

Early Cambrian bioconstructions in the Zavkhan Basin of western Mongolia

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Abstract – The Neoproterozoic–Cambrian succession in the Zavkhan Basin of western Mongolia preserves early Cambrian bioconstructions of Nemakit–Daldynian to Botomian age. As elsewhere (Siberia, Morocco), the Nemakit–Daldynian bioconstructions in the upper Tsagaan Oloom Formation to lower Bayan Gol Formation interval were purely calcimicrobial. Spectacular calcimicrobial ‘patch reefs’ of presumed Tommotian age are present in the lower Bayan Gol Formation. In contrast, late Atdabanian–early Botomian bioconstructions are varied and well developed in the upper Salaany Gol Formation including, in addition to calcimicrobial bioherms, *Gordonophyton–Razumovskia* crusts, radiocyathan–archaeocyathan bioherms and thickets of the ramose archaeocyath *Cambrocycathellus*.

These latter Zavkhan Basin buildups show some ecological and sedimentological features in common with coeval bioconstructions in South Australia, which also developed under a tectonically active regime.

1. Introduction

The Zavkhan Basin of western Mongolia is one of the terranes within the Ural–Okhotsk Fold Belt. In this area, ocean basin formation was initiated by rifting during the Riphean (Khomontovsky & Gibsher, 1996, this issue). Subsequent spreading during the Riphean may have been responsible for the extrusion of subalkali basalts within grabens and rifts (Dzabkhan Formation). Spreading continued during the early Cambrian and thick, shallow water siliciclastic–carbonate sediments (Tsagaan Oloom, Bayan Gol and Salaany Gol formations) were deposited within the Zavkhan Terrane (Mossakovsky *et al.* 1992). These sedimentary rocks contain substantial bioconstructions, especially in areas adjacent to faults bordering uplifts (Kheraskova, 1986).

This Neoproterozoic–Cambrian succession (Fig. 1) rests unconformably on pre-Upper Riphean basement. The succession commences with the Dzabkhan Formation, which consists of volcanogenic rocks (dacite, rhyolite, basalt, andesite, tuff) resting on basal conglomerate, with minor arkose, quartz sandstone, siltstone and dolostone, altogether about 2500 m thick. It is overlain concordantly by the Tsagaan Oloom Formation: 1000–1500 m of dolostone, limestone and minor phosphorite and siliciclastic rocks. The conformably succeeding Bayan Gol Formation (up to 940 m thick) is a mixed siliciclastic–carbonate unit of sandstone, mudstone and conglomerate with limestone intervals. The overlying 400-m-thick Salaany Gol Formation signals a return to carbonate deposition, with widespread archaeocyathan–calcimicrobial buildup development. Fine and coarse siliciclastic rocks of the Khayrkhan

Formation (over 200 m thick) rest unconformably on previous units (Voronin *et al.* 1982; Dorjnamjaa & Bat-Ireedui, 1991).

In the Khasagt-Khayr Khan Range (Fig. 2), the widespread yet stratigraphically constrained occurrence of the late Neoproterozoic stromatolite *Boxonia grumulosa* is taken to indicate a pre-Nemakit–Daldynian (hence pre-Cambrian) age for the medial Tsagaan Oloom Formation (Lindsay *et al.* 1996, this issue). Small skeletal fossils of Siberian and Chinese aspect allow the recognition of the early Nemakit–Daldynian *Anabarites trisulcatus* Zone in the upper Tsagaan Oloom Formation, and the late Nemakit–Daldynian *Purella antiqua* Zone spanning the Tsagaan Oloom Formation–Bayan Gol Formation transition. Putative early to middle Tommotian faunas are found through the remainder of the Bayan Gol Formation (Khomontovsky & Gibsher, 1996, this issue; but see Section 2.a below). Late Atdabanian to early Botomian archaeocyaths characterize the Salaany Gol Formation. A more diverse fauna of Botomian archaeocyaths, with some elements reworked, is present in the Khayrkhan Formation (Voronin *et al.* 1982). The Tsagaan Oloom and Bayan Gol formations have been subdivided as numbered units by Gibsher & Khomontovsky (1990) and Gibsher *et al.* (1991) (Fig. 1).

From observations at Salaany Gol, Tsagaan Gol, Bayan Gol and Tayshir (Fig. 2) during the IGCP 303 field workshop in August–September 1993, the present paper gives a preliminary overview of early Cambrian bioconstruction in the Zavkhan Basin. Primary contributions of the authors are in sedimentology (A. Gandin), ecology (R. Wood, P. D. Kruse) and taxonomy (F. Debrenne), compiled by P. D. Kruse.

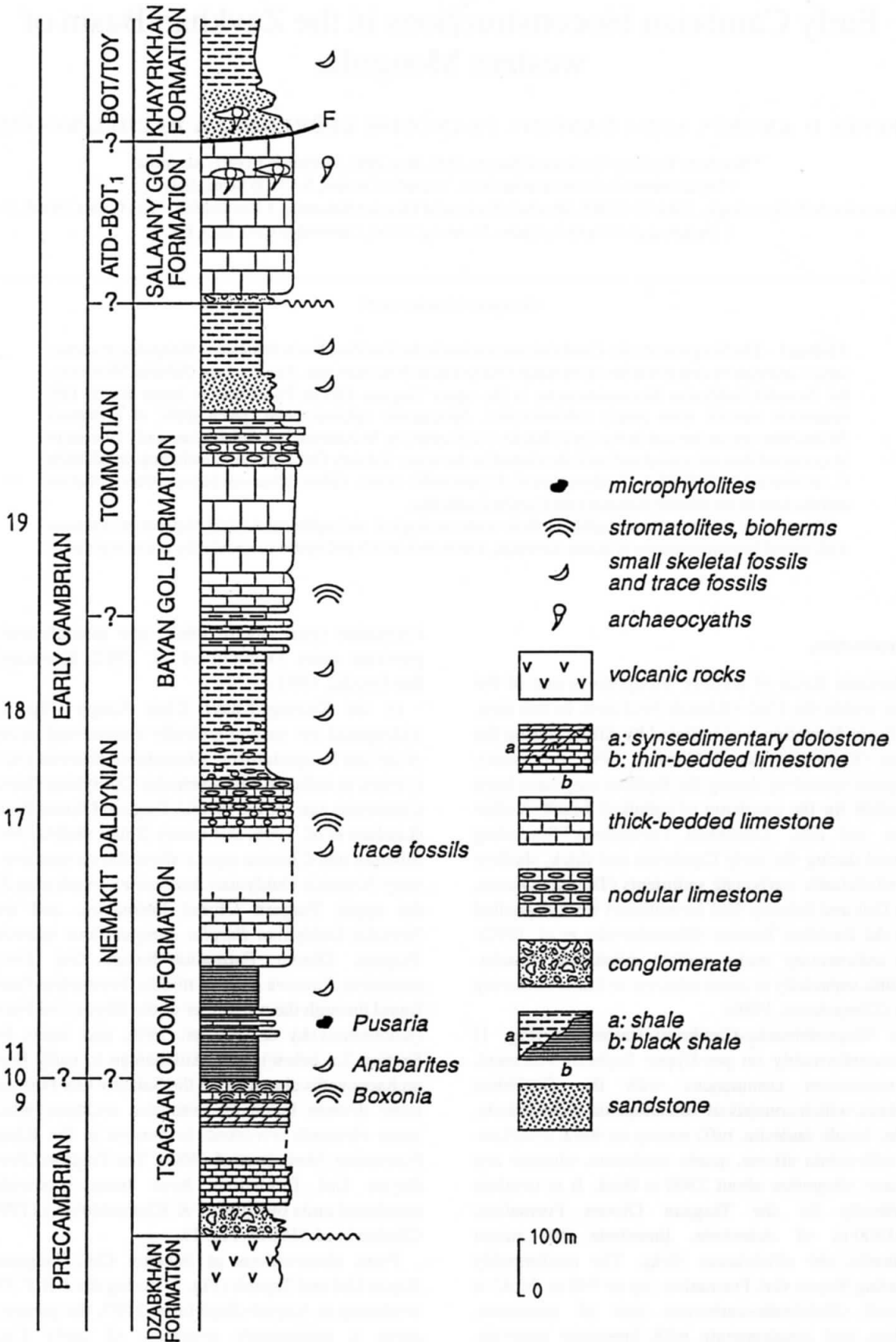


Figure 1. Schematic stratigraphic column of Precambrian–Cambrian succession in the Zavkhan Basin, western Mongolia. Informal Bayan Gol section unit numbers of Gibsher & Khomentovsky (1990) and Gibsher *et al.* (1991) are shown at left.

