Confirmation of a Middle Jurassic age for the Eedemt Formation in Dundgobi Province, southeast Mongolia: constraints from the discovery of new spinicaudatans (clam shrimps)

GANG LI, HISAO ANDO, HITOSHI HASEGAWA, MASANOBU YAMAMOTO, TAKASHI HASEGAWA, TOHRU OHTA, NORIKO HASEBE and NIIDEN ICHINNOROV

Li, G., Ando, H., Hasegawa, H., Yamamoto, M., Hasegawa, T., Ohta, T., Hasebe, N. & Ichinnorov, N., 2014. Confirmation of a Middle Jurassic age for the Eedemt Formation in Dundgobi Province, southeast Mongolia: constraints from the discovery of new spinicaudatans (clam shrimps). *Alcheringa 38*. ISSN 0311-5518.

Two spinicaudatan species, *Triglypta eedemtensis* Li sp. nov. and *Dundgobiestheria mandalgobiensis* Li gen. et sp. nov., are described on the basis of scanning electron microscopy (SEM) imaging of newly collected specimens from paper-thin laminated black shale of the Eedemt Formation exposed at the Eedemt locality in the Khootiin Khotgor coal mine region of Dundgobi Province in southeast Mongolia. *Triglypta eedemtensis* is ornamented mainly with puncta and a punctate fine reticulum; radial lirae occur only on two or three growth bands near the venter. The small spinicaudatan *Triglypta* is a common component of the Middle Jurassic *Euestheria ziliujingensis* fauna and *Sinokontikia* fauna, and is a typical taxon in the Middle Jurassic lacustrine sequences of northern Hebei and the Junggar and Turpan basins of the Xinjiang Autonomous District of China; however, it does not occur in stratigraphically higher units elsewhere. Therefore, the age of the Eedemt Formation should be considered Middle Jurassic rather than Early Cretaceous. The Eedemt Formation is much older than the Early Cretaceous Shinekhudag Formation in the Shine Khudag area of southeast Mongolia.

Gang Li [gangli@nigpas.ac.cn], State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, East Beijing Road 39, Nanjing 210008, PR China; Hisao Ando [ando@mx.ibaraki.ac.jp], Department of Earth Sciences, Faculty of Science, Ibaraki University, Bunkyo 2-1-1, Mito 310-8512, Japan; Hitoshi Hasegawa [hase@num.nagoya-u.ac.jp], Nagoya University Museum, Nagoya University, Nagoya 464-8601, Japan; Masanobu Yamamoto [myama@ees.hokudai.ac.jp], Faculty of Environmental Earth Science, Hokkaido University, Sapporo 060-0810, Japan; Takashi Hasegawa [jh7ujr@staff.kanazawa-u.ac.jp], Faculty of Natural System, Institute of Science and Engineering, Kanazawa University, Kanazawa 920-1192, Japan; Tohru Ohta [tohta@waseda.jp], Department of Earth Sciences, School of Education, Waseda University, Tokyo 169-8050, Japan; Noriko Hasebe [hasebe@staff.kanazawa-u.ac.jp], Institute of Nature and Environmental Technology, Kanazawa University, Kanazawa 920-1192, Japan; Niiden Ichinnorov [iichka@yahoo.com], Paleontological Center, Mongolian Academy of Sciences, Enkhtaivan Avenue-63, Ulaanbaatar-210351, P.O.B. 260, Mongolia. *Received 31.8.2013; revised 14.11.2013; accepted 19.11.2013.*

Key words: Jurassic spinicaudatans, conchostracans, clam shrimps, taxonomy, biostratigraphy, lacustrine deposits, Dundgobi Province, Mongolia.

SPINICAUDATANS (clam shrimps, 'conchostracans') are small, bivalved branchiopod crustaceans with a chitinous carapace and have a long geological history extending back to the Devonian. Although there are only 16 extant genera in three families (Zhang *et al*. 1976, Brtek 1997), they were much more prosperous during the Mesozoic. They are commonly abundant and widely distributed in freshwater lacustrine deposits of that age. Consequently, they are useful for biostratigraphic subdivision and correlation of Mesozoic non-marine successions (Rohn *et al*. 2005, Stigall & Hartman 2008, Gallego 2010). Their life cycles are short, for example, in the recent species *Eulimnadia stoningtoensis* Berry, 1926, death occurs about 23 days after an individual hatches from the egg (Chen & Shen 1985). Extant species normally inhabit quiet alkaline, freshwater pools, but they are also found in temporary water bodies in which physical and chemical conditions are favourable. Usually, only one species inhabits a particular pool; in rare cases one or two other species may also be present (Chen *et al*. 2007, Li *et al*. 2009). These ecological characteristics have some potential to provide palaeoenvironmental information of the fossil-bearing deposits.

Taxonomical and biostratigraphical investigations on the late Mesozoic clam shrimps of Mongolia have a relatively short history. The pioneering systematic research on Mongolian fossil clam shrimp faunas was carried out on Jurassic to Cretaceous coal and oil-shale deposits by Novojilov (1954). Recently, Yuan & Chen (2005) examined ostracod and spinicaudatan assemblages of the Shinekhudag Formation in the Shine Khudag area (one classical locality for the Lower Cretaceous oil-shale deposits), and came to the conclusion that the Shinekhudag Formation could be correlated

http://dx.doi.org/10.1080/03115518.2014.870834

with the well-known Early Cretaceous Jehol-Biota-bearing Jiufotang Formation of western Liaoning Province, northeastern China (Chen & Jin 1999, Chang *et al*. 2003, Zhou *et al*. 2003, Li *et al*. 2007).

Extensive exploration for fossil fuel resources and research on terrestrial palaeoenvironments (of intra-continental regions of eastern Eurasia) have been undertaken on the oil-shale-bearing deposits in Mongolia over the last two decades (Johnson *et al*. 2003, Johnson & Graham 2004, Ichinnorov *et al*. 2008). The Eedemt Formation (Ando *et al*. 2011) at the Eedemt locality, Dundgobi Province (Fig. 1), contains organic-rich oil-shale deposits, and has been traditionally correlated with the Lower Cretaceous Shinekhudag or Dorogot Formation based on lithological similarities (Khosbayar 1977, Bat-Erdene & Enkhtugs 1987, Bat-Erdene 1992). It is necessary to obtain precise age constraints on the Eedemt Formation via detailed biostratigraphical analysis and correlation before the fossil biota can be used in the reconstruction of the regional palaeoclimate and the conditions contributing to oil-shale accumulation (Yamamoto *et al*. 1993, 1998). We carried out a systematic and biostratigraphic study of newly discovered and well-preserved spinicaudatans from the Eedemt Formation at the Eedemt locality, southeast Mongolia, to resolve the age of this unit.

Geological and stratigraphical setting of the Eedemt locality

The Eedemt locality (Khosbayar 1977) is located in the Khootiin Khotgor Valley of Dundgobi Province (Fig. 1). Here, the two studied sections of the Eedemt Formation are about 80 m (ED-A) and 20 m (ED-B) thick (Fig. 2), respectively, and are composed mainly of paper-shale, oil-shale, silty mudstone and siltstone, which host abundant fossil remains (e.g., molluscs, ostracods, spinicaudatans, insects and plants). The oil-shale-bearing Eedemt Formation overlies the coal-bearing deposits of the Lower–Middle Jurassic Khootiin Khotgor Formation (Ichinnorov *et al*. 2008). The Khootiin Khotgor coal mine is located about 2 km west of the Eedemt section, in the central part of the Khootiin Khotgor Valley.

Biostratigraphical and palaeontological studies have been conducted to determine the age of the Eedemt Formation at the Eedemt locality since the last quarter of the twentieth century. Based on lithological similarities, Khosbayar (1977) initially correlated the Eedemt Formation with the Lower Cretaceous Dorogot Formation of northeastern Mongolia, the age of which was confirmed by evidence from fossil mollusc, ostracod and clam shrimp faunas (Khosbayar 1977). The Dorogot Formation is considered to be coeval with the Lower Cretaceous Shinekhudag Formation in southeastern Mongolia (Khand *et al*. 2000). Sodov (1980) reported some plant fossils from the Eedemt locality, and described two new species of *Heilungia* and *Pityospermum*. He determined an Early Cretaceous age for the Eedemt Formation, although similar floral assemblages dominated by *Heilungia mongoliensis* were already described by Vakhrameev & Lebedev (1972) from the Middle Jurassic sediments in the Tsagan-Shibetu locality in northwestern Mongolia. Sodov (1985) further reported *Cladophlebis sokolovii* and *Raphaelia diamensis* from the Eedemt Formation. Based on the common

