

A New Species of *Amsassia* from the Ordovician of Korea and South China: Paleobiological and Paleogeographical Significance

Mirinae LEE¹, Heeju PARK¹, Nguyen Viet TIEN², Suk-Joo CHOH³,
Robert J. ELIAS⁴ and Dong-Jin LEE^{1,*}

¹ Department of Earth and Environmental Sciences, Andong National University, Andong, 36729, Republic of Korea

² Institute of Geological Sciences–Vietnam Academy of Science and Technology (IGS – VAST), Hanoi, 100000, Socialist Republic of Vietnam

³ Department of Earth and Environmental Sciences, Korea University, Seoul, 02841, Republic of Korea

⁴ Department of Geological Sciences, The University of Manitoba, Winnipeg, R3T 2N2, Canada

Abstract: A new species of the probable calcareous alga *Amsassia*, *A. koreanensis*, is recognized from the Duwibong Formation (Middle Ordovician, Darriwilian) of the Taebaeksan Basin in mid-eastern Korea. This is the first report of the genus from the Korean Peninsula, expanding its geographical range to the eastern Sino-Korean Block. The new species also occurs in the Xiazhen Formation (Upper Ordovician, Katian) at Zhuzhai in the South China Block. *Amsassia koreanensis* is the smallest species of this modular genus, having a maximum module diameter of 0.28 mm. Module increase is by bipartite, tripartite and quadripartite types of longitudinal axial fission, but unlike other species of the genus, quadripartite fission is common. The types of fission are comparable to those in some Tetradiida (now Prismostylales, florideophycean rhodophyte algae), although the processes of fission are different. The distribution of *A. koreanensis* further strengthens the biogeographical connection between the Sino-Korean and South China blocks, suggesting that these two paleocontinents were located closer together during the Middle to Late Ordovician than previously speculated.

Key words: *Amsassia koreanensis* sp. nov., Ordovician, Sino-Korean Block, South China Block, paleobiology, paleogeography.

1 Introduction

Amsassia is a problematic modular organism with a coral-like skeleton, diagnosed by closely united to partially separated modules and module increase by longitudinal axial fission involving infoldings of the wall (Hill, 1981; Sun et al., 2014). Since the first report of this genus from the Upper Ordovician of Mountain Shoria in Siberia (Sokolov and Mironova, 1959), *Amsassia* has mostly been recorded from the Middle to Upper Ordovician of Asia, including north-central China (Ye et al., 1995; Bian et al., 1996; Sun et al., 2014), southern China (Yi, 1974; Lin and Webby, 1989; Niu et al., 2007; Lee et al., 2012), northwestern China (Wang, 1993; Zhou and Dean, 1996; Wang et al., 2012), Kazakhstan (Bondarenko, 1963; Nikitin and Popov, 1996; Popov et al., 1997; Popov et al., 2002; Popov and Cocks, 2006) and

Siberia (Bondarenko and Ulitina, 2009). A single occurrence has also been reported from the Upper Ordovician of Arctic Canada (Bolton, 2000).

Amsassia has traditionally been identified as a tabulate coral (Sokolov and Mironova, 1959) and assigned to Tetradiida (Sokolov, 1962), Lichenariida (Yu and Zhang, 1963) or Chaetetida (Hill, 1981). The tetradiid *Tetradium*, however, was recently considered to be a florideophycean rhodophyte alga (Steele-Petrovich, 2009a, b, 2011; the widely known, traditional names of the order and genus are used in the present paper, rather than the replacement names Prismostylales and *Prismostylus*). The tabulate affinity of the lichenariid *Lichenaria* has been confirmed (Elias et al., 2008), whereas chaetetids have been accepted as coralline sponges (Hartman and Goreau, 1972). *Amsassia* may represent an extinct group of algae, as suggested by a recent analysis of growth characteristics and morphological comparisons (Sun et al., 2014). This

* Corresponding author. E-mail: djlee@andong.ac.kr

genus is probably more widespread paleogeographically and more significant paleoecologically than once realized, because of misidentifications in earlier literature (Lee et al., 2014; Sun et al., 2014).

In this study, a new species of *Amsassia* is recognized from the Middle Ordovician Duwibong Formation in Korea and the Upper Ordovician Xiazhen Formation in southeastern China. The morphological characteristics of *A. koreanensis* sp. nov. expand our knowledge of the range of variability in the genus and contribute to a better understanding of its biological affinity. This species is the first representative of *Amsassia* to be found in the eastern part of the Sino-Korean Block, and also occurs in the South China Block. The distribution of *A. koreanensis* therefore has significant paleogeographical implications.

2 Geological Setting and Material

The Cambro-Ordovician Joseon Supergroup in the Taebaeksan Basin crops out in the mid-eastern part of the Korean Peninsula (Fig. 1a). This supergroup comprises a mixed clastic-carbonate succession, which unconformably overlies Precambrian basement rocks and is unconformably overlain by upper Paleozoic–lower Mesozoic siliciclastics of the Pyeongan Supergroup (Chough et al., 2000; Chough, 2013; Fig. 1b). The Taebaek Group, consisting of ten lithostratigraphic units, is a subunit of the Joseon Supergroup (Choi et al., 2004; Choi and Chough, 2005).

The Duwibong Formation is the uppermost unit of the Taebaek Group, and is composed of carbonates and calcareous shales deposited in open marine platform environments (Chough et al., 2000; Lee et al., 2001). The formation gradationally overlies black shales of the Jigunsan Formation and is unconformably overlain by coarse sandstones of the Carboniferous Manhang Formation (Choi et al., 2004; Kwon et al., 2006). The age of the Duwibong Formation is estimated to be Darriwilian based on recognition of the *Plectodina onychodonta* and *Aurilobodus serratus* conodont biozones (Lee and Lee, 1990).

The *Amsassia* specimens from the Duwibong Formation used in this study were collected from packstones and grainstones at three localities at the Seokgaejae, Sorotgol and Manhangjae sections (Fig. 1b). We follow Sun et al. (2014) in using the terms corallum/coralla, calice/calices and tabula/tabulae when describing *Amsassia*, which has a superficially coral-like skeleton. Because of their very small size, coralla of *A. koreanensis* are nearly inconspicuous at the outcrop and slab scales; they are only recognizable by microscopic observation. Over 200 thin sections containing coralla of the species were prepared for observation and analysis. A total of 108 coralla (44

from Seokgaejae, 19 from Sorotgol, 45 from Manhangjae) were selected for description in this study.

An additional 28 coralla of *Amsassia* from southeastern China, which are regarded as conspecific with *A. koreanensis*, were also included in this study. They are from the Xiazhen Formation at Zhuzhai, located in the Jiangshan–Changshan–Yushan area (JCY area) in the eastern part of the South China Block (Fig. 1a, c). The Xiazhen Formation (Fig. 1d), estimated to be Katian in age based on the *Dicellograptus complexus* graptolite biozone (Zhang et al., 2007), is one of the most fossiliferous Ordovician units in the JCY area. It is composed of mixed carbonate-clastic deposits containing abundant stromatoporoids, corals, brachiopods, calcareous algae, calcimicrobes, trilobites and mollusks (Zhan et al., 2002; Li et al., 2004; Zhang et al., 2007; Lee et al., 2012; Lee, 2013; Dai et al., 2015). The depositional environment of the formation has been interpreted to represent a shallow platform with successive shallowing upward trends (Lee et al., 2012). Specimens of *A. koreanensis* occur within lime mudstones in the middle part of the formation.