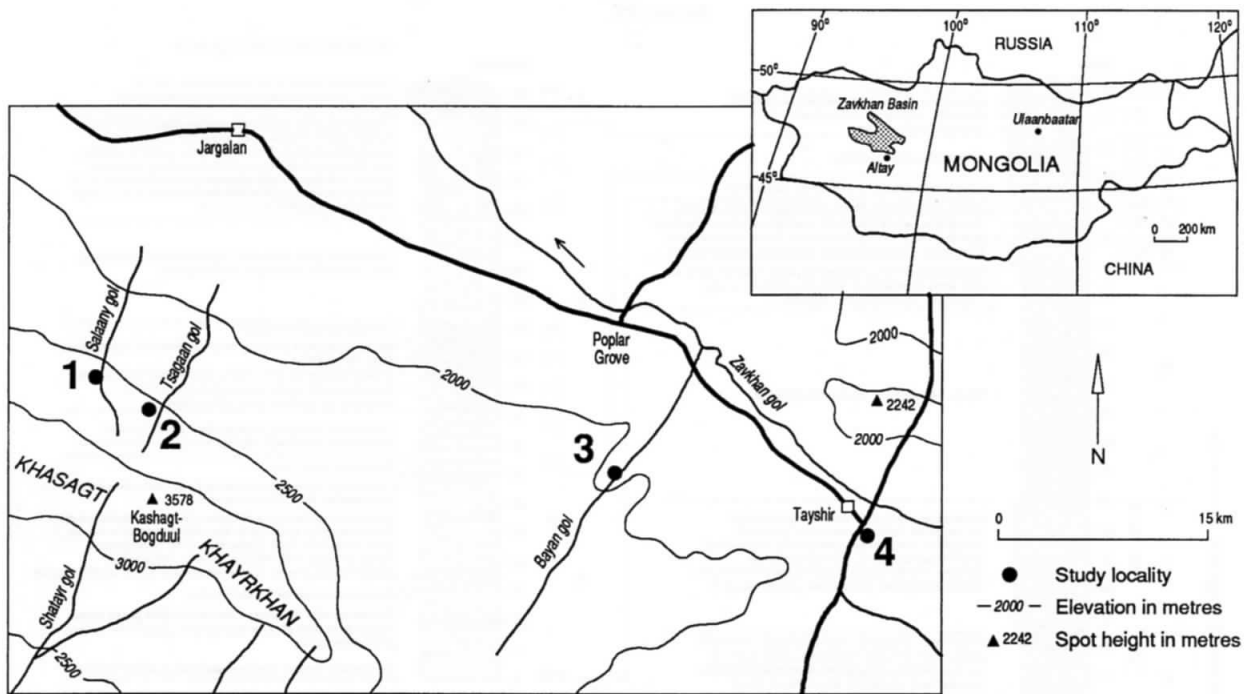


Figure 2. Map of the Khasagt-Khayr Khan Range area, Zavkhan Basin, showing study localities: 1 – Salaany Gol; 2 – Tsagaan Gol; 3 – Bayan Gol; 4 – Tayshir.

Although archaeocyaths originated in neighbouring Siberia at the beginning of the Tommotian, they did not migrate to Mongolia until the late Atdabanian (Rozaov, 1980; Kirschvink & Rozaov, 1984). Hence Nemakit-Daldynian and Tommotian bioconstructions in the Tsagaan Oloom and Bayan Gol formations are without exception purely calcimicrobial, forming dendrolites and stromatolites (Drozdova, 1980). In the study area, only the late Atdabanian–early Botomian buildups of the Salaany Gol Formation include archaeocyaths and other metazoans as bioconstructors.

2. Bioconstruction

2.a. Nemakit-Daldynian

Sections at Bayan Gol and Tsagaan Gol preserve the oldest studied bioconstructions in the Zavkhan Basin. These are purely calcimicrobial, found in the interval straddling the conformable Tsagaan Oloom Formation–Bayan Gol Formation transition. Correlations using small skeletal fossils place these units within the late Nemakit-Daldynian *Purella antiqua* Zone (Khomentovsky & Gibsher, 1996, this issue). Overlying Bayan Gol strata are early to middle Tommotian in age (Khomentovsky & Gibsher, 1996, this issue; Evans *et al.* 1996, this issue; Brasier *et al.* 1996, this issue) or could even represent strata removed beneath the sub-Tommotian unconformity in Siberia (Brasier *et al.* 1996, this issue). These Bayan Gol strata also bear calcimicrobial bioconstructions (not discussed here), in some cases intimately associated with ooid shoals, but ‘patch reefs’

of putative Tommotian age at Tayshir are described in Section 2.b.1.

2.a.1. Bayan Gol

The section in Bayan Gol ravine is complicated by numerous thrust faults. Calcimicrobial bioconstructions were observed in a thrust slice toward the southern end of the ravine (Gibsher *et al.* 1991). A measured section in the lower part of this thrust slice (Fig. 3) encompasses upper unit 17 and lower unit 18 of previous authors (Fig. 1).

Calcimicrobial bioconstructions are abundant in the interval 20–30 m below the top of the Tsagaan Oloom Formation (unit 17; beds B to D in Fig. 3), in grey stylobedded limestone with thin brown-dolomitized interbeds. The bioconstructions are domal bioherms of *Korilophyton* sp. up to 1 m in height and 2 m in diameter, some showing concentric growth. *Tarthinia* is a minor component (Fig. 4a). The biohermal interval is surmounted by low-angle cross-bedded peloid-coated grain limestone (bed E in Fig. 3) above which bioconstructions become uncommon in association with occasional flat pebble breccias and rare ministromatolites (bed I in Fig. 3). These latter bioconstructions are also composed of *Korilophyton* and minor *Tarthinia*.

A prominent 3 m interval of pink/grey boundstone in lower unit 18 (beds R to S in Fig. 3) preserves in its lower portion (bed R) stylobedded calcimicrobial *Korilophyton* biostromes passing upward into bioherms up to 10 cm in height and 20 cm in length (Fig. 4b). These latter may be colonized by red digitate ministromatolites. (Certain

BAYAN GOL

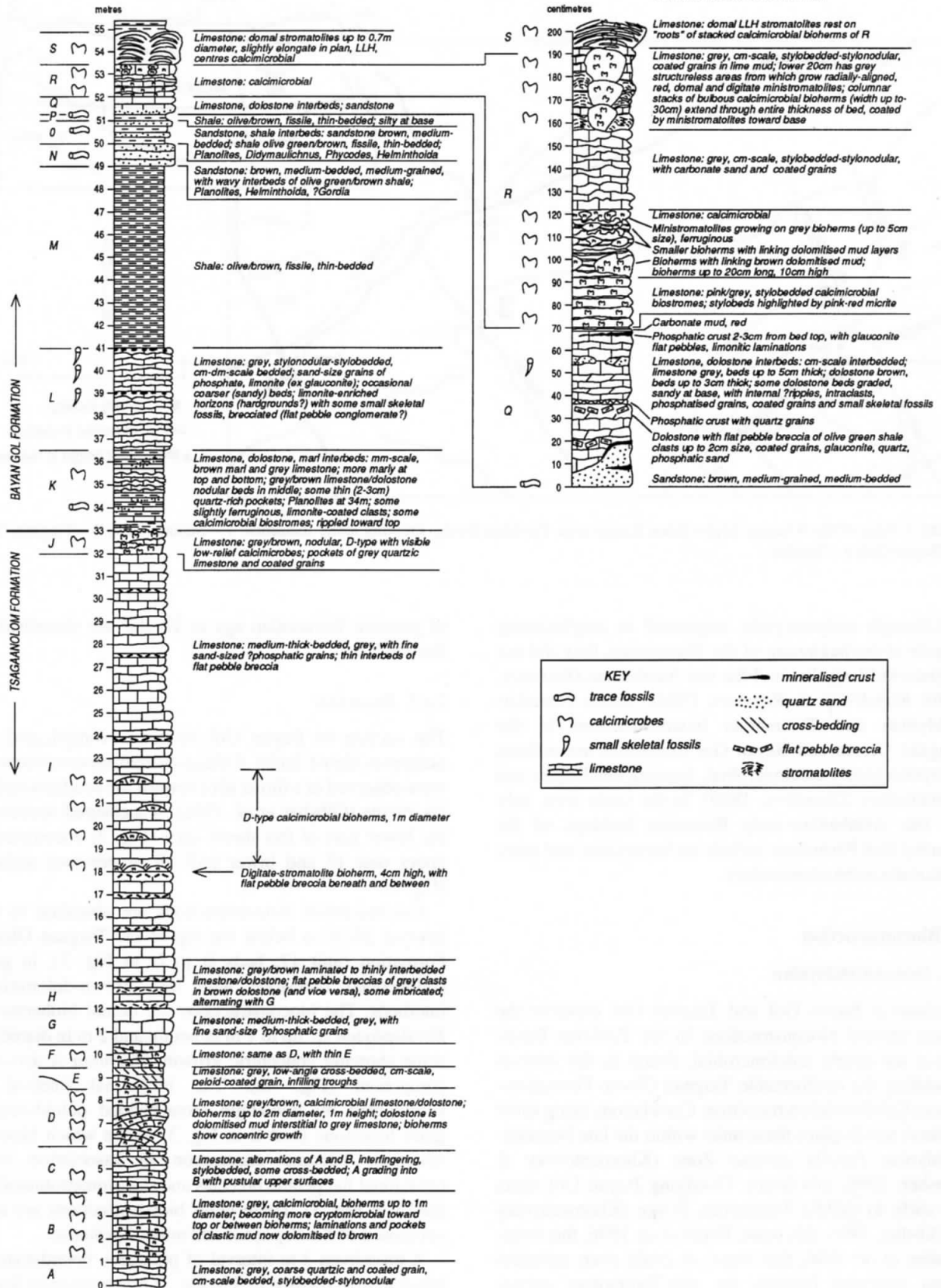


Figure 3. Detailed stratigraphic column through Tsagaan Oloom Formation–Bayan Gol Formation transition (late Nemakit-Daldynian *Purella antiqua* Zone) in Bayan Gol section.