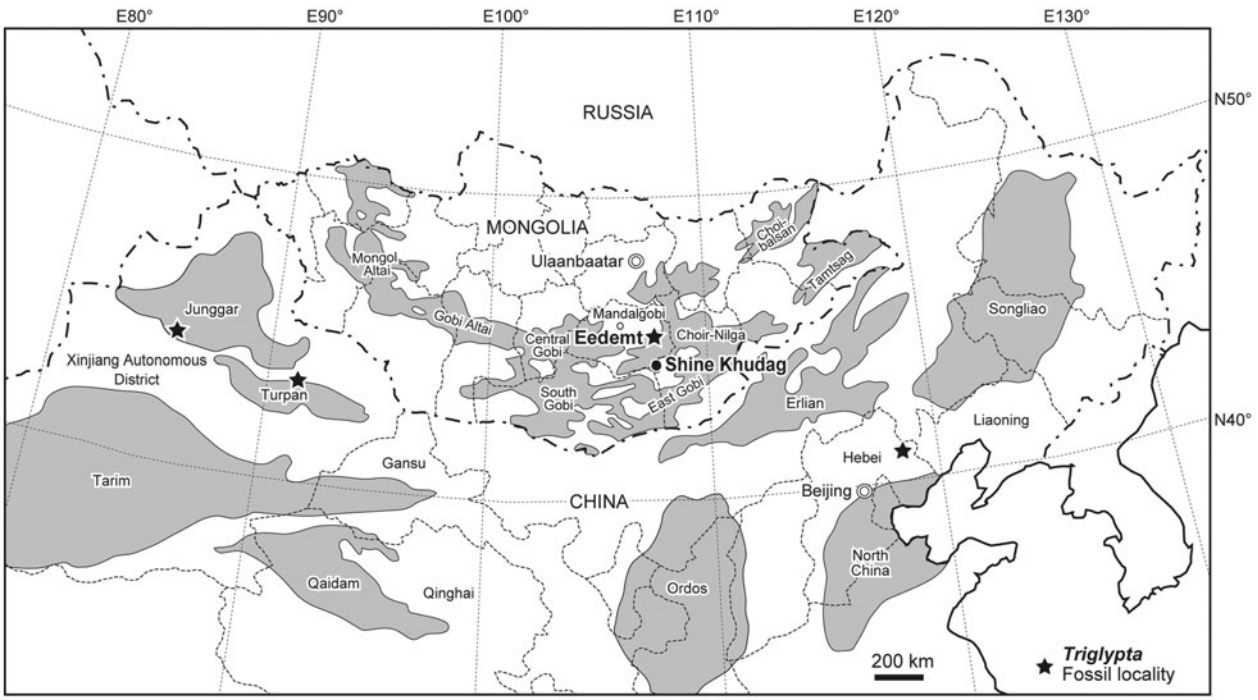

Fig. 1. Schematic map showing the Jurassic–Cretaceous basins in Mongolia and China, and the fossil localities hosting *Triglypta* in China and Mongolia.

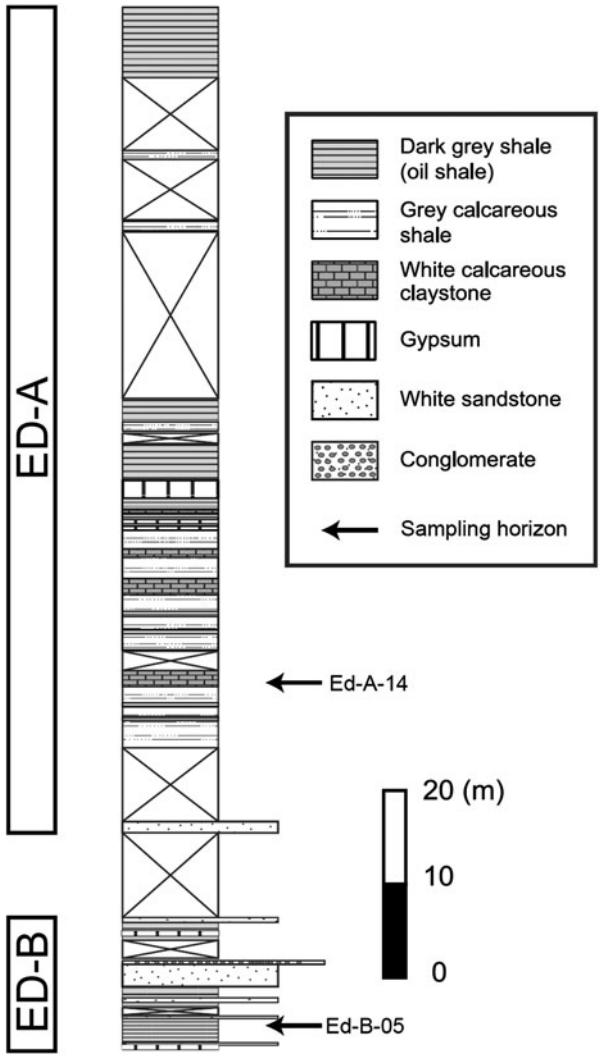

Fig. 2. Lithological logs of the Eedemt Formation in the Eedemt sections A and B, showing the levels yielding fossil spinicaudatans.

occurrence of *Heilungia* in the Upper Jurassic to Lower Cretaceous sequences in Russia, Sodov (1990) concluded that the oil-shale-bearing Eedemt Formation may include Upper Jurassic deposits.

Based on floral evidence, Khosbayar & Popov (1986) subdivided the coal-bearing deposits and overlying oil-shale-bearing deposits in the Khootiin Khotgor Valley into four formations, viz., in ascending order: the Lower and Middle Jurassic Kholboo Khongor Formation (lower part of the coal-bearing deposits), the Upper Jurassic Ulaan Ereg Formation (upper part of the coal-bearing deposits) and the Lower Cretaceous Dorogot and Kerulen formations (lower and upper parts of the oil-shale deposits, respectively). Oil-shale deposits around Eedemt were assigned to the Lower Cretaceous Dorogot Formation, which was interpreted to be coeval with the Shinekhudag Formation (Khosbayar 1977, Bat-Erdene & Enkhtugs 1987, Bat-Erdene 1992). Although Khosbayar & Popov (1986) mentioned some clam shrimp species, such as *Pseudoestheria* sp. and *Bairdestheria* sp., they did not provide detailed descriptions.

Recently, Ichinnorov *et al*. (2008) conducted a palynostratigraphic study of the coal-bearing deposits of the Khootiin Khotgor Formation in the Khootiin Khotgor coal mine, and inferred an Early–Middle Jurassic age for the studied sequence, which is consistent with the macrofloral evidence. During a field survey in August 2009, we had an opportunity to investigate bore cores taken from the vicinities of the Eedemt locality and the Khootiin Khotgor coal mine. Our study of the core revealed a gradual lithological transition from the coal-bearing deposits of the Khootiin Khotgor Formation to the overlying oil-shale deposits of the Eedemt Formation without evidence of an obvious unconformity. Therefore, there should be no significant time gap between the oil-shale deposits of the Eedemt Formation and the underlying coal-bearing Khootiin Khotgor Formation.

Material and method

The spinicaudatan specimens were collected from the Eedemt Formation during the field survey at the Eedemt locality in the Khootiin Khotgor Valley of Dundgobi Province, southeast Mongolia, in August 2009. The strata are nearly horizontal and are composed of paper-shale, oil-shale and silty mudstone, with abundant ostracods and spinicaudatans. Two sections were investigated, viz., the Eedemt A (ED-A: 45°41′10″N, 107°43′20″E) and Eedemt B (ED-B: 45°40′27″N, 107°43′00″E) sections (Fig. 2). The ED-A section is stratigraphically higher than the ED-B section.

In most previous studies, light microscopy has been used to investigate the taxonomy of fossil clam shrimps. This means that some microstructures of potential taxonomical value were difficult to discern. We use SEM for detailed observation of the carapace surface microstructure and light microscopy for elucidating general morphology. We also used the invert function of the graphic software to reverse the digital photo images taken from the external moulds of the specimens to generate images simulating the positive morphology of the carapace's outer surface.

Systematic palaeontology

We follow the recent classification of spinicaudatans by Martin & Davis (2001). Use of Conchostraca Sars, 1867 as a taxonomic unit has been abandoned because *Cyclestheria* Sars, 1887, having a unique direct development of the brood, has been removed from the suborder Spinicaudata Linder, 1945 and placed in the suborder Cyclestherida Sars, 1899, which is of equal taxonomic rank as the remaining Spinicaudata and Cladocera Latreille, 1829.

The figured specimens are deposited in the collections of the Ibaraki University, Mito, Japan.