The diameter of modules in *Amsassia* was determined from each transverse section cut perpendicular or nearly perpendicular to the growth axis of the corallum. Measurements were obtained by using image processing software ('ImageJ'; Schneider et al., 2012). The diameter of a module was calculated as the average of the shortest wall-to-wall distance and the largest corner-to-corner distance within a module (i.e., the cement-filled part), which has traditionally been expressed as the diameter of a corallite in favositid tabulate corals (Scrutton, 1981). In order to determine the average mature module size for the corallum, the ten largest modules, largest 10% of modules and largest 20% of modules from each corallum were selected and measured. The results (Table 1) show clearly that the average mature module size and its variation are not distinctly different for the coralla of *A. koreanensis* among different localities. Furthermore, data based on the largest 10% of modules from each corallum are sufficient for comparison, as suggested by Lee and Noble (1988). Figured specimens are deposited in the Geological Collections, Natural Heritage Center (NHCG) of Cultural Heritage Administration at Daejeon, Korea.

3 Morphological Features and Mode of Modular Increase

All coralla of *A. koreanensis* from Korea are incomplete due to fragmentation and abrasion (Fig. 2a). It is apparent, however, that they were originally very small with mostly hemispherical shapes. The largest specimen is 3.8×3.7

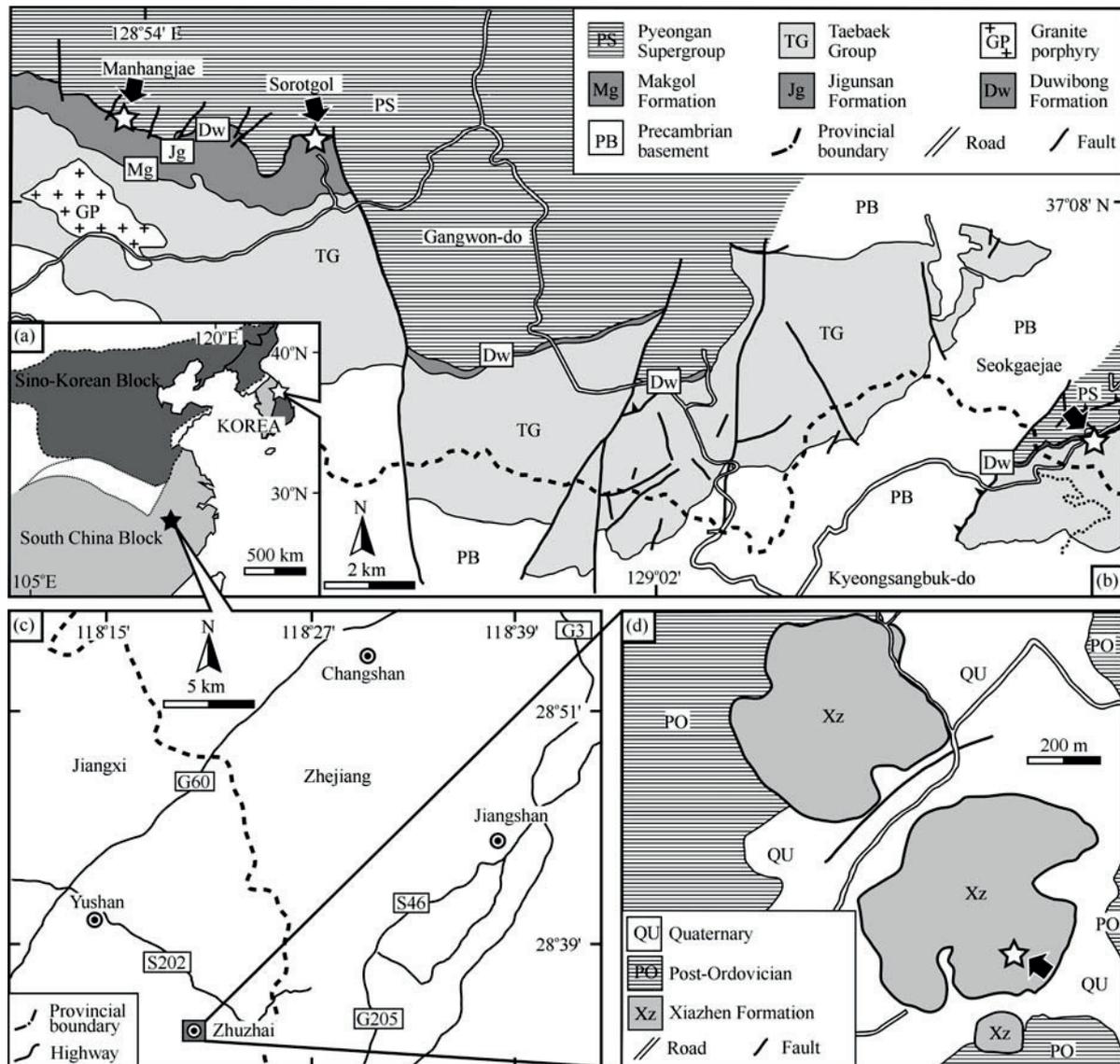


Fig. 1. Maps of the study areas in Korea and China.

(a) Simplified tectonic elements of eastern Asia showing the Sino-Korean Block (dark shading) and South China Block (light shading), and study areas of the Taebaeksan Basin in mid-eastern Korea (white star) and Zhuzhai in southeastern China (black star); (b) Geological map of the three study localities in Korea (white stars with black arrows): Seokgaejae, Sorotgol and Manhangjae; the Taebaek Group (lower part, medium solid shading; uppermost part, dark solid shading) is overlain by the Pyeongan Supergroup (shaded with horizontal lines); the uppermost three formations of the Taebaek Group (Makgol, Jigunsan and Duwibong in ascending order; dark solid shading) are undifferentiated at Sorotgol and Manhangjae; (c) Study area in southeastern China, near Yushan in the JCY area; (d) Geological map of the study locality in China at Zhuzhai, where the Xiazhen Formation occurs as thrust faulted inliers on top of Mesozoic sedimentary rocks; the fossil locality is marked with a white star and black arrow. Modified from Zhou and Graham (1996), Chough et al. (2000), Lee et al. (2012) and Chough (2013).

Table 1 Mature module diameter (mm) of *Amsassia koreanensis* from the Duwibong Formation at three localities in Korea (eastern Sino-Korean Block) and from the Xiazhen Formation at Zhuzhai, China (South China Block)

Localities	Nc.	Largest 10 modules per corallum					Largest 10% of modules per corallum					Largest 20% of modules per corallum					
		min.	max.	avg.	s.d.	n	min.	max.	avg.	s.d.	n	min.	max.	avg.	s.d.	n	
Korea	Seokgaejae	44	0.05	0.27	0.13	0.03	392	0.07	0.23	0.13	0.03	175	0.07	0.23	0.13	0.03	318
	Sorotgol	16	0.07	0.23	0.14	0.04	143	0.11	0.22	0.16	0.03	52	0.10	0.22	0.16	0.03	100
	Manhangjae	43	0.06	0.26	0.14	0.04	425	0.08	0.28	0.17	0.03	180	0.08	0.28	0.16	0.03	310
China	Zhuzhai	21	0.05	0.23	0.10	0.04	172	0.06	0.28	0.13	0.05	78	0.06	0.28	0.13	0.06	136

Nc. = number of measured coralla, min. = minimum, max. = maximum, avg. = average, s.d. = standard deviation, n = number of measured modules.

mm across and 2.5 mm high. The coralla from China are also mostly hemispherical (Fig. 2b), with the largest measuring 2.5×1.7 mm across and 0.9 mm high.