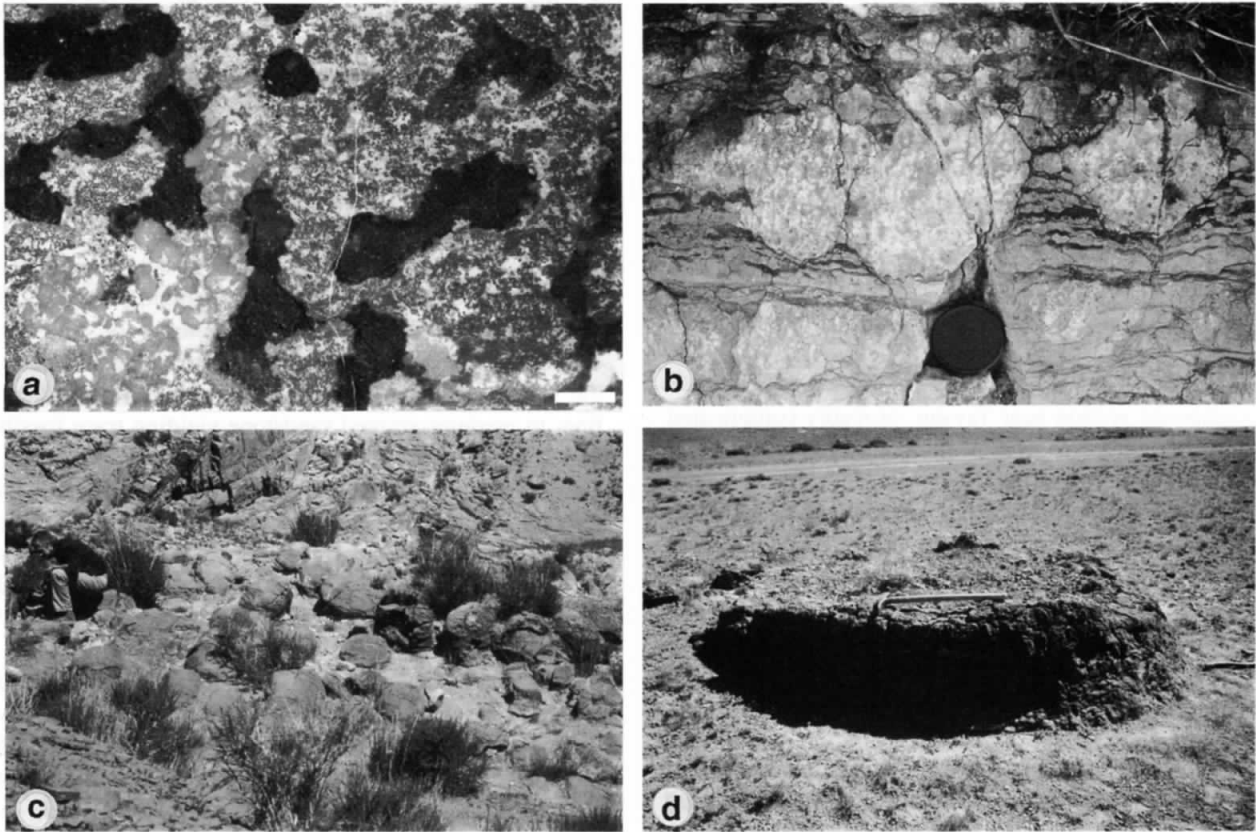


Figure 4. (a) Tsagaan Oloom Formation at Bayan Gol (*Purella antiqua* Zone); bedding-normal thin-section photomicrograph of *Korilophyton-Tarthinia* bioherm in bed D (Fig. 3). Scale bar = 1 mm. (b, c) Bayan Gol Formation at Bayan Gol (*Purella antiqua* Zone). (b) *Korilophyton* bioherms in bed R (Fig. 3). Lens cap 50 mm in diameter. (c) Domal stromatolites in bed S (Fig. 3). Figure at left for scale. (d) Bayan Gol Formation at Tayshir ('Tommotian' Stage); spectacular flat-topped *Gordonophyton* 'patch reef'. Hammer about 1 m in length.

areas within the *Korilophyton* bushes show a vague segmentation of filaments suggestive of *Gordonophyton*, a genus otherwise unknown before the Tommotian. This example reinforces the view of Mankiewicz (1992) that such generic distinctions may be diagenetic artifacts.) Some burrows and other cavities within the *Korilophyton* boundstone preserve geopetal micrite pellet infills; the more common argillaceous lime mud internal cavity sediments may include cryptic burrows.

In the upper portion of bed R, bioconstructions occur as columnar-stacked *Korilophyton* bioherms, the stacks extending through an overall thickness of 30 cm. Again, red, planar and digitate ministromatolites have colonized the bioherm margins, extending outward to also encrust the surrounding grey lime mud substrate. The lime mud is microburrowed by an infaunal deposit-feeding organism (James & Kobluk, 1978; Wood, Zhuravlev & Chimed Tseren, 1993).

The association of these calcimicrobial bioconstructions with flat pebble breccias, coated grains, dolomite and glauconite favours a shallow subtidal marine depositional environment with some inter- to supratidal influence.

The bioherm stacks provide the substrate for the development of domal stromatolites (Fig. 4c; bed S in

Fig. 3), here interpreted as growth into shallower, presumably intertidal waters. Thereafter, stromatolite growth was abruptly terminated by progradation of clastic sediment.

2.a.2. Tsagaan Gol

The Tsagaan Gol valley section exposes a monocline dipping to the southwest, complicated by a single zone of thrust faults (Gibsher & Khomentovsky, 1990). In the nomenclature of these authors, unit 34 in the lower Bayan Gol Formation (equivalent to part of Bayan Gol section unit 18) consists of centimetre-scale bedded grey limestone and thinner marl interbeds with scattered phosphatic grains (including small skeletal fossils). Rare, small bioherms up to 3.5 m in length and 15 cm in thickness, constructed by bushy to dendritic masses of the calcimicrobe *Korilophyton*, are scattered through an interval 3–5 m above the base of unit 34. They initiate on undisturbed beds and show rounded upper surfaces. Lacking traction current structures, unit 34 might represent a sheltered, open lagoon to restricted shelf environment – the low-energy counterpart to the calcimicrobial interval described above from bed R (Fig. 3) at Bayan Gol.

Calcimicrobes reported from the preceding *Anabarites trisulcatus* Zone at Tsagaan Gol include '*Epiphyton*' sp., *Renalcis polymorphus*, *Botominella lineata* and *Korilophyton inopinatum* (Korobov, 1980; Endonzhams & Lkhasuren, 1988). Unit 34 is separated from overlying calcimicrobe-bearing Tommotian limestones (unit 36, equivalent to Bayan Gol section unit 19) by 30 m of glauconitic calcareous green-brown sandstone and siltstone (unit 35) bearing trace fossils of early Cambrian aspect.

2.a.3. Tayshir

A composite section near Tayshir, probably complicated by thrusts, embraces several intervals of calcimicrobial bioconstruction (Fig. 5).

Bioconstructions of uncertain age (Nemakit-Daldynian or Tommotian) are present in the upper Tsagaan Oloom or lower Bayan Gol Formation (1–8 m interval in Fig. 5), above a trace fossil assemblage of *Didymaulichnus* and *Planolites*. The bioconstructions are within two intervals of grey, centimetre-scale stylobedded to stylonodular, partially quartzic limestone with some low-angle cross-bedding.

Associated trace fossil-bearing olive green shale to fine sandstone throughout the composite section includes broken and corroded quartz, composite microgranular quartz (recrystallized glass) and albite and oligoclase feldspar indicating acidic, possibly rhyolitic volcanic activity before or contemporaneous with sedimentation. These may represent material reworked from the Dzabkhan Formation. Associated ooids, however, have carbonate nuclei implying a provenance unaffected by the terrigenous influx, perhaps on the distal shelf. Glauconite occurs commonly as deep green, rounded grains, presumed to be reworked from deeper, open shelf environments (Odin, 1985).