Order DIPLOSTRACA Gerstaecker, 1866
Suborder SPINICAUDATA Linder, 1945
Superfamily EOSESTHERIOIDEA Zhang & Chen in Zhang *et al*., 1976
Family POLYGRAPTIDAE Novojilov, 1954 (Wang & Liu 1980)

Discussion. The subfamily Polygraptinae Novojilov, 1954 was raised to family status by Wang & Liu (1980), assigned to the superfamily Lioestherioidea Raymond, 1946, and includes taxa with small-diameter reticulation on the upper part of the carapace and radial lirae on the ventral part (Shen *et al*. 1982). Since Holub & Kozur (1981) revised the superfamily Lioestheroidea Raymond, 1946 to include taxa with nodules and/or spikes on a large umbo, *Polygrapta* Novojilov, 1946 was moved to Euestheriidae Defretin-Lefranc, 1965 of the superfamily Eosestherioidea Zhang & Chen in Zhang *et al*., 1976 (Chen & Shen 1985). Considering the difference between the punctate reticulation of *Polygrapta* and the reticulation style in *Euestheria* Depéret & Mazeran, 1912, Polygraptidae is retained here and assigned to Eosestherioidea.

Triglypta Wang, 1984

Type species. *Triglypta pingquanensis* Wang, 1984; Middle Jurassic Jiulongshan Formation, Pingquan, Hebei Province, northern China.

Emended diagnosis. Carapace small–medium; umbo small; growth bands on the dorsal part of the carapace ornamented with evenly distributed puncta; growth bands in the middle part of the carapace ornamented with small, punctate reticulations (lumina about 0.02–0.03 mm in diameter); growth bands in the ventral part of the carapace ornamented with radial lirae, intercalated with puncta (after Wang 1984).

Distribution. Jiulongshan Formation, Northern Hebei Province, Toutunhe and Qiketai formations, Xinjiang Autonomous District of China, and Eedemt Formation, Eedemt area, Dundgobi Province, southeast Mongolia; Middle Jurassic.

Triglypta eedemtensis Li sp. nov. (Figs 3, 4)

Diagnosis. Carapace ovate in outline; fine radial lirae occurring only on 2–3 growth bands near the ventral margin.

Figured specimens. ED-B-05-1, holotype, external mould of a left valve; ED-B-05-2, external mould of a right valve; ED-B-05-3, ED-B-05-4, ED-B-05-5 and ED-B-05-6: four sets of displaced valves.

Etymology. Eedemt is the name of the fossil locality.

Dimensions. Figured specimens (ED-B-5-1, holotype, ED-B-5-2, ED-B-5-3, ED-B-5-4, ED-B-5-5 and ED-B-5-6) are measured as follows, respectively: number of growth lines, >11, 16, 20, 15, >13 and >16; length (mm), 4.6, 5.3, 4.4, 3.1, 4.8 and 4.2; height (mm), 2.9, 3.8, 2.9, 2.0, 3.1 and 2.9.

Description. Carapace small–medium, 2.8–5.3 mm long, 1.9–3.8 mm high, with an ovate outline; anterior margin widely rounded, posterior margin narrowly rounded; umbo narrow and small, located on the anterior part of the dorsal margin; growth lines 11–20 in number; growth bands wide in the upper and middle parts of the carapace, becoming narrower near the ventral margin; growth bands in the dorsal part of the carapace ornamented with evenly distributed puncta (about 2–3 μm in diameter), expressed as small tubercles on the external mould (Fig. 3B, 4H); growth bands between flat growth lines in the ventral part of the carapace ornamented with small punctate reticulations (lumina 0.02–0.03 mm in diameter, with about 4–10 puncta within one mesh; Fig. 3D, F), expressed as grouped tubercles on the external mould (Fig. 3C, E, G); narrow growth bands near the ventral margin ornamented with radial lirae, between which puncta are radially aligned (Fig. 4C, D).

Comparison. The new species is similar to *Triglypta pingquanensis* Wang, 1984 (from the Middle Jurassic Jiulongshan Formation of Northern Hebei Province) and *T. tianshanensis* Wang, 1985 (from the Middle Jurassic Toutunhe Formation of the Xinjiang Autonomous District) in carapace outline. However, the new species differs from *T. pingquanensis* in having more growth bands in the dorsal part of the carapace ornamented with evenly distributed puncta, and having radial lirae only on two or three narrow growth bands near the ventral margin. In *T. pingquanensis*, the evenly distributed puncta are limited to a few growth bands near the umbo, and radial lirae are well developed in the ventral part of the carapace. The new species differs from *T. tianshanensis* in that the latter has few growth bands ornamented with punctate reticulations and radial lirae. Considering the representation of the three kinds of ornamentation occupying the shell surface areas, *T. tianshanensis* may be more primitive because most of its carapace growth bands are ornamented with evenly distributed puncta; whereas *T. pingquanensis* may be more derived because its radial lirae are well developed in the ventral part of the carapace. The new species may be a transitional taxon because the puntate reticulation is well developed in the middle part of the carapace. This transitional character favours a Middle Jurassic age for the new species.

Occurrence. Middle Jurassic Eedemt Formation at Eedemt, the Khootiin Khotgor Valley area, Dundgobi

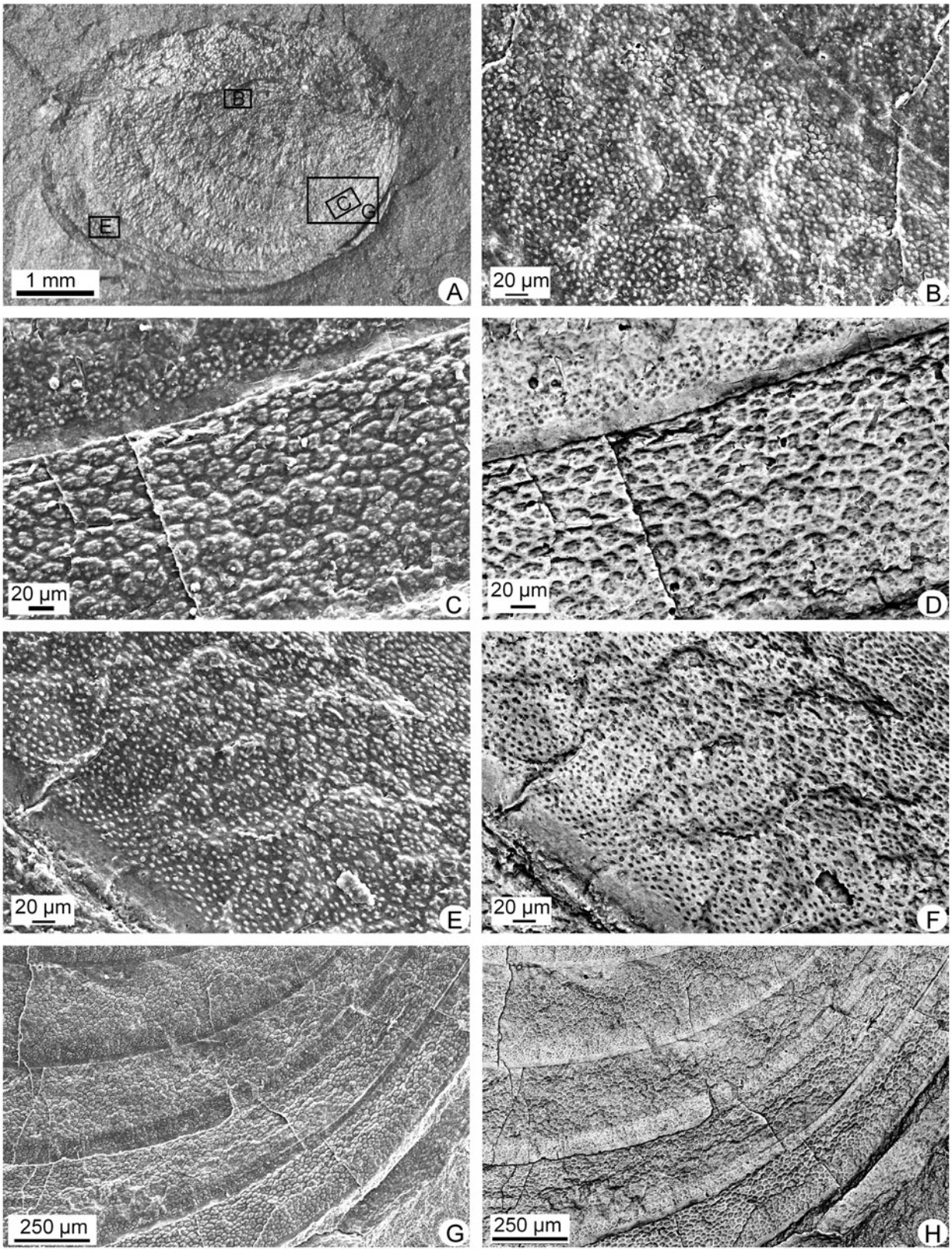

Fig. 3. *Triglypta eedemtensis* Li sp. nov. **A**, External mould of a left valve, holotype, ED-B-05–1, light microscopy image. **B**, Evenly distributed minute tubercles on the external mould of growth bands near the umbo, SEM image. **C**, Regularly grouped minute tubercles on the external mould of growth bands in the anterior ventral part of the carapace, SEM image. **D**, An inverted contrast image of Fig. 3C, showing the punctate reticulations on growth bands in the anterior ventral part of the carapace. **E**, Circularly grouped delicate tubercles on the upper part of the growth band, and the radially aligned minute tubercles on the lower part of the growth band in the posterior ventral part of the external mould, SEM image. **F**, An inverted contrast image of Fig. 3E, showing the punctate reticulations on the upper part of the growth band, and radially aligned puncta on the lower part of the growth band of the carapace. **G**, Clustered minute tubercles on growth bands in the anterior ventral part of the external mould, SEM image. **H**, An inverted contrast image of Fig. 3G, showing punctate reticulations on growth bands in the anterior ventral part of the carapace.