In transverse sections, the corallum structure is seen to be phacelocerioid. The modules are polygonal to subpolygonal in closely packed areas, and subrounded to irregular where

modules are separated by micrite (Fig. 2c–f). The average diameter of mature modules in coralla from the different localities is shown in Table 1. Overall, the range is 0.06 to 0.28 mm (based on the largest 10% of modules in each corallum). The walls are poorly preserved and their microstructure is unrecognizable. Considering the comparatively good preservation of foliated walls in co-occurring bryozoans (*Nicholsonella*; Xia, F.S., pers. comm. 2013; Oh et al., 2013), it is suggested that coralla of *A. koreanensis* may have originally been composed of aragonite.

In longitudinal sections (Fig. 2b, g–h), the modules are straight or slightly undulate, and filled with calcite cement. Tabulae are not recognized, though it is uncertain whether they were originally absent or were present but obscured by diagenesis. The calice of each module is a shallow, micrite-filled depression with a slightly concave bottom (Fig. 2b, g–h). Septa are absent (Fig. 2c–f).

Module increase by axial fission is evident in longitudinal sections (Fig. 2b, h). Because of the very small size of coralla and modules, it was not feasible to undertake a detailed study of increase based on transverse serial sections, as done by Sun et al. (2014) for the relatively large species *A. shaanxiensis*. However, based on transverse sections of *A. koreanensis* showing modules in various stages of fission (Fig. 3), it is inferred that infoldings of the wall resulted in temporary septum-like structures which extended and joined to divide the module longitudinally. Bipartite, tripartite and quadripartite types of longitudinal fission are recognized (Fig. 3). The frequency of each type of fission varies among the localities (Table 2).

4 Systematic Paleontology

The classification of *Amsassia* above the genus level is unresolved. Previous assignments to the Lichenariida (tabulate corals), Chaetetida (coralline sponges) and

Tetradiida (now Prismostylales; florideophycean rhodophyte algae) are problematic (Sun et al., 2014; present study). We regard *Amsassia* as a probable calcareous alga, possibly with a relation to tetradiids.

Genus *AMSASSIA* Sokolov and Mironova, 1959

1959 *Amsassia* Sokolov and Mironova, p. 1151.

1981 *Amsassia* Sokolov and Mironova; Hill, p. F513.

2014 *Amsassia* Sokolov and Mironova; Sun, Elias and Lee, p. 1081.

Type species: *Amsassia raduguini* Mironova in Sokolov and Mironova, 1959 from the Amsass Suite, lower Upper Ordovician of Mountain Shoria, western Siberia.

Diagnosis: Growth form massive, structure phacelocerioid. Transverse shape of modules rounded in loosely packed areas to polygonal in densely packed areas. Calice of module is shallow depression with slightly concave bottom. Diameter of modules 0.06–1.7 mm. Modules increase by longitudinal fission involving infoldings of wall: bipartite, tripartite, or quadripartite. Tabulae rare.

Remarks: The diagnosis is slightly modified from Sun et al. (2014). It takes into account the small size of modules in *A. koreanensis*, and recognition that features of the calice are characteristic of the genus.

Amsassia koreanensis sp. nov.

Figs. 2 and 3

Derivation of name: The new species is named for Korea.

Types: Holotype NHCG 10868 (one thin section, 10868-1; Fig. 3a), Manhangjae. Paratypes NHCG 10869 (one thin section, 10869; Fig. 2d), Seokgaejae, and NHCG 10870 (one thin section, 10870; Fig. 2f), Sorotgol. Duwibong Formation (Middle Ordovician, Darriwilian), mid-eastern Korea.

Material: One hundred and eight specimens including the types (44 from Seokgaejae in Samcheok, Gangwon-do; 19 from Sorotgol in Taebaek, Gangwon-do; 45 from Manhangjae in Jeongseon, Gangwon-do), Duwibong Formation (Middle Ordovician, Darriwilian), mid-eastern Korea (Fig. 1b). Twenty-eight specimens, Xiazhen Formation (Upper Ordovician, Katian), Zhuzhai in Yushan, Jiangxi, southeastern China (Fig. 1c–d).

Diagnosis: Small species of *Amsassia* with diameter of modules 0.06–0.28 mm. Modules increase by bipartite, tripartite and quadripartite longitudinal fission; all three types common.

Description: Coralla massive with phacelocerioid structure, up to 3.8 × 3.7 mm across and 2.5 mm high. In transverse section, modules polygonal to subpolygonal in

Table 2 Types of longitudinal fission in *Amsassia koreanensis* from the Duwibong Formation at three localities in Korea and from the Xiazhen Formation at Zhuzhai, China, number of occurrences (and percentage of total number of occurrences) are shown for each locality and for the combined data

Localities		Bipartite	Tripartite	Quadripartite	Sum
Korea	Seokgaejae	5 (17.9%)	14 (50.0%)	9 (32.1%)	28
	Sorotgol	3 (42.9%)	2 (28.6%)	2 (28.6%)	7
	Manhangjae	14 (25.9%)	18 (33.3%)	22 (40.7%)	54
China	Zhuzhai	14 (42.4%)	13 (39.4%)	6 (18.2%)	33
	Total	36 (29.5%)	47 (38.5%)	39 (32.0%)	122