The bioconstructions are bulbous to prolate calcimicrobial bioherms of bushy *Korilophyton* (and/or *Gordonophyton*?) up to 2.5 m in height and 1–3 m in length. Some bioherms commence as narrow, columnar structures, expanding at their summits to become broad domes. Others show ragged lateral margins, interfingering with the adjacent sediment.

Sedimentary structures suggest a low-energy shallow marine depositional environment with intermittent higher-energy episodes generating cross-bedding. Pockets of ooid-bearing limestone in overlying beds imply shoaling into episodically high-energy conditions.

2.b. 'Tommotian'

2.b.1. Tayshir

Apparently conformable above the upper Tsagaan Oloom/lower Bayan Gol Formation section at Tayshir, but possibly separated from it by a thrust, is a 360-m-thick section of moderately dipping Bayan Gol Formation termed Tayshir I (Fig. 5). It is richly

fossiliferous, yielding a putative Tommotian small skeletal fauna including *Cambrotubulus decurvatus*, *Nomgoliella rotunda*, *Latouchella parva*, *L. korobkovi*, *Barskovia* sp., *Ilsanella* sp. and *Hyolithellus* sp., in association with a diverse trace fossil assemblage including *Oldhamia*, *Cochlichnus* and *Helminthopsis* (Dorjnamjaa & Bat-Ireedui, 1991; Goldring & Jensen, 1996, this issue).

Overlying Tayshir I, but again possibly separated from it by a thrust, is a gently dipping section of grey limestone with spectacular outcrop of ring-like calcimicrobial bioherms similar to patch reefs. Locally, the section commences with green-brown, thin-bedded, fine- to medium-grained sandstone yielding trace fossils including *Didymaulichnus*, *Cochlichnus* and *Planolites*. This passes up-section through a 1–2-m-thick transitional interval of ooid (or microphytolite)-bearing glauconitic sandstone and quartzic limestone into 2–5 m of grey medium-bedded *Gordonophyton* biostromes with local pockets of fine-grained glauconitic sandstone and ooid sediment.

The 'patch reef' bioherms surmount the section, and are fully exposed at two known localities ('Discovery Site' and 'Ovoo Site' in Fig. 5) as isolated and conjoined mounds up to 3 m in diameter and 0.7 m in height (Fig. 4d). They have smooth, steep sides and, as preserved, show flattened, concave or slightly domal tops. These *Gordonophyton* masses grew as a series of concentric 10–20-cm-thick increments from a central nucleating point (Fig. 6). Some domes are slightly elongate, forming ellipses. In plan view they exhibit some northeasterly alignment, but there is no demonstrable overall alignment to any prevailing current.

The bioherms are surrounded by green-brown, laminated to thin-bedded, glauconitic shale to fine sandstone variously ooid-bearing or rich in small skeletal fossils. The phosphatized skeletal fossils (a fauna of molluscs and siphonogonuchitids) also form accumulations adhering to the bases of bioherms. Some bioherms show ragged lateral margins indicative of episodic sedimentation and subsequent regrowth over new substrate. Phosphatization presumably occurred during periods of little or no sediment influx.

Both bioherms and biostromes, here and lower in the section (see Section 2.a.3), incorporate growth cavities filled with mudstone and smaller, irregular dissolution cavities with geopetal infill. Cements are poorly developed, consisting of short needle-like fibres, fibrous calcite (similar to fascicular optic type) or coarse microsparite. The needle-like fibres, probably a pseudomorph of aragonite (James & Klappa, 1983; Grotzinger & Reed, 1983), appear to be composed of coarse microcrystalline calcite with microsparitic texture. Microsparite comprising the internal cavity mud displays the same texture, suggesting a high Mg content for the original lime mud (aragonite?) (Folk, 1974; Longman, 1977).

These bioherms evidently grew in very shallow,

TAYSHIR

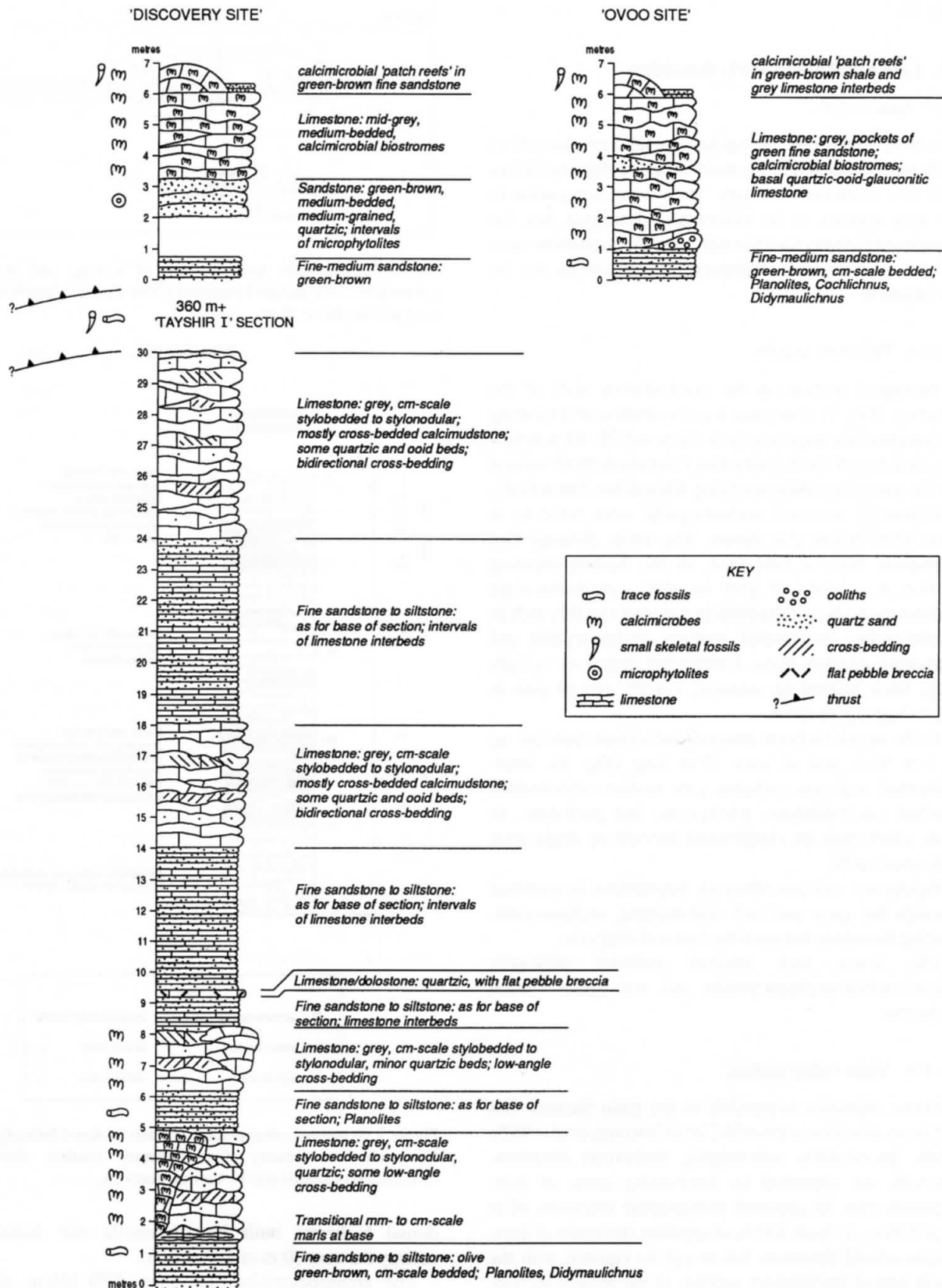


Figure 5. Detailed stratigraphic column through Tsagaan Oloom Formation–Bayan Gol Formation transition (late Nemakit-Daldynian *Purella antiqua* Zone to Tommotian) in Tayshir composite section.

episodically agitated waters. Their flat upper surfaces suggest that in some cases they grew up to sea level (Fig. 6).

2.c. Late Atdabanian–early Botomian

2.c.1. Salaany Gol

Excellent exposures of calcimicrobial–archaeocyathan reefs were examined in the main valley of Salaany Gol as well as a southwest tributary. The overall succession in the area appears to be tectonically deformed, but the uppermost Salaany Gol Formation in the immediate area of the southwestern tributary is considered to be undisturbed.

2.c.1.a. Tributary section

A measured section up the northwestern wall of the tributary (Fig. 7) illustrates the distribution of bioherms in two intervals respectively 0–10 m and 28–40 m below the local top of the Salaany Gol Formation (here incised by the unconformably overlying Khayrkhan Formation). Additionally, scattered archaeocyaths were noted to at least 43 m below this datum. The entire Salaany Gol Formation here is limestone; in the bioherm-bearing portion it consists of grey to pink, centimetre-scale undulatory beds, stylobedded in part and variably rich in calcimicrobes, transported sponges, archaeocyaths and khasaktiid coralomorphs. Underlying limestone is light grey, thick-bedded to massive, calcite veined and in places vaguely mottled.

