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

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Abstract: A new species of the probable calcareous alga *Amsassia, A. koreanensis*, is recognized from the Duwibong Formation (Middle Ordovician, Darrillian) 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 Webbly, 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 Ultina, 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 affinty 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
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 Darrwilian 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 Xiazheng 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 Xiazheng 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 corallum 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 $3.8 \times 3.7$
mm across and 2.5 mm high. The corallum 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. shaamxiensis*. 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 *Ams sia* above the genus level is unresolved. Previous assignments to the Lichenariida (tabulate corals), Chaetetida (coralline sponges) and Tetardiida (now Pristosyllae; florideophycean rhodophyte algae) are problematic (Sun et al., 2014; present study). We regard *Ams sia* as a probable calcareous alga, possibly with a relation to tetradiids.

**Genus Ams sia** Sokolov and Mironova, 1959 1959 *Ams sia* Sokolov and Mironova, p. 1151. 1981 *Ams sia* Sokolov and Mironova; Hill, p. F513. 2014 *Ams sia* Sokolov and Mironova; Sun, Elias and Lec, p. 1081.

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

**Diagnosis:** Growth form massive, structure phaceloceroid. 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.

*Ams sia 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), Seokgajae, 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 Seokgajae 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, Xiazheng Formation (Upper Ordovician, Katian), Zhuzhai in Yushan, Jiangxi, southeastern China (Fig. 1c–d).

**Diagnosis:** Small species of *Ams sia* 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 phaceloceroid 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 *Ams sia koreanensis* from the Duwibong Formation at three localities in Korea and from the Xiazheng Formation at Zhuzhai, China, number of occurrences (and percentage of total number of occurrences) are shown for each locality and for the combined data

<table>
<thead>
<tr>
<th>Localities</th>
<th>Bipartite</th>
<th>Tripartite</th>
<th>Quadrupartite</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seokgajae</td>
<td>5</td>
<td>14</td>
<td>9</td>
<td>28</td>
</tr>
<tr>
<td>Korea</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sorotgol</td>
<td>(17.9%)</td>
<td>(50.0%)</td>
<td>(32.1%)</td>
<td></td>
</tr>
<tr>
<td>Manhangjae</td>
<td>2</td>
<td>18</td>
<td>22</td>
<td>54</td>
</tr>
<tr>
<td>Korea</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sorotgol</td>
<td>14</td>
<td>13</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>Manhangjae</td>
<td>(25.9%)</td>
<td>(33.3%)</td>
<td>(40.7%)</td>
<td></td>
</tr>
<tr>
<td>China</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zhuzhai</td>
<td>14</td>
<td>13</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>China</td>
<td>(42.4%)</td>
<td>(39.4%)</td>
<td>(18.2%)</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>36</td>
<td>47</td>
<td>39</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>(29.5%)</td>
<td>(38.5%)</td>
<td>(32.0%)</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 2. Thin section photomicrographs of *Amsassia koreanensis* from the Daeibong 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 fissure of modules (black arrows); (c), Transverse section; note the phaeolocerid structure with micrite between some modules (white arrows); (d), Transverse section; white arrows indicate micrite infilling spaces between modules in phaeoloid 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 fissure of modules (black arrows). (a), NHCG 10872; (d), paratype NHCG 10869; (g), NHCG 10874, Seokgassetae, Korea; (b), (c), NHCG 10871, Zhuzhai, China; (e), NHCG 10873-1; (h), NHCG 10875, Manhangtai, Korea; (f), paratype NHCG 10870, Sorotgel, Korea. Scale bar in (a, d–h) = 0.5 mm; scale bar in (b, c) = 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. Tabulac not recognized.

**Discussion:** Although they differ in geographical location and geological age, the coralla of *Amsassia* described above from mid-eastern Korea (Darrwilian) and Zhuhai, 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 Zhuhai (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 shaaxiensis differs from A. koreanensis in having distinctively larger modules (Fig. 4a). In addition, A. shaaxiensis 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. shaaxiensis 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 quadrupartite types of fission were recognized in only one species, A. shaaxiensis (Sun et al., 2014). Quadrupartite fission is rare in A. shaaxiensis, 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 tetrads including a branching species, Rhabdotetradium jiangshanense from the Upper Ordovician of southeastern China (Kwon et al., 2012). In addition to quadrupartite fission, which is typical of tetrads, bipartite and tripartite fission were common in R. jiangshanense under conditions of ecological stress. Although the processes of increase were different in Amsassia and tetrads (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. seshanensis 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 phaceloceridoid 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; Fligel, 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 these 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 Orдовician 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 koreamensis* 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. chaetetoides*), and Laurussia (*A. flowers*). 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. 352), Yu and Zhang (1985, 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. 3–5, 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 Gaweda (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 = Laurussia, 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) Xiazhenv Formation at Zhuzhai, South China, respectively. The new species is characterized by considerably smaller diameter than any other species of Ammassasia 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 Ammassasia 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.

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