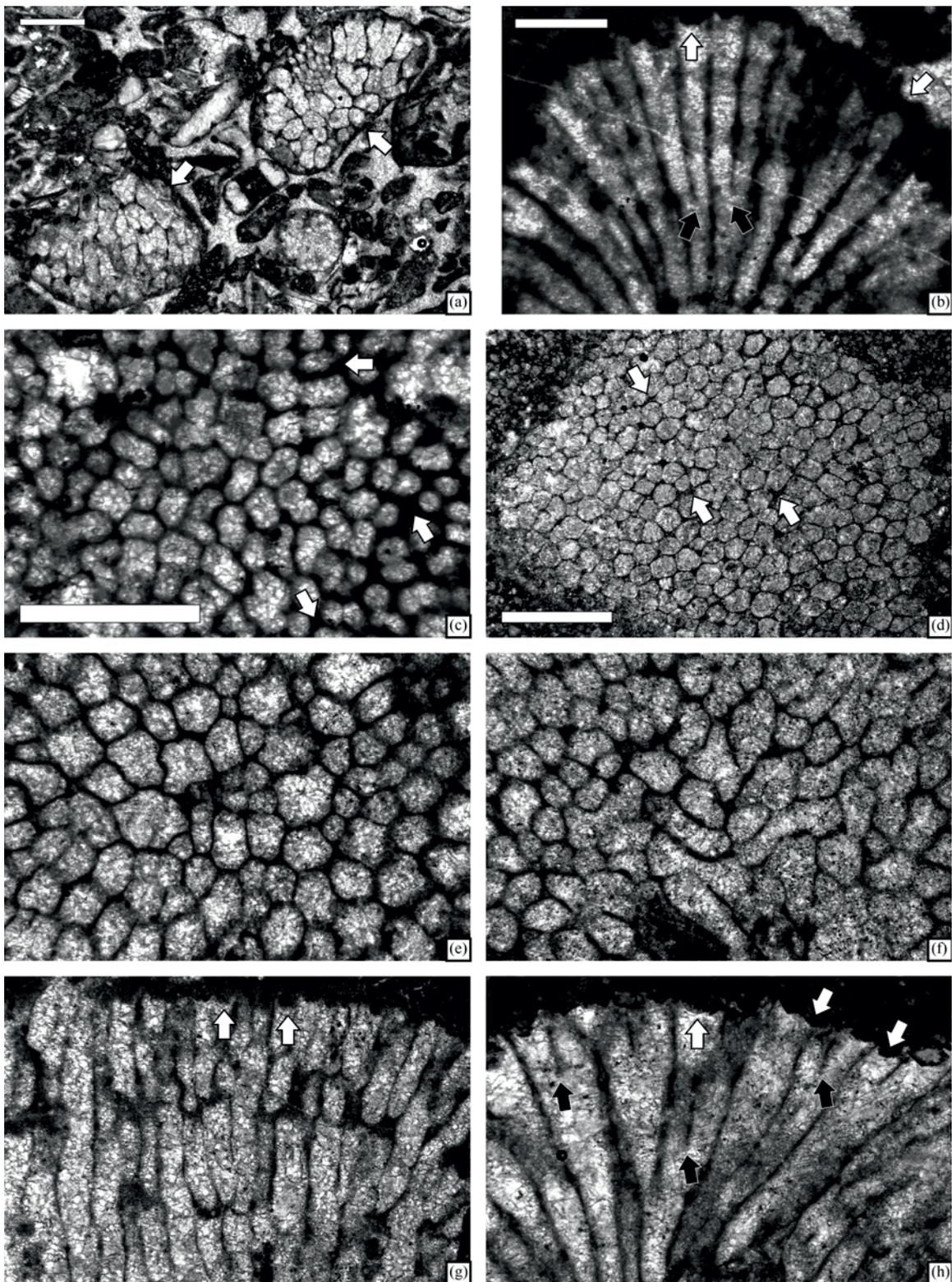


Fig. 2. Thin section photomicrographs of *Amsassia koreanensis* from the Duwibong Formation (Middle Ordovician), Korea, and the Xiazhen Formation (Upper Ordovician), southeastern China.

(a), Abraded and fragmented coralla (white arrows) occurring in grainstone facies; (b), Longitudinal section; note the concave bottom of calices (white arrows) and longitudinal axial fission of modules (black arrows); (c), Transverse section; note the phacelocerial structure with micrite between some modules (white arrows); (d), Transverse section; white arrows indicate micrite infilling spaces between modules in phaceloid areas; (e), (f), Slightly oblique transverse sections; (g), Slightly oblique longitudinal section; note the concave bottom of calices (white arrows); (h), Longitudinal section; note the concave bottom of calices (white arrows) and longitudinal axial fission of modules (black arrows). (a), NHCG 10872; (d), paratype NHCG 10869; (g), NHCG 10874, Seokgaejae, Korea; (b), (c), NHCG 10871, Zhuzhai, China; (e), NHCG 10873-1; (h), NHCG 10875, Manhangjae, Korea; (f), paratype NHCG 10870, Sorotgol, Korea. Scale bar in (a, d-h) = 0.5 mm; scale bar in (b, c) = 0.25 mm.

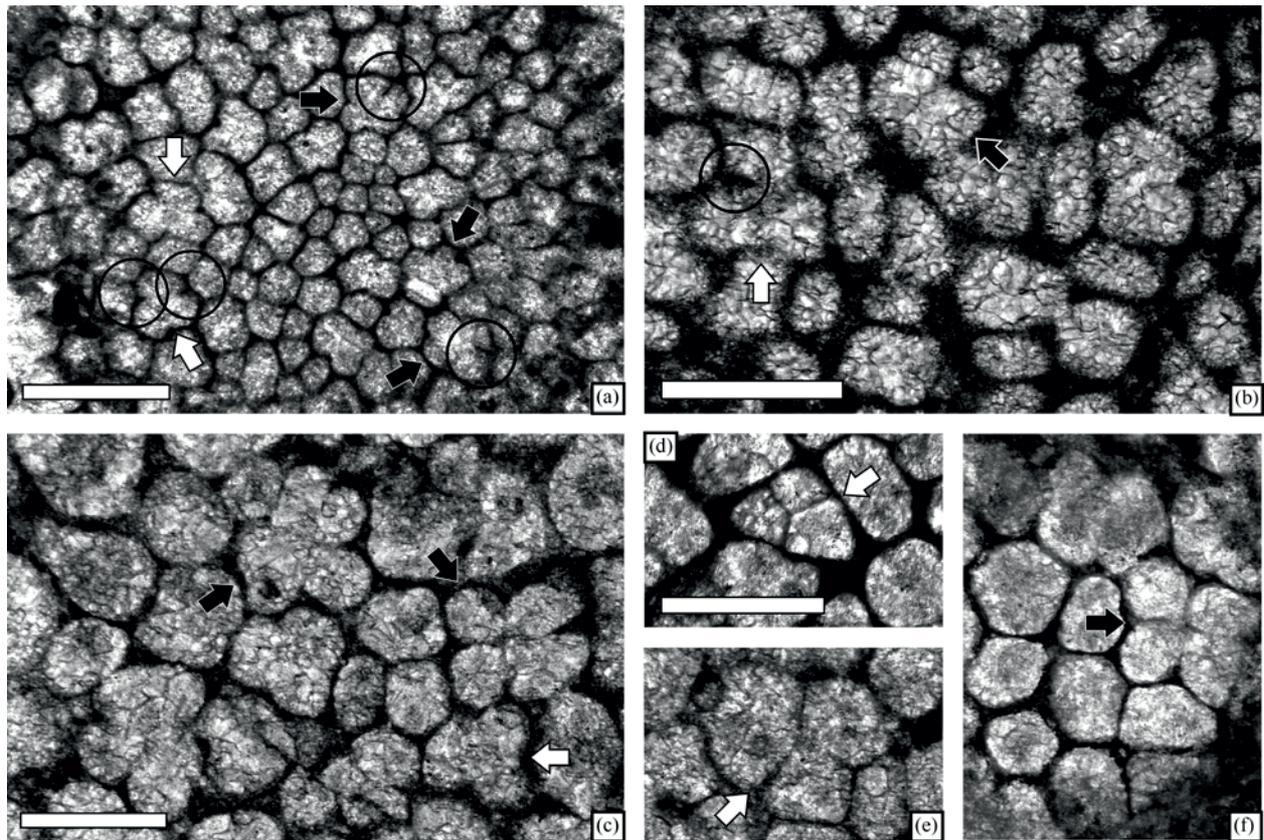


Fig. 3. Thin section photomicrographs of axial fission in *Amsassia koreanensis* from the Duwibong Formation (Middle Ordovician), Korea, and the Xiazhen Formation (Upper Ordovician), southeastern China.

(a), Transverse section; note the variable shape and size of modules undergoing tripartite (white arrows) and quadripartite fission (black arrows), and the development of dividing walls within a few modules (black circles); (b), Transverse section; note tripartite (white arrow) and quadripartite fission (black arrow) of modules, and development of a dividing wall within a module (black circle); (c), Transverse section; note tripartite (white arrow) and quadripartite fission (black arrows) of modules; (d), (e), Transverse sections; note tripartite fission of modules (white arrows); (f), Transverse section; note quadripartite fission of a module (black arrow), showing infolding of the outer wall and development of dividing walls. (a), Holotype NHCG 10868-1, Manhangjae, Korea; (b), NHCG 10896, Zhuzhai, China; (c), NHCG 10872; (e), NHCG 10876; (f), NHCG 10877, Seokgaejae, Korea; (d), NHCG 10875, Manhangjae, Korea. Scale bar in (a) = 0.5 mm; scale bar in (b, c, d–f) = 0.25 mm.

closely packed areas, subrounded to irregular in loosely packed areas with modules separated by micrite. Range of module diameters 0.06–0.28 mm (based on largest 10% of modules in each corallum; Table 1). In longitudinal section, modules straight or slightly undulate. Calice of module is shallow depression with slightly concave bottom. Mode of module increase is longitudinal axial fission; bipartite, tripartite and quadripartite types common (Table 2). During increase, infoldings of wall yield temporary septum-like structures which extend and join to divide module longitudinally. Tabulae not recognized.