In the upper bioherm interval, individual reefs are up to 5 m thick and at least 10 m long (Fig. 8). Inter-biohermal sediment includes grey medium-stylobedded bioclast calcimudstone, wackestone and packstone, in beds which may be compressed beneath or drape over individual reefs.

Patchy red calcimicrobe-rich boundstone is scattered through the grey and red, stylobedded, archaeocyath-bearing limestone between the two reef intervals.

The lower reef interval includes pink-grey calcimicrobial–archaeocyathan and red calcimicrobial bioherms.

2.c.1.b. Main valley section

Tectonic repetition is possible in the main Salaany Gol valley section (see section N-224 of Voronin *et al.* 1982), where prominently outcropping biohermal limestone intervals are separated by intervening areas of non-exposure over an apparent stratigraphic thickness of at least 330 m. At least 100 m of apparent thickness of grey, calcite-veined limestone below can be equated with the lower part of the tributary section. In the present section, this latter interval additionally includes grey *Batinevia* and red *Gordonophyton* bioherms and a 4–10-m-thick unit of pink quartz-granule conglomerate with carbonate matrix and with ooid-rich flat pebbles at the base. Low

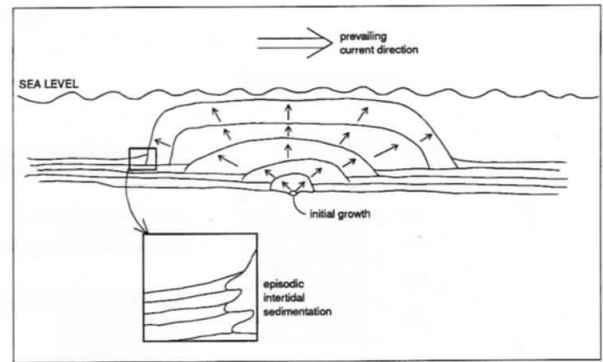


Figure 6. Schematic reconstruction of ecology and growth parameters of Bayan Gol Formation ('Tommotian') 'patch reefs' in upper Tayshir section.

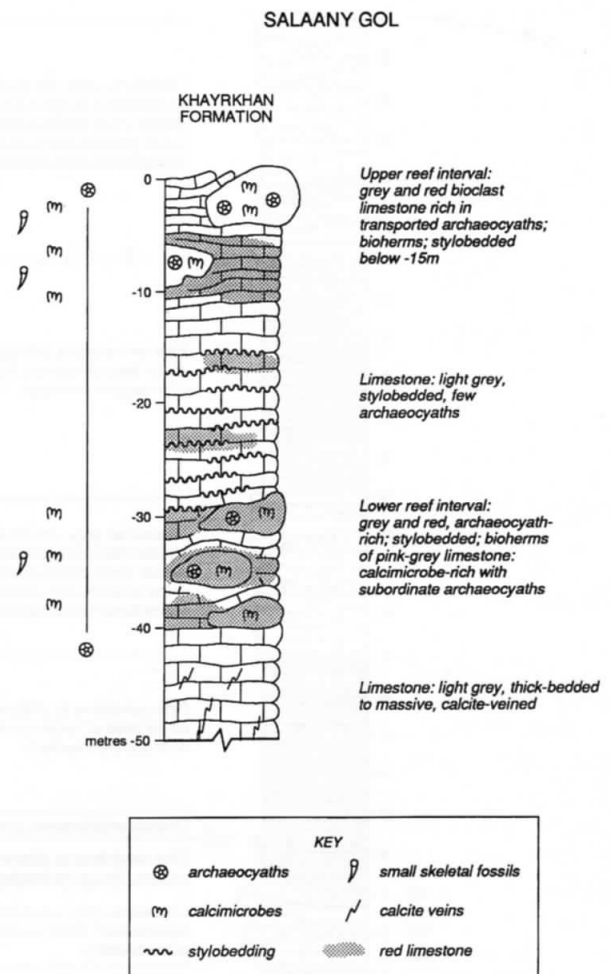


Figure 7. Schematic stratigraphic column of upper Salaany Gol Formation in Salaany Gol tributary section showing distribution of fossils and biohermal intervals.

domal bioherms built by *Girvanella* and *Batinevia* occupy the next 80 m of the section.

The archaeocyath-bearing units (180–330 m above the base of the section) include biohermal boundstones and interbiohermal light grey stylobedded bioclast grainstone, packstone and floatstone with abundant transported archaeocyaths.

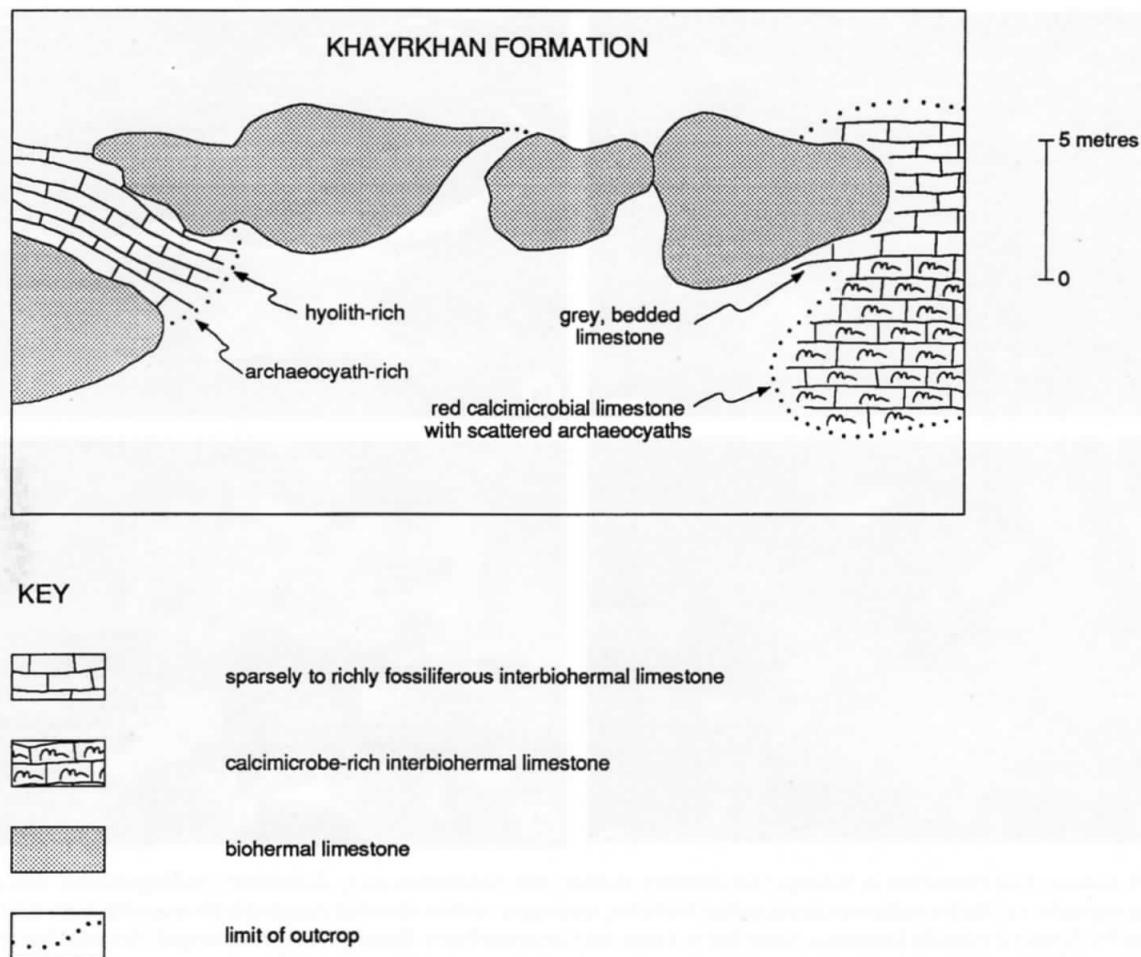


Figure 8. Field sketch of a 25-m-wide traverse of the Salaany Gol Formation upper biohermal interval in the Salaany Gol tributary section illustrating relationship between biohermal and interbiohermal rocks.

2.c.1.c. Lithology and depositional environment

Biohermal and interbiohermal observations from both sections are here treated collectively.

Interbiohermal lime mud consists exclusively of microsparite, often rich in silt-size siliciclastic detritus. In biohermal boundstones, such microsparite acts as geopetal internal sediment in some growth cavities.

Occasional ooids showing well-developed radial-concentric cortices around *Batinevia* nuclei are scattered through bioclastic-siliciclastic grainstones associated with *Batinevia* bafflestone, and within internal sediments of growth cavities in the lowermost bioconstructions of the main valley section. Siliciclastic detritus (including quartz of volcanic provenance) is common to locally abundant.

Bioherms were initiated directly on grainstone substrate, and were quickly lithified to develop a prominent peripheral cement rim indicating palaeorelief of a few centimetres.