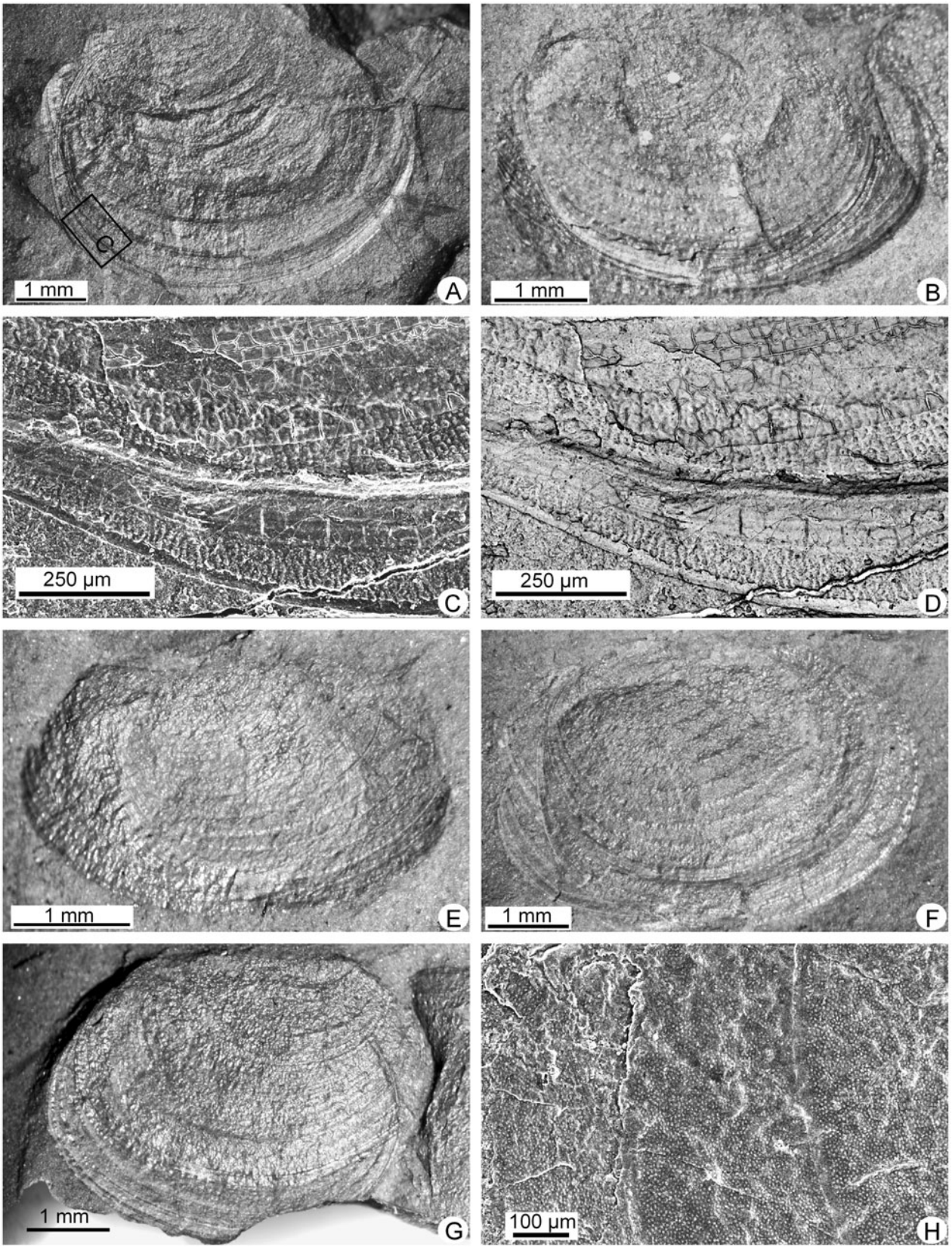

Fig. 4. Triglypta eedemtensis Li sp. nov. **A**, External mould of a right valve, ED-B-05–2, light microscopy image. **B**, Displaced carapaces, ED-B-05–3, light microscopy image. **C**, External mould of ornamentation on growth bands in the anterior ventral part of the carapace of the specimen in Fig. 4A, showing the radially aligned grouped delicate tubercles, SEM image. **D**, Inverted contrast image of Fig. 4C, showing fine and crowded radial lirae intercalated with radially aligned puncta. **E**, Displaced carapaces, ED-B-05–4, light microscopy image. **F**, Displaced carapaces, ED-B-05–5, light microscope image. **G**, Displaced carapaces, ED-B-05–6, light microscopy image. **H**, External mould of ornamentation on growth bands in the posterior dorsal part of the carapace of the specimen in Fig. 3A, showing evenly distributed small tubercles, SEM image.

Province, Southeast Mongolia.

Family LOXOMEGAGLYPTIDAE Novojilov, 1958

Dundgobiestheria Li gen. nov.

Type species. *Dundgobiestheria mandalgobiensis* Li gen. et sp. nov.; Eedemt Formation at Eedemt, the Khootiin Khotgor Valley area, Dundgobi Province, southeast Mongolia.

Diagnosis. Carapace of medium size; growth bands in the dorsal part of carapace ornamented with thick-walled, large-diameter reticulations (lumina 30–100 μm in diameter), consisting of irregular small tubercles on the original shell; growth bands in the ventral part of the carapace ornamented with radially aligned small tubercles and relict reticulation on the original shell; growth lines narrow, ornamented with rounded or radially elongated minute tubercles.

Discussion. Growth band ornamentation of mixed large-diameter reticulations in the dorsal part and fine-walled and crowded radial lirae in the ventral part of the carapace occur in several fossil spinicaudatan taxa of the Nestoriidae Shen & Chen, 1984, such as *Pseudograpta* Novojilov, 1954, *Nestoria* Krasinetz, 1963 and *Monilestheria* Shen & Chen, 1984. All three taxa have wide and prominent growth lines, but only *Monilestheria* has nodules on the growth lines. The new genus can be readily differentiated by its minute nodules on narrow growth lines that are not as prominent as in *Monilestheria*. The new genus is also similar to *Paleoleptestheria* Novojilov, 1954 (Family Loxomegaglyptidae Novojilov, 1958) because both have large diameter reticulation, but *Dundgobiestheria* differs from the latter by having radially aligned minute tubercles and faint relict reticulation on narrow growth bands near the ventral margin of the carapace. Furthermore, the new genus also has small tubercles in the large-diameter reticulations on growth bands in the dorsal part of the carapace. Considering the large-sized reticulate ornamentation and the weakly defined growth lines, the new genus is similar to *Paleoleptestheria*, which is a key taxon in the Middle Jurassic *Sinokontikia* fauna of northern China.

Dundgobiestheria mandalgobiensis Li sp. nov. (Figs 5, 6)

Diagnosis. Carapace of medium size, elliptical or quadrate in outline.

Figured specimens. ED-A-14-1, holotype, a right valve; ED-A-14-2, external mould of a left valve; ED-A-14-3, external mould of a left valve; ED-A-14-4, displaced carapaces.

Etymology. Dundgobi is a province of southeast Mongolia, and Mandalgobi is the capital of Dundgobi Province where the studied fossils were collected.

Dimensions. Figured specimens (ED-A-14-1, ED-A-14-2, ED-A-14-3 and ED-A-14-4) are measured as follows, respectively: number of growth lines, 26, 26, >23 and >20; length (mm), 7.2, 7.3, 8.6 and 6.8; height (mm), 4.9, 5.0, 5.3 and 5.0.

Description. Carapace medium in size, elliptical or quadrate in outline; umbo narrow and small, located in the anterior part of the dorsal margin; growth lines narrow, ornamented with rounded (Fig. 5G) or radially elongate minute tubercles (Fig. 6H); wide growth bands on the dorsal part of the carapace ornamented with large-sized reticulations, within which irregular small tubercles also occur, mesh diameter about 30–50 μm on the growth bands near the umbo (Fig. 5B), but the meshes become larger on growth bands ventrally (Fig. 5D), lumina diameter about 50–100 μm (Fig. 6D), and meshes become radially elongated on growth bands in the anterior ventral part of the carapace (Fig. 5F), mesh wall thick and strong; growth bands near the ventral margin ornamented with radially aligned minute tubercles (Fig. 5E, G, H), with large-sized (diameter) relict reticulations.