Discussion: Although they differ in geographical location and geological age, the coralla of *Amsassia* described above from mid-eastern Korea (Darrivilian) and Zhuzhai, China (Katian) cannot be distinguished by consistent morphological differences. The diameters of modules from the three Korean localities and the Chinese locality are closely similar (Table 1). All of these coralla are therefore regarded as conspecific and are identified as

a new species, *A. koreanensis*. *Amsassia* has been reported previously from the Xiazhen Formation at Zhuzhai (Lee et al., 2012, p. 394, fig. 12Aa), but module diameters of the figured specimens (0.39–0.48 mm) are much larger than those of *A. koreanensis* and indicate that the specimens represent a different species.

Amsassia koreanensis is distinguished from other species of the genus by its small size. The maximum module diameter (0.28 mm) is less than that of *A. minima* (0.4 mm) from the mid-Upper Ordovician of South China and *A. sheshanensis* (0.4 mm) from the Middle Ordovician of Inner Mongolia (Fig. 4a). In *Amsassia*, tripartite and quadripartite types of module increase were previously recognized in *A. shaanxiensis* from the Middle and Upper Ordovician of the Ordos Basin in the western part of the Sino-Korean Block (Sun et al., 2014). Quadripartite fission, however, is rare in *A. shaanxiensis* but common in *A. koreanensis*. In both species, the calice of modules is a shallow depression with a slightly concave bottom.

Amsassia shaanxiensis differs from *A. koreanensis* in having distinctively larger modules (Fig. 4a). In addition, *A. shaanxiensis* shows rare, complete tabulae that are periodically developed, whereas tabulae are not observed in *A. koreanensis*.

5 Discussion

5.1 Paleobiological Significance

Sun et al. (2014) suggested that the corallum of *Amsassia* was originally composed of aragonite, based on petrographic examination of *A. shaanxiensis* from the Middle and Upper Ordovician of north-central China. That interpretation is supported by the present study, in which *A. koreanensis* was found to be poorly preserved in comparison with co-occurring fossils known to have been originally calcitic.

The mode, process and types of module increase in *A. koreanensis* have been reported previously in *Amsassia* (Sun et al., 2014). Until now, however, tripartite and quadripartite types of fission were recognized in only one species, *A. shaanxiensis* (Sun et al., 2014). Quadripartite fission is rare in *A. shaanxiensis*, but comparatively common in *A. koreanensis*. Fission into four equal parts is considered to be unknown in animals but common in algae (Steele-Petrovich, 2009a, b).

It is noteworthy that the types of longitudinal axial fission in *A. koreanensis* are comparable to those of some tetradiids including a branching species, *Rhabdotetradium jiangshanense* from the Upper Ordovician of southeastern China (Kwon et al., 2012). In addition to quadripartite fission, which is typical of tetradiids, bipartite and tripartite fission were common in *R. jiangshanense* under conditions of ecological stress. Although the processes of increase were different in *Amsassia* and tetradiids (see Sun et al., 2014), they could result in the same types of fission. Perhaps this is an indication that these extinct taxa, thought to be algae, are related to one another.

Amsassia koreanensis is the smallest known species of the genus, with a maximum module diameter less than that of *A. minima* from the mid-Upper Ordovician of South China and *A. sheshanensis* from the Middle Ordovician of Inner Mongolia (Fig. 4). The range of module diameters of *A. koreanensis* (0.06–0.28 mm) partly overlaps with that of *Solenopora* (0.03–0.18 mm), which is regarded as a probable chaetetid sponge (Riding, 2004). *Solenopora* is composed of closely packed modules (Chuvashov and Riding, 1984). *Amsassia* differs fundamentally in having phaceloceroid structure (Figs. 2d, 3c–f), which is indicative of individuality and would be unexpected in a sponge (Sun et al., 2014). The shallow calice with a slightly concave bottom, which is a characteristic of

modules in *Amsassia* (Sun et al., 2014, fig. 4B; Fig. 2b, g–h), is not present in *Solenopora* (Riding, 2004, fig. 2; Flügel, 2004, pl. 55). *Amsassia koreanensis* is therefore not considered to be related to *Solenopora*.

5.2 Paleogeographical Implications

The paleogeographical reconstruction of peri-Gondwanan landmasses – in particular, the relative location of the Sino-Korean and South China blocks during the Ordovician – is as yet unresolved (e.g., Li and Powell, 2001; Cocks and Torsvik, 2004). Recent studies indicate that the South China Block and the Sino-Korean Block may have occupied relatively similar paleolatitudes near the paleoequator during the early Paleozoic (Cocks and Torsvik, 2004; Torsvik and Cocks, 2009, 2013). Previous estimations based on shelly fossils (Torsvik and Cocks, 2009) suggested that those blocks may have been widely separated from one another. On the other hand, a recent analysis based on detrital zircon and trilobites demonstrated similarity between Cambrian clastic sedimentary rocks in the Taebaeksan Basin of Korea, southeastern north China (Shaanxi), and northeastern India, which was part of Gondwana (McKenzie et al., 2011). This suggests that the Sino-Korean Block may have been part of Gondwana, possibly with the South China Block nearby during the Cambrian (McKenzie et al., 2011).

It has been suggested that *Amsassia* first appeared on the Sino-Korean and Tarim blocks in the Middle Ordovician and dispersed to other areas (e.g., South China, Kazakhstan, Siberia) during the Middle to Late Ordovician (Lee et al., 2014; Fig. 4). It is noteworthy that species of *Amsassia* with relatively small modules (diameter 0.08–0.6 mm) are mostly reported from the eastern Sino-Korean Block (modern orientation) and South China, whereas those with rather large modules (0.5–1.66 mm) originated on the western Sino-Korean Block (modern orientation) and then appeared in Tarim, Kazakhstan and Siberia. The discovery of *A. koreanensis* in the Middle and Upper Ordovician of the eastern Sino-Korean and eastern South China blocks is the first reported occurrence of the same sessile Ordovician species on both blocks. This suggests that during the Middle to Late Ordovician, the two blocks may have been positioned closer than previously speculated. Additional fossil evidence is needed to elucidate the reconstruction of Ordovician peri-Gondwanan paleogeography.