Three bioherm types are recognized (see Section 2.c.1.d). Cements are well developed in all three types, commonly occluding cavities in boundstones and bafflestones, as well as intergranular porosity in grainstones. Cement types include:

(a) Slightly arcuate fans of long, microsparitic calcite needles forming irregular, bladed areas showing sweeping extinction. These may represent pseudomorph botryoidal aragonite.

(b) Shorter needle-like fibres surrounding calcimicrobial masses, very like the aragonitic cement figured by James & Ginsburg (1979) and Grotzinger & Reed (1983).

(c) Fans of long, bladed crystals of pseudomorph aragonite apparently grown replacively within the matrix (Fig. 9a).

(d) Abundant type 3 fibrous cement of James & Klappa (1983) lining cavities. Such cavities are generally occluded by prismatic or equant calcite.

(e) Flat-topped conical bundles, similar to type 2 of James & Klappa (1983), oriented normal to the substrate, exhibiting sweeping extinction and sharp boundaries between bundles.

(f) Prismatic calcite, directly encrusting cavity walls or post-dating first-stage cements.

(g) Equant calcite is uncommon, either as the final occlusion of cavities or as the only cement occluding geopetal structures and in tectonic fractures. This cement type, together with types (a), (d) and (e), is strongly

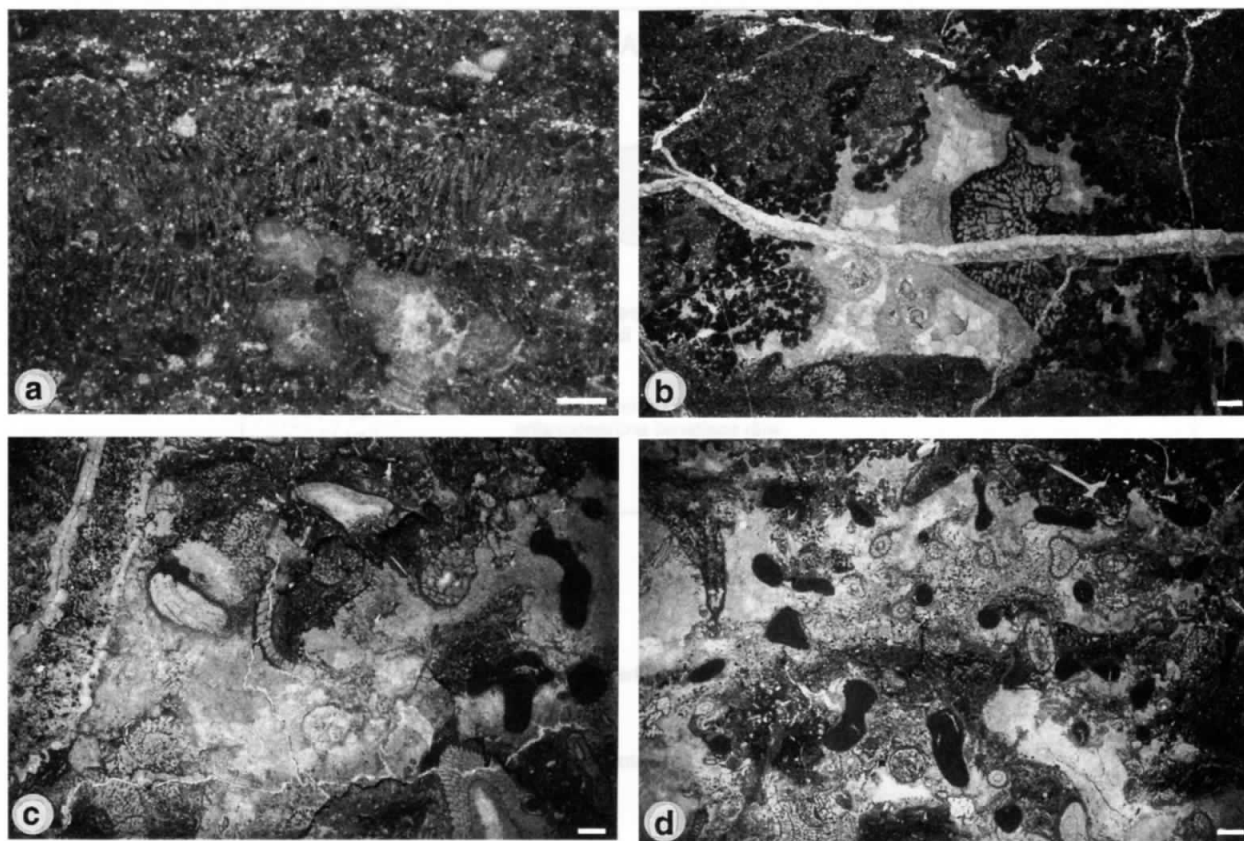


Figure 9. Salaany Gol Formation in Salaany Gol tributary section (late Atdabanian–early Botomian); bedding-normal thin-section photomicrographs. (a) Radiocyathan–archaeocyathan bioherm; transverse section showing pseudomorph aragonite botryoid cement encrusted by *Tarthinia rotunda* Drozdova. Scale bar = 1 mm. (b) *Gordonophyton*–*Razumovskia* crust; cryptic dictyofavine archaeocyath and possibly in part cryptic *Tarthinia* and *Gordonophyton* in shelter cavity. Note fibrous rimming cement. Scale bar = 1 mm. (c) Radiocyathan–archaeocyathan bioherm; radiocyath *Girphanovella georgensis* (Rozanov) (at left) and possible cryptic community of *Archaeolynthus solidimurus* (Vologdin), a dictyofavine archaeocyath and coralmorph *Racovskia mongolica* Vologdin. Scale bar = 2 mm. (d) Radiocyathan–archaeocyathan bioherm; coralmorph *Racovskia mongolica* Vologdin (dark) and archaeocyath *Cambrocyathellus pannonicus* (Fonin). Note radiocyath nesasters and microburrowing of geopetal cavity infills (top right). Scale bar = 2 mm.

deformed, with multiple twinning and curved lamellae.

The above cement types have been widely reported from Early Cambrian bioconstructions (James & Klappa, 1983; Gandin & Debrenne, 1984; Debrenne, Gandin & Rowland, 1989; Debrenne, Gandin & Gangloff, 1990; Rees, Pratt & Rowell, 1989; James & Gravestock, 1990; Wood, Zhuravlev & Chimed Tseren, 1993) and from modern reefs (James & Ginsburg, 1979).

Apart from cement types (f), considered a product of near-surface diagenesis in contact with mixed marine and meteoric waters, and (g), commonly interpreted as late diagenetic (burial under the influence of non-marine fluids), all the remaining cement types show morphologies and relationships indicative of early marine precipitation in sea-water of high Mg concen-

tration (Folk, 1974; James & Klappa, 1983). The abundance of marine cements and occasional elongate fibres and large botryoids further suggest high-energy conditions during growth of these buildups.

2.c.1.d. Ecology

The three types of bioconstruction recognized here are:

(1) *Gordonophyton*–*Razumovskia* crusts. This bioconstructional type consists of crust-like intergrowths of the calcimicrobes *Gordonophyton* (Fig. 10a) and *Razumovskia* supporting a cryptic community of coralmorphs, cribriocyaths and archaeocyaths in shelter cavities. Crusts are interpreted to have had a relief of little more than a few centimetres above the substrate. Much bioclastic

Figure 10. Salaany Gol Formation in Salaany Gol tributary section (late Atdabanian–early Botomian); bedding-normal thin-section photomicrographs. (a) *Gordonophyton*–*Razumovskia* crust; *Gordonophyton* bush with incremental growth. Scale bar = 1 mm. (b) Radiocyathan–archaeocyathan bioherm; ramose *Cambrocyathellus* domain with probable cryptic community of *Nochoroicyathus chassaktuensis* (Vologdin) and *Cambrocyathellus communis* (Fonin). Scale bar = 2 mm. (c) Radiocyathan–archaeocyathan bioherm; ramose *Cambrocyathellus* domain showing framework of *Cambrocyathellus communis* with scattered regular archaeocyaths (*Tumulocyathus pustulatus* Vologdin and *Nochoroicyathus certus* (Voronin)). Scale bar = 2 mm. (d) Calcimicrobial bioherm; *Batinevia* community. Scale bar = 2 mm.