Occurrence. Middle Jurassic Eedemt Formation at Eedemt, the Khootiin Khotgor Valley area, Dundgobi Province, southeast Mongolia.

Biostratigraphy and correlation

In northern China, the non-marine Middle and Upper Jurassic sequences yield rich fossil assemblages assigned to the Yanliao Biota (Zhou & Wang 2010). These assemblages include excellently preserved insects, clam shrimps, salamanders, pterosaurs, feathered dinosaurs, mammals and plants (Shen *et al*. 2003, Ji *et al*. 2006, Hu *et al*. 2009, Ren *et al*. 2009, Luo *et al*. 2011, Yuan *et al*. 2013), and have been studied in great detail from the following three regions: western Liaoning and northern Hebei provinces (Chen 2003) and northern Xinjiang Autonomous District (Fig. 7). The Middle Jurassic sequences have been subdivided into two formations in both western Liaoning and northern Hebei provinces. The upper unit is a volcanic succession (e.g., the Lanqi Formation in western Liaoning and the Tiaojishan Formation in northern Hebei; 288–2900 m thick), consisting of greyish purple andesite, andesitic agglomerate, greyish black basalt, tuffaceous sandstone and mudstone. Radiometric dates from this unit range from 165 Ma to 153 Ma (Zhang *et al*. 2008). The lower unit is a lacustrine sequence (e.g., the Haifanggou Formation in western Liaoning and the Jiulongshan Formation in northern Hebei). The

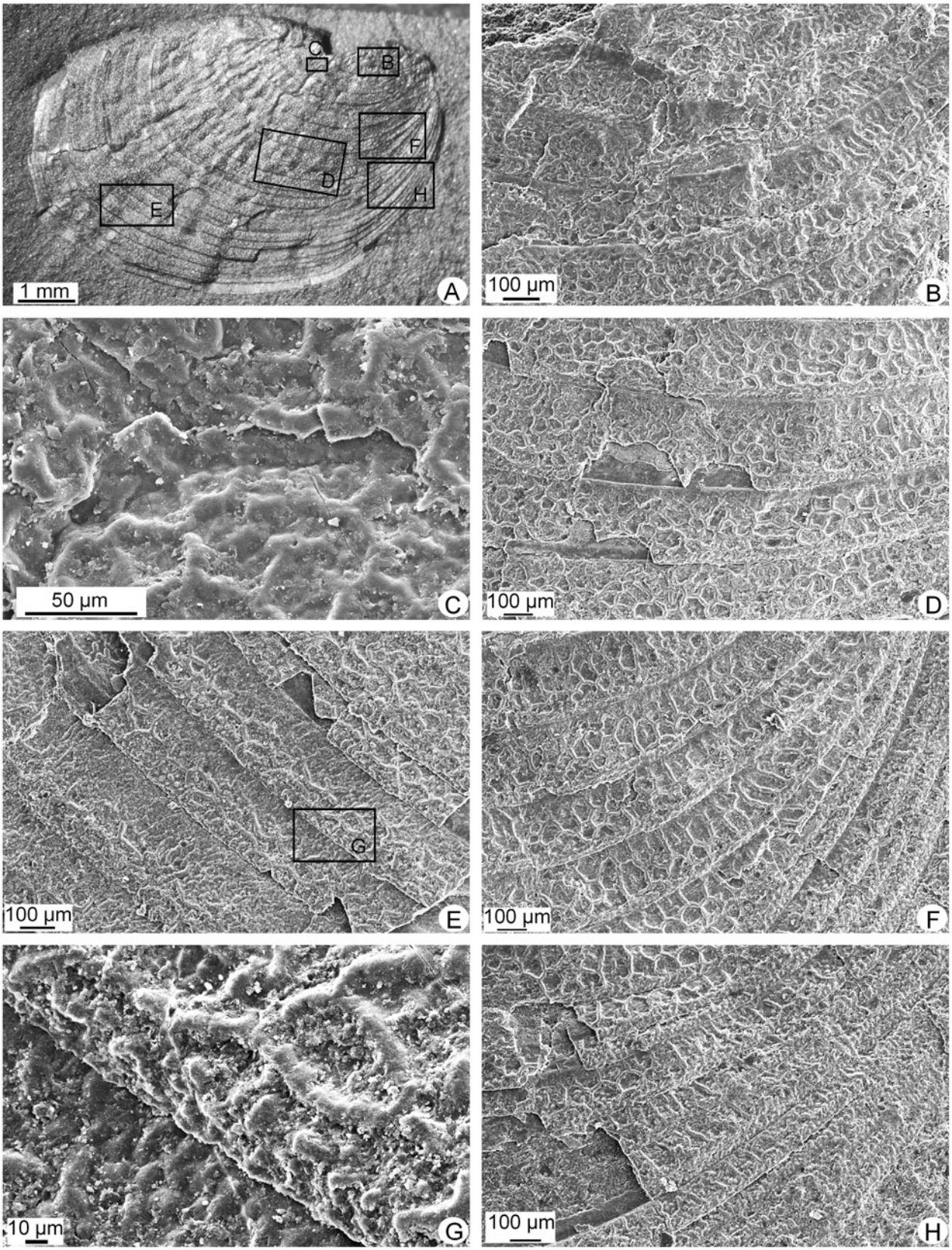

Fig. 5. *Dundgobiestheria mandalgobiensis* Li gen. & sp. nov. All are SEM images, except where indicated. **A**, Right valve, ED-A-14–1, light microscopy image. **B**, Reticulations on growth bands in the anterior dorsal part of the carapace. **C**, Faint irregular tubercles in reticulations on growth bands in the dorsal part of the carapace. **D**, Reticulations on growth bands in the middle part of the carapace. **E**, Radially aligned small tubercles in relict large-sized reticulation on growth bands in the posterior ventral part of the carapace. **F**, Reticulations in the anterior part of the carapace. **G**, Tubercles on a growth line in the posterior ventral part of the carapace. **H**, Large-sized reticulation on growth bands and small tubercles on growth lines in the anterior ventral part of the carapace.