6 Conclusions

A new species of probable calcareous alga *Amsassia*, *A. koreanensis* is recognized from the Middle Ordovician (Darriwilian) Duwibong Formation of Taebaeksan Basin,

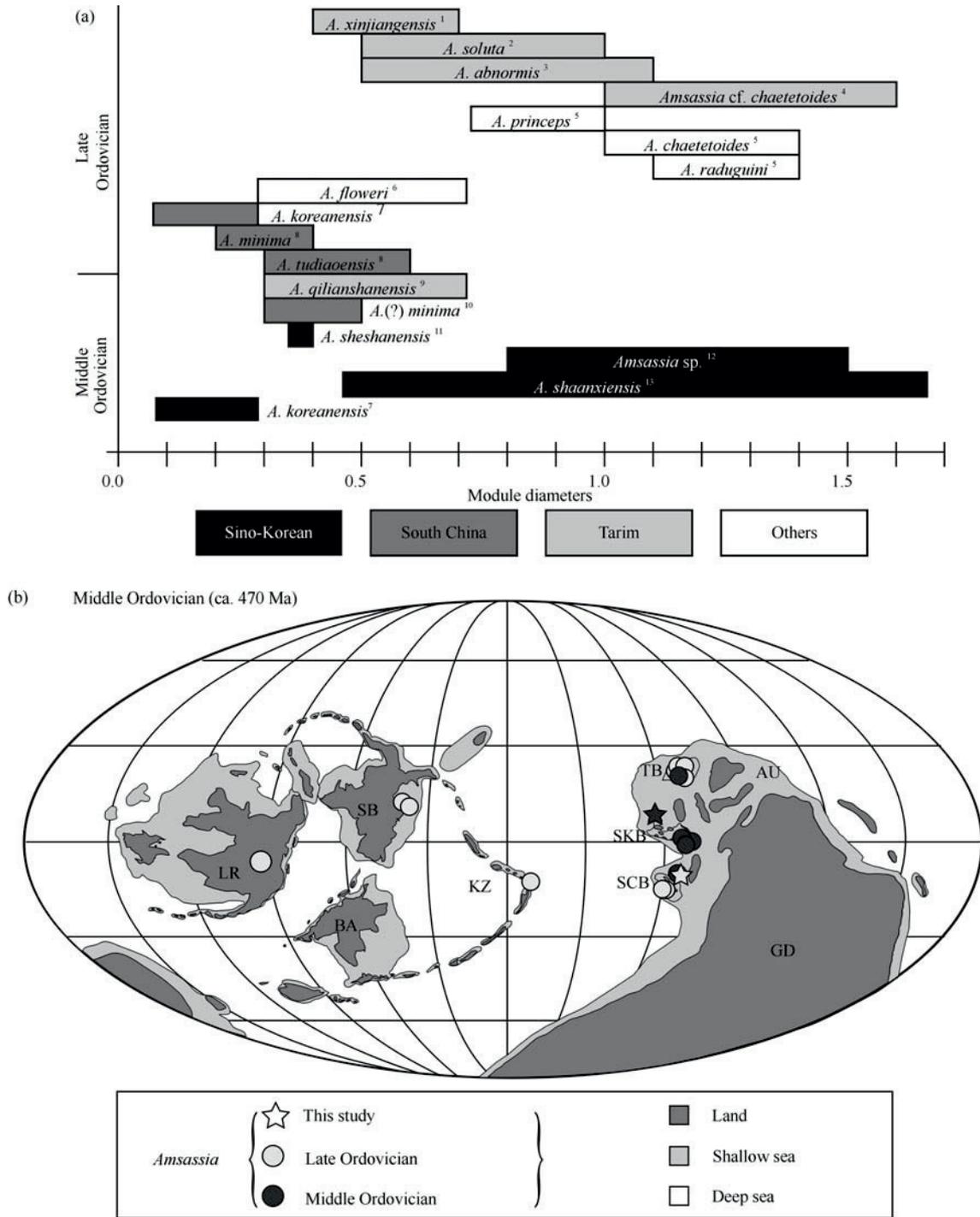


Fig. 4. Module size and paleogeographical distribution of species of *Amsassia*.

(a), Range of module diameters in *Amsassia koreanensis* and species of *Amsassia* previously described from the Sino-Korean Block, South China Block, Tarim Block, and other paleocontinents including Siberia (*A. princeps*, *A. radugini*), Kazakhstan (*A. chaetoides*) and Laurentia (*A. floweri*). The species of *Amsassia* are grouped as Middle and Late Ordovician, but are not arranged in stratigraphic order within those groups. Sources of data: ¹Wang (1993, figs. 1, 3–4); ²Yu (1962, p. 76, pl. 34, figs. 4a–b, pl. 35, figs. 1a–d, 2–3); ³Yu (1962, p. 76, pl. 34, figs. 2a–c, 3); ⁴Yu (1961, p. 332), Yu and Zhang (1963, p. 287, pl. 90, fig. 7a–b); ⁵Sokolov and Mironova (1959, p. 1152); ⁶Bolton (2000, pl. 6, fig. 5, pl. 7, figs. 1–6); ⁷this paper; ⁸Yang et al. (1978, p. 226); ⁹Li and Lin (1982, p. 80, pl. 25, fig. 4a–b); ¹⁰Lin and Chow (1980, p. 33); ¹¹Deng (1984, pl. 5, fig. 1a–b); ¹²Ye et al. (1995, pl. 5, figs. 3–4); ¹³Sun et al. (2014, figs. 3–4, 6–9);

(b), Distribution of *Amsassia* plotted on a Middle Ordovician paleogeographical map (ca. 470 Ma); base map modified after Scotese (2001), Webby (2002), Blakey (2008), Golonka and Gawęda (2012) and Burrett et al. (2014); placement of Sino-Korean, South China and Tarim blocks based on Metcalfe (2013), Burrett et al. (2014) and Cho et al. (2014); LR = Laurentia, BA = Baltica, SB = Siberia, KZ = Kazakhstan, GD = Gondwana, SKB = Sino-Korean Block, SCB = South China Block, TB = Tarim Block, AU = Australia.

Korea and the Upper Ordovician (Katian) Xiaozhen Formation at Zhuzhai, South China, respectively. The new species is characterized by considerably smaller diameter than any other species of *Amsassia* reported to date. Modules of *A. koreanensis* increase by bipartite, tripartite, and quadripartite longitudinal axial fissions, which are comparable with those in some Tetradiida. The present study represents first documentation of *Amsassia* from the Korean Peninsula of eastern Sino-Korean Block. The occurrence of *A. koreanensis* from the Middle Ordovician of Sino-Korean Block and Late Ordovician of South China Block, respectively, suggests close proximity of these two paleocontinents during Middle to Late Ordovician.

Acknowledgements

This study was supported by a grant from 2015 Research Fund of Andong National University. J.-H. Lee (Chungnam National University) provided constructive comments on the initial manuscript. We thank H.J. Cho, N.K. Kim and J. Jeon (Andong National University) for preparation of thin sections. The reviewer and editor are acknowledged for their helpful suggestions.