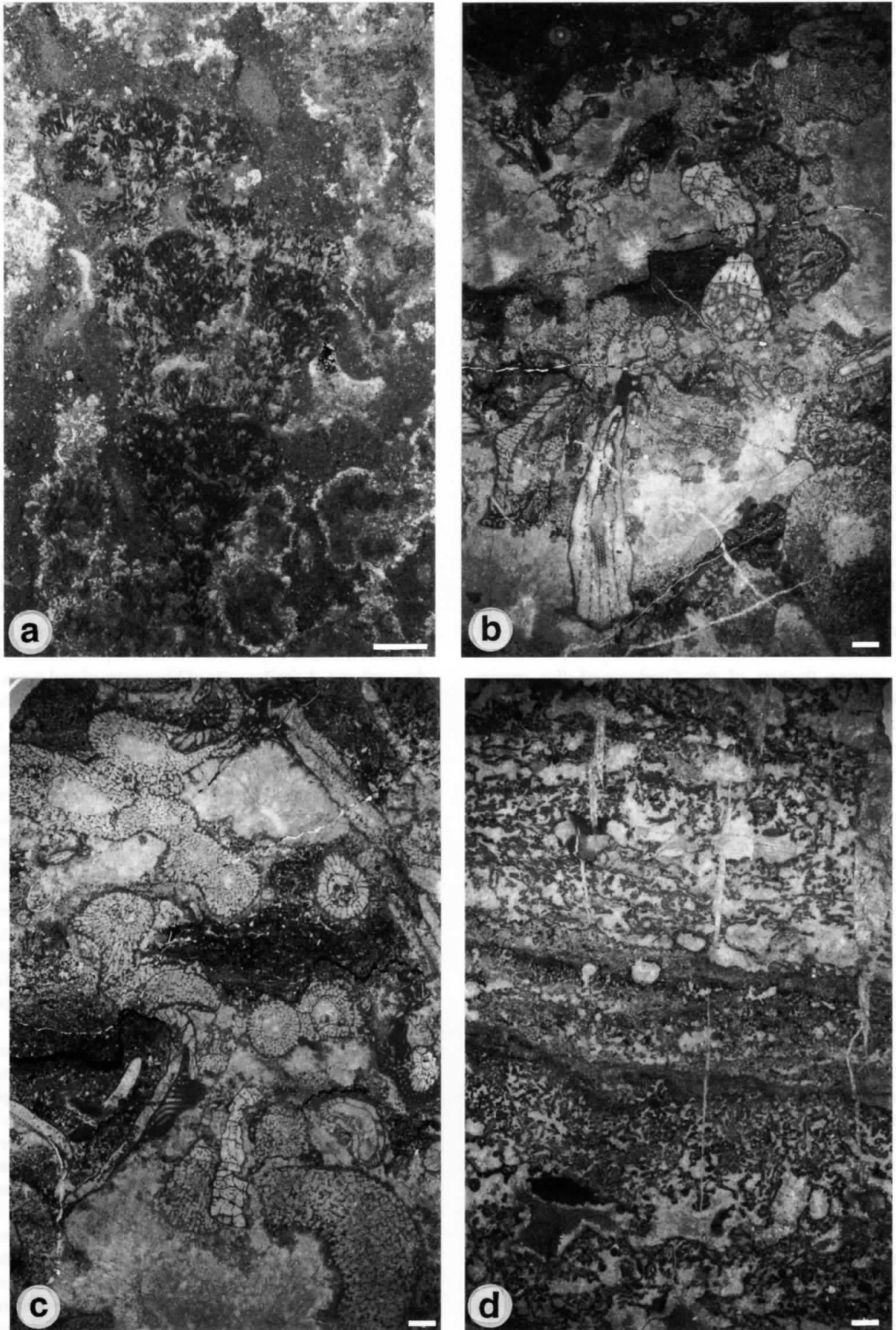


Figure 10. For legend see facing page.

debris of radiocyath nesasters, cancelloriid sclerites, *Dodecaactinella* sponge spicules, stenothecoid fragments and hyoliths is also present. A diverse archaeocyathan assemblage (Table 1) is dominated by *Archaeopharetra marginata* together with abundant ramose *Cambrocyathellus pannonicus* and *C. tuberculatus* and the coralomorph *Edelsteinia*. Mud in sheltered areas is commonly microburrowed.

The coralomorphs *Khasaktia* and *Edelsteinia* occur almost exclusively as cryptobionts. They in turn provide the substrate for the subsequent attachment of other crypt dwellers such as the archaeocyaths *Alataucyathus jaroshevitschi*, *Ichnosocyathus changaiensis*, *Dictyocyathus confertus* and *Cambrocyathellus tuberculatus*, as well as calcimicrobes (Zhuravlev & Wood, 1995).

(2) Radiocyathan–archaeocyathan bioherms. These buildups are dominated by the radiocyath *Girphanovella georgensis* together with a diversity of archaeocyaths and the coralomorphs *Hydroconus*, *Edelsteinia* and *Khasaktia* (Fig. 9c, d). The most common elements of the diverse and abundant archaeocyathan fauna are *Cambrocyathellus pannonicus*, *C. tuberculatus* and *C. communis*. *Okulitchicyathus* sp. served a binding function, in that adjacent individuals were often conjoined by secondary thickening. Calcimicrobes are relatively minor, most commonly encrusting archaeocyaths; extensive calcimicrobial bushes are uncommon. Conversely, mud- and cement-rich domains predominate.

As well, small domains within buildups are dominated by ramose thickets of the *Cambrocyathellus* species (Fig. 10b, c). Thickets were locally stabilized by exothecal secondary thickening or syndimentary fibrous cement. Small solitary archaeocyaths acted as dwellers within the thickets.

Abundant bioclastic debris of cancelloriids and hexactinellide and demosponge spicules occurs together with considerable microburrower activity within sheltered red argillaceous and grey lime mud areas. Dictyofavine archaeocyaths, calcimicrobes and cribricyaths are locally cryptic, and cribricyaths additionally encrust archaeocyaths. Pseudomorph aragonite fans and clotted red micrite are common.

Peribiohermal sediment includes similar red argillaceous and grey lime mud typically rich in archaeocyaths and shelter cavities, but virtually devoid of cryptic organisms.

(3) Calcimicrobial bioherms. These include layered fabric of intergrown erect bushes of *Gordonophyton* sp., *Batinevia* sp., *Proaulopora* sp. and rafts of *Razumovskia* sp. several centimetres in thickness (Fig. 10d). Archaeocyaths (among which *Cambrocyathellus tuberculatus* is most common) and assorted bioclastic debris are associated.

3. Discussion

Calcimicrobial bioherms and biostromes of inferred Nemakit-Daldynian and Tommotian age are widespread in the Zavkhan Basin. They were constructed by *Renalcis*, *Korilophyton*, *Tarthinia* and *Botominella*,

among other forms. Nemakit-Daldynian bioherms were domal to stacked–columnar at least, while by Tommotian time domal, bulbous, prolate or columnar–oblate examples are known. Burrows in internal cavity infills within late Nemakit-Daldynian *Korilophyton* boundstone at Bayan Gol represent the oldest known record of cryptic metazoans (Zhuravlev & Wood, 1995).

Except at Tsagaan Gol, these bioconstructions are associated with cross-bedded coated grain (including ooid) limestones, flat pebble breccias, mini- and megastromatolites, dolomite and glauconite implying a relatively high-energy shallow subtidal environment, in some cases with peritidal influence, and subject to intermittent diminution of sedimentation rate allowing the development of mineralized crusts and small skeletal fossil concentrations. Nemakit-Daldynian bioherms were also able to grow in sheltered open-lagoon to restricted-shelf settings lacking traction current structures at Tsagaan Gol, but these bioherms are smaller and less common than elsewhere. Overall, it is apparent that calcimicrobial bioconstruction in this time interval was favoured by higher-energy conditions and was also able to proceed despite a moderate influx of non-carbonate detrital sediment.

Late Atdabanian–early Botomian calcimicrobial crusts, calcimicrobial bioherms and radiocyathan–archaeocyathan bioherms are recognized in the Salaany Gol Formation at Salaany Gol. The Salaany Gol Formation is also exposed at Zuune Arts, some 60 km to the northeast. A similar suite of bioconstructional types is reported from the Zuune Arts succession, where oolites and stromatolites are abundant (Wood, Zhuravlev & Chimed Tseren, 1993), but the biohermal biota is less diverse. Wood, Zhuravlev & Chimed Tseren (1993) identified the richest faunal diversity in the highly tiered radiocyath-dominated community at Zuune Arts, which they interpreted as having occupied a slightly deeper-water (though nevertheless moderate- to high-energy) setting than the associated shallow, energetic-water calcimicrobe-dominated communities at that locality. The absence of such shallow-water indicators as oolites and stromatolites at Salaany Gol, together with the presence of a more diverse biota, suggests that this succession represents bioconstruction on a yet deeper and more open part of the Zavkhan shelf.