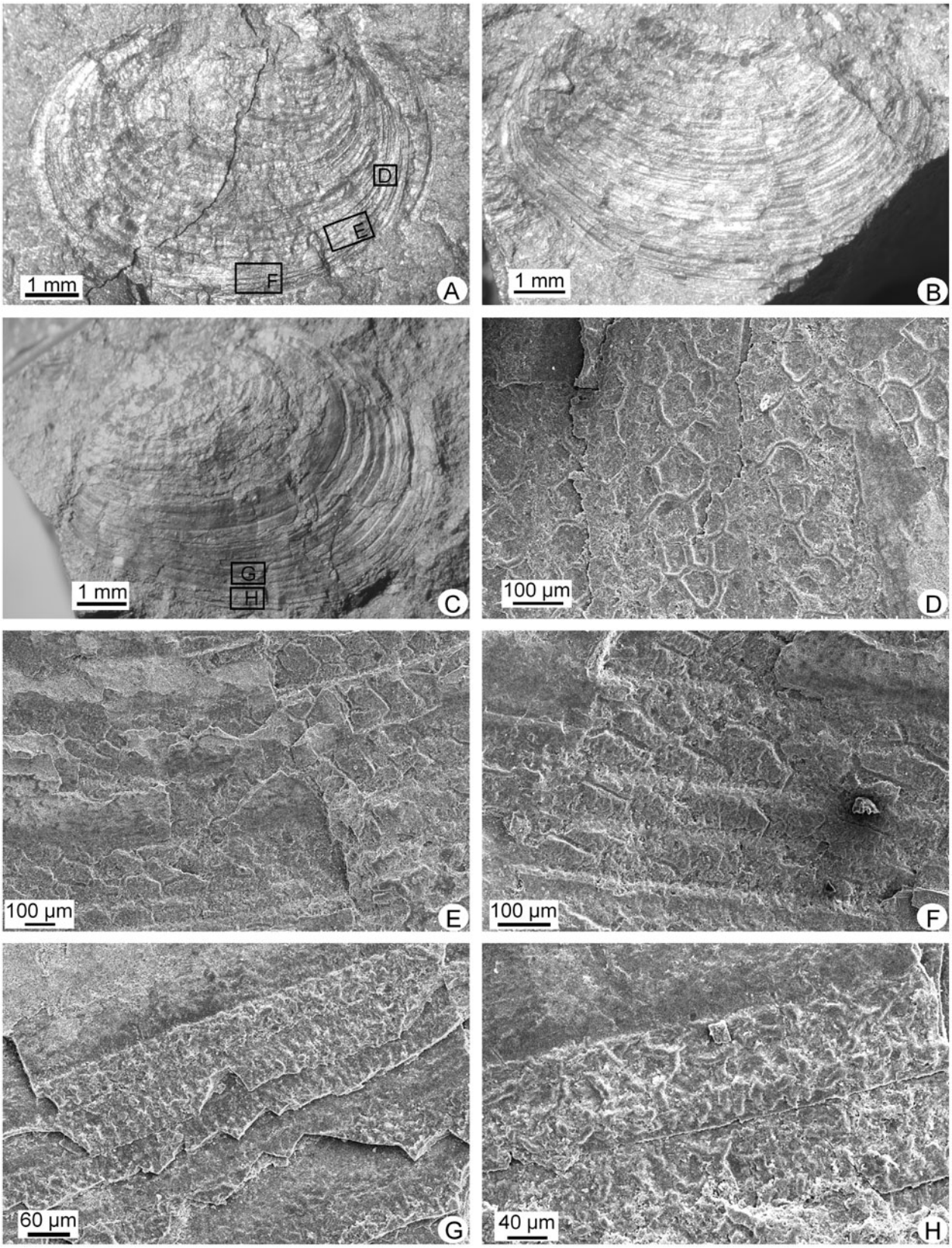

Fig. 6. Dundgobiestheria mandalgobiensis Li gen. et sp. nov. All are SEM images, except for Fig. 6A–C, which are light microscopy images. **A**, External mould of a left valve, ED-A-14–2. **B**, External mould of a left valve, ED-A-14–3. **C**, Displaced carapaces, ED-A-14–4. **D**, Large-sized reticulations on a growth band in the anterior part of the carapace of the specimen in Fig. 6A. **E,** External mould of large-sized reticulations on growth bands in the anterior ventral part of the carapace of the specimen in Fig. 6A. **F**, External mould of large-sized reticulations on growth bands in the ventral part of the carapace of the specimen in Fig. 6A, showing faint radial lirae on large tubercles. **G**, Radially aligned small tubercles on growth bands in the ventral part of the carapace of the specimen in Fig. 6C. **H**, Showing radially elongated tubercles on growth lines of the specimen in Fig. 6C.

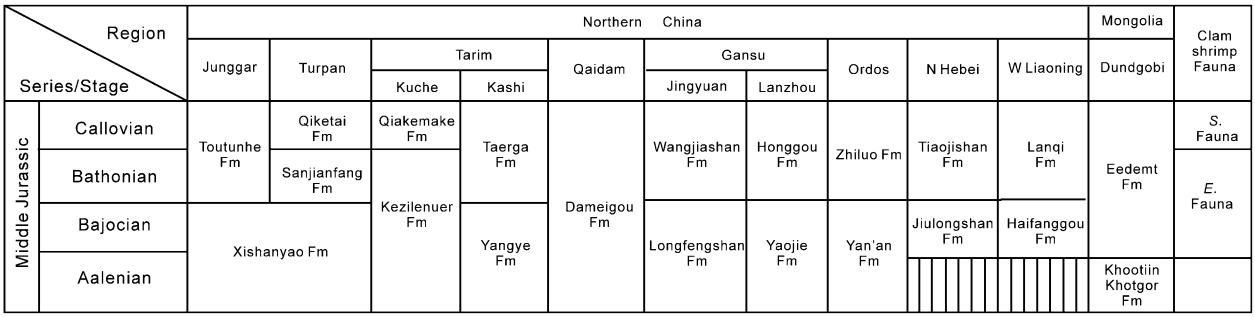

Fig. 7. Stratigraphic correlation chart of the Middle Jurassic sequences of northern China and the Eedemt locality of Mongolia. *E*. Fauna: *Euestheria ziliujingensis* Fauna; *S*. Fauna: *Sinokontikia* Fauna (after Li & Matsuoka 2012).

Haifanggou Formation (269 m thick), unconformably overlying the Lower Jurassic coal-bearing Beipiao Formation, consists of yellowish green sandstones and shales with ignimbrites, yielding a *Euestheria ziliujingensis* clam shrimp fauna (Chen 2003). The Jiulongshan Formation (560–830 m thick), unconformably overlying either Lower Triassic strata or Archaean metamorphic rocks, consists mainly of brown conglomerate, dark brown coarse-grained sandstone, fine-grained sandstone, muddy siltstone, yellowish green mudstone intercalated with pale and greenish ignimbrite, yielding *Triglypta pingquanensis* Wang 1984 and *Euestheria* sp.

The Middle Jurassic Toutunhe Formation (654 m thick) in the Junggar Basin of the Xinjiang Autonomous District consists of greyish green, purplish red and yellowish green, thin-bedded, fine-grained sandstone, siltstone and mudstone, with black shale and coal laminae, and yields a *Triglypta* clam shrimp assemblage, including *T. manasica*, *T. ovata* and *T. tianshanensis*. Its upper part contains no fossil clam shrimps, but a Callovian *Sinokontikia* fauna has been recovered in correlative sequences in northwestern China, such as the upper Qiketai Formation of the Turpan Basin, the uppermost Wangjiashan Formation of Jingyuan, and the Honggou Formation of Tianzhu in Gansu Province (Shen 2003; Fig. 7). The *Sinokontikia* fauna comprises about 20 species in seven genera (Li & Matsuoka, 2012), and contains *Triglypta ovata* Wang, 1985, *T.* sp. cf. *T. pingquanensis* Wang, 1984, *T. tianshanensis* Wang, 1985 and *T. yingzuishigouensis* Wang, 1985, which are described from the Qiketai Formation of the Turpan Basin (Wang 1985).

Two Middle Jurassic clam shrimp biogeographical provinces have been identified on the Eurasian continent. One is the *Skyestheria* fauna from the Great Estuarine Group of Skye in northern Scotland, whose Middle Jurassic (Bajocian–Bathonian) age is constrained by marine fossil evidence (Chen & Hudson 1991). The other biogeographic province is typified by the Middle Jurassic (Bajocian–Bathonian) *Euestheria ziliujingensis* fauna in East Asia (Chen *et al*. 2007). The *Skyestheria* fauna comprises eight species in six genera (Chen & Hudson 1991), but only *Euestheria trotternishensis* Chen & Hudson, 1991 can be used to correlate with the *Euestheria ziliujingensis* fauna, because the simple puncta ornamentation of *E. trotternishensis* is very similar to that of *Qaidamestheria* Wang, 1983 of the *Euestheria ziliujingensis* fauna, which comprises about 20 species in three genera, and the common associates are *Euestheria ziliujingensis* Chen in Zhang *et al*., 1976, *E. haifanggouensis* Chen in Zhang *et al*., 1976, *E. complanata* Chen in Zhang *et al*., 1976, *Qaidamestheria dameigouensis* Wang, 1983 and *Triglypta pingquanensis* Wang, 1984, among others. The *Euestheria ziliujingensis* fauna is biostratigraphically significant because of its consistent stratigraphic occurrence and extremely wide geographical distribution in the Middle Jurassic lacustrine deposits of northern China (Zhang *et al*. 1976, Chen & Shen 1983, Shen 2003, Shen *et al*. 2003, Li & Matsuoka 2012; Fig. 7).

The newly discovered spinicaudatans from the Eedemt Formation provide good age constraints for the oil-shale deposits in the Eedemt locality. The ED-B section sequence, i.e., the lower part of the Eedemt Formation in the southern part of the Eedemt locality, contains a monospecific *Triglypta* assemblage (Fig. 2), and can be correlated with the *Euestheria ziliujingensis* fauna bearing sequences in northern China. The ED-A section sequence (in the northern part of the Eedemt locality; stratigraphically above the ED-B section) yields a new spinicaudatan genus, *Dundgobiestheria* Li, which is similar to *Paleoleptestheria* Novojilov, 1954 because both taxa have thick-walled and large-sized reticulate ornamentation. Because the later taxon is an important associate of the *Sinokontikia* fauna in northern China, we correlate the *Dundgobiestheria* assemblage of the ED-A section sequence with the *Sinokontikia* fauna of the Qiketai Formation in the Turpan Basin of the Xinjiang Autonomous District of China (Fig. 7). Recently, a SHRIMP zircon U–Pb radiometric age of 164.6 ± 1.4 Ma for a tuff layer in the lower Qigu Formation in the Junggar Basin (Wang & Gao 2012) further confirmed the Middle Jurassic age for the underlying Toutunhe and Qiketai formations of the Xinjiang Autonomous District. Therefore, the oil-shale-bearing Eedemt Formation can not be correlated with the Lower Cretaceous Dorogot or Shinekhudag

formations of Mongolia but can be correlated with the Middle Jurassic sequences in northern China (Fig. 7).

Conclusions

The newly recovered spinicaudatans provide useful age constraints for the Mongolian Jurassic sedimentary succession and biostratigraphic schemes. Systematic evaluation of the spinicaudatan species from the Eedemt Formation of southeast Mongolia and biostratigraphical correlations with the widely distributed Mesozoic sequences in northern China reveal that the oil-shale-bearing Eedemt Formation is of late Middle Jurassic age. This central East Eurasian succession was deposited under a warm and seasonal humid climate.

