and some other carbonaceous multicellular organisms (for example, *Tawuia*) are known from the Neoproterozoic, it has been assumed that the multicellular organisms appeared at ~900 to 1000 Ma (*12*).

The Tuanshanzi fossils we have described imply that megascopic multicellular organisms originated at 1700 Ma or earlier. These new data have implications for the understanding of the evolution and other related aspects of Precambrian life. For example, now that the abundance of megascopic metaphytes in the Tuanshanzi Formation is known, the more primitive multicellular and unicellular eukaryotes and even the metazoans may have begun to appear on Earth much earlier than most researchers have estimated (*14*). In addition, theories of the evolution of the Precambrian atmosphere, hydrosphere, and other sedimentary environments that relate to the evolution of Precambrian life must be reexamined in light of the new data.

Table 1. Characteristics of most leaflike megafossils from the Tuanshanzi Formation.

Type	Blades				Stipes	Holdfasts
	Form	Width (mm)	Length (mm)	Length/ width		
1	Spoonlike or tadpolelike	0.4 to 4	5 to 34	6 to 8	Obscure	Discal?
2	Lanceolate	1.2 to 10	6 to 30	3 to 4.3	Ribbonlike	Rhizoidal
3	Elongated lanceolate to ribbonlike	1.3 to 2.6	6 to 20	9 to 10	Obscure	Rhizoidal

REFERENCES AND NOTES

1. H. J. Hofmann and C. Jinbiao, *Can. J. Earth Sci.* **18**, 443 (1981).
2. H. J. Hofmann, in (*14*), pp. 349–357.
3. Z. Shixing *et al.*, *Biostratigraphic Sequence of the Middle-Upper Proterozoic on North China Platform* (Geological Publishing House, Beijing, 1994).
4. Z. Shixing and C. Huineng, *Precambrian Res.* **57**, 135 (1992).
5. C. Jinbiao, Z. Huimin, Z. Shixing, Z. Zhen, W. Zhengang, in *Research on Precambrian Geology—The Sinian Suberathem in China* (Science and Technology Press, Tianjin, 1980), pp. 56–114.
6. Z. Fudao, *Sci. Sin.* **2**, 151 (1977).
7. L. Huaikun, L. Huiming, L. Songnian, *Geology-Geochemistry* **24**, 43 (1995).
8. L. Songnian and L. Huimin, *Bull. Chin. Acad. Geol. Sci.* **22**, 137 (1991).
9. D. Rulin and T. Lifu, *Acta Geol. Sin.* **3**, 183 (1985).
10. H. C. Bold and M. J. Wynne, *Introduction to the Algae* (Prentice-Hall, Englewood Cliffs, NJ, 1978), pp. 267–343; F. E. Fritsch, *The Structure and Reproduction of the Algae* (Cambridge Univ. Press, Cambridge, 1959), vol. 2, pp. 18–43.
11. T.-M. Han and B. Runnegar, *Science* **257**, 232 (1992).
12. S. Bengtson, M. Fedonkin, J. H. Lipps, in (*14*), pp. 433–435.
13. C. Menge and X. Zongzheng, *Sci. Geol. Sin.* **4**, 317 (1991); ———, *Acta Palaeontol. Sin.* **31**, 513 (1992); ——— and Y. Xunlai, *ibid.* **33**, 392 (1994).
14. J. W. Schopf and C. Klain, Eds., *The Proterozoic Biosphere* (Cambridge Univ. Press, Cambridge, 1992).

15. We thank Y. Yan for assistance during the primary stage of this project; Y. Xing, C. Duan, and F. Cao for discussing the reliability of the fossils; and H. J. Hofmann for review and comments on the English version of the manuscript. Supported by the Tianjin Institute of Geology and Mineral Resources, Chinese Academy of Geological Sciences.

31 March 1995; accepted 25 August 1995