Manuscript received May 4, 2015

accepted Sep. 23, 2015

edited by Fei Hongcai and Kristian P. Saether

References

- Bian, L.Z., Fang, Y.T., and Huang, Z.C., 1996. Late Ordovician reef types and characters in the border areas of Zhejiang and Jiangxi. In: Fan, J.S. (ed.), *The Ancient Organic Reefs of China and their Relations to Oil and Gas*. Beijing: Ocean Press, 54–75 (in Chinese).
- Blakey, R.C., 2008. Gondwana paleogeography from assembly to breakup—a 500 m.y. odyssey. In: Fielding, C.R., Frank, T.D., and Isbell, J.L. (eds.), *Resolving the Late Paleozoic Ice Age in Time and Space*. Boulder: Geological Society of America, Special Paper, 441: 1–28.
- Bolton, T.E., 2000. Ordovician megafauna, southern Baffin Island, Nunavut. *Geological Survey of Canada, Bulletin*, 557: 39–158.
- Bondarenko, O.B., 1963. Convergences in tabulate corals of the genera *Liopora* and *Nyctopora* from the Upper Ordovician deposits of the Tarbagatay Range. *International Geology Review*, 5: 1501–1509.
- Bondarenko, O.B., and Ulitina, L.M., 2009. Ordovician corals of the Siberian and Mongolian basins: taxonomic diversity, morphogenesis, and occurrence. *Paleontological Journal*, 43: 1439–1457.
- Burrett, C., Zaw, K., Meffre, S., Lai, C.K., Khositantont, S., Chaodumrong, P., Udchacho, M., Ekins, S., and Halpin, J., 2014. The configuration of Greater Gondwana—evidence from LA ICPMS, U-Pb geochronology of detrital zircons from the Palaeozoic and Mesozoic of Southeast Asia and China. *Gondwana Research*, 26: 31–51.
- Cho, D.L., Lee, S.R., Koh, H.J., Park, J.B., Armstrong, R., and Choi, D.K., 2014. Late Ordovician volcanism in Korea constrains the timing for breakup of Sino-Korean Craton from Gondwana. *Journal of Asian Earth Sciences*, 96: 279–286.
- Choi, D.K., and Chough, S.K., 2005. The Cambrian-Ordovician stratigraphy of the Taebaeksan Basin, Korea: a review. *Geosciences Journal*, 9: 187–214.
- Choi, D.K., Chough, S.K., Kwon, Y.K., Lee, S.B., Woo, J., Kang, I., Lee, H.S., Lee, S.M., Sohn, J.W., Shinn, Y.J., and Lee, D.J., 2004. Taebaek Group (Cambrian-Ordovician) in the Seokgaejae section, Taebaeksan Basin: a refined lower Paleozoic stratigraphy in Korea. *Geosciences Journal*, 8: 125–151.
- Chough, S.K., 2013. *Geology and Sedimentology of the Korean Peninsula*. Amsterdam: Elsevier, 363.
- Chough, S.K., Kwon, S.T., Ree, J.H., and Choi, D.K., 2000. Tectonic and sedimentary evolution of the Korean peninsula: a review and new view. *Earth-Science Reviews*, 52: 175–235.
- Chuvashov, B., and Riding, R., 1984. Principal floras of Palaeozoic marine calcareous algae. *Palaeontology*, 27: 487–500.
- Cocks, L.R.M., and Torsvik, T.H., 2004. Major terranes in the Ordovician. In: Webby, B.D., Paris, F., Droser, M.L., and Percival, I.G. (eds.), *The Great Ordovician Biodiversification Event*. New York: Columbia University Press, 61–67.
- Dai, M., Liu, L., Lee, D.J., Peng, Y., and Miao, A., 2015. Morphometrics of *Heliolites* (Tabulata) from the Late Ordovician, Yushan, Jiangxi, South China. *Acta Geologica Sinica* (English Edition), 89(1): 38–54.
- Deng, Z.Q., 1984. Middle-Upper Ordovician corals from the marginal areas of the Ordos Platform, China. *Bulletin of Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences*, 8: 305–322 (in Chinese).
- Elias, R.J., Lee, D.J., and Woo, S.K., 2008. Corallite increase and mural pores in *Lichenaria* (Tabulata, Ordovician). *Journal of Paleontology*, 82: 377–390.
- Flügel, E., 2004. *Microfacies of Carbonate Rocks: Analysis, Interpretation and Application*. Berlin: Springer, 976.
- Golonka, J., and Gawęda, A., 2012. Plate tectonic evolution of the southern margin of Laurussia in the Paleozoic. In: Sharkov, E. (ed.), *Tectonics – Recent Advances*. InTech, 261–282. DOI: 10.5772/50009.
- Hartman, W.D., and Goreau, T.F., 1972. *Ceratoporella* (Porifera: Sclerospongiae) and the chaetetid ‘corals’. *Transactions of the Connecticut Academy of Arts and Sciences*, 44: 133–148.
- Hill, D., 1981. Tabulata. In: Teichert, C. (ed.), *Treatise on Invertebrate Paleontology, Part F: Coelenterata, Supplement 1, Rugosa and Tabulata, Vol. 2*. Boulder and Lawrence: Geological Society of America and University of Kansas Press, F430–F669.
- Kwon, S.W., Park, J., Choh, S.J., Lee, D.C., and Lee, D.J., 2012. Tetradiid-siliceous sponge patch reefs from the Xiaozhen Formation (late Katian), southeast China: a new Late Ordovician reef association. *Sedimentary Geology*, 267–268: 15–24.
- Kwon, Y.K., Chough, S.K., Choi, D.K., and Lee, D.J., 2006. Sequence stratigraphy of the Taebaek Group (Cambrian-Ordovician), mideast Korea. *Sedimentary Geology*, 192: 19–55.
- Lee, D.C., 2013. Late Ordovician trilobites from the Xiaozhen