Acknowledgements

This study was supported by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (B21403008, leader: H. Ando), the Major Basic Research Projects of the Ministry of Science and Technology, China (National 973 Project 2012CB822004), National Natural Science Foundation of China (41172010). We thank Dr. B. Delgertsogt (Mineral Resources Authority of Mongolia), Dr. R. Barsbold and Dr. Y. Khand (Paleontological Center, Mongolian Academy of Science) for their fruitful discussions and help in the field survey. Great thanks go to Prof. Hiromichi Hirano (Department of Earth Sciences, School of Education, Waseda University) for providing study room and necessary equipment, and to Prof. Yanbin Shen and Prof. Peiji Chen (Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences) for constructive communications. Thanks also go to Prof. O.F. Gallego (Universidad Nacional del Nordeste, Argentina) and Dr. A.L. Stigall (Ohio University, USA) for their critical reviews and constructive comments. Special thanks go to Dr. S. McLoughlin (Swedish Museum of Natural History, Sweden) for carefully smoothing the English text. The SEM micrographs were taken with the help of Mr. H. Miura and Mr. H. Koyasu, through the courtesy of the Hitachi S-2380 and 3400 facilities (Department of Earth Sciences, School of Education, Waseda University).

References

Ando, H., Hasegawa, H., Hasegawa, T., Ohta, T., Yamamoto, M., Hasebe, N., Li, G. & Ichinnorov, N., 2011. Jurassic–Cretaceous lacustrine deposits in the East Gobi Basin, southeast Mongolia. *Journal of Geological Society of Japan 117*, 11–12.

Bat-Erdene, D., 1992. *Nature of Distribution and Formational Condition of Coal Basins in the Mongolian Orogenic Belt*. Doctoral thesis, Moscow University, 326 pp. (in Russian, unpublished)

Bat-Erdene, D. & Enkhtugs, O., 1987. *Distribution and Formation of Coal Deposits and Coal-Bearing Basins*. Ulaanbaatar, 37 pp. (in Russian)

Berry, E.W., 1926. New species of *Eulimnadia*. *American Journal of Science*, *Series 5, 11*, 429–433.

Brtek, J., 1997. Checklist of the valid and invalid names of the "large branchiopods" (Anostraca, Notostraca, Spinicaudata and Laevicaudata), with a survey of the taxonomy of all branchiopods. *Zborník Slovenského Národného Múzea Prírodné Vedy 43*, 3–66.

Chang, M.M., Chen, P.J., Wang, Y.Q., Wang, Y. & Miao, D.S., eds, 2003. *The Jehol Biota – the Emergence of Feathered Dinosaurs, Beaked Birds and Flowering Plants*. Shanghai Scientific and Technical Publishers, Shanghai, 208 pp.

Chen, P.J., 2003. Jurassic Biostratigraphy of China. In *Biostratigraphy of China*. Zhang, W.T., Chen, P.J. & Palmer, A., eds, Science Press, Beijing, 423–463.

Chen, P.J. & Hudson, J., 1991. The conchostracan fauna of the Great Estuarine Group, Middle Jurassic, Scotland. *Palaeontology 15*, 515–545.

Chen, P.J. & Jin, F., eds, 1999. *Jehol Biota. Palaeoworld*, *11*, 1–342.

Chen, P.J. & Shen, Y.B., 1983. Jurassic and Cretaceous conchostracan biogeographic provinces of China. In *Palaeobiogeographic Provinces of China*. Lu, Y.H., Mu, E.Z., Zhou, M.Z., Yang, Z.Y., Wang, Y., Yue, S.X., Xu, R., Yang, J.Z., Li, X.X., Hao, Y.C., Gu, Z.W., Hou, Y.T., Yu, J.H., Zhang, R.D., Sun, A.L., Yu, C.M., Wu, X.Z., Tao, N.S., Xiang, L.W., Di, R.J. & Chen, P.J., eds, Science Press, Beijing, 131–141. (in Chinese)

Chen, P.J. & Shen, Y.B., 1985. *An Introduction to Fossil Conchostraca*. Science Press, Beijing, 241 pp., 26 pls. (in Chinese)

Chen, P.J., Li, G. & Batten, D.J., 2007. Evolution, migration and radiation of late Mesozoic conchostracans in East Asia. *Geological Journal 142*, 391–413.

Defretin-Lefranc, S., 1965. Etude et révision des phyllopodes Conchostracés en provenance d'U.R.S.S. *Annales De La Société Géologique Du Nord 85*, 15–48.

Depéret, C. & Mazeran, P., 1912. Les Estheria du Permien d'Autun. *Bulletin De La Société d'Histoire Naturelle d'Autun 25*, 165–174.

Gallego, O.F., 2010. A new crustacean clam shrimp (Spinicaudata: Eosestheriidae) from the Upper Triassic of Argentina and its importance for 'conchostracan' taxonomy. *Alcheringa 34*, 179–195.

Gerstaecker, A., 1866. Crustacea (Erste Halfe). In *Die Klassen Und Ordungen Der Thier-Reichs, 5 (Part 1, Arthropoda)*. Bronn, H.G., ed., C.F. Winter, Leipzig and Heidelberg, 1320, 49 pls.

Holub, von V. & Kozur, H., 1981. Revision einiger Conchostracen-Faunen des Rotliegenden und biostratigraphische Auswertung der Conchostracen des Rotliegenden. *Geologisch-Paläontologische Mitteilungen Innsbruck 11*, 39–94.

Hu, D., Hou, L., Zhang, L. & Xu, X., 2009. A pre-*Archaeopteryx* troodontid theropod from China with long feathers on the metatarsus. *Nature 461*, 640–643.

Ichinnorov, N., Purevsuren, S. & Buyantegsh, B., 2008. Preliminary result of palynological study of the Khootiin Khotgor locality. *MUST, Geology Journal 19*, 81–86. (in Mongolian)

Ji, Q., Luo, Z.X., Yuan, C.X. & Tabrum, A.R., 2006. A swimming mammaliaform from the Middle Jurassic and ecomorphological diversification of early mammals. *Science 311*, 1123–1127.

Johnson, C.L. & Graham, S.A., 2004. Sedimentology and reservoir architecture of a synrift lacustrine delta, southeastern Mongolia. *Journal of Sedimentary Research 74*, 770–785.

Johnson, C.L., Greene, T.J., Zinniker, D.A., Moldowan, M.J., Hendrix, M.S. & Carroll, A.R., 2003. Geochemical characteristics and correlation of oil and nonmarine source rocks from Mongolia. *American Association of Petroleum Geologists Bulletin 87*, 817–846.

Khand, Y., Badamgarav, D., Ariunchimeg, Y. & Barsbold, R., 2000. Cretaceous system in Mongolia and its depositional environments. *Cretaceous Environments of Asia 17*, 49–79.

Khosbayar, P., 1977. Stratigraphy of Jurassic and Cretaceous deposits in Nyalga depression (North-East Mongolia). *Geological Problems of Mongolia 3*, 55–66. (in Russian)

Khosbayar, P. & Popov, Y.A., 1986. Mesozoic sediments of the Khootiin Khotgor Valley, Eastern Mongolia. *Geological Problems of Mongolia 6*, 46–59. (in Russian)

Krasinetz, S.S., 1963. On the significance of bivalved phyllopod crustaceans (Conchostraca) for the stratigraphy of upper Mesozoic freshwater-continental beds of eastern Transbaikalia. *Materials on*

the Geology and Mineral Resources in Chita Province 1, 32–63. (in Russian)

Latreille, P.A., 1829. Les crustacés, Les Arachnides, Les Insectes. In *Le règne Animal distribué d'après Son Organisation; Pour Servir De Base à l'histoire Naturelle Des Animaux Et d'introduction à l'anatomie comparée*. Cuvier, G., ed., Déterville, Paris, 4, 1–508.

Li, G. & Matsuoka, A., 2012. Jurassic clam shrimp ("conchostracan") faunas in China. *Science Report of Niigata University (Geology) 27*, 73–88.

Li, G., Shen, Y.B. & Batten, D.J., 2007. *Yanjiestheria, Yanshania* and the development of the *Eosestheria* conchostracan fauna of the Jehol Biota in China. *Cretaceous Research 28*, 225–234.

Li, G., Wan, X.Q., Batten, D., Bengtson, P., Xi, D.P. & Wang, P.J., 2009. Spinicaudatans from the Upper Cretaceous Nenjiang Formation of the Songliao Basin, northeast China: taxonomy and biostratigraphy. *Cretaceous Research 30*, 687–698.

Linder, F., 1945. Affinities within the Branchiopoda with notes on some dubious fossils. *Arkiv för Zoologi 37A*, 1–28.

Luo, Z.X., Yuan, C.X., Meng, Q.J. & Ji, Q., 2011. A Jurassic eutherian mammal and divergence of marsupials and placentals. *Nature 476*, 442–445.

Martin, J.W. & Davis, G.E., 2001. An updated classification of the Recent Crustacea. *Natural History Museum of Los Angeles County, Science Series 39*, 1–124.