Overall, the archaeocyathan assemblage of the Salaany Gol Formation shows a clear species-level commonality with Siberian faunas. It is typified by simply organized archaeocyaths: *Archaeolynthus*, *Dokidocyathus*, *Nochoroicyathus* and *Rotundocyathus*, with simple outer and/or inner walls, are most abundant among the regular archaeocyaths (Table 1). Such morphologies are thought to have been common in relatively agitated conditions where archaeocyaths were able to utilize the strength of ambient currents for filter feeding (Debrenne & Zhuravlev, 1996). In contrast, those genera considered characteristic of calm environments are relatively insignificant: forms with complicated outer

Table 1. Faunal list for upper Salaany Gol Formation in Salaany Gol section

	GR	RA	RC	CB
Archaeocyaths				
<i>Archaeolynthus solidimurus</i> (Vologdin)	+	+	+	+
<i>Tumulioylnthus tubexternus</i> (Vologdin)	+	+	a	+
<i>Dokidocyathus tuvaensis</i> Rozanov	+	+	+	+
<i>Nochorocyathus misertumulus</i> (A. Zhur.)	+	+	+	
<i>Nochorocyathus amplus</i> (Vologdin)	+	+		
<i>Nochorocyathus certus</i> (Voronin)	+	+	+	+
<i>Nochorocyathus concinnus</i> (Voronin)	+	+	+	
<i>Nochorocyathus chassaktuensis</i> (Vologdin)	a	+	+	
<i>Nochorocyathus howelli</i> (Vologdin)	+	+	+	
<i>Orbicyathus mongolicus</i> Vologdin	+	?	r	
<i>Urcyathus</i> sp.	+	+		
<i>Ajacyathus mongolicus</i> Voronin	+	+		
<i>Robustocyathellus abundans</i> (Vologdin)	+	+	r	
<i>Rotundocyathus floris</i> (Voronin)	+	+	+	
<i>Rotundocyathus levigatus</i> (Vologdin)	+	+	+	
<i>Leptosocyathus</i> sp.		+		
<i>Ichnusocyathus changaiensis</i> (Vologdin)	+	+		
<i>Baikalocyathus</i> ex. gr. <i>mirus</i> Rozanov	+	+		
<i>Bipallicyathus manifestus</i> A. Zhur.	+	+		
<i>Pretiosocyathus subtilis</i> Rozanov	+	+		?
<i>Ladaeyathus melnikovae</i> A. Zhur.	+	+	+	
<i>Tumulocyathus pustulatus</i> Vologdin	+		+	?
<i>Plicocyathus stellatus</i> (Voronin)	+			+
<i>Sclerocyathus floridus</i> (Voronin)	+			+
<i>Tologicyathus</i> sp.	+	+	+	
? <i>Fallicyathus fructosus</i> A. Zhur.	+			
<i>Mennericyathus shoriensis</i> (Rozanov)		+	?	+
<i>Capsulocyathus irregularis</i> (Zhuravleva)	+		+	
<i>Fransuaeacyathus</i> sp.		+	+	
<i>Alatacyathus jaroschevitschi</i> (Zhuravleva)	+	+	a	
? <i>Acanthinocyathus</i> sp.		+		
<i>Cambrocyathellus communis</i> (Fonin)	+	a	+	
<i>Cambrocyathellus tuberculatus</i> (Vologdin)	a	a	a	a
<i>Cambrocyathellus pannonicus</i> (Fonin)	a	a	a	
<i>Okulitchicyathus</i> sp. nov.	+	+	+	+
<i>Dictyocyathus confertus</i> (Fonin)	+		+	+
<i>Chouberticyathus lepidus</i> (Fonin)	+	+	?	
<i>Archaeopharetra marginata</i> (Fonin)	d	+	+	+
<i>Spinocyathus mongolicus</i> Fonin		+		+
<i>Tabulacyathellus bidzhaensis</i> Missarzhevskiy	+	+	+	
<i>Dictyofavina</i> - <i>Syringocnemidida</i>		?	+	+
Problematic organisms				
<i>Cribricyathus</i>	a	+	+	+
<i>Hydroconus tenuis</i> (Vologdin)	+	a	+	+
<i>Khasaktia intermedia</i> (Sayutina)	+	a	+	+
<i>Edelsteinia</i> - <i>Rackovskaia</i> sp.	d	+	+	+
<i>Girphanovella georgensis</i> (Rozanov)	n	a	n	n
Spiculate sponges				
Spicules (hexactinellide + monaxon)	a	a		
<i>Dodecaactinella</i>	+	+	+	
Small skeletal fossils				
Coleolids	+	+		
Chancelloriids	a	a	+	+
Hyaloliths	+	+		
? Molluscs		+		
Calcimicrobes				
<i>Renalcis polymorphus</i> (Maslov)	+		+	
<i>Tarthinia rotunda</i> Drosdova	+	+		
<i>Epiphyton</i> sp.	a	+	+	
<i>Tubomorphophyton</i> sp.		+	+	d
<i>Gordonophyton</i> sp.	+			
<i>Botominella</i> sp.	+			+
<i>Batinevia</i> sp.	+	f	+	d
<i>Girvanella</i> sp.	+	+		
<i>Razumovskia</i> sp.			+	+
<i>Angulocellularia</i> sp.	+		+	
<i>Proaulopora</i> sp.			+	+
Soft-bodied organisms				
Microburrowers	a	a		

Faunas are listed according to biohermal associations: GR = *Gordonophyton*–*Razumovskia* crusts; RA = radiocyathan–archaeocyathan bioherms; RC = ramose *Cambrocyathellus* domains in RA; CB = calcimicrobial bioherms. a = abundant; d = dominant; f = fragments; n = disarticulated nesasters; r = rare; + = present.

walls are scarce and those with scaled inner walls are represented only by the rare and morphologically simple genus *Leptosocyathus*. Most archaeocyaths with additional outer wall elements (e.g. *Alataocyathus* with multiperforate tumuli) were cryptic and were not therefore affected by turbulent open surface conditions (Zhuravlev & Wood, 1995). The deposition of the Salaany Gol Formation under reasonably high-energy conditions is supported by associated lithological features such as well-developed marine cements and more or less abundant grainstones and packstones.

The late Atdabanian–early Botomian Zavkhan Basin bioconstructions can be compared with those of the same age range in neighbouring Siberia and Gondwana. During this interval the Zavkhan Basin was subject to a tectonically active regime. On the more stable Siberian Platform the late Atdabanian archaeocyathan community was more diverse, but pure calcimicrobial reefs dominated (Zhuravleva, 1972; Sundukov & Varlamov, 1979).

Relative to eastern Gondwana, the Zavkhan Basin bioconstructions show similarities to some of the coeval South Australian reef types recognized by James & Gravestock (1990), which also developed under a tectonically active regime. In the Flinders Ranges, these authors identified a range of reef types which they categorized broadly as low-energy archaeocyath–sponge mud mounds (intrashelf depression or ?slope) and high-energy archaeocyath–calcimicrobe bioherms. Among the latter are a variety of bioherm types, attributed to environments ranging from relatively low-energy platform interior to relatively high-energy shelf margin. Most similar to the Salaany Gol buildups are the moderate-energy, open-shelf archaeocyath-dominant archaeocyath–*Renalcis* boundstones, which are likewise cement-rich, with cavities bearing cryptic *Renalcis*. In contrast, late Atdabanian bioherms of the Fleurieu Peninsula, developed in mud-dominated, deeper ramp locales, lack large cavities rimmed with multiple submarine cements (Alexander & Gravestock, 1991).

Late Atdabanian buildups in central Australia include high-energy, intermittently emergent reef shoal complexes (associated with coquina-laden channels, grainstones and packstones) and lateral to deeper water, low-energy bioherms. However, pervasive dolomitization hampers discrimination of biohermal components (Kennard, 1991).

On the northern Gondwana margin, Atdabanian (early Ovetiense Stage) bioherms in the Sierra de Cordoba region of Spain range from those developed in terrigenous fine sandstone (including abundant bioclasts and ooids) to those constructed in purer carbonate sediments. The interpreted palaeoenvironment (Moreno-Eiris, 1988) is of a carbonate platform with shallow reef complexes, localized ooid bars and episodic terrigenous input – in these latter aspects, unlike the depositional environment at Salaany Gol. Bioherms on ooid bars in an active setting subject to terrigenous input (as at Arroyo Pedroche) are mainly archaeocyath bafflestone, while

more calcimicrobe-rich bioherms with abundant associated archaeocyathan talus (Las Ermitas), assigned to the high-energy shelf margin, possess cores dominantly of calcimicrobe boundstone.

Coeval lower-energy buildups are known from Morocco (Debrenne, 1975). Slightly younger (early Botomian) buildups in the Matoppa Member of Sardinia include low-energy protected shelf to high-energy platform margin types (Gandin & Debrenne, 1984; Debrenne, Gandin & Debrenne, 1993).

While calcimicrobial bioconstructions are widely distributed from at least late Nemakit-Daldynian time, their archaeocyath-bearing counterparts were confined to the Siberian Platform throughout the Tommotian Stage, where they developed a variety of mud- and calcimicrobe-rich mounds in generally low-energy settings (Zhuravleva, 1972; Kruse, Zhuravlev & James, 1995). Nemakit-Daldynian to Botomian calcimicrobial buildups of the Zavkhan Basin thus represent a conservative bioconstructional model. During Atdabanian time, archaeocyaths migrated along the northern and eastern margins of Gondwana and may also have reached Laurentia (Debrenne, Rozanov & Zhuravlev, 1990). In these regions they developed a range of internal architectures in differing environmental conditions. Among these, the Zavkhan Basin radiocyathan–archaeocyathan bioherms represent the moderate- to high-energy spectrum, with archaeocyaths, mud and cement dominant.

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