- Formation in Zhuzhai, Jiangxi Province, China. *Acta Palaeontologica Polonica*, 58: 855–882.
- Lee, D.C., Park, J., Woo, J., Kwon, Y.K., Lee, J.G., Guan, L., Sun, N., Lee, S.B., Liang, K., Liu, L., Rhee, C.W., Choh, S.J., Kim, B.S., and Lee, D.J., 2012. Revised stratigraphy of the Xiazhen Formation (Upper Ordovician) at Zhuzhai, South China, based on palaeontological and lithological data. *Alcheringa*, 36: 387–404.
- Lee, D.J., and Noble, J.P.A., 1988. Evaluation of corallite size as a criterion for species discrimination in favositids. *Journal of Paleontology*, 62: 32–40.
- Lee, K.W., and Lee, H.Y., 1990. Conodont biostratigraphy of the Upper Choson Supergroup in Jangseong-Dongjeom area, Gangwon-do. *Journal of Paleontological Society of Korea*, 6: 188–210.
- Lee, M., Sun, N., Choh, S.J., and Lee, D.J., 2014. A new Middle Ordovician reef assemblage from north-central China and its palaeobiogeographical implications. *Sedimentary Geology*, 310: 30–40.
- Lee, Y.I., Hyeong, K., and Yoo, C.M., 2001. Cyclic sedimentation across a Middle Ordovician carbonate ramp (Duwibong Formation), Korea. *Facies*, 44: 61–74.
- Li, Y., Kershaw, S., and Mu, X., 2004. Ordovician reef systems and settings in South China before the Late Ordovician mass extinction. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 204: 235–254.
- Li, Y.X., and Lin, B.Y., 1982. Subclass Tabulata. In: Xi'an Institute of Geology and Mineral Resources (eds.), *Atlas of Fossils in Northwestern China, Shanxi-Gansu-Ningxia Region Volume 1, Early Paleozoic Section*. Beijing: Geological Publishing House, 50–83.
- Li, Z., and Powell, C.M., 2001. An outline of the palaeogeographic evolution of the Australasian region since the beginning of the Neoproterozoic. *Earth-Science Reviews*, 53: 237–277.
- Lin, B.Y., and Chow, X.H., 1980. Fossil corals from Middle Ordovician in Jiangshan, Zhejiang. *Chinese Academy of Geological Sciences, Institute of Geology Journal*, 1: 28–45.
- Lin, B.Y., and Webby, B.D., 1989. Biogeographic relationships of Australian and Chinese Ordovician corals and stromatoporoids. In: Jell, P.A., and Pickett, J.W. (eds.), *Fossil Cnidaria 5*. Brisbane: Memoir of the Association of Australasian Palaeontologists, 8: 207–217.
- McKenzie, N.R., Hughes, N.C., Myrow, P.M., Choi, D.K., and Park, T., 2011. Trilobites and zircons link north China with the eastern Himalaya during the Cambrian. *Geology*, 39: 591–594.
- Metcalf, I., 2013. Gondwana dispersion and Asian accretion: tectonic and palaeogeographic evolution of eastern Tethys. *Journal of Asian Earth Sciences*, 66: 1–33.
- Nikitin, I.F., and Popov, L.E., 1996. Strophomenid and triplesiid brachiopods from an Upper Ordovician carbonate mound in central Kazakhstan. *Alcheringa*, 20: 1–20.
- Niu, X., Feng, C., and Liu, J., 2007. Formation mechanism and time of Qianzhong Uplift. *Marine and Petroleum Geology*, 12: 46–50 (in Chinese).
- Oh, J.R., Choh, S.J., and Lee, D.J., 2013. A new Middle Ordovician skeletal-dominated reef association from Korea. *Geological Society of America, Abstracts with Programs*, 45: 329.
- Popov, L.E., and Cocks, L.R.M., 2006. Late Ordovician brachiopods from the Dulankara Formation of the Chu-Ili Range, Kazakhstan: their systematics, palaeoecology and palaeobiogeography. *Palaeontology*, 49: 247–283.
- Popov, L.E., Cocks, L.R.M., and Nikitin, I.F., 2002. Upper Ordovician brachiopods from the Anderken Formation, Kazakhstan: their ecology and systematics. *Bulletin of the Natural History Museum, Geology Series*, 58: 13–79.
- Popov, L.E., Holmer, L.E., and Gorjansky, V.J., 1997. Late Ordovician and early Silurian trimerellide brachiopods from Kazakhstan. *Journal of Paleontology*, 71: 584–598.
- Riding, R., 2004. *Solenopora* is a chaetetid sponge, not an alga. *Palaeontology*, 47: 117–122.
- Schneider, C.A., Rasband, W.S., and Eliceiri, K.W., 2012. NIH Image to ImageJ: 25 years of image analysis. *Nature Methods*, 9: 671–675.
- Scotese, C.R., 2001. *Atlas of Earth History*. Arlington: Paleomap Project 1, 52.
- Scrutton, C.T., 1981. The measurement of corallite size in corals. *Journal of Paleontology*, 55: 307–319.
- Sokolov, B.S., 1962. Gruppya Chaetetida, podklass Tabulata, podklass Heliolitoidea. In: Orlov, Y.A. (ed.), *Osnovy paleontologii*. Moscow, 222–379 (in Russian).
- Sokolov, B.S., and Mironova, N.V., 1959. O novom rode ordovikskikh korallov Zapadnoy Sibiri i Severnogo Kazakhstana. *Akademiya Nauk SSSR, Doklady*, 129: 1150–1153 (in Russian).
- Steele-Petrovich, C.T., 2009a. The biological reconstruction of *Tetradium* Dana, 1846. *Lethaia*, 42: 297–311.
- Steele-Petrovich, C.T., 2009b. Biological affinity, phenotypic variation and palaeoecology of *Tetradium* Dana, 1846. *Lethaia*, 42: 383–392.
- Steele-Petrovich, C.T., 2011. Replacement name for *Tetradium* Dana, 1846. *Journal of Paleontology*, 85: 802–803.
- Sun, N., Elias, R.J., and Lee, D.J., 2014. The biological affinity of *Amsassia*: new evidence from the Ordovician of North China. *Palaeontology*, 57: 1067–1089.
- Torsvik, T.H., and Cocks, L.R.M., 2009. The Lower Palaeozoic palaeogeographical evolution of the northeastern and eastern peri-Gondwanan margin from Turkey to New Zealand. In: Bassett, M.G. (ed.), *Early Palaeozoic Peri-Gondwana Terranes: New Insights from Tectonics and Biogeography*. London: Geological Society, Special Publications, 325, 3–21.
- Torsvik, T.H., and Cocks, L.R.M., 2013. Gondwana from top to base in space and time. *Gondwana Research*, 24: 999–1030.
- Wang, B.Y., 1993. New data of the Middle–Late Ordovician biota in Altun Mountains of Xinjiang. *Chinese Science Bulletin*, 38: 1974–1976.
- Wang, J.P., Deng, X.J., Wang, G., and Li, Y., 2012. Types and biotic successions of Ordovician reefs in China. *Chinese Science Bulletin*, 57: 1160–1168.
- Webby, B.D., 2002. Patterns of Ordovician reef development. In: Kiessling, W., Flügel, E., and Golonka, J. (eds.), *Phanerozoic Reef Patterns*. Tulsa: SEPM Special Publication, 72, 129–180.
- Yang, S.W., Jin, C.T., and Zhou, X.Y., 1978. Subclass Tabulata. In: Guizhou Stratigraphic and Paleontological Working Team (eds.), *Atlas of Fossils in Southwestern China, Guizhou Region Volume 1, Cambrian–Devonian*. Beijing: Geological Publishing House, Beijing, 161–251.
- Ye, J., Yang, Y.Y., Xu, A.D., Zheng, B.Y., Zuo, Z.F., Zhou, Y., Li, J.S., Li, Z.X., Song, G.C., and Yong, Y.X., 1995.

- Ordovician Reefs in South-Western Margin Ordos Basin*. Beijing: Geological Publishing House, 80 (in Chinese).
- Yu, N., 1974. A preliminary study on the stratigraphical distribution and zoogeographical province of the Ordovician corals of China. *Acta Geologica Sinica*, 1: 5–23 (in Chinese with English abstract).
- Yu, C.M., 1961. On the corals from the “Nanshan Series”, with reference to the age of the “Gulang Limestone”. *Acta Palaeontologica Sinica*, 9: 329–335 (in Chinese).
- Yu, C.M., 1962. Middle Silurian fossil corals of the northern Qilian Mountains. In: Institute of Geology and Palaeontology, Chinese Academy of Sciences, Institute of Geology, Chinese Academy of Geological Sciences, and Beijing Institute of Geology (eds.), *Geology of Qilian Mountains, Vol. 4*. Beijing: Science Press, 13–109 (in Chinese).
- Yu, C.M., and Zhang, Z.C., 1963. Subclass Tabulata. In: Yu, C.M., Wu, W.S., Zhao, J.M., and Zhang, Z.C. (eds.), *Fossil Corals in China*. Beijing: Science Press, 214–288.
- Zhan, R.B., Rong, J.Y., Jin, J., and Cocks, L.R.M., 2002. Late Ordovician brachiopod communities of southeast China. *Canadian Journal of Earth Sciences*, 39: 445–468.
- Zhang, Y.D., Chen, X., Yu, G.H., Goldman, D., and Liu, X., 2007. *Ordovician and Silurian Rocks of Northwest Zhejiang and Northeast Jiangxi Provinces, SE China*. Hefei: University of Science and Technology of China Press, 189.
- Zhou, D., and Graham, S.A., 1996. The Songpan–Ganzi complex of the West Qinling Shan as a Triassic remnant ocean basin. In: Yin, A., and Harrison, T.M. (eds.), *The Tectonic Evolution of Asia*. Cambridge: Cambridge University Press, 281–299.
- Zhou, Z., and Dean, W.T., 1996. *Phanerozoic Geology of Northwest China*. Beijing: CRC Press, 316.

About the first author

Mirinae LEE, Female; born in 1990, Geoje, Korea; graduated from the Korea University (M.Sc.) in 2014; now a Ph.D. student in Andong National University, Korea; research interests: Early Paleozoic corals and coral-like organisms, paleoecology and paleobiogeography.

E-mail: amsassia@anu.ac.kr