Novojilov, N., 1946. New Phyllopoda from the Permian and Triassic deposits of the Nordwick-Khatanga Region. *Nedra Arktiki 1* 172–202, pls 1–3. (in Russian with English Summary)

Novojilov, N., 1954. Upper Jurassic and Cretaceous conchostracans from Mongolia. *Transactions of the Palaeontological Institute, USSR Academy of Sciences 48*, 7–124. (in Russian)

Novojilov, N., 1958. Recueil d'articles sur les Phyllopodes Conchostracés. *Service d'Information Géologique, Annales, Bureau De Recherches Géologiques, Géophysiques Et Minières 26*, 1–135, 9 pls.

Raymond, P.E., 1946. The genera of fossil Conchostraca—an order of bivalved Crustacea. *Bulletin of the Museum of Comparative Zoology at Harvard College 96*, 217–307, 6 pls.

Ren, D., Labandeira, C., Santiago-Blay, J.A., Rasnitsyn, A., Shih, C.K., Bashkuev, A., Logan, M.A.V., Hotton, C.L. & Dilcher, D., 2009. A probable pollination mode before angiosperms: Eurasian, long-proboscid scorpionflies. *Science 326*, 840–847.

Rohn, R., Shen, Y.B. & Dias-Brito, D., 2005. A new Coniacian–Santonian conchostracan genus from the Bauru Group, south-east Brazil: taxonomy, palaeobiogeography and palaeoecology. *Cretaceous Research 26*, 581–592.

Sars, G.O., 1867. *Histoire Naturelle Des Crustacés d'Eau Douce Norvège*. C. Johnson, Christiania (Oslo), 145 pp.

Sars, G.O., 1887. On *Cyclestheria hislopi* (Baird), a new generic type of bivalve Phyllopoda; raised from dried Australian mud. *Det Kongelige Norske Videnskabers Selskabs Forhandlinger 1*, 3–60.

Sars, G.O., 1899. On some Indian Phyllopoda. *Archiv for Mathematik Og Naturvidenskab 22*, 3–27, pls 1–4.

Shen, Y.B., 2003. Conchostracan Fauna. In *Jurassic in the North of China, 1, Stratum Introduction*. Deng, S.H., Yao, Y.M., Ye, D.Q., Chen, P.J., Jin, F., Zhang, Y.J., Xu, K., Zhang, Y.C., Yuan, X.Q. & Zhang, S.B., eds, Petroleum Industry Press, Beijing, 50–58. (in Chinese)

Shen, Y.B. & Chen, P.J., 1984. Late Middle Jurassic conchostracans from the Tuchengzi Formation of W Liaoning, NE China. *Bulletin of the Nanjing Institute of Geology and Palaeontology, Academia Sinica 9*, 309–326, 8 pls. (in Chinese, English abstract)

Shen, Y.B., Wang, S.E. & Chen, P.J., 1982. Conchostraca. *Palaeontological Atlas of Northwest China, Shaanxi, Gansu, Ningxia Volume, Part 3, Mesozoic and Cenozoic*. Xi'an Institute of Geology and Mineral Resources Geological Publishing House, Beijing, 52–70, pls 18–29. (in Chinese)

Shen, Y.B., Chen, P.J. & Huang, D.Y., 2003. Age of the fossil conchostracans from Daohugou of Ningcheng, Inner Mongolia. *Journal of Stratigraphy 27*, 311–313. (in Chinese, English abstract)

Sodov, J., 1980. New species of *Heilungia* and *Pityospermum* from Mesozoic sediments of South-Eastern Mongolia. *Paleontological Journal 4*, 131–133. (in Russian)

Sodov, J., 1985. About the age of Mesozoic sediments of Khootiin Khotgor Valley by paleobotanic data. *Geological Problems of Mongolia 9*, 177–184. (in Russian)

Sodov, J., 1990. *Stratigraphic and Paleobotanic Characteristics of Jurassic Sediments of Mongolia*. Geology and Mineral Resorces of Mongolian Peoples Republic, Nedra, Moscow, 163–167. (in Russian)

Stigall, A.L. & Hartman, J.H., 2008. A new spinicaudatan genus (Crustacea: 'Conchostraca') from the Late Cretaceous of Madagascar. *Palaeontology 51*, 1053–1067.

Vakhrameev, V.A. & Lebedev, E.L., 1972. Novyj vid *Heilongia* iz jury Mongolii [New species of *Heilungia* from Jurassic of Mongolia]. *Paleontologicheskij Zhurnal 1*, 144–147. (in Russian)

Wang, S.E., 1983. Some Jurassic–Cretaceous conchostracans from Qinghai. *Acta Palaeontologica Sinica 22*, 459–467. (in Chinese, English abstract)

Wang, S.E., 1984. New Jurassic-Cretaceous conchostracans from northern Hebei and Nei Mongol. *Acta Palaeontologica Sinica 23*, 726–737, 3 pls. (in Chinese, English abstract)

Wang, S.E., 1985. New Jurassic-Cretaceous conchostracans from northern Hebei and Nei Mongol. *Professional Papers of Stratigraphy and Palaeontology 12*, 1–12. (in Chinese, English abstract)

Wang, S.E. & Gao, L.Z., 2012. SHRIMP U-Pb dating of zircons from tuff of Jurassic Qigu Formation in Junggar Basin, Xinjiang. *Geological Bulletin of China 31*, 503–509. (in Chinese, English abstract)

Wang, S.E. & Liu, S.W., 1980. Fossil Conchostracans. In *Mesozoic Strata and Palaeontology of the Shanxi-Gansu-Ningxia Basin, Part 2*. Institute of Geology, Chinese Academy of Geological Sciences, ed., Geological Publishing House, Beijing, 84–110. (in Chinese)

Yamamoto, M., Bat-Erdene, D., Ulziikhishig, P., Enomoto, M., Kajiwara, Y., Takeda, N., Suzuki, Y., Watanabe, Y. & Nakajima, T., 1993. Preliminary report on geochemistry of Lower Cretaceous Dsunbayan oil shales, eastern Mongolia. *Bulletin of the Geological Survey of Japan 44*, 685–691.

Yamamoto, M., Bat-Erdene, D., Ulziikhishig, P., Watanabe, Y., Imai, N., Kajiwara, Y., Takeda, N. & Nakajima, T., 1998. Organic geochemistry and palynology of Lower Cretaceous Zuunbayan oil shales. *Bulletin of Geological Survey of Japan 49*, 257–274.

Yuan, F.T. & Chen, P.J., 2005. Early Cretaceous Crustacea (Ostracoda, Conchostraca) from the Shine-Khudug Formation of SE Mongolia. *Acta Palaeontologica Sinica 44*, 25–35. (in Chinese, English abstract)

Yuan, C.X., Ji, Q., Meng, Q.J., Tabrum, A.R. & Luo, Z.X., 2013. Earliest evolution of multituberculate mammals revealed by a new Jurassic fossil. *Science 341*, 779–783.

Zhang, W.T., Chen, P.J. & Shen, Y.B., 1976. *Fossil Conchostraca of China*. Science Press, Beijing, 325 pp., 138 pls. (in Chinese)

Zhang, H., Wang, M.X. & Liu, X.W., 2008. Constraints on the upper boundary age of the Tiaojishan Formation volcanic rocks in West Liaoning-North Hebei by LA-ICP-MS dating. *Chinese Science Bulletin 53*, 3574–3584.

Zhou, Z.H. & Wang, Y., 2010. Vertebrate diversity of the Jehol Biota as compared with other lagerstätten. *Science China-Earth Sciences 53*, 1894–1907.

Zhou, Z.H., Barrett, P.M. & Hilton, J., 2003. An exceptionally preserved Lower Cretaceous ecosystem. *Nature 421*, 807–814.

Alcheringa: An Australasian Journal of Palaeontology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/talc20

Confirmation of a Middle Jurassic age for the Eedemt Formation in Dundgobi Province, southeast Mongolia: constraints from the discovery of new spinicaudatans (clam shrimps)

Gang Li, Hisao Ando, Hitoshi Hasegawa, Masanobu Yamamoto, Takashi Hasegawa, Tohru Ohta, Noriko Hasebe & Niiden Ichinnorov
Published online: 14 Jan 2014.

To cite this article: Gang Li, Hisao Ando, Hitoshi Hasegawa, Masanobu Yamamoto, Takashi Hasegawa, Tohru Ohta, Noriko Hasebe & Niiden Ichinnorov , Alcheringa: An Australasian Journal of Palaeontology (2014): Confirmation of a Middle Jurassic age for the Eedemt Formation in Dundgobi Province, southeast Mongolia: constraints from the discovery of new spinicaudatans (clam shrimps), Alcheringa: An Australasian Journal of Palaeontology, DOI: 10.1080/03115518.2014.870834

To link to this article: http://dx.doi.org/10.1080/03115518.2